A New Transmitted Reference Pulse Cluster System for UWB Communications

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Abstract—A new form of transmitted reference technique is proposed in this letter, where compactly spaced or multiple contiguous reference and data pulses are used for transmission. This structure enables a simple, robust and practical autocorrelation detector to be implemented in the receiver. It is also compatible with the signal format proposed within IEEE 802.15.4a Working Group for coherent and non-coherent systems. Simulation results show that this new transmitted reference system outperforms the non-coherent system by about 1.3-1.9 dB for 802.15.4a channel model 1 and 1.3-2.3 dB for channel model 8, while offering similar implementation complexity compared to that of the non-coherent system.

Index Terms—Ultra-wideband (UWB), transmitted reference (TR), dual pulse (DP), pulse cluster, low complexity transceiver

I. INTRODUCTION

The transmitted reference (TR) technique for ultra-wideband (UWB) communications was introduced fairly recently by [1]. It has been a subject of extensive study in the literature [1]-[12] (and references therein) since then. The TR auto-correlation receiver does not need to estimate the dense multipath UWB channel and collects channel energy in a much easier way than in a coherent rake receiver. Moreover, frequency dependent effects of a UWB channel are straightforwardly taken into account by the TR scheme. Conventional TR schemes use pulse doublet consisting of a reference pulse and a data pulse separated by a large interval to represent information data. Only when the two pulses are spaced further than the channel impulse response length, there will be no inter-pulse interference (IPI) between the received data and reference pulses. However, a major hurdle to practical implementation of a TR system is the requirement of accurate long and wideband delay lines. Implementing a delay line longer than 10 ns for UWB signals is not acceptable for a practical system [7], [13].

In [1], a delay hopped TR system was first proposed. Variations to this original TR scheme were presented in [3]-[6]. Performance analysis of TR systems were carried out in [5]-[11]. A frequency multiplexed TR was proposed in [12], where the data and reference waveforms were multiplexed in disjoint frequency bands. In order to overcome the long delay line challenge, a dual pulse (DP) scheme that uses two contiguous pulses to transmit data was proposed in [14]. The delay between the reference and data pulses is then only a pulse width. Due to the low power spectrum requirement imposed by the FCC regulation, a bit is transmitted using multiple "frames" which repeat the bit waveform over a symbol duration. This technique is widely used to increase the received signal-to-noise ratio (SNR) and obtain reasonable error performance. Three types of DP receivers were analyzed in [15]. To effectively reduce the effect of IPI and increase the SNR, the received signal was averaged over frames in [15], but this operation again requires a delay line as long as a frame duration. In this letter, we further extend the idea of dual pulse and transmitted reference techniques to arrive at a simple design that allows short delay lines less than 10 ns and achieves better performance than non-coherent systems. The proposed structure is compatible with IEEE 802.15.4a proposals such as [16]. Due to space limitation, we focus on describing the new scheme in this letter and leave out the performance analysis.

II. SYSTEM MODEL AND PULSE CLUSTER STRUCTURE

In a TR or DP [14], [15] system, information is carried by a pulse pair in a frame: a reference pulse and a data pulse separated by $T_d$ seconds. To increase the signal-to-noise ratio (SNR) of the system, the same pulse pair is re-transmitted over $N_f$ frames. Using binary pulse amplitude modulation, a TR or DP signal can be represented by

$$\bar{s}(t) = \sqrt{\frac{E_b}{2N_f}} \sum_{m=-\infty}^{\infty} \sum_{i=0}^{N_f-1} [g(t-mT_s-iT_f) + b_m g(t-mT_s-iT_f-T_d)]$$

where $b_m \in \{+1, -1\}$ is the m-th bipolar information bit, $g(t)$ is the composite pulse with duration $T_p$ resulting from the convolution of the transmitted pulse $g_{tr}(t)$ and the receiver filter matched to $g_{tr}(t)$. $T_s$ is the symbol/bit duration determined by the bit rate, $T_f$ is the frame interval, $N_f$ is the number of repeated frames for one bit, and $E_b$ is the average energy per bit. In the existing TR literature, the pulse delay $T_d$ was proposed to be long enough to avoid inter-pulse interference (IPI), and the frame duration $T_f$ is often related to the symbol duration by $T_s = N_f T_f$. To improve signal to noise ratio, a TR receiver may perform analog averaging of the received pulses for a number of frames. However, this again requires a delay line whose duration is as long as $T_f$. Large $T_d$ and $T_f$ lead to large delay lines which pose serious implementation challenges in practical UWB systems. The DP scheme proposed in [14] and [15] can be represented by (1) with $T_d = T_p$. Hence, the DP structure only requires short delay lines, but at the same time, suffers from IPI due to
the compactly spaced pulses. For the multiple frames scenario where \(N_f > 1\), IPI can be alleviated by averaging multiple received signal frames or using the iDP scheme in [14] and [15]. Either way, it requires frame long delay line to perform analog averaging or iDP processing. Moreover, in both TR and DP methods, inter-symbol interference (ISI) and inter-frame interference (IFI) are likely to occur when \(T_d\) and \(T_f\) are small relative to the channel delay spread. Although there was some analysis in the literature applicable to the IPI case, it was unknown how to address the adverse effect of IPI.

The objectives of this letter are to design, 1) for a given data rate \((1/T_p)\) and \(N_f\), the pulse structures that require practically short delay lines (i.e., small \(T_d\)) and result in minimal ISI; 2) a simple, robust detection scheme that achieves reasonable performance even in the presence of IPI and/or IPI.

Considering the advantage of the DP pulse structure and the need for multiple frames, we propose to use multiple contiguous DP pulses or multiple closely and evenly spaced reference and data pulses as shown in Fig. 1 to represent information data. This closely packed TR/DP pulse structure is referred to as TR pulse cluster structure in this letter. Three key points of this structure are: 1) The length of the cluster, \(T_a\), is not equal to the symbol duration. Instead, a cluster only occupies one time slot, shown as \(S\) in Fig. 1, with length \(T_a = N_f T_f \ll T_s\). This compact cluster structure leaves more blank space in each symbol than having \(2N_f\) pulses scattered in the whole symbol duration, and hence leading to low or no ISI; 2) \(T_f = 2T_d\). All pulses are evenly spaced in a cluster to achieve improved performance. More explanation will be given later; 3) The delay \(T_d\) should be shorter than 10 ns. In Fig. 1, we use \(T_d = T_p\) in (a) and \(T_d = 2T_p\) in (b). Considering a multiple access scenario, we can divide a symbol duration into multiple time slots as shown in Fig. 1, and each user occupies a different time slot where a TR pulse cluster resides. The proposed TR pulse cluster and symbol structure are compatible with the signal structure presented in IEEE 802.15.4a proposals [16]. If time hopping is desired, it can be performed on TR pulse clusters from time slot to time slot instead of hopping within each cluster. Similarly, scrambling should be carried out on a pulse cluster basis.

The proposed pulse cluster is transmitted over a UWB channel and then goes through a lowpass filter matched to \(g_a(t)\) in the receiver. The receiver performs auto-correlation on the received signal and its \(T_d\) delayed version. The decision variable (DV) for the \(m\)-th bit is given by

\[
D = \int_{mT_d + T_1}^{mT_d + T_2} r(t) r^*(t - T_d) dt. \tag{2}
\]

The choice of the integration interval \([T_1, T_2]\) is critical to the success of the detection scheme. In order to ensure that we capture all the energy in the received pulse cluster, we select \(T_1 = T_d + T_h, T_2 = T_d + (N_f - 1)T_f + T_h\), where \(T_1\) and \(T_h\) are the beginning and end of the UWB channel for integration, respectively. Usually \(T_1\) is close to time arrival of the first significant path of the channel, especially in a line-of-sight (LOS) environment, and the interval \([T_1, T_h]\) should include sufficient channel energy for detection. Such choices of \(T_1\) and \(T_2\) guarantee that auto-correlation covers the significant channel portion plus a duration of \((N_f - 1)T_f\) related to the pulse cluster width. It is obvious from (2) that the receiver is very simple and only needs \(T_d\) long delay line. Choosing \(T_f = 2T_d\) allows the data pulse of one frame in \(r(t - T_d)\) to line up with the reference pulse of the succeeding frame in \(r(t)\), and hence results in additional auto-correlation of the desired components containing information data. Such design even outperforms the conventional TR receiver operation that performs auto-correlation within one frame and then averages over multiple frames. TR pulse cluster is fundamentally different from the delay hopped TR system in [1] or time hopping TR systems in the literature.

### III. Simulation

In this section, we present simulation results for the performance of the proposed TR cluster system as illustrated in Fig. 1(a), the non-coherent pulse position modulation (PPM) and a conventional TR system in two representative channels, i.e., IEEE 802.15.4a CM1 and CM8 channels. CM1 models strong line-of-sight channels and CM8 models extremely large delay spread channels [17]. The non-coherent PPM system employs either all “+1” or all “−1” pulse cluster placed at different time slots within a symbol and the position of the pulse cluster represents information data. The conventional TR system spreads out \(N_f\) reference and data pulse pairs evenly in one symbol duration. We did not include time hopping in the conventional TR but it is expected that the performance will be worse with time hopping. Here is a description of the system parameters. The transmitter pulse shape filter and the receiver filter are the root raised cosine (RRC) pulses with roll-off factor \(\beta = 0.25\). The zero-to-zero main lobe width of the RRC pulse is \(T_p = 2.02\) ns, and a truncated RRC pulse of duration \(8T_p\) is used in the simulation. The pulse cluster is composed of 8 contiguous pulses, i.e., \(N_f = 4\). The pulse cluster length is then \(T_a = 16.16\) ns. Low bit rates of 2 Mbps for CM1 and 1 Mbps for CM8 are simulated, and hence the system is ISI free. The sampling frequency used in the simulation is 3.952 GHz. The integration interval related parameters \(T_1\) and \(T_h\) are determined as the beginning and end paths of the channel with magnitude larger than a fraction of the channel maximum magnitude. In other words, any multipath components before \(T_1\) and after \(T_h\) are smaller than \(s \cdot \max(\alpha_k)\), where \(s = 0.3\) in the simulation), the scale factor and \(\alpha_k\) is the \(k\)-th path gain. For each channel model, the final BER is obtained by averaging the BERs of 100 channels.

Fig. 2 shows that at BER = \(10^{-3}\) in CM1 channels, TR pulse cluster outperforms conventional TR and non-coherent with “+1” pulses by about 1.9 dB, and non-coherent with “−1” pulses by about 1.3 dB. The performance gaps are wider at medium SNRs but get narrowed at higher SNRs, especially for conventional TR. The relative performance between non-coherent detection with “+1” pulse cluster and “−1” pulse cluster is channel dependent. Fig. 3 shows that in CM8 channels, TR pulse cluster outperforms non-coherent with “+1” pulses by about 2.3 dB and non-coherent with “−1” pulses by about 1.3 dB at BER = \(2 \times 10^{-3}\). The conventional TR scheme significantly lags behind the new TR pulse cluster scheme in performance and the ease of implementation.
This letter has proposed a new TR pulse cluster structure that repeatedly sends closely spaced TR/DP pulses. This method allows a simple and robust receiver to be implemented, i.e., analog front end, symbol rate sampling and short delay line requirement, overcoming a major hurdle (long delay lines) of conventional TR receivers. Simulation results have shown superior performance of the proposed scheme over non-coherent and conventional TR systems.

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REFERENCES