Role of Pulses in Ultra Wideband Systems

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Abstract— UWB pulses are the unique labels of UWB systems. This paper investigates the role of pulse systematically and highlights the central position of the pulse in UWB systems. Four system properties related closely to the pulse are discussed: propagation properties, capacity, interference to existing systems and performance of correlation receivers. The properties of pulses which function directly on every aspect are highlighted. Novel viewpoint is provided for the evaluation of capacity and interference. Suggestions are given on the pulse design, with emphasis on the whole system performance.

I. INTRODUCTION

UWB systems are defined with respect to the spectrum property of the transmitted signals [1], rather than any other properties. This indicates the importance of the pulse in a UWB system. Seemingly, UWB provides a method of spectrum reuse in modern communication systems by transmitting extremely narrow pulses. With their energy spreading over a very large bandwidth, UWB signals exhibit very low power spectrum density, and can coexist with conventional systems peacefully. Many advantages of UWB systems, such as huge capacity, potential all-digital implementations, low complexity and low link budget, are closely related to the properties of this pulse.

However, the importance of the pulse to UWB systems has not received enough attention yet. Today, generally considered factors on the selection and design of the pulse are concentrated in the regulation (FCC constraint) and energy efficiency (flatness of power spectrum). Some researchers also start to consider other factors [2]–[4]. While these approaches intend to emphasize a globally optimal design, none of them actually makes it. For example, in [3], referring to the dominant eigenvectors of a channel matrix, a numerical approach is proposed to provide orthogonal pulses for multiple access. However, the steep mainlobe and large sidelobe of autocorrelation and crosscorrelation functions of the pulses imply a high sensitivity of receiver performance with respect to synchronization errors. Thus, to achieve a globally optimal design, we need to understand the role of pulses in UWB systems comprehensively.

In this paper, we study the role of pulses in UWB systems systematically and endeavor to conclude the essential

properties of the pulse that contribute directly to the whole system performance. Four main aspects will be investigated: propagation properties, capacity, interference to existing systems and performance of receivers. The remaining part of this paper is organized as follows. In Section II, general pulses used in UWB systems are introduced. In Section III, propagation characteristics of UWB pulses are discussed, with emphasis on the difference between UWB pulses and sinusoidal waves. In Section IV, the influence of pulses on the system capacity is discussed for both AWGN channels and fading channels. In Section V, UWB interference to existing systems is investigated from both frequency domain and time domain viewpoint. In Section VI, the less noticed contribution of pulses to receiver performance is highlighted.

II. PULSES IN UWB SYSTEMS

According to the definition of UWB signals by the FCC in [1], any pulse with a fractional bandwidth ≥ 0.20 or a 10dB UWB bandwidth ≥ 500MHz can be used as a basic UWB pulse. In practice, the selection of pulses depends on many factors. The radiation efficiency[1] and spectrum shape are the two of general concerns. Since the transmitted UWB signal is usually a baseband signal, the basic pulse should not have a DC component to allow effective radiation[2]. In addition, to maximize the radiated power within the FCC constraints, the pulse should have a flat spectrum over the desired bandwidth. Among pulses with definite mathematical expressions, typically used pulses include Gaussian monocycles, Gaussian doublet, Rayleigh monocycles and Manchester monocycles, each referring to a particular application (see [5], [6] for detailed information). Some numerical methods are also proposed to achieve better spectrum shape [2], [4]. Because of their excellent resolution ability in both time and frequency domain, Gaussian monocycles are most widely used and studied so far. In this paper, Gaussian monocycles and pulse position modulated (PPM) time-hopping (TH) systems are exemplified wherever specific pulses and signalling schemes are involved.

The basic Gaussian waveform has the form of

$$\omega_0(t; t_p) = e^{-2\pi(\frac{t}{t_p})^2},\qquad(1)$$

where t_p parameterizes the effective width of the pulse. Gaussian monocycles, denoted by $\omega_n(t; t_p)$, are the scaled

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[1]It is defined as the ratio of the power radiated to the total power supplied to the radiator at a given frequency.

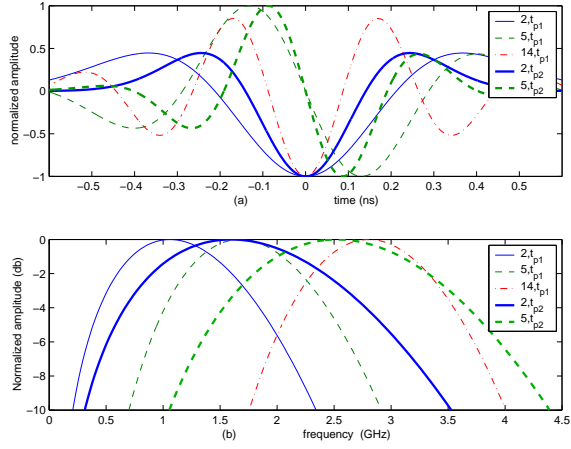[2]In carrier systems, this requirement is not necessary.

Fig. 1. (a) Time domain waveforms, and (b) frequency spectrum of n-order Gaussian monocycles, where $t_{p1} = 0.7521$ns, $n = 2, 5, 14$; $t_{p2} = 0.5$ns, $n = 2, 5$.

Fig. 2. Normalized autocorrelation of n-order Gaussian monocycles, where $t_{p1} = 0.7521$ns, $n = 2, 5, 14$; $t_{p2} = 0.5$ns, $n = 2, 5$.

and/or differentiated versions of the basic Gaussian waveform. The n-order monocycle can be expressed as

$$\omega_n(t; t_p) = \frac{\mathrm{d}^{(n)}}{\mathrm{d}t^n}(e^{-2\pi(\frac{t}{t_p})^2}). \quad (2)$$

The Fourier Transform of the monocycle $\omega_n(t; t_p)$ is

$$W_n(f; t_p) = \frac{t_p}{\sqrt{2}}(j2\pi f)^n e^{-\pi t_p^2 f^2/2}, \quad (3)$$

where $j = \sqrt{-1}$ is the imaginary unit.

Figure 1 shows the time domain waveform and frequency spectrum of several Gaussian monocycles. Fig. 2 shows their autocorrelations. Since all Gaussian monocycles have infinite extent in the time domain, for practical usage, we define the effective pulse width T_ω as the width containing most energy of the pulse, which is about $2t_p$. From Fig. 1, we can see that 1) with n increasing, the spectrum shifts toward the high-frequency end, while its bandwidth remains roughly unchanged; and 2) with t_p decreasing, the spectrum shifts toward the high-frequency end, and its bandwidth is enlarged. Approximately, for two same order monocycles with respective parameters t_{p1} and t_{p2}, the following relationships hold in terms of their center frequencies f_{c1} and f_{c2}, and UWB bandwidths B_1 and B_2,

$$f_{c2}/f_{c1} = B_2/B_1 = t_{p1}/t_{p2}. \quad (4)$$

Thus by adjusting the values of n and t_p, pulses satisfying the FCC regulations can be constructed readily. For historical reasons, the exemplified Gaussian monocycles used in this paper do not necessarily follow the FCC regulations, however the extensions to FCC pulses are usually straightforward.

III. PROPAGATION CHARACTERISTICS

A. Antenna and Near-Far Field

The characteristic of UWB antennas is usually simplified as a differentiation operation. This point agrees to the general "far zone" definition in narrowband radio systems, when the
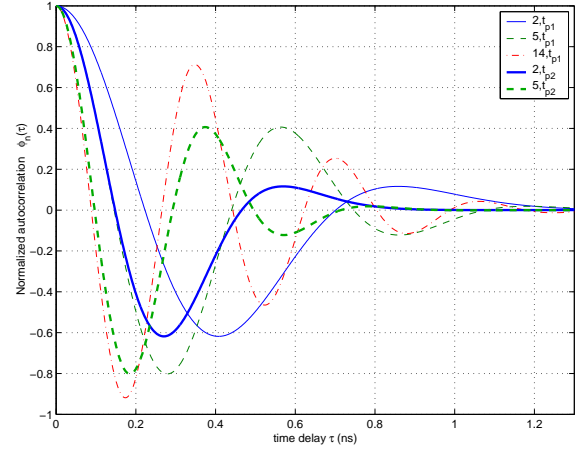
distance between the transmitter and receiver is much larger than the wavelength of the carrier signal. On the contrary, in the "near zone", an integration operator is more appropriate for the electric field. For sinusoidal signals, the shape of waveform does not change after derivation or integration operation except phase-shift. However, for non-sinusoidal signals, such as Gaussian monocycles, the wave shape may change and the bound between near and far zone may be totally different from the sinusoidal case. Let us consider an example below.

For the Hertzian dipole antenna, the following distance condition has been derived to distinguish the farfield from nearfield in [7]:

$$r^2 \gg c^2 \left| \frac{\int s(t)\mathrm{d}t}{\frac{\mathrm{d}s(t)}{\mathrm{d}t}} \right| \qquad \text{for the electric vector } \vec{\mathrm{E}}(\vec{r}, t), \quad (5)$$

where r is the distance between the transmitter and receiver, c is the speed of light in free space, $s(t)$ is the exciting current. This equation is based on the assumption that the magnitude of the electric vector $\vec{\mathrm{E}}$ in the nearfield should be much larger than that in the farfield. When the current $s(t)$ is sinusoidal, (5) can be reduced to $r \gg \lambda/(2\pi)$. While for Gaussian monocycles defined in (2), (5) becomes

$$r^2 \gg r_0^2 = \begin{cases} c^2 \left| \frac{-t_p^4}{4\pi t_p^2 - 16\pi^2 t^2} \right|, & \text{for 1-order monocycles;} \\ c^2 \left| \frac{-t_p^4}{12\pi t_p^2 - 16\pi^2 t^2} \right|, & \text{for 2-order monocycles.} \end{cases} \quad (6)$$

The energy of the pulse concentrates in the period $[-t_p, t_p]$. The denominators of both equations in (6) could approach zeros during this period, and r_0 will become extremely large when this happens, as shown in Fig. 3. The figure highlights that far and near fields for Gaussian monocycles are not well-defined in terms of this antenna since both fields vary with time, and are hardly distinguished by a certain bound. It is also obvious that this threshold varies with different pulses. Thus we should be careful when dealing with the near/far field problem in UWB systems.
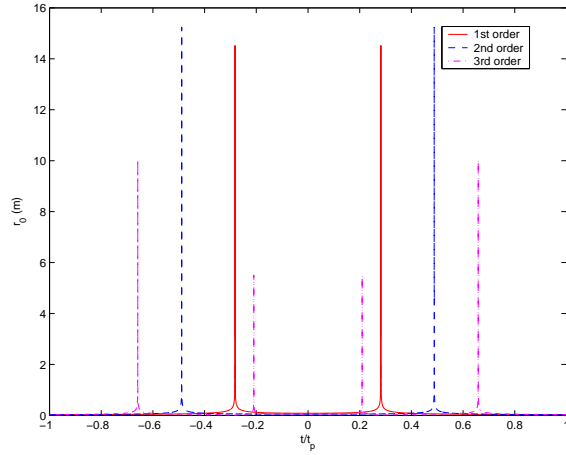
Fig. 3. The bound r_0 of near/far field as a function of t/t_p for Gaussian monocycles of order 1, 2 and 3.

B. Distortions of Wave Shape

Notable waveform distortion could happen to UWB signals between transmitter and receiver due to their ultra wide bandwidth and frequency-dependent propagation. Conventional coherent detection using correlators may be unsuitable for these signals unless adaptive template signals could be constructed and updated in real time.

In the sense of the unpredictable Channel Impulse Response (CIR), instant detection algorithms might outperform statistics-based algorithms, and maximizing the instantaneous SNR could be an effective metric for the design of detection algorithms.

As a matter of fact, the high possibility of distortion also degrades the significance of waveform design.

C. Highlights of Channel Properties

Recently, many efforts have been contributed to characterize the UWB channel [8]. Because of the instability and disagreement between these findings, especially on the amplitude fading distribution, a widely accepted UWB model could not emerge in a short term. However, some properties of the channel can be confirmed without resorting to a detailed channel model.

1) Immunity to Multipath: Multipath fading is a continuous wave phenomenon. Fading inevitably occurs in conventional systems when continuous sinusoidal waves are transmitted inside buildings, as signals reflect off objects and suffer destructive cancellation and construction addition. However, UWB is not a continuous but a transient wave in terms of its ultra narrow width and low duty cycle. Reflected waveforms have very little chance to overlap.

2) Relatively Small Link Budget: As UWB pulses are immune to multipath fading, the link budget in UWB systems will be smaller than that in conventional sinusoidal systems.

3) Frequency Selectivity: The coherence bandwidth of a channel approximately equals the reciprocal of the multipath rooted-mean-squared (RMS) delay. For UWB signals, the RMS delay is usually in the range $[10, 40]$ns evidenced by most measurements [8]. Then the bandwidth of UWB signals are much larger than the coherence bandwidth, and UWB channels are typically frequency selective.

4) Slow Fading: In an indoor environment, the moving of people is the main factor causing the change of a channel model. The transit time of pedestrians is usually in the order of 100 milliseconds. For a typical UWB application with data rate 100Mbps, within 100 millisecond, 10Mb data can be conveyed. Thus, the assumption that the channel is slow fading is reasonable.

IV. IMPACT ON THE CAPACITY

A. UWB Capacity in AWGN Channels

According to the Shannon capacity theorem [9], in AWGN channels, UWB systems can potentially provide huge capacity. However, this capacity is only achievable when both the inputs and outputs are Gaussian distributed. For systems with discrete inputs, e.g., M-ary PPM UWB systems, the above capacity formula is no longer strictly applicable. The capacity of these systems can be investigated from first principles. For example, in [10], the capacity of a PPM UWB system is analyzed based on a so-called "pure PPM model", that is, an AWGN channel model with power-constrained discrete M-ary PPM inputs and unconstrained continuous outputs. The obtained capacity expressions are independent of the shape of the used pulse. However, the results based on this pure PPM model actually exaggerate the capacity of a UWB system as shown in [11]. To bound the capacity more tightly, new models should be constructed to reflect all critical components of a UWB system. The resulted averaged capacity conditional on an overall system can provide a metric of both performance and information rate achievable by the specific system. As an example, an extended model containing a correlation receiver and soft decision decoding is considered in [11]. The obtained unshaped capacity (UC), achieved when inputs are equally probable, is a function of the bit signal-to-noise ratio and autocorrelation of the pulse.

Figure 4 shows the unshaped capacity of a M-ary PPM UWB system for various bit-SNRs in the single-user case where a second-order Gaussian monocycle is used. As comparisons, results based on a "pure PPM" model given in [10] are also shown. It is obvious that the former is significantly different from the latter: larger M need not lead to higher unshaped capacity. This is due to the contribution from autocorrelation function of the pulse.

B. UWB Capacity in Multipath Channels

In [12], [13], from an information-theoretic view, it has been shown that the very large bandwidth on fading multipath channels cannot be effectively utilized by spread-spectrum systems that spread the available power uniformly over both time and frequency. This result holds when the receiver does not have the full knowledge of the channel, even though it knows either the multipath delays or gains separately, or the statistics of the channel. In [12], Telatar and Tse claim that, the mutual
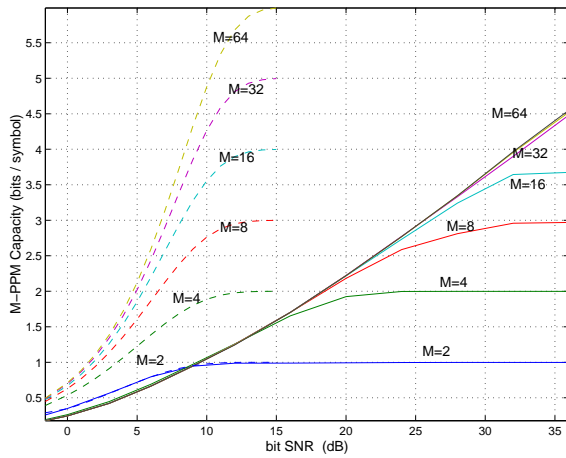
Fig. 4. Capacity of a M-ary PPM UWB system for various bit-SNRs in the single-user case. Solid line: unshaped capacity given in [11]; Dashed line: capacity given in [10].

information achievable using spread-spectrum signals through a multipath fading channel depends crucially on how the signal energy is divided among the resolvable paths. If there are only a few dominant paths, the achievable mutual information is close to the capacity of the AWGN channel when the channel gains are perfectly known. Otherwise, the mutual information achievable is very small, being inversely proportional to the number of resolvable paths. In [13], Médard and Gallager suggest that to achieve good channel utilization, ultra wide-band systems using uniform signaling over time and gigahertz frequency bandwidth should only operate over quasi-static channels.

Intuitively, these findings above can be explained as follows. In the presence of noise, the channel state information cannot be correctly estimated, and the estimation error usually increase with the SNR decreasing. When the number of resolvable multipath is significantly large, the estimation errors in the path gains and delays preclude effective combining of the multipaths. To summarize, the multipath diversity benefits the system only up to a certain point. This phenomenon has been observed in the RAKE receiver design [14].

Thus, the UWB capacity in multipath channels might decrease significantly compared to that in AWGN channels because of the spreading of low energy over a number of resolvable multipaths [8]. However, UWB could possibly be an exception due to its impulsive property and relatively low duty cycle. To date, only very limited work on this topic has been reported [15], further work is needed to clarify this problem.

V. Impact on the Interference

A. Frequency Domain Viewpoint - Power Spectrum Density

The interference of UWB signals to conventional systems is usually evaluated in the frequency domain using the power spectrum density (PSD) method. Many results based on this method have been reported, e.g., see a comprehensive analysis in [16].

The PSD usually consists of two components: the continuous component and the discrete one. The continuous spectrum is regulated by the shape of the pulse, and the discrete spectrum lines arise from the periodical transmission of pulse sequence. The random time jitter caused by spreading sequence and modulation will influence the intensity of the discrete spectrum lines. It is also possible to shift away or reduce part of spectral lines in some particular part of the spectrum to avoid interference through careful design of the these parameters.

From the viewpoint of the frequency domain, the interference can be evaluated by calculating the in-band interference power from the power spectrum samples over the victim receiver's IF bandwidth. The discrete spectrum lines are the main interference sources compared to the raised noise figure caused by the continuous PSD of UWB pulses. The less and weaker of the spectrum lines fall within the victim's bandwidth, the smaller the interference is.

Based on the above analysis, pulse has less influence on the interference. However, a pulse with flat PSD seems more like AWGN to a victim receiver and has less impact on it.

B. Time Domain Viewpoint

It is argued that the PSD measure, originating in harmonic analysis and relating to autocorrelation function, is an inappropriate measure of transient signals like UWB [17]. Alternatively, we consider this interference problem in the time domain below.

1) Gaussian Approximation: According to the central limit theorem, if the number of UWB transmitters, N_u, is large enough, the aggregate interference will resemble the AWGN. Some usages of this approximation can be found in [18]. When N_u is small, it has been reported that the approximation may have low accuracy [19], [20].

However, it is not necessary to require a number of users to make a reasonable Gaussian assumption from the standpoint of victim receivers. This makes sense when the bandwidth property of narrowband receivers is taken into consideration. When any narrow pulse with a wide bandwidth, e.g., a UWB pulse, is passed through a filter with a narrower bandwidth, the output essentially equals the impulse response of the filter and has a pulse width approximately equal to the reciprocal of the receiver bandwidth [21]. Any narrowband receiver acts as a narrowband filter for the UWB pulse. In the output of the receiver, the pulse becomes wider, the peak-to-average power of the signal decreases, and continuous output pulses may overlap depending upon the pulse repetition frequency (PRF) and extent of dithering. If PRF is small compared to the bandwidth of the receiver, overlap does not happen. Thus the output shows a noise-like spectrum and their amplitude distributions are non-Gaussian. On the other hand, when the PRF is high enough to cause pulse overlap, any random variation in the pulse spacing results in destructive and constructive addition of adjacent pulses. Thus even when only a few UWB transmitters are active, the amplitude of UWB aggregate interference could

be Gaussian distributed. This has been testified in [22] for a CDMA receiver. Therefore, in the sense of interference control, UWB systems with higher PRF can coexist more peacefully with conventional systems due to the resemblance between the aggregate interference and the Gaussian noise. Accordingly, in the frequency domain, higher PRF leads to sparser spectral lines which implies weaker interference as well.

When focusing on the pulse solely, wider pulses have a higher possibility of overlapping after filtering, and are more like AWGN to narrowband receivers.

2) Dithering Effect and "Phase" Distribution: Time jitters introduced by time-hopping codes, PPM and multiple access are capable of shifting and randomizing the positions of spectrum lines in the frequency domain. Then what are their effects in the time domain? We try to answer this question from the angle of the aggregated "phase" distribution below.

Consider a situation where a multipath channel and N_u users are present. Assume the multipath delay τ is a continuous random variable uniformly distributed on $[0, T_m]$, where T_m is the maximal multipath delay. Introduce another continuous random variable θ to represent the multi-user asynchronism. In a frame period T_f, the time position of user k's one multipath signal can be expressed as $\varphi_k = (b_j + \tau + \theta)_k$ where b_j is the time dithering introduced by PPM modulations. Thus, the position where one multipath signal may appear can be represented as

$$\varphi = \sum_{k=1}^{N_u} \varphi_k = \sum_{k=1}^{N_u} (b_j + \tau + \theta)_k. \qquad (7)$$

Assume all these variables are mutually independent, the pdf of φ can be computed as $f(\varphi) = \otimes_{k=1}^{N_u} f(\varphi_k)$, i.e., the pdf of the sum φ equals the convolutions from $f(\varphi_1)$ to $f(\varphi_{N_u})$. Fig. 5 shows this distribution for some values of N_u where it is assumed that b_j has discrete equal-probability distribution and θ is uniformly distributed in a frame period. From the figure, we can see that when the number of transmitters increase, the time dithering b_j, caused by the time-hopping codes and PPM, is being smoothed, and φ is approximately uniformly distributed in a period. It implies that in the time domain, the effect of time jitter will be weakened quickly in a multiuser and multipath environment.

VI. IMPACT ON RECEIVER PERFORMANCE

A. Performance Limits of Synchronizers

It is known that in the presence of noise, perfect synchronization cannot be achieved, and timing errors usually imply marked degradation of receiver performance in UWB systems [23]. Thus pulses with good resistance to sync error are preferred. In [24], we studied the theoretical bound of synchronization error for a general pulse using the Cramer Rao Lower Bound (CRLB). In an AWGN channel, for an
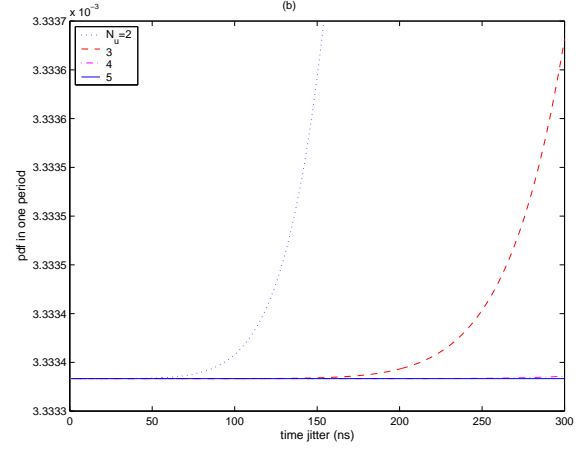

Fig. 5.   The pdf of the aggregate "phase" φ of UWB signals in the time domain for different number of users.

unmodulated monocycle, the CRLB is given by

$$\text{CRLB} = \frac{1}{\text{SNR}} \frac{\int_{-\infty}^{+\infty} \omega_n^2(t; t_p) dt}{\int_{-\infty}^{+\infty} \dot{\omega}_n{}^2(t; t_p) dt}, \qquad (8)$$

where the SNR is with respect to the observation period.

Translated into the frequency domain, (8) becomes

$$\text{CRLB} = \frac{1}{\text{SNR}} \frac{\int_{-\infty}^{+\infty} |W_n(f; t_p)|^2 df}{\int_{-\infty}^{+\infty} f^2 |W_n(f; t_p)|^2 df}, \qquad (9)$$

where $W_n(f; t_p)$ is the Fourier Transform of $\omega_n(t; t_p)$.

According to the properties of the Fourier Transform of derivatives of functions, we find explicit relationships exist between the CRLBs of Gaussian monocycles with different n but same t_p, that is,

$$\frac{\text{CRLB}_n}{\text{CRLB}_{n+1}} = \frac{\int_{-\infty}^{+\infty} |W_n(f; t_p)|^2 df \cdot \int_{-\infty}^{+\infty} f^4 |W_n(f; t_p)|^2 df}{\left(\int_{-\infty}^{+\infty} f^2 |W_n(f; t_p)|^2 df \right)^2}$$
$$> 1, \qquad (10)$$

where the inequality follows from an application of Schwarz's inequality. This inequality implies that higher order monocycles have the potential for better performance in the sense of lower synchronization error variance.

For monocycles with different t_p but same n, the ratio between their CRLBs can be found as

$$\frac{\text{CRLB}_{t_{p1}}}{\text{CRLB}_{t_{p2}}} = \left(\frac{t_{p1}}{t_{p2}} \right)^2, \qquad (11)$$

which implies that monocycles with smaller t_p (narrower effective pulse width) have the potential for better synchronization performance.

B. Correlation Receivers

A less noticed fact in the literature is, the pulse also contributes to the output of the detector, and directly affects the performance of signal detection. In [25], we investigated the influence for several channel situations, including ideal single

user AWGN channel, non-ideal synchronous, multipath fading and multiple access interference. Basically, this influence results from the modulation and low duty cycle of the signal, and is revealed by investigating its autocorrelation function. If the autocorrelation of a pulse has a broader mainlobe and smaller sidelobe, the system using this pulse has superior property in general.

For completeness, we sum up the findings in [25] here. In a PPM TH UWB systems, for Gaussian monocycles,

- pulses with larger n imply higher SNR gain in single user and asynchronous multiple access channel but inferior interference resistance ability; and
- pulses with smaller t_p imply higher SNR gain in asynchronous multiple access channel but inferior interference resistance ability.

VII. Conclusions

We have elaborated some critical roles that pulses play in UWB systems, as summarized in Table I. In the table, the left column lists the performance that the pulse has impact on, the middle column gives the corresponding pulse properties that functions directly, and the right column shows other factors that contribute to the performance, accordingly. There are still some issues not covered, e.g., pulse generation and the complexity related to hardware implementation. Nevertheless, our investigation highlights and consolidates the central position of the basic pulse in UWB systems, which strongly proposes that the design of pulse should be considered in terms of the overall system performance.

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TABLE I

BRIEF OF THE RELATIONSHIP BETWEEN UWB PULSES AND SYSTEM PERFORMANCE.

Items	Related pulse's properties	Other factors
Capacity	Autocorrelation, bandwidth	Channel
Interference	Pulse width, PSD	PRF
Energy efficiency	Flatness of PSD	Hardware
FCC Regulation	PSD	PRF
Synchronization	Frequency spectrum	Modulations
Correlator performance	Correlation functions	Modulations, Duty Cycles