A New Transmitted Reference Pulse Cluster System for UWB Communications

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***Abstract*— To meet the implementation constraint posed by ultra-wideband (UWB) delay lines, a new transmitted reference pulse cluster (TRPC) structure is proposed where a group of reference and data pulses with short, uniform spacing is used for transmission. This structure enables a simple, robust and practical auto-correlation detector to be implemented in the receiver. It overcomes the major hurdle to practical implementation of conventional transmitted reference systems, that is, the long wideband delay line requirement. TRPC is also compatible with the signal format proposed within the IEEE 802.15.4a Working Group for coherent and non-coherent systems. The performance of the proposed TRPC receiver and non-coherent pulse position modulation (NC-PPM) with energy detection are analyzed and compared. Simulation results show that TRPC outperforms the conventional TR, NC-PPM, the recently proposed dual pulse scheme and the frequency shifted reference system. In particular, it achieves power saving over NC-PPM by about 1.3-1.9 dB for IEEE 802.15.4a channel model 1 and 1.3-2.3 dB for channel model 8.**

***Index Terms*— Ultra-wideband (UWB), transmitted reference pulse cluster (TRPC), dual pulse (DP), noncoherent detection, bit error rate (BER)**

I. Introduction

The transmitted reference (TR) technique has attracted substantial interest from the academia and industry since its introduction to ultra-wideband (UWB) communication by [1], due to its simple structure and robust performance. TR does not require explicitly estimating dense multipath UWB channels and collects channel energy more easily compared to a coherent rake receiver. Moreover, frequency dependent effects of a UWB channel are straightforwardly taken into account by the TR scheme. For 802.15.4a low rate applications with data rate at 1Mbps to 2Mbps, the transmitted reference technique with autocorrelation receivers and simple energy detection schemes become right choices considering the performance-cost tradeoff.

The TR technique is a subject of extensive study in the literature [1]–[12] (and references therein). A delay hopped TR system was first proposed in [1], and experiment results were presented in [2]. Variations to this original TR scheme were presented in [3]- [6]. Performance analysis of TR systems were carried out in [5]- [11]. In conventional TR schemes, information data is represented by a pulse doublet consisting of a reference pulse and a data pulse. Normally the same pulse doublet is repeated in multiple frames for one bit because the low power spectrum required by the FCC regulation limits the amplitude of each pulse doublet. A TR receiver can exploit the multiple frame structure to increase the received signal-to-noise ratio. To avoid inter-pulse interference (IPI), the delay T_d between the reference pulse and the data pulse within one frame is required to be longer than the length of the channel impulse response, T_m. For a UWB channel, T_m typically ranges from 50 ns to more than 100 ns. Moreover, to be free of inter-frame interference (IFI), the frame length T_f should be larger than twice the T_d. That is, $T_d > T_m$ and $T_f > 2T_d > 2T_m$. A TR receiver needs T_d long delay lines to perform autocorrelation and sometimes even T_f long delay lines to achieve analog noise averaging over multiple frames. Analog noise averaging refers to the process where the received signal is first added frame by frame to average out noise, requiring frame long delay lines. Then autocorrelation within the aggregated frame follows. In practice, however, implementing accurate wideband delay lines longer than 10 ns is unacceptable for a UWB system [7], [13].

To address the long delay line problem of TR, a frequency multiplexed TR was proposed in [12] where the data and reference waveforms were multiplexed in disjoint frequency bands. Recently, authors in [14] proposed a frequency shifted reference (FSR) scheme to avoid the use of delay lines in the traditional TR system. In [15], a dual pulse (DP) scheme that used two contiguous pulses to transmit data was proposed. The delay between the reference and data pulses is then only of pulse width T_p, which means the DP receiver only needs T_p long delay lines. The downside of this scheme is the presence of IPI due to closely spaced reference and data pulses and hence degraded performance compared to the conventional TR. It was proposed in [15] and [16] to mitigate IPI by analog averaging over multiple received DP frames before autocorrelation, or to completely remove IPI by using the *i*DP scheme. However, either solution required frame long delay lines as in the conventional TR system, except that in DP the frame length can be half the frame length in TR, i.e., $T_{f,DP} > T_m$. Therefore, the delay line problem is addressed at the price of inferior performance or frame long delay lines are required to achieve the same performance as TR. Other papers, for example, [17], analysed the delay hopped TR scheme proposed in [1] with small T_d's. The system with IPI was modeled mathematically and efforts were focused on digital signal processing algorithm design in the receiver. The matched filter receiver, blind multiple symbol receiver and

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iterative receiver were proposed in [17], all of which have higher implementaion complexity than the conventional TR receiver but without the long delay line requirement.

In this letter, we propose a new TR pulse cluster (TRPC) structure that repeats a closely spaced pulse pair every $2T_d$ seconds, where T_d is the short separation between the reference pulse and the data pulse within the pair. In other words, uniform spacing is achieved among all reference and data pulses in the cluster. Suppose $T_d = T_p$, then we have a cluster composed of identical dual pulses placed side by side. At first sight, this seems counter-intuitive as IPI would be very severe in a UWB channel when so many pulses are placed closely together. However, we will show in this letter through analysis and simulation that TRPC outperforms the conventional TR scheme, dual pulse, non-coherent pulse position modulation (NC-PPM) and the frequency shifted reference system. Furthermore, TRPC only requires short delay lines and low implementation complexity comparable to that of NC-PPM.

The rest of the letter is organized as follows. The system model and performance analysis of TR pulse cluster are presented in Section II. In Section III, the performance of a non-coherent pulse position modulation system with a similar implementation complexity to the TR pulse cluster system is studied. Performance comparisons of TRPC, NC-PPM, the conventional TR and FSR are given in Section IV and Section V concludes the paper.

II. System Model and Performance Analysis

The new pulse structure, TRPC, is shown in Fig. 1. A dual pulse pair composed of a reference pulse and a data pulse with short delay T_d is repeated uniformly by every $2T_d$ seconds. Mathematically, the TRPC signal (including the receiver matched filter) can be represented by

$$\begin{aligned}\hat{s}(t) &= \sqrt{\frac{E_b}{2N_f}} \sum_{m=-\infty}^{\infty} \sum_{i=0}^{N_f-1} [g(t - mT_s - 2iT_d) \\ &\quad + b_m g(t - mT_s - (2i+1)T_d)] \\ &= \sqrt{\frac{E_b}{2N_f}} \sum_{m=-\infty}^{\infty} s_{b_m}(t - mT_s) \end{aligned} \quad (1)$$

where E_b is the average energy per bit, N_f is the number of repeated dual pulse pairs in one cluster, $g(t)$ is the composite pulse with duration T_p resulting from the convolution of the transmitter pulse $g_{tr}(t)$ and the receiver filter matched to $g_{tr}(t)$, T_s is the symbol duration determined by the bit rate, $b_m \in \{+1, -1\}$ is the m-th bipolar information bit, and $s_{b_m}(t) = \sum_{i=0}^{N_f-1} g(t-2iT_d) + b_m \sum_{i=0}^{N_f-1} g(t-(2i+1)T_d)$. The delay T_d between the reference pulse and data pulse can be set as short as T_p, or $T_p \leq T_d < 10$ ns. The pulse cluster width is then $T_u = 2N_f T_d$. The TRPC bearing data "+1" is called the "+1" pulse cluster and the other "-1" pulse cluster, as given by

$$\begin{aligned} s_{+1}(t) &= \sum_{i=0}^{N_f-1} g(t-2iT_d) + g(t-(2i+1)T_d) \\ s_{-1}(t) &= \sum_{i=0}^{N_f-1} g(t-2iT_d) - g(t-(2i+1)T_d). \end{aligned} \quad (2)$$

Since $s_{+1}(t) \neq -s_{-1}(t)$, the difference between the "+1" and "-1" pulse clusters is not simply a (-1) factor. This is in contrast to the conventional binary phase shift keying (BPSK) modulation.

Unlike the conventional TR that looses 3 dB in signal power due to the transmission of the non-information bearing reference pulse, the reference pulses in TRPC can be used with the data pulses in the previous pairs to collect energy for data detection, in addition to the energy collected as in the conventional TR. This is illustrated in Fig. 2. In this figure, a "-1" pulse cluster is transmitted, where $N_f = 4$. The solid pulses denote the reference pulses and the dashed pulses denote the data pulses. The energy of each pulse is $E_b/2N_f$. At the receiver, the received signal is autocorrelated with its T_d delayed copy. Assuming an additive white Gaussian noise (AWGN) channel, the overall energy collected for data detection in TRPC is given by

$$E_{\text{TRPC}} = (2N_f - 1) \cdot \frac{E_b}{2N_f} \approx E_b. \quad (3)$$

Whereas in the conventional TR system, energy is only collected for the correlation between the data pulses and reference pulses within the pairs, as illustrated by the four blank rectangles in Fig. 2. That is,

$$E_{\text{conventionalTR}} = N_f \cdot \frac{E_b}{2N_f} = \frac{1}{2} E_b. \quad (4)$$

Theoretically, the energy collected in TRPC could be arbitrarily close to E_b by increasing N_f. In implementation, N_f can not be too large because in this case, the energy per pulse would be too low to combat the noise effect. In other words, a large N_f would lead to a longer pulse cluster and also a longer integration interval, which would introduce more noise to the autocorrelation receiver and impair the performance. As a result, N_f is a parameter that can be optimized in the TR pulse cluster structure. Apparently, the uniform spacing among all reference and data pulses in the cluster is crucial to the performance of TRPC and the cluster is treated as a whole entity in the detection. This is fundamentally different from the delay hopped TR in the literature.

In realistic UWB channels, the interference among the reference and data pulses caused by multipaths will be present. The UWB channel described by IEEE 802.15.4a channel models can be generalized as [18]

$$h(t) = \sum_{k=0}^{K-1} \alpha_k \delta(t - \tau_k) \quad (5)$$

where α_k and τ_k are the complex amplitude and delay of the k-th multipath. The received signal after the lowpass matched filter $g_{tr}(t)$ can then be written as

$$\begin{aligned} r(t) &= \sum_{k=0}^{K-1} \alpha_k \hat{s}(t-\tau_k) + n(t) \\ &= \sqrt{\frac{E_b}{2N_f}} \sum_{k=0}^{K-1} \alpha_k \sum_{m=-\infty}^{\infty} s_{b_m}(t-\tau_k-mT_s) + n(t) \\ &= \sqrt{\frac{E_b}{2N_f}} \sum_{m=-\infty}^{\infty} q_m(t-mT_s) + n(t) \end{aligned} \quad (6)$$

where $q_m(t) = \sum_{k=0}^{K-1} \alpha_k s_{b_m}(t-\tau_k)$, and $n(t)$ is the complex additive white Gaussian noise filtered by $g_{tr}(t)$. The auto-correlation function of $n(t)$ is given by $R_n(\tau) = E[n^*(t)n(t+\tau)] = N_0 R_{tr}(\tau)$, where $R_{tr}(\tau) = \int_{-\infty}^{\infty} g_{tr}(t) g_{tr}(t+\tau)dt$ and N_0 is the power spectral density of the complex white Gaussian noise.

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

$$D = \int_{mT_s+T_1}^{mT_s+T_2} r(t) r^*(t-T_d)dt. \quad (7)$$

The receiver makes a decision on "+1" if Re$\{D\} > 0$, and "-1" if Re$\{D\} < 0$. 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 the integration interval as follows: $T_1 = T_d + T_l$, $T_2 = T_d + 2(N_f-1)T_d + T_h + T_p = (2N_f-1)T_d + T_h + T_p$, where T_l and T_h are the beginning and end time of the UWB channel for integration, respectively. Usually T_l is close to be the time-of-arrival (TOA) of the first significant path of the channel, especially in a line-of-sight (LOS) environment, and the interval $[T_l, T_h]$ should include sufficient channel energy for detection. Such choices of T_1 and T_2 guarantee that the auto-correlation covers the significant channel portion plus a duration of $2(N_f-1)T_d + T_p$ related to the pulse cluster width. It is obvious from (7) that the receiver is very simple and only needs T_d long delay line.

Some discussions on TRPC are presented here.

Remark 1 (Noise reduction due to short integration interval): Note that in TRPC, the integration length of the autocorrelation detector is around the cluster width plus the significant channel portion. In the conventional TR, integration performed in each frame is over the pulse width plus the significant channel portion, and it is done with N_f frames. The effective integation length in the conventional TR is much longer than that in TRPC. Due to the short integration interval, the noise component included in the TRPC detection is much smaller, leading to substantial performance improvement over the conventional TR, especially when the system signal-to-noise ratio is not very high.

Remark 2 (Simple detector with noise averaging): In the conventional TR and DP systems, noise averaging can be carried out in two ways. The received signal can be first added frame over frame for analog noise averaging and then followed by autocorrelation. Or autocorrelation is first performed in each frame and the results are added to reduce noise in the decision variable. The former has better performance, but requires frame long delay lines. In the proposed receiver for TRPC, the second type of noise averaging is implicitly performed in the operation. The detector delays the received cluster by T_d and then performs correlation on the whole cluster. The summation procedure for noise averaging is automatically included by the integrator in TRPC. Moreover, additional energy for data detection is collected in the correlation due to the uniform structure of TRPC, as explained in the paragraph after (7).

Remark 3 (ISI free and possible multiple-access): In the TRPC system, since T_d is much shorter than 10 ns and the repetition within one symbol is $N_f = 4$, we have the pulse cluster width $T_u = 2N_f T_d < 80$ ns. For $T_d = 2.02$ ns, $T_u = 16.16$ ns. Given low data rate transmission such as 1Mbps in 802.15.4a channels, the pulse cluster only occupies a small portion of the symbol duration, which is indicated as S in Fig. 1. It is known that the average delay of 802.15.4a channels is in the range of [50, 200] ns. Therefore after the pulse cluster is passed through the multipath channel, the resulting signal is still shorter than the symbol duration. By "squeezing" the signal within a small portion of the symbol duration, it minimizes the occurrence of ISI. This is in contrast to the conventional TR where pulses are spread over the whole symbol duration in the form of multiple frames.

Moreover, 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. 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, if to be used, should be carried out on a pulse cluster basis as well.

Next we derive the bit error rate (BER) of TRPC conditional on a given UWB channel. The subsequent analysis on (7) involves only one symbol, hence the subscript m is omitted for convenience. Assuming the symbol interval T_s is sufficiently long so that there is no inter-symbol interference (ISI), we have

$$\begin{aligned} D &= D_1 + D_2 + D_3 + D_4 \\ D_1 &= \frac{E_b}{2N_f} \int_{T_1}^{T_2} \sum_{l=0}^{K-1} \sum_{k=0}^{K-1} \alpha_l \alpha_k^* s(t-\tau_l) s^*(t-\tau_k-T_d)dt \\ &= \frac{E_b}{2N_f} \int_{T_1}^{T_2} q(t) q^*(t-T_d)dt \\ D_2 &= \sqrt{\frac{E_b}{2N_f}} \int_{T_1}^{T_2} q(t) n^*(t-T_d)dt \\ D_3 &= \sqrt{\frac{E_b}{2N_f}} \int_{T_1}^{T_2} q^*(t-T_d) n(t)dt \\ D_4 &= \int_{T_1}^{T_2} n(t) n^*(t-T_d)dt \end{aligned} \quad (8)$$

where D_1 is the signal-signal component, D_2 and D_3 are the random variables (RVs) representing the signal-and-noise product, and D_4 is an RV accounting for the noise-noise product. It can be easily shown that $E[D_2 + D_3] = 0$ and

$$m_D(b_m) = E[\mathrm{Re}\{D\}] \approx \mathrm{Re}\{D_1\} = \frac{E_b}{2N_f}\int_{T_1}^{T_2} \mathrm{Re}\{q(t)q^*(t-T_d)\}dt = \frac{E_b}{2N_f}[(2N_f-1)E_gE_hb_m + \sum_{l=K_1}^{K_2}\sum_{\substack{k=K_1\\k\neq l}}^{K_2} \mathrm{Re}\{\alpha_l\alpha_k^*\}R_{ss}(|T_d-\tau_l+\tau_k|)] \quad (9)$$

$E[D_4] \approx 0$ as $T_d \geq T_p$. Therefore, the mean of $\mathrm{Re}\{D\}$ is given by (9), where E_g is the energy in the pulse $g(t)$, $E_h = \sum_{k=K_1}^{K_2} |\alpha_k|^2$ is the channel energy collected by the integration interval $[T_1, T_2]$, and $R_{ss}(\tau) = \int_{-\infty}^{\infty} s(t)s(t+\tau)dt$. The first term is the TRPC energy collected from multipaths for data detection, and the second term represents the IPI. Analysis for D_2, D_3 and D_4 is similar to [16], [7]. These RVs can be closely approximated as Gaussian distributed, especially now that a pulse cluster is longer than a single dual pulse. To calculate the bit error rate of TRPC, we need to know the variance of the Gaussian RV $\mathrm{Re}\{D\}$. It can be easily shown that Gaussian RVs $D_2 + D_3$ and D_4 are independent, therefore the variance of $\mathrm{Re}\{D\}$ is the sum of $\sigma_{23}^2(b_m) = \mathrm{Var}[\mathrm{Re}\{D_2 + D_3\}]$ and σ_4^2. In particular,

$$\sigma_4^2 = \mathrm{Var}[\mathrm{Re}\{D_4\}] = \frac{N_0^2}{2}\int_{-\frac{T_i}{\sqrt{2}}}^{\frac{T_i}{\sqrt{2}}} (\sqrt{2}T_i - 2|y|)R_{tr}^2(\sqrt{2}y)dy \quad (10)$$

where $T_i = T_2 - T_1$, and $\sigma_{23}^2(b_m)$ is given by (11).

The probability of error for the TRPC scheme conditioned on the channel realization $\mathbf{h}$ is then given by

$$P(e|\mathbf{h}) = \frac{1}{2}Q\left(\frac{-m_D(-1)}{\sqrt{\sigma_{23}^2(-1)+\sigma_4^2}}\right) + \frac{1}{2}Q\left(\frac{m_D(1)}{\sqrt{\sigma_{23}^2(1)+\sigma_4^2}}\right) \quad (12)$$

where $\mathbf{h} = \{(\alpha_k, \tau_k)|k = 0, ..., K-1\}$.

III. Non-coherent Detection of PPM

The proposed TR pulse cluster and symbol structure are compatible with the signal structure presented in the IEEE 802.15.4a standard [19]. The standard, however, uses non-coherent pulse position modulation with energy detection. NC-PPM has similar implementation complexity to TRPC, and therefore the relative performance of the two is of interest. The PPM signal $s(t)$ specified in the IEEE 802.15.4a standard consists of 8 pulses with short, uniform spacing instead of a single pulse for one information bit to meet FCC mask. During the m-th bit interval $t \in [(m-1)T_s, mT_s]$, the transmitted signal (including the receiver matched filter) is given by

$$\tilde{s}(t) = (1-b_m)\sqrt{\frac{E_b}{2N_f}}s(t) + b_m\sqrt{\frac{E_b}{2N_f}}s(t-\frac{T_s}{2}) \quad (13)$$

where the information bit $b_m \in \{0, 1\}$ decides which part of the symbol interval that $s(t)$ sits in. Since $s(t)$ in [19] has similar structure to TRPC, we can use either the "+1" pulse cluster $s(t) = s_{+1}(t)$ or the "-1" pulse cluster $s(t) = s_{-1}(t)$ for transmission. As the "+1" pulse cluster is not the antipolar version of the "-1" pulse cluster, it is expected that the PPM structures adopting "+1" and "-1" pulse cluster would give different BER performance. The received signal after going through the UWB channel and AWGN is then given by

$$r(t) = \sum_{k=0}^{K-1} \alpha_k\tilde{s}(t-\tau_k) + n(t) = \sqrt{\frac{E_b}{2N_f}}v(t) + n(t) \quad (14)$$

where $v(t) = \sqrt{\frac{2N_f}{E_b}}\sum_{k=0}^{K-1} \alpha_k\tilde{s}(t-\tau_k)$. The receiver employs two simple energy detectors to demodulate the received signal. The outputs of the two energy detectors are given by

$$V_0 = \int_{T_1}^{T_2} |r(t)|^2 dt \quad (15)$$

and

$$V_1 = \int_{T_1+\frac{T_s}{2}}^{T_2+\frac{T_s}{2}} |r(t)|^2 dt. \quad (16)$$

If $V_0 > V_1$, a decision on "0" is made; otherwise, a decision on "1" will be made. The integration interval is determined using the method similar to the TR pulse cluster system, where $T_1 = T_l$ and $T_2 = T_h + 2(N_f - 1)T_d$ with the interval $[T_l, T_h]$ containing sufficient energy of the channel.

Suppose "0" is transmitted, the energy detector output V_0 can be further written as

$$V_0 = D_1 + D_2 + D_3 + D_4 \quad (17)$$

where

$$\begin{aligned} D_1 &= \frac{E_b}{2N_f}\int_{T_1}^{T_2} |v(t)|^2 dt \\ D_2 &= \sqrt{\frac{E_b}{2N_f}}\int_{T_1}^{T_2} v(t)n^*(t)dt \\ D_3 &= \sqrt{\frac{E_b}{2N_f}}\int_{T_1}^{T_2} v^*(t)n(t)dt \\ D_4 &= \int_{T_1}^{T_2} |n(t)|^2 dt. \end{aligned} \quad (18)$$

The energy detector output V_1 is given by

$$V_1 = \int_{T_1+\frac{T_s}{2}}^{T_2+\frac{T_s}{2}} |n(t)|^2 dt. \quad (19)$$

The final decision variable is then given by

$$D = V_0 - V_1 = D_1 + D_2 + D_3 + D_4 - V_1. \quad (20)$$

Again, D can be approximated as a Gaussian RV with mean D_1. Because D_2, D_3, D_4 and V_1 are independent, the variance of D is given by

$$\begin{aligned} \sigma_D^2 &= \frac{E_bN_0}{N_f}\int_{T_1}^{T_2}\int_{T_1}^{T_2} \mathrm{Re}\{v(t)v^*(t')\}R_{tr}(t'-t)dtdt' \\ &+2N_0^2\int_{-\frac{T_i}{\sqrt{2}}}^{\frac{T_i}{\sqrt{2}}} (\sqrt{2}T_i - 2|y|)R_{tr}^2(\sqrt{2}y)dy. \end{aligned} \quad (21)$$

$$\begin{aligned}
\sigma_{23}^2(b_m) &= \text{Var}[\text{Re}\{D_2\}] + \text{Var}[\text{Re}\{D_3\}] + 2\text{E}[\text{Re}\{D_2\}\text{Re}\{D_3\}] \\
\text{Var}[\text{Re}\{D_2\}] &= \frac{E_b N_0}{4N_f}\int_{T_1}^{T_2}\int_{T_1}^{T_2} \text{Re}\{q(t)q^*(t')\}R_{tr}(t'-t)dtdt' \\
\text{Var}[\text{Re}\{D_3\}] &= \frac{E_b N_0}{4N_f}\int_{T_1}^{T_2}\int_{T_1}^{T_2} \text{Re}\{q(t-T_d)q^*(t'-T_d)\}R_{tr}(t'-t)dtdt' \\
E[\text{Re}\{D_2\}\text{Re}\{D_3\}] &= \frac{E_b N_0}{4N_f}\int_{T_1}^{T_2}\int_{T_1}^{T_2} \text{Re}\{q(t)q^*(t'-T_d)\}R_{tr}(t'-t+T_d)dtdt' \qquad (11)
\end{aligned}$$

Therefore, the conditional probability of error for the non-coherent detection of binary PPM is expressed as

$$P(e|\mathbf{h}) = P(D < 0) = Q\left(\frac{D_1}{\sigma_D}\right). \qquad (22)$$

IV. Simulation and Numerical Results

In this section, we present simulation and numerical results for the performance of the proposed TRPC system, the non-coherent pulse position modulation 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 (LOS) channels and CM8 models Non-LOS (NLOS) channels with an extremely large delay spread [18]. 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) pulse 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 $T_u = 16.16$ ns. Low bit rates of 2 Mbps for CM1 and 1 Mbps for CM8 are studied, and hence the system is ISI free. The sampling rate of the receiver analog-to-digital (A/D) device is equal to the symbol rate, i.e., 2 MHz and 1 MHz for CM1 and CM8 channels respectively. The integration interval related parameters T_l 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_l and after T_h are smaller than $s \cdot \max(|\alpha_k|_{k=0}^{K-1})$, where s ($= 0.3$ in the simulation) is the scale factor and α_k is the k-th path gain.

Fig. 3 shows that at BER $= 10^{-3}$ in CM1 channels, TR pulse cluster outperforms NC-PPM with “+1” pulses by about 1.9 dB, and NC-PPM with “-1” pulses by about 1.3 dB. The performance gap between TRPC and the conventional TR is wider at medium SNRs because of the noise reduction in TRPC due to short integration intervals. At higher SNRs, the IPI effect is more dominant and hence the performance gain mainly comes from the extra energy collected in TRPC. The relative performance between non-coherent detection with “+1” pulse cluster and “-1” pulse cluster is channel dependent. Fig. 4 shows that in CM8 channels, TRPC outperforms NC-PPM with “+1” pulses by about 2.3 dB and NC-PPM with “-1” pulses by about 1.3 dB at BER $= 2 \times 10^{-3}$. The conventional TR scheme significantly lags behind the new TRPC scheme in terms of performance and implementation. This indicates that the extra energy collected by TRPC over TR, and the noise reduction and ISI reduction due to its compact structure exceed the penalty caused by inter-pulse interference. The performance gain of TRPC in CM8 NLOS channels is larger than in CM1 channels since CM8 channels are more sparesely spread over longer time duration and hence result in less IPI and more noise reduction. Both figures demonstrate agreement between semi-analytical and simulation results for the performances of TRPC and non-coherent PPM schemes.

Fig. 5 plots the effect of T_d on the performance of TRPC in CM1 and CM8 channels, respectively. These are the simulation results obtained with 1000 channel realizations. In general, the gaps among using different T_d’s are not significant. At high SNRs (> 16 dB), $T_d = 5T_p$ slightly outperforms $T_d = T_p$, especially in CM8 channels. This figure indicates that shorter delay lines such as T_p-long is preferred in TRPC and the benefit brought by larger T_d is not obvious.

A practical imperfect factor at implementation is the delay offset between receiver and transmitter. Since TRPC requires delay lines on the order of a few pulse widths, accurate short delay is much easier to realize than long wideband delays. Moreover, the delay offset can be minimized at the manufacturing stage as long as the transmitter and the receiver use the same length delay lines. Fig. 6 shows the effect of delay offset on the performance of TRPC. When the receiver delay T_d is $\frac{1}{16}T_p$ longer than the T_p delay used in the transmitter, a small degradation is incurred in CM1 channels. The degradation is about 0.3 dB in CM8 channels at BER $= 10^{-3}$.

Fig. 7 presents the effect of N_f on the performance of TR pulse cluster system in CM1 and CM8 channels. As mentioned before, N_f is the repetition times of the reference-data pulse pairs. It is observed that in both channels, the best performance is achieved when $N_f = 4$. As expected, an N_f as large as 8 leads to poorer performance than a smaller N_f (such as 4 or 6) because of the noise effect. On the other hand, $N_f = 2$ underperforms $N_f = 4$ because the former collects $3/4E_b$ and the latter get $7/8E_b$ in the receiver, as shown in (3). Moreover, the fact that the curves of $N_f = 2$ and $N_f = 8$ in CM1 channels cross can be explained similarly. Recall that the integration length is approximately the length of the channel containing significant energy plus the cluster width. In CM1 channels, the width of a cluster with a large

N_f can be often larger than the significant channel length. The $N_f = 2$ curve outperforms $N_f = 8$ at low to medium SNRs because the smaller cluster width at $N_f = 2$ leads to much shorter integration interval than $N_f = 8$ and hence less noise included in the decision statistics. When SNR is medium or low, the TRPC performance is dominated by the noise effect and therefore $N_f = 2$ leads to better performance than $N_f = 8$. As SNR increases, the noise effect is less pronounced. According to eq. (3), $N_f = 8$ results in $15/16E_b$ energy collected, compared to $3/4E_b$ for $N_f = 2$. Therefore $N_f = 2$ has worse bit error rate than $N_f = 8$ at high SNRs.

Fig. 8 compares the BER performance of TRPC and FSR in CM1, CM4 and CM8 channels. CM4 models office NLOS environments and the data rate simulated is 1Mbps. For fair comparison, the peak power and the average power of both schemes are set to be equal, which leads to $N_{f,FSR} = 6N_{f,TRPC} = 24$ [14]. It is shown in Fig. 8 that TRPC outperforms FSR in all three types of channels. The building blocks of the TRPC and FSR receivers are very similar, except that the short delay line in TRPC is replaced by a mixer in FSR.

V. Conclusion

This paper has proposed a new TR pulse cluster structure that consists of a group of identical dual pulses with uniform spacing. This method allows a simple and robust receiver to be implemented, i.e., analog front end, symbol rate sampling and short delay lines, overcoming a major hurdle (long delay line requirement) of conventional TR receivers. Simulation results have shown superior performance of the proposed scheme over non-coherent PPM with energy detection, conventional TR, dual pulse and frequency shifted reference systems in multipath UWB channels.

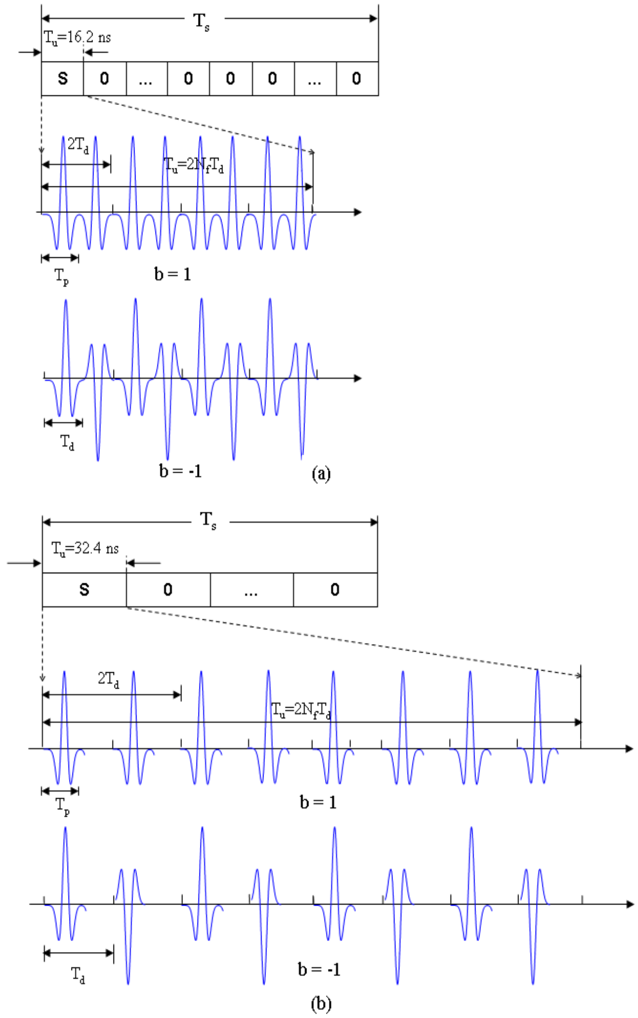

Fig. 1. The proposed TR pulse cluster structure

References

[1] R. Hoctor and H. Tomlinson, "Delay-hopped transmitted-reference RF communications," in *IEEE Conf. Ultra Wideband Syst. Techno.*, May 2002, pp. 265–269.

[2] N. V. Stralen, A. Dentinger, K. W. II, R. Hoctor, and H. Tomlinson, "Delay-hopped transmitted-reference experimental results," in *IEEE Conf. Ultra Wideband Syst. Techno.*, May 2002, pp. 93–98.

[3] H. Zhang and D. L. Goeckel, "Generalized transmitted-reference UWB systems," in *IEEE Conf. Ultra Wideband Syst. Techno.*, Nov. 2003, pp. 16–19.

[4] S. Franz and U. Mitra, "On optimal data detection for UWB transmitted reference systems," in *Proc. IEEE Global Telecomm. Conf. (Globecom)*, Dec. 2003, pp. 744–748.

[5] Y.-L. Chao and R. A. Scholtz, "Optimal and suboptimal receivers for ultra-wideband transmitted reference systems," in *Proc. IEEE Global Telecomm. Conf. (Globecom)*, Dec. 2003, pp. 759–763.

[6] J. D. Choi and W. E. Stark, "Performance of ultra-wideband communications with suboptimal receivers in multipath channels," *IEEE J. Select. Areas Commun.*, pp. 1754–1766, Dec. 2002.

[7] S. Gezici, F. Tufvesson, and A. F. Molisch, "On the performance of transmitted-reference impulse radio," in *Proc. IEEE Global Telecomm. Conf. (Globecom)*, Nov. 2004, pp. 2874–2879.

[8] T. Q. S. Quek and M. Win, "Analysis of UWB transmitted-reference communication systems in dense multipath channels," *IEEE J. Select. Areas Commun.*, pp. 1863–1874, Sept. 2005.

[9] K. Witrisal, G. Leus, M. Pausini, and C. Krall, "Equivalent system model and equalization of differential impulse radio UWB," *IEEE J. Select. Areas Commun.*, pp. 1851–1862, Sept. 2005.

[10] Y.-L. Chao and R. A. Scholtz, "Ultra-wideband transmitted reference systems," *IEEE Trans. Veh. Technol.*, pp. 1556–1569, Sept. 2005.

[11] Z. Xu, B. M. Sadler, and J. Tang, "Data detection for UWB transmitted reference systems with inter-pulse interference," in *Proc. IEEE Intl. Conf. Acoustics, Speech and Signal Processing (ICASSP)*, vol. III, 2005, pp. 601–604.

[12] W. Gifford and M. Win, "On transmitted-reference UWB communications," in *Proc. Asilomar Conf. Signals, Systems and Computers*, Nov. 2004, pp. 1526–1531.

[13] M. Casu and G. Durisi, "Implementation aspects of a transmitted-reference UWB receiver," *Wireless Communications and Mobile Computing*, pp. 537–549, May 2005.

[14] D. L. Goeckel and Q. Zhang, "Slightly frequency-shifted reference ultra-wideband (uwb) radio," *IEEE Trans. Commun.*, pp. 508–519, Mar. 2007.

[15] X. Dong, A. C. Y. Lee, and L. Xiao, "A new UWB dual pulse transmission and detection technique," in *Proc. IEEE Intl. Conf. Comm. (ICC)*, May 2005, pp. 2835–2839.

[16] X. Dong, L. Xiao, and A. C. Y. Lee, "Performance analysis of dual pulse transmission in UWB channels," *IEEE Commun. Lett.*, pp. 626–628, Aug. 2006.

[17] Q. H. Dang, A. Trindade, A.-J. van der Veen, and G. Leus, "Signal model and receiver algorithms for a transmit-reference ultra-wideband communication system," *IEEE J. Select. Areas Commun.*, pp. 773–779, Apr. 2006.

[18] A. F. Molisch, K. Balakrishnan, C.-C. Chong, S. Emami, A. Fort, J. Karedal, J. Kunisch, H. Schantz, U. Schuster, and K. Siwiak, "Ieee 802.15.4a channel model - final report," IEEE P802.15-04-0662-00-004a, Tech. Rep., Oct. 2004.

[19] I. Lakkis, "Modulation summary for tg4a," IEEE P802.15-05-617-01-004a, Tech. Rep., Oct. 2005.

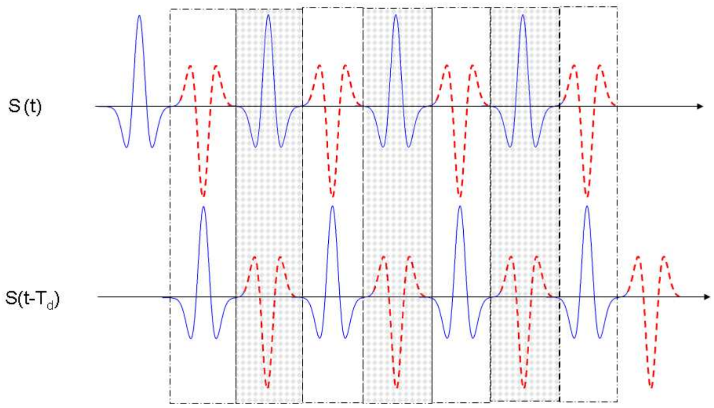

Fig. 2. Energy collection in the receiver of the proposed TR pulse cluster

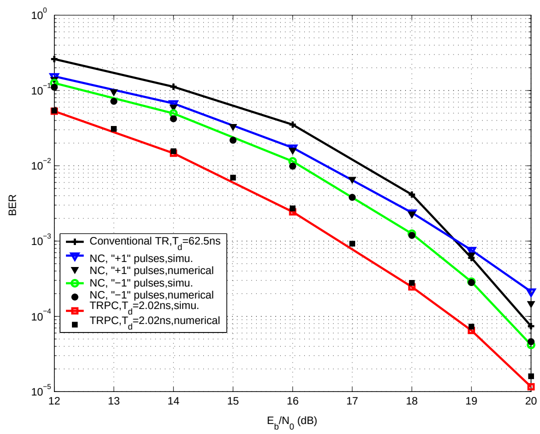

Fig. 3. The BER of TRPC and non-coherent systems in CM1 channels, with $N_f = 4$.

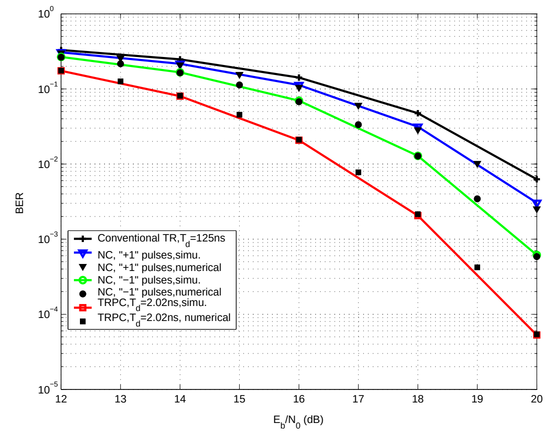

Fig. 4. The BER of TRPC and non-coherent systems in CM8 channels, with $N_f = 4$.

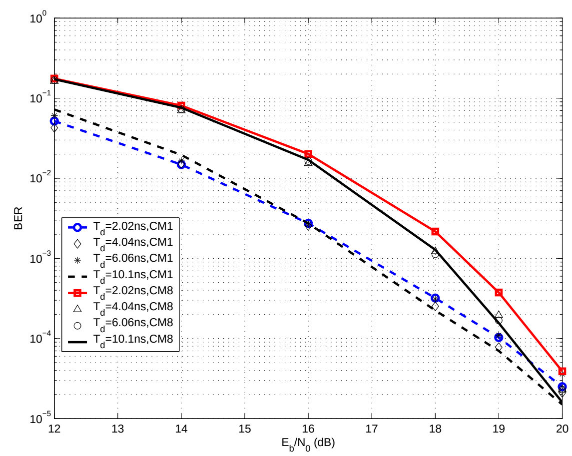

Fig. 5. The BER of TRPC systems with different T_ds in CM1 and CM8 channels.

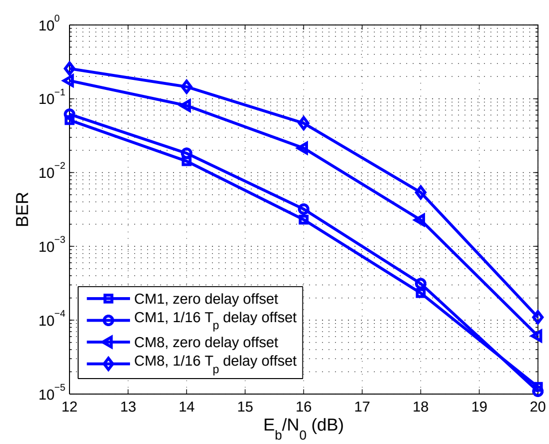

Fig. 6. The effect of delay offset on the BER of TRPC systems in CM1 and CM8 channels.

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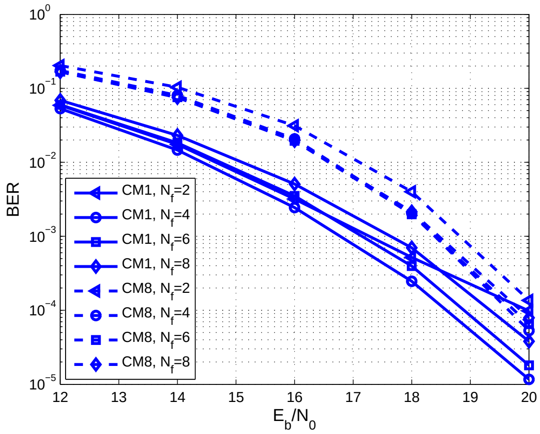

Fig. 7. The BER of TRPC in CM1 and CM8 channels with different N_fs.

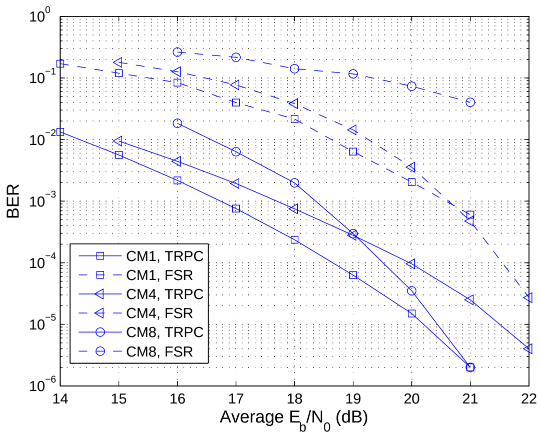

Fig. 8. Comparison of the BERs of TRPC and FSR in CM1, CM4 and CM8 channels.

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