A New Pseudo-random Pulse Sequences Aided Noise Suppression Scheme for UWB Transmitted Reference Communication System

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Summary
Recently Ultra-wideband (UWB) transmitted reference (TR) system has drawn considerable attention in many wireless sensor network location applications due to its low complexity. Its major drawback is serious performance degradation for a very noisy correlation template. In this paper, a new noise suppression scheme for UWB-TR communication system is presented by replacing the repetitive reference pulses with multiple short pseudo-random reference pulse sequences. The receiver uses them to estimate the channel impulse response and based on this to form an improved template which removes the parts mainly consist of noise and gives the multipath components that have better signal-to-noise ratio higher weights. The proposed system is described and its performance in a multipath channel is analyzed and simulated. The result shows that this scheme can effectively suppress a template's noise level and the proposed system has a better bit-error-ratio performance than that of a conventional averaged TR system.
Key words:
Noise suppression, Pseudo-random (PN) sequence, Transmitted reference (TR), Ultra-wideband (UWB) communications, Wireless sensor network (WSN)

1. Introduction

Wireless sensor networks (WSN) can be used in a wide variety of application areas such as medical health monitoring, target detection and tracking, environmental monitoring, industrial process monitoring, home network, and tactical systems. In recent years, Ultra-wideband (UWB) technology has been found to possess a number of inherent properties that are well suited to WSN applications. In particular, UWB systems have the inherent robustness to multipath propagation, have low emission power and noise-like signal, and have very good time domain resolution allowing for centimeter level location, so it is ideal for many self-organized wireless sensor networks applications [1]-[3].

Because of the high complexity of UWB Rake receiver, a simple transmitted reference (TR) system has drawn considerable attention recently. A basic UWB-TR system operates by transmitting a pair of unmodulated (reference) and modulated (data) short pulses and employing the former as the correlation template to demodulate the latter [4]. Its major drawback is serious performance degradation because the template composed of only one received reference pulse is very noisy. Considering that UWB indoor multipath channel can be regarded as time-invariant over many bit durations [5], an improved TR system transmits some repetitive reference pulses before the data signals and then averages them to form a cleaner template. This method can reduce the noise level of the template in some degree and the system is known as averaged transmitted reference (ATR) system [6].

Since the UWB multipath components arrive in clusters and the distribution of total components is sparse [7], assuming that we characterize UWB channel using the discrete time impulse response model, we can find a large number of time bins either consist of only noise or contain weak signal far less than noise. After received by a TR correlation detector, these time bins contribute little to signal energy capture, but greatly raise the noise level of decision variable. Especially when the signal-to-noise ratio (SNR) of received signals is low, the noise-on-noise term caused by these harmful time bins will seriously degrade detection performance [8]. However, none of the existing TR receivers exploits this property until now. In this paper, we try to exploit it and present a novel noise suppression scheme using pseudo-random (PN) pulse sequences. In contrast to ATR system, the proposed system replaces the repetitive reference pulses with multiple short PN reference sequences composed of pulses with corresponding polarity. The receiver uses them to sound the channel impulse response (CIR) $h(t)$ due to the fine autocorrelation function of a PN sequence and the extremely sharp waveform of a UWB pulse. By averaging, the estimated CIR $\hat{h}(t)$ with better SNR can be obtained. Then a noise threshold is subtracted from $|\hat{h}(t)|$ in order to remove those harmful time bins described above and only remain those useful time bins with good SNR whose amplitudes exceed the noise threshold. The result can be

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regarded as a weight distribution to multiply on the average waveform of all received reference pulses to form an improved correlation template. On the one hand, this correlation template gives the multipath components that have better SNR higher weights, so the signal energy combination is effective. On the other hand, this correlation template gets rid of the parts that contribute little to signal energy capture but large to raise noise level, so the harmful noise-on-noise term of decision variable is suppressed greatly. Considering above two aspects, the detection performance of the proposed system will improves significantly than that of ATR system at the cost of a limited complexity.

The paper is organized as follows. We firstly describe the system model of proposed scheme and analyze its detection performance in a multipath channel in Section 2. Section 3 presents the numerical results and discussion. Conclusions are given in Section 4.

2. System Model and Performance Analysis

We consider a single user UWB-TR noise suppression system using binary phase-shift keying (BPSK) modulation in a multipath channel with additive white Gaussian noise (AWGN). As shown in Fig. 1, a frame of transmitted data consists of M identical short PN reference sequences and subsequent N_d modulated data bits. Each PN reference sequence consists of N pulses with corresponding polarity. Each bit is composed of N_p repetitive pulses in order to gain adequate bit energy. The pulse repetition interval is T_p, and $T_d=N_pT_p$ is the bit repetition interval. In order to simplify the ensuing analysis, assuming that T_p is larger than the delay spread of the channel to avoid inter-pulse interference. Thus the transmitted signal $s(t)$ can be written as

$$\begin{aligned} s(t) &= \sum_{m=1}^{M}\sum_{i=1}^{N} b_i p(t - mNT_p - iT_p) \\ &+ \sum_{j=1}^{Nd}\sum_{k=1}^{Np} c_j p(t - MNT_p - jT_d - kT_p) \end{aligned} \quad (1)$$

where $b_i \in \{+1,-1\}$ is the ith element of the PN sequence $\{b_1, \ldots, b_i, \ldots, b_N\}$, $c_j \in \{+1,-1\}$ is the jth modulated data bit, $p(t)$ is a UWB short pulse with energy E_p. Since the antennas and the multipath channel will severely distort the received UWB pulse waveform, here we consider all these effects into the CIR $h(t)$ and describe it using the discrete time impulse response model as follows:

$$h(t) = \sum_{l=1}^{L} a_l \delta(t - l\Delta\tau) \quad (2)$$

where a_l is the multipath gain of the lth time bin, L is the total number of time bins, $\Delta\tau$ is the time bin duration which is set to be sufficiently small so that every time bin contains either only a multipath component or none. Assuming that $h(t)$ is time-invariant over a frame data duration, so the received signal $r(t)$ is

$$r(t) = s(t) * h(t) + n(t) \quad (3)$$

where * denotes convolution operation, $n(t)$ is a zero mean AWGN with two-sided power spectral density of $N_0/2$.

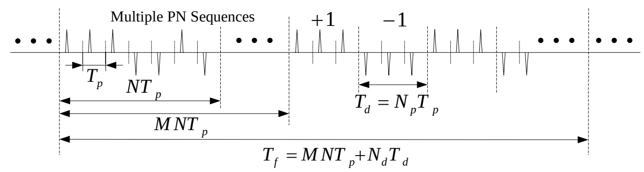


Fig. 1 A frame of transmitted data.

The receiver structure of this proposed system is shown in Fig. 2. Firstly, every received PN reference sequence $r_{PN}(t)$ is extracted and sent to a filter matched to the transmitted PN reference sequence $s_{PN}(t)$. It is critical that this filter is matched to the whole pulses of a transmitted PN reference sequence, and not just a UWB short pulse, so we call this a PN sequence matched filter. The filter can be easily implemented by using a bank of correlators with sliding window algorithm [9]. We denote its impulse response as $h_f(t) = s_{PN}(-t)$, so the output of the matched filter $\hat{h}_m(t)$ can be written as

$$\begin{aligned} \hat{h}_m(t) &= r_{PN}(t) * h_f(t) = \left(s_{PN}(t) * h(t) + n(t)\right) * h_f(t) \\ &= R_{s_{PN}}(t) * h(t) + n(t) * s_{PN}(-t) \end{aligned} \quad (4)$$

where $R_{s_{PN}}(t)$ is the autocorrelation function of $s_{PN}(t)$. Because a PN sequence has a fine autocorrelation function and a UWB short pulse has extremely sharp waveform, thus $R_{s_{PN}}(t)$ will be similar to $\delta(t)$ function when $t=0$, even if the PN sequence length N is a moderate value. Assuming that we use maximal length PN sequences, also called m sequences, $R_{s_{PN}}(t)$ can be written as

$$R_{s_{PN}}(t) = \begin{cases} 1, & t = 0 \\ -\dfrac{1}{N}, & t \neq 0, t = iT_p \\ 0, & t \neq 0, t \neq iT_p \end{cases} \quad (5)$$

We assume perfect synchronization and substitute (5) into (4), then

$$\hat{h}_m(t) = h(t) - \frac{1}{N}\sum_{i=1}^{N-1} h(t - iT_p) + n(t) * s_{PN}(-t) \qquad (6)$$

By averaging all of the $\hat{h}_m(t)$ of M identical PN reference sequences, the estimated CIR $\hat{h}(t)$ with better SNR can be obtained as follows:

$$\begin{aligned}\hat{h}(t) &= h(t) - \frac{1}{N}\sum_{i=1}^{N-1} h(t - iT_p) + \frac{\sum_{m=1}^{M} n_m(t) * s_{PN}(-t)}{M} \\ &= h(t) - e_h(t) + n_h(t)\end{aligned} \qquad (7)$$

In (7), the second item $e_h(t)$ is negligible compared to the first item $h(t)$ when N is large. Thus we can approximately express $\hat{h}(t)$ as

$$\begin{aligned}\hat{h}(t) &\approx h(t) + n_h(t) \\ &= \sum_{l=1}^{L} a_l \delta(t - l\Delta\tau) + n_h(t)\end{aligned} \qquad (8)$$

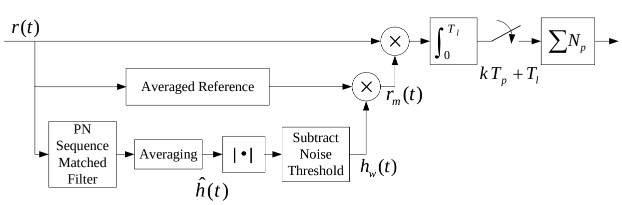


Fig. 2 The receiver structure

Next, a noise threshold Y_0 is subtracted from the absolute value $|\hat{h}(t)|$ in order to remove those harmful time bins mainly consist of noise. As a result, the L' ($L'<L$) strongest amplitude time bins with good SNR will be selected and remained in the output $h_w(t)$. Assuming that the number of reference pulses used for the CIR estimation $M \times N$ is large, a fairly accurate estimated $h_w(t)$ can be obtained and in which the noise $n_h(t)$ is small compared to the multipath gain $a_{l'}$. If we normalized Y_0 as one unit amplitude, Therefore we can approximately express $h_w(t)$ as

$$h_w(t) \approx \sum_{l'}^{L'} |a_{l'}| \delta(t - l'\Delta\tau) \qquad |a_{l'}| > 1 \qquad (9)$$

Considering the element polarities of the PN reference sequences, the averaged received reference signal $r_{avg}(t)$ is

$$\begin{aligned} r_{avg}(t) &= \frac{\sum_{m=1}^{M}\sum_{i=1}^{N} b_i \left(b_i p(t) * h(t) + n_{i,m}(t) \right)}{MN} \\ &= p(t) * h(t) + \frac{\sum_{m=1,i=1}^{MN} b_i n_{i,m}(t)}{MN} \\ &= \sum_{l=1}^{L} a_l p(t - l\Delta\tau) + \frac{\sum_{m=1,i=1}^{MN} b_i n_{i,m}(t)}{MN} \end{aligned} \qquad (10)$$

Thus $h_w(t)$ can be regarded as a weight distribution to multiply on $r_{avg}(t)$ to form an improved correlation template $r_m(t)$ as follows:

$$r_m(t) = r_{avg}(t) h_w(t) \qquad (11)$$

Then each subsequent received data pulse is multiplied with $r_m(t)$ and integrated over the time T_l. The sampling output statistic $z_{c,k}$ is given by

$$\begin{aligned} z_{c,k} &= \int_0^{T_l} r_m(t) r_{j,k}(t) d(t) \\ &= \int_0^{T_l} \left(\sum_{l=1}^{L} a_l p(t - l\Delta\tau) + \frac{\sum_{m=1,i=1}^{MN} b_i n_{i,m}(t)}{MN} \right) \left(\sum_{l'}^{L'} |a_{l'}| \delta(t - l'\Delta\tau) \right) \\ &\qquad \left(c_j \sum_{l=1}^{L} a_l p(t - l\Delta\tau) + n_{j,k}(t) \right) d(t) \\ &= \int_0^{T_l} c_j \sum_{l'}^{L'} |a_{l'}| a_{l'}^2 p^2(t - l'\Delta\tau) d(t) + \int_0^{T_l} c_j \sum_{l'}^{L'} |a_{l'}| a_{l'} p(t - l'\Delta\tau) \frac{\sum_{m=1,i=1}^{MN} b_i n_{i,m}(t)}{MN} d(t) \\ &\quad + \int_0^{T_l} \sum_{l'}^{L'} |a_{l'}| a_{l'} p(t - l'\Delta\tau) n_{j,k}(t) d(t) + \int_0^{T_l} \sum_{l'}^{L'} |a_{l'}| \frac{\sum_{m=1,i=1}^{MN} b_i n_{i,m}(t)}{MN} n_{j,k}(t) d(t) \\ &= U + X_1 + X_2 + X_3 \end{aligned} \qquad (12)$$

Assuming that the three noise items X_1, X_2 and X_3 approximate to be statistic independent zero mean Gaussian distributions, when c_j=1, the decision statistics $z_{1,k}$ can be written as

$$\begin{aligned} E\{z_{1,k}\} &= E\{U\} = E_p \sum_{l'}^{L'} |a_{l'}|^3 \\ Var\{z_{1,k}\} &\approx E\{X_1^2\} + E\{X_2^2\} + E\{X_3^2\} \\ &= \frac{E_p N_0}{2MN} \sum_{l'}^{L'} |a_{l'}|^4 + \frac{E_p N}{2} \sum_{l'}^{L'} |a_{l'}|^4 + \frac{N_0^2}{4MN} \sum_{l'}^{L'} |a_{l'}|^2 \end{aligned} \qquad (13)$$

The N_p sampling outputs $z_{1,k}$ are accumulated to produce the decision statistic of each bit z_1 as follows:

$$E\{z_1\} = N_p E_p \sum_{l'}^{L'} |a_{l'}|^3$$

$$Var\{z_1\} = (\frac{MN+1}{2MN}) N_p E_p N_0 \sum_{l'}^{L'} |a_{l'}|^4 + \frac{N_p N_0^{\ 2}}{4MN} \sum_{l'}^{L'} |a_{l'}|^2 \quad (14)$$

Considering BPSK is an antiploar modulation, so the bit error ratio (BER) of this proposed system P_e is

$$P_e = Q\left(\sqrt{\frac{E\{z_1\}^2}{Var\{z_1\}}}\right) = Q\left(\sqrt{\frac{\left(N_p E_p \sum_{l'}^{L'} |a_{l'}|^3\right)^2}{(\frac{MN+1}{2MN}) N_p E_p N_0 \sum_{l'}^{L'} |a_{l'}|^4 + \frac{N_p N_0^{\ 2}}{4MN} \sum_{l'}^{L'} |a_{l'}|^2}}\right) = Q\left(\sqrt{\frac{N_p}{(\frac{MN+1}{2MN})[\frac{\sum_{l'}^{L'} |a_{l'}|^4}{(\sum_{l'}^{L'} |a_{l'}|^3)^2}](\frac{N_0}{E_p}) + \frac{1}{4MN}[\frac{\sum_{l'}^{L'} |a_{l'}|^2}{(\sum_{l'}^{L'} |a_{l'}|^3)^2}](\frac{N_0}{E_p})^2}}\right) \quad (15)$$

We can also obtain the BER of ATR system P_{eATR} under the same conditions as

$$P_{eATR} = Q\left(\sqrt{\frac{N_p}{(\frac{MN+1}{2MN})(\frac{N_0}{E_p}) + \frac{1}{4MN}(\frac{N_0}{E_p})^2}}\right) \quad (16)$$

Compare (15) with (16), the difference lies in the coefficients of $\frac{N_0}{E_p}$ and $(\frac{N_0}{E_p})^2$. Since $|a_{l'}| > 1$, we can proved that $\frac{\sum_{l'}^{L'} |a_{l'}|^4}{(\sum_{l'}^{L'} |a_{l'}|^3)^2}$ and $\frac{\sum_{l'}^{L'} |a_{l'}|^2}{(\sum_{l'}^{L'} |a_{l'}|^3)^2}$ are both less than 1, thus $P_e<P_{eATR}$. That is to say, the proposed TR system has a superior detection performance than that of ATR system.

3. Simulation Results and Discussion

In this section, the performance of the proposed UWB-TR noise suppression system in a multipath channel with AWGN is evaluated and compared to that of the ATR system. Considering the situation of many indoor WSN applications, we use the IEEE 802.15.3a CM3 multipath channel model [5]. The CM3 model represents 4-10m NLOS multipath environment with a root-mean-square (RMS) delay spread of 15ns. Assuming N_p=5, we choose UWB pulse repetition frequency (PRF) to be 10MHz so that ISI can be negligible. We assume perfect system synchronization. The UWB pulse $p(t)$ is the second derivative of the Gaussian pulse with duration of 0.2ns. The short PN sequence is m sequence with length N equals to 7 and 15 respectively. For convenience, we also set the number of PN reference sequences M = 7 and 15 respectively. Other simulation parameters use the following settings: N_d=500, T_p=T_l=10*ns*.

Fig. 3 presents the performance of proposed UWB-TR system and the performance of corresponding ATR system in CM3 channel for (N=M=7 and N=M=15). In the following figures, we simply represent the proposed UWB-TR system as ‘PNTR(N,M)’.

It can be seen that the BER performance of the proposed system is better than that of the corresponding ATR system at all E_b/N_0 for N=M=7 case and N=M=15 case. It verifies the results of the analysis above and shows that this method can significantly improve the detection performance of TR system.

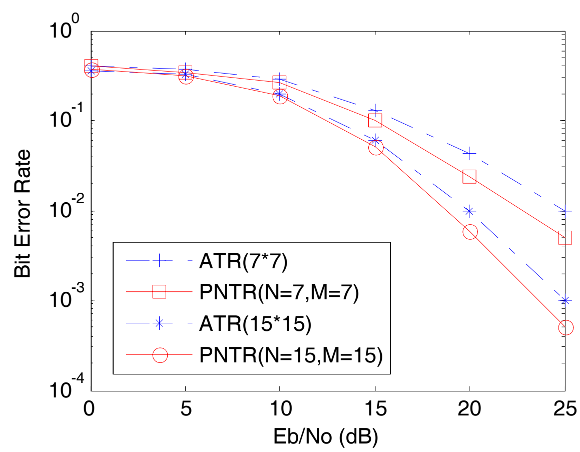


Fig.3 Performance comparison in CM3 channel for (N=M=7 and N=M=15)

Fig. 4 shows the performance of proposed UWB-TR system and the performance of corresponding ATR system in CM3 channel for (N=7, M=15 and N=15, M=7). We can see that with the equal total number of the reference pulses, the proposed UWB-TR system (*N*=7, *M*=15) has more superior performance than that of (*N*=15, *M*=7). It shows that the short PN sequence is enough to sound the CIR due to the extremely sharp waveform of a UWB pulse and the repetitive number of PN reference sequences *M* acts a more significant role to obtain the estimated CIR with better SNR than the length of PN sequence *N*.

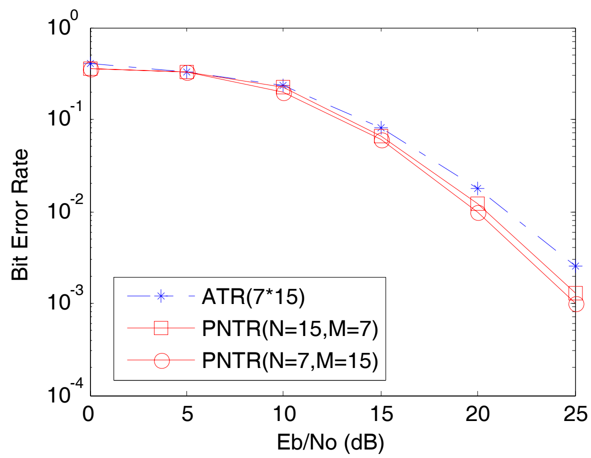


Fig.4 Performance comparison in CM3 channel for (*N*=7, *M*=15 and *N*=15, *M*=7)

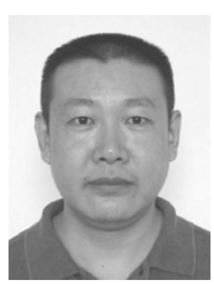
It must be noted that the proposed system requires a large number of reference pulses ($M \times N$) in order to obtain a fairly accurate CIR. Thus its information rate is not high. Considering these repetitive PN reference sequences can be also used to achieve system synchronization [10], so we should unite the channel sounding described above with the system synchronization by sharing all reference pulses. In this way, we can raise the information rate and also reduce the cost of implementing in some degree.

4. Conclusions

In this paper, we have proposed a new PN pulse sequences aided noise suppression scheme for UWB-TR communication system. In contrast to a commonly used ATR system, the proposed system replaces the repetitive reference pulses with multiple short PN reference pulse sequences. The receiver uses them to estimate the multipath CIR $h(t)$ and based on this to form an improved correlation template which removes the parts mainly consist of noise and gives the multipath components that have better signal-to-noise ratio higher weights. This turns out to improve the performance considerably. The analysis and simulation result verify this point and show that the proposed system has a superior BER performance compared with an ATR system. The scheme can be applied in many low-cost UWB wireless sensor network applications to achieve the better data communication. We believe that wireless sensor network based on UWB-TR communication technology will be applied to more industry areas in the future due to its inherent advantages.

References

[1] I. F. Akyildiz, S. Weilian, Y. Sankarasubramaniam, and et al, "A survey on sensor networks," *IEEE Communications Magazine*, vol. 40, issue 8, pp. 102-114, August 2002.
[2] J. Sachs, P. Peyerl, M. Roßberg: A New UWB-Principle for Sensor-Array Application, *IMTC99*, May, 1999 in Venice, Italy.
[3] K. Pahlavan, et al. An overview of wireless indoor geolocation techniques and systems, in: C.G. Omidyar (Ed.), *Mobile and Wireless Communications Networks Lecture Notes in Computer Science 2000*, LNCS 1818, Springer, Berlin, 2000, pp. 1–13.
[4] R. T. Hoctor and H.W. Tomlinson, "Delay-hopped transmited-reference RF communications," *Proc. IEEE Conference on Ultra Wideband Systems and Technologies*, pp.265-270. 2002.
[5] J. Foerster, IEEE P802.15 Doc, “Channel Modeling Sub-committee Report Final,” *IEEE P802.15-02/368r5-SG3a*, Dec. 2002.
[6] Y. L. Chao and R. A. Scholtz, “Optimal and suboptimal receivers for ultra-wideband transmitted reference systems”, *GLOBECOM*, pp. 759-763, December 2003.
[7] A. F. Molisch, J. R. Foerster, and M. Pendergrass, "Channel Models for Ultra-wideband Personal Area Networks," *IEEE Wireless Communications Magazine*, vol. 10, no. 6, pp. 14-21, December 2003.
[8] S. Franz and U. Mitra, “On Optimal Data Detection for UWB Transmitted Reference Systems”, *IEEE Global Telecommunications Conference*, vol.2, pp.744-748, December 2003.
[9] J. Proakis, *Digital Communications*, 4th ed. New York: McGraw-Hill, 2001.
[10] A. Rabbachin and I. Oppermann, “Synchronization analysis for UWB systems with a low-complexity energy collection receiver,” *Proc. Joint UWBST and IWUWBS*, pp. 288–292, May 2004.



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