A New UWB Dual Pulse Transmission and Detection Technique

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Abstract—A new UWB signaling technique based on dual pulse transmission is presented in this paper. The proposed technique is simple, robust, and based on an autocorrelation type of receiver structure. Several detection schemes with different implementation complexity are presented and their performances are studied by Monte-Carlo simulations. Comparison of the proposed new designs to the transmitted reference system is also carried out in the paper.

I. INTRODUCTION

The ultra-wideband (UWB) impulse radio has attracted enormous interests from both academia and industry recently. Typically, a UWB impulse radio communication system employs very narrow pulses for transmission and the extremely short duration of these pulses leads to high multipath resolution and fading immunity. Although the resolvable multipaths provide diversity that can be employed to enhance performance, the challenge for the receiver is how to efficiently capture the energy from all these multipaths. If a rake structure is used, a large number of rake fingers must be implemented, which is prohibited in practice due to high complexity and high cost. Moreover, a UWB channel may distort the shape of the transmitted pulse [1]. Due to the ultra wide bandwidth, distinct frequency components in a signal may react differently to propagation environments. A receiver filter matched to the transmitted pulse in coherent detection may not work well if the pulse shape is distorted by the channel.

All these considerations motivate the design of the new transmission and detection scheme in this paper. The idea is rather simple: using a reference sub-pulse together with a modulated sub-pulse to constitute a dual pulse (DP) structure as the basic pulse transmission unit, as shown in Fig. 1. Since the two narrow sub-pulses are of the same shape and one after another, it is expected that the channel affects them in a similar manner. For each resolvable multipath, the first half portion of the received pulse can then be used as a noisy reference for detection and energy collection of the second half, i.e., the modulated sub-pulse. This autocorrelation receiver performs essentially non-coherent detection. Fig. 2 depicts the receiver block diagram. An improved dual-pulse transmission scheme and receiver structure to remove the “self interference” in the received dual pulses are illustrated in Figs. 3-4.

Although the initial idea of the new scheme is focused on the pulse design perspective, it can be considered as a special form of the transmitted reference (TR) system. The UWB transmitted reference system was first proposed in [2] and [3], where a reference pulse and a modulated pulse separated by delay $D$ seconds constitute a pulse pair to represent one bit information. The delay $D$ is larger than the maximum delay spread of the channel plus one pulse duration to avoid the interference between the received reference pulse and the data pulse [2]. It was demonstrated that UWB-TR systems have simple implementation and robust performance. Performance analysis of UWB transmitted reference was first presented in [4], while optimal and suboptimal receivers were derived and analyzed in [5]. The authors in [6] presented a generalized optimal receiver structure that takes into account variable number of reference and data pulses. A different generalization of the TR technique was proposed in [7], where a signaling set is composed of sequences of pulses with different delays and weights. In [8], the authors studied pilot waveform assisted modulation scheme which can be considered as another generalization of the TR method. In [9], the performance of multiple pulse multiple delay modulation for UWB multiple access was investigated. Also, a differential UWB scheme was proposed in [10].

The TR method in general has several advantages over a coherent receiver. It does not require explicit channel estimation, or a large number of fingers in a rake receiver. It is robust to possible channel distortion on pulse shape. Easy and simple synchronization makes it a good candidate for bursty traffic. The drawbacks of the TR system are the inferior performance to ideal coherent detection and lower data rates because of the transmission of reference signals. In this paper, we propose a dual pulse scheme that not only maintains the advantages of TR systems, but also achieves higher data rate and provides more benefits than the conventional TR method. The remainder of this paper is organized as follows. Section II describes the dual pulse transmission scheme and several detection schemes. In Section III, an improved version of transmission and detection scheme is proposed to avoid the potential self interference between the received dual pulses caused by closely spaced multipaths. Section IV summarizes the merit of the proposed schemes and discusses simulations results. The performance of the proposed technique is then compared to the transmitted reference system. Finally, conclusions are drawn in Section V.

II. TRANSMISSION AND DETECTION TECHNIQUE

In this newly proposed system, a basic ultra-wideband pulse $p(t)$ of duration $T_w$ is composed of two sub-pulses: the sub-pulse $g_{tr}(t)$ which has non-zero values in the first half interval $[0, T_w/2]$ and the sub-pulse $s_2(t)$ in the second half interval $[T_w/2, T_w]$. The energy of $g_{tr}(t)$ is denoted as $E_{B_t}/2$. The sub-pulse $s_2(t)$ has a fixed relationship with the first sub-pulse...
accounts for the general case where there is mismatch between \( g_{rx}(t) \) and \( g_{tr}(t) \). The receiver first passes the received signal through a lowpass filter that has one-sided bandwidth \( W \) and unit magnitude. The bandwidth of the lowpass filter is large enough that the information bearing signal is passed without distortion and the noise is limited to within the filter bandwidth. The noise process after the lowpass filter is denoted by \( n(t) \). The resolvable paths are assumed to arrive at integer multiples of \( T_w \), but the exact delays \( \{\tau_l\} \) are not known or not estimated.

The receiver first multiplies the received signal by its \( T_w \)-delayed copy and then integrates the product every \( T_w \) seconds for the latter \( T_w/2 \) duration, i.e.,

\[
D_l = \sum_{j=0}^{N_l-1} \int_{jT_f+T_w}^{(j+1)T_f+T_w} r(t)(t-T_w/2) dt, \quad l = 0, \ldots, L_l-1
\]

where \( L_l = T_{mds}/T_w \) is the total number of possible paths and \( T_{mds} \) is the maximum delay spread of the channel. If consider the realistic IEEE channels CM1 to CM4 [11] that have multipaths spaced closer than a pulse duration \( T_w \), we calculate \( D_l \)'s by

\[
D_l = \sum_{j=0}^{N_l-1} \int_{jT_f+T_w/2}^{(j+1)T_f+T_w/2} r(t)(t-T_w/2) dt, \quad l = 0, \ldots, L_l-1
\]

where \( L_l = 2T_{mds}/T_w \). This is identical to that shown in Fig. 2, but different from (3). Although not shown here, simulations find (4) leads to better performance than (3) in CM1 to CM4. The decision variable \( D \) can be generated from \( L_l \) independent \( D_l \)'s as

\[
D = \sum_{l=0}^{L_l-1} T(D_l)
\]

where \( T(D_l) \) is a testing function that can take three different forms. The purpose of different combining schemes is to try to collect \( D_l \)'s that contain signal components as a result of multipath arrivals, not the \( D_l \)'s corresponding to the noise in-between paths. We use

1) **Generalized selection combining.** In this method, we select and sum the \( D_l \)'s with \( L \) largest absolute values. The test function for GSC is given by

\[
T(D_l) = \begin{cases} D_l, & \text{if } |D_l| \geq |D^{(L)}| \\ 0, & \text{if } |D_l| < |D^{(L)}| \end{cases}
\]

where \( D^{(L)} \) is the one that has the \( L \)-th largest absolute value among all \( D_l \)'s.

2) **Absolute threshold generalized selection combining.** This method compares each autocorrelation output \( D_l \) to a fixed threshold \( D_{th} (> 0) \). All the \( D_l \)'s with absolute values larger than \( D_{th} \) are then selected and combined. The absolute threshold test function is given by

\[
T(D_l) = \begin{cases} D_l, & \text{if } |D_l| \geq D_{th} \\ 0, & \text{if } |D_l| < D_{th} \end{cases}
\]
3) **Normalized threshold generalized selection combining.** Normalized threshold GSC differs from AT-GSC in how the threshold is determined. Instead of using a preset absolute threshold value, NT-GSC forms its threshold as a fixed fraction \( \eta_{th} \) of \( D_{max} = \max |D_i| \), i.e., \( D_{th} = \eta_{th}D_{max} \). Define

\[
T(D_i) = \begin{cases} 
D_i, & \text{if } |D_i| \geq \eta_{th}D_{max} \\
0, & \text{if } |D_i| < \eta_{th}D_{max}
\end{cases}
\]  

Due to space limitations, we have to leave out a unified analysis developed for the performance of noncoherent GSC, AT-GSC and NT-GSC which will be presented in [12]. Note that unlike the diversity combining in rake receivers, the three noncoherent combining schemes proposed here are easy to implement, since the single integrate-and-dump device has already output all \( D_i \)'s and it is only a matter of how to compute (likely in a DSP) the final decision statistics \( D \).

An even simpler detection method referred to as “DP over \( T_{ir} \)” that requires the same sampling rate as the TR scheme is given by

\[
D = \sum_{j=0}^{N_p-1} \int_{jT_f + T_{ir}}^{(j+1)T_f + T_{ir}} r(t) r(t - \frac{T_w}{2}) dt
\]

where \( T_{ir} \leq T_f \) is the autocorrelator integration length for the DP and TR scheme.

Since the received first sub-pulse \( g_{ref}(t) \) of each symbol is identical for all symbols, we can reduce the noise variance on the received first sub-pulse (reference) by averaging the received signals over several frames. The number of frames \( N_p \) to average over is dependent on the fading rate of the channel and the implementation complexity constraint.

**III. IMPROVED DP TRANSMISSION AND DETECTION**

In practice, there may be multiple paths that are spaced much closer than a dual pulse width \( T_w \). These unresolvable multi-paths will probably distort the transmitted dual pulse and cause self interference between the reference sub-pulse and the data sub-pulse. Here we present an improved version of the dual pulse transmission and detection scheme to overcome this problem. Often the same UWB dual pulse is transmitted more than once to increase the received SNR for detection. Suppose \( N_s = 2 \). We consider two dual pulses, \( p_1(t) \) and \( p_2(t) \), as one processing unit and invert the reference sub-pulse in the second dual pulse \( p_2(t) \) before transmission, as shown in Fig. 3.

As shown in the receiver block diagram Fig. 4, we construct the reference template and the received data signal as

\[
r_{ref}(t) = r_1(t - T_f) - r_2(t)
\]

and

\[
r_{dat}(t) = r_1(t - T_f) + r_2(t)
\]

where \( r_1(t) \) and \( r_2(t) \) are the received pulses corresponding to \( p_1(t) \) and \( p_2(t) \), respectively. The decision variable is given by

\[
D = \int r_{ref}(t - \frac{T_w}{2}) r_{dat}(t) dt
\]

where the integration can be performed over the whole frame as in the TR system, or only every \( T_w/2 \) duration and then follow the combining methods described in Section II. There is another advantage of the proposed dual pulse structure for \( N_s = 2 \). Since the transmitted reference sub-pulses have positive and negative alternating amplitude levels, the power spectrum of this type of dual pulse signals has no discrete spectral lines regardless of the sub-pulse shape \( g_{ref}(t) \), which is a very desirable characteristic. Increased implementation complexity of this improved scheme is the price paid for better performance.

**IV. DISCUSSION AND NUMERICAL RESULTS**

The attractive properties of the proposed dual pulse scheme can be summarized as follows:

1) The data rate of the proposed dual pulse system doubles the conventional TR system, since the reference sub-pulse and the modulated sub-pulse are side by side, eliminating the spaced frame length delay between a reference pulse and a data pulse in a TR system.

2) The delay unit in the receiver is only half the duration of the transmitted dual pulse, and therefore is much shorter than the frame delay required in the conventional TR system. Note that implementing accurate short delays is easier than long delays [2].

3) The dual pulse system is less sensitive to time variation of the channel compared to the TR method and the pilot waveform assisted modulation, because there is no time gap between the reference sub-pulse and the modulated data sub-pulse. This also means within a fixed channel coherence time, there are more received reference sub-pulses to be averaged over to reduce the noise effect.

4) The dual pulse system retains the same merits of TR systems, such as robust performance, simple implementation (especially for DP over \( T_{ir} \)) and easy timing acquisition. Frame timing is required for the DP system with noise averaging, but there is no need to estimate either the multipath delays or the multipath gains.

The sub-pulse used in the simulation is the second derivative of the Gaussian pulse \( g_{ref}(t) = \{1 - 4\pi(t - T_w'/2)/T_d\} \exp\{(-2\pi(t - T_w'/2))^2/T_d^2\} \), where \( T_d = 0.2877 \) ns and the sub-pulse width \( T_w' \) is set at 0.7 ns. The receiver lowpass filter with Hamming window has 50 taps and a bandwidth of 14.4 GHz. The simulation sampling rate is 30 GHz. For each channel model, the bit error probability is obtained from averaging the BER over 100 channel realizations.

Figs. 5-8 plot the BER performance of the DP system with different detection schemes, and the conventional TR technique in UWB channels CM1-CM4, respectively. Averaging the received reference sub-pulse signal over \( N_p = 50 \) frames to reduce the noise in the reference template is also performed in these figures. As expected, the performance is significantly improved with noise averaging in all plots. For the TR and one type of DP systems, the integration of the product \( r(t)r(t - T_w/2) \) is over an interval \( T_{ir} \) less than the whole frame duration so that the more noisy trail close to the end of the frame is not included in the decision variable. This results in improved performance over integrating over the whole frame.
For the DP schemes in the four channel models studied, the GSC, AT-GSC, NT-GSC and the DP over $T_{ir}$, receivers have similar performance using the parameters shown in Figs. 5-8, with or without reference sub-pulse noise averaging. The number of branches selected in GSC and the normalized threshold in NT-GSC are parameters whose values will influence the error probability of the respective system. The TR system has close performance to the DP systems in CM2 to CM4. In the CM1 channel, the TR scheme slightly outperforms the DP systems at the high signal-to-noise ratio (SNR). This is because the channel model CM1 has a line-of-sight (LOS) component and the majority of the channel energy is concentrated in the first few closely spaced paths, which may result in strong self interference for the DP system and the interference effect becomes more dominant at high SNR’s. For CM2 to CM4 channels, the multipaths are more widely spreaded into longer time durations, resulting in less inter-path interference. Moreover, the system performances (both DP and TR) in different channel models degrade from CM1 to CM4, as expected. The degradations from CM1 to CM4, however, are not very significant for either the DP or TR system studied, which demonstrates the robustness of the autocorrelation receivers in different channel environments.

The performance of the improved DP scheme is plotted for CM1 to CM4 in Figs. 9-12, respectively. Since $N_s = 2$, these figures have at least 3 dB performance gain over the corresponding Figs. 5-8. In Fig. 9 for CM1, the improved scheme has less interference between the received reference sub-pulse and the data sub-pulse, and hence closing the performance gap at high SNR’s between the DP and TR systems. In Figs. 10-12, the improved DP scheme slightly outperforms the TR system with noise averaging.

V. CONCLUSION

A novel dual pulse transmission and auto-correlation detection scheme for UWB communications has been presented. It has several advantages over the conventional transmitted reference scheme, such as higher data rate and implementation edge, while retaining the many benefits a TR system possesses. A new improved structure has further enhanced the system performance. The performance of several different detection and combining schemes has been studied by simulations. The proposed dual pulse scheme permits a simple, low cost, and robust UWB transceiver. To further increase the transmission data rate, mechanisms for combating intersymbol interference caused by reducing frame duration must be designed and included in the receiver.

REFERENCES


Fig. 1. Illustration of the transmitted dual pulse structure for on-off keying and binary phase shift keying.

Fig. 2. Receiver block diagram.

Fig. 3. Illustration of the improved dual pulse structure for binary phase shift keying with the pulse repetition number $N_s = 2$.

Fig. 4. Receiver block diagram of the improved system.
Fig. 8. Performance of the DP system employing noncoherent GSC, AT-GSC and NT-GSC for CM1 channels.

Fig. 9. Performance of the improved DP system employing noncoherent GSC, AF-GSC and NT-GSC for CM1 channels.

Fig. 10. Performance of the improved DP system employing noncoherent GSC, AF-GSC and NT-GSC for CM2 channels.

Fig. 11. Performance of the improved DP system employing noncoherent GSC, AF-GSC and NT-GSC for CM3 channels.

Fig. 12. Performance of the improved dual pulse system employing noncoherent GSC, AT-GSC and NT-GSC for CM4 channels.