UWB Autocorrelation Receiver Based on Average Differential Transmitted Reference

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Abstract—There are strong noise components included in the reference signal and the received signal of the ultra-wideband (UWB) differential transmitted reference (DTR) autocorrelation receiver, which impact on the receiver's performance seriously. Therefore this paper proposes a autocorrelation receiver based on average differential transmitted reference (ADTR). This receiver averages the received signals within every frame of the previous symbol period to form the new reference signal. The received signals within each frame of the current symbol interval are also averaged to construct the new received signal, which is correlated with the new reference signal to restore the transmitted symbols. Theoretical analysis and simulation results confirm that BER performance of ADTR autocorrelation receiver is better than the DTR receiver. Compared with DTR receiver, the signal to noise ratio gains of the ADTR receiver are 1.1dB with \( N_s = 3 \) and 2.1dB with \( N_s = 6 \) respectively when BER = 10^{-4}.

Index Terms—ultra-wideband, transmitted reference, differential transmitted reference (DTR), average differential transmitted reference (ADTR), and autocorrelation receiver

I. INTRODUCTION

In the recent years, ultra-wideband (UWB) of indoor short-range high-speed wireless communication technology has received more and more attentions from industry and academia. It uses very short duration pulses to deliver information and Rake receiver to receive the signal. Channel Estimation for UWB Rake receiver is undoubtedly a great challenge [2]. In order to avoid the problem of the channel estimation, the paper [3] proposes Transmitted Reference (TR) receiver. TR technology utilizes part of the received signal as the reference signal to demodulate the received signal. TR transmitter embeds the message signal and reference signal into the channel with time or frequency interval, which is enough small to ensure that the message signal and reference signal experience approximately channel fading. It is called Conventional Transmitted Reference (CTR) system [4]. CTR system uses 50% of time and energy to send the reference signal, so the energy efficiency and efficiency are very low [5]. In order to improve the energy and transmission efficiencies, the transmitter can also embed the differential encoded message signal into transmitting signal as a reference signal. In this way, the reference signal is the delay version of the previous message signal. This differential encoded TR system is called Differential Transmitted Reference (DTR) system [6]. The CTR / DTR system uses a reference signal containing noise, which is different from the traditional correlator. Therefore the correlator output contains a non-Gaussian noise component [7] and the reference signal containing noise degrades performance of the receiver [8][9]. A method to improve the receiver performance is to reduce the effect of noise in the reference signal. The TR system average several reference signal to reduce the noise impact in the reference signal comes into being, which is called the Average Transmitted Reference (ATR) system [6]. Assuming that the receiver knows some relevant information of channel response, the paper [10] proposes the TR-UWB receiver based on the statistical invariance principle. The paper [11] studies the binary phase shift keying transmitted reference UWB receiver's sensitivity to synchronization error over additive white Gaussian noise and multipath fading channels. Compared to the Rake receiver, TR receiver is not sensitive to synchronization error and is more sensitive to Signal to Interference and Noise Ratio (SINR). In order to reduce unit delay requirement in traditional transmitted reference UWB receiver so as to deal with broadband signals, the literature [12] proposes small frequency shift reference UWB signal transmission method.

Compared with the CTR system, the performance of the ATR system is improved, but the system still need to transmit a special reference signal. So energy and transmission efficiency is still low. Although the DTR system is no need to send a special reference signal and improve the energy and transmission efficiency, but the reference signal and the received signal still contains a
strong noise component, which reduces its performance. In order to improve the performance of the system, energy and transmission efficiencies at the same time, this paper presents the Average Differential Transmitted Reference (ADTR) UWB autocorrelation receiver with BPSK modulation. The ADTR system transmits the same form signal as the DTR system transmits. While the ADTR receiver averages the received signals within every frame of the previous symbol period to construct new reference signal, which is be used to demodulate the current symbol. The received signals within each frame in the current symbol interval are also averaged as the new reference, which be correlated with the new reference signal to recover the transmitted symbols. The receiver ensures the useful signal is constant, reduces the impact of noise on the receiver performance, and improves the bit error rate (BER) performance of the receiver.

II. SIGNAL MODEL

In this paper, the ADTR system adopts the Binary Phase Shift Keying (BPSK) modulation. Multiuser communication can be performed by the methods of direct sequence (DS) spreading codes or time-hopping codes. For simplicity, this paper only considers the case of single-user environment. \( b_j \in \{0,1\} \) present transmitted binary symbol and \( b_j \) are differential encoded into bipolar symbols \( d_j \in \{-1,1\} \), which is subject to a uniform probability distribution. UWB multipath channel recommended by IEEE 802.15.3a is adopted, which includes \( L \) multipaths. \( a_i \) and \( \tau_i \) present gain and delay of the \( i \)th path. \( p_0(t) \) is the transmitted UWB monopulse, whose width is \( T_p \). The received pulse is \( p_r(t) \), whose energy is \( E_p \). Every bit is transmitted over \( N_s \) pulses with average period \( T_I \). The energy and period of every bit are \( E_{p,n} = N_sE_p \) and \( T_I = N_sT_p \) respectively. The bandwidth of front band-pass filter of the receiver is \( W \). The integration time of the correlator of the receiver is \( T_I \).

The ADTR system transmits not special reference signal but the pulse sequence modulated by differential encoded bipolar binary symbol. The transmitted signal can be present as

\[
s_r(t) = \sum_{j=0}^{N_s} \sum_{k=0}^{N_s-1} d_j p_{r,n}(t - jT_p - kT_f - \tau_i).
\]  

After it passed through the multipath channel with Additive White Gaussian Noise (AWGN) and Band-pass filter, the received signal can be written as

\[
r(t) = \sum_{j=0}^{N_s} \sum_{k=0}^{N_s-1} \alpha_j d_j p_{r,n}(t - jT_p - kT_f - \tau_i) + n(t), \tag{2}
\]

where \( n(t) \) presents AWGN whose mean and variance are zero and \( N_0/2 \) respectively.

Consider the received signal in the \( n \)th (\( n > 1 \)) symbol interval. Its expression is

\[
r_n(t) = \sum_{k=0}^{N_s-1} \sum_{l=0}^{N_s-1} \alpha_i d_{n} p_{r,n}(t - nT_p - kT_f - \tau_i), \tag{3}
\]

where \( n(t) \) presents AWGN in the \( n \)th (\( n > 1 \)) symbol interval.

III. DTR RECEIVER

The structure of DTR autocorrelation receiver is shown in Fig.1. The DTR the receiver signal delays the received signal in the previous symbol until the current symbol interval, multiples it by the received signal in the current symbol interval integrates them in every frame and sums the integral results in all frame to form the correlator output about the current symbol. Then the sign decision is performed according to the sum.

\[
Z(n) = \sum_{k=0}^{N_s-1} \sum_{l=0}^{N_s-1} \alpha_i d_{n} p_{r,n}(t - nT_p - kT_f - \tau_i) \cdot n(t), \tag{4}
\]

where

\[
\begin{align*}
&n_1 = \sum_{k=0}^{N_s-1} \sum_{l=0}^{N_s-1} \alpha_i d_{n} p_{r,n}(t - nT_p - kT_f - \tau_i) \cdot n(t), \tag{5} \\
&n_2 = \sum_{k=0}^{N_s-1} \sum_{l=0}^{N_s-1} \alpha_i d_{n} p_{r,n}(t - nT_p - kT_f - \tau_i) \cdot (t - nT_p) \cdot n(t), \tag{6} \\
&n_3 = \sum_{k=0}^{N_s-1} \sum_{l=0}^{N_s-1} \alpha_i d_{n} p_{r,n}(t - nT_p - kT_f - \tau_i) \cdot n(t) \cdot (t - nT_p), \tag{7}
\end{align*}
\]

\( n_1, n_2 \) and \( n_3 \) can be approximated as independent zero-mean Gaussian variables [13-15].whose variable are respectively.
\[ E\{n^2_1\} = E\left\{ \sum_{k=0}^{N-1} \int n_{T_b+kT_f}^{T_b+kT_f} \sum_{l=0}^{L-1} \alpha_l d_{n-1} \right\} \]
\[ p_{re}(t-nT_b-kT_f-\tau_j)n_0(t)dt \]
\[ = \int n_{T_b+kT_f}^{T_b+kT_f} \sum_{l=0}^{L-1} \alpha_l d_{n-1} \]
\[ p_{re}(t-nT_b-kT_f-\tau_j)dt \]
\[ = \frac{N_0}{2} N_s E_p \sum_{l=0}^{L-1} \alpha_l^2 \]
\[ E\{n^2_2(t-T_b)\} \]
\[ = \frac{N_0}{2} N_s E_p \sum_{l=0}^{L-1} \alpha_l^2 \]
\[ E\{n^2_3\} = E\left\{ \sum_{k=0}^{N-1} \int n_{T_b+kT_f}^{T_b+kT_f} \right\} \]
\[ q_{n-1,m}(t) = \sum_{l=0}^{L-1} \alpha_l d_{n-1} \]
\[ p_{re}\left[t-(n-1)T_b-(N_s-1)T_f-\tau_j\right] \]
\[ = +n_{n-1,m}\left[t-(N_s-1-m)T_f\right] \]
\[ m_{n-1}(t) = \sum_{l=0}^{L-1} \alpha_l d_{n-1} \]
\[ p_{re}\left[t-(n-1)T_b-(N_s-1)T_f-\tau_j\right] \]
\[ + \frac{1}{N_s} \sum_{m=0}^{N_s-1} n_{n-1,m}\left[t-(N_s-1-m)T_f\right] \]
\[ m_{n-1}(t) \]

where \( E\{x\} \) denotes mathematical expectation of \( x \).

So we can obtain BER of the DTR receiver:
\[ P_{eDTR} = Q\left( \sqrt{\frac{E^2[Z(n)]}{E\{n^2_1\} + E\{n^2_2\} + E\{n^3\}}} \right) \]
\[ = Q\left( \sqrt{\frac{\left( \sum_{l=0}^{L-1} \alpha_l^2 E_{n_0} \right)^2}{N_0 E_p \sum_{l=0}^{L-1} \alpha_l^2 + \frac{N_0}{2} W T_f N_s^2}} \right) \]

where \( Q(x) \) denotes \( Q \) function.
B. Performance Analysis of the ADTR Receiver

According to the work procedure of the ADTR autocorrelation receiver, we can get the judgment variable on \( b_n \):

\[
Z(n) = \sum_{k=0}^{N-1} \int_{nT_k - (N_s-1)T_f + T_f}^{nT_k - (N_s-1)T_f} m_{n-1}(t - T_b) m_n(t) dt
\]

\[= E_p \sum_{l=0}^{l-1} \alpha_l^2 d_{n-l} d_n + n_1 + n_2 + n_3, \quad (16)\]

where three noise terms \( n_1, n_2 \) and \( n_3 \) can be approximated as independent zero-mean Gaussian variables[13-15]. They can be written respectively as

\[n_1 = d_{n-1} \frac{1}{N_s} \sum_{m=0}^{N_s-1} \sum_{l=0}^{l-1} \int_{nT_k - (N_s-1)T_f + T_f}^{nT_k - (N_s-1)T_f} \alpha_l dt\]

\[p_{re} \left[ t - nT_b - (N_s - l)T_f - \tau_f \right], \quad (17)\]

\[n_{n,m} \left[ t - (N_s - l)T_f \right] dt\]

\[n_2 = d_n \frac{1}{N_s} \sum_{m=0}^{N_s-1} \sum_{l=0}^{l-1} \int_{nT_k - (N_s-1)T_f + T_f}^{nT_k - (N_s-1)T_f} \alpha_l dt\]

\[p_{re} \left[ t - nT_b - (N_s - l)T_f - \tau_f \right], \quad (18)\]

\[n_{n-1,m} \left[ t - (N_s - l - m)T_f - T_b \right] dt\]

\[n_3 = \frac{1}{N_s^2} \sum_{k=0}^{N_s-1} \sum_{m=0}^{N_s-1} \int_{nT_k - (N_s-1)T_f + T_f}^{nT_k - (N_s-1)T_f} n_{n,k} dt\]

\[p_{re} \left[ t - nT_b - (N_s - l)T_f - \tau_f \right], \quad (19)\]

\[n_{n-1,m} \left[ t - (N_s - l - m)T_f - T_b \right] dt\]

So we can obtain that

\[E\{n_1^2\} = E\left[ d_{n-1} \sum_{m=0}^{N_s-1} \sum_{l=0}^{l-1} \int_{nT_k - (N_s-1)T_f + T_f}^{nT_k - (N_s-1)T_f} \alpha_l dt\right]\]

\[p_{re} \left[ t - nT_b - (N_s - l)T_f - \tau_f \right], \quad (20)\]

\[n_{n,m} \left[ t - (N_s - l)T_f \right] dt\]

\[E\{n_2^2\} = E\left[ d_n \sum_{m=0}^{N_s-1} \sum_{l=0}^{l-1} \int_{nT_k - (N_s-1)T_f + T_f}^{nT_k - (N_s-1)T_f} \alpha_l dt\right]\]

\[p_{re} \left[ t - nT_b - (N_s - l)T_f - \tau_f \right], \quad (21)\]

\[n_{n-1,m} \left[ t - (N_s - l - m)T_f - T_b \right] dt\]

\[E\{n_3^2\} = E\left[ \frac{1}{N_s^2} \sum_{k=0}^{N_s-1} \sum_{m=0}^{N_s-1} \int_{nT_k - (N_s-1)T_f + T_f}^{nT_k - (N_s-1)T_f} n_{n,k} dt\right]\]

\[p_{re} \left[ t - nT_b - (N_s - l)T_f - \tau_f \right], \quad (22)\]

\[n_{n-1,m} \left[ t - (N_s - l - m)T_f - T_b \right] dt, \quad (23)\]
\[
E\{n_i^2\} = \mathbb{E} \left[ \frac{1}{N_s^2} \sum_{n=1}^{N_s-1} \sum_{k=0}^{N_s-1} \{n_k - (N_s-1)T_f + T_f\} \right] \\
= \frac{1}{N_s^2} \sum_{m=1}^{N_s-1} \sum_{k=0}^{N_s-1} \{n_k - (N_s-1)T_f + T_f\} .
\]

Consider the mean of \( Z(n) \) and obtain that
\[
E\{Z(n)\} = \mathbb{E} \sum_{i=0}^{L-1} \alpha_i d_m d_n .
\]

So we can acquire the BER expression of the ADTR autocorrelation receiver:
\[
P_e^{ADTR} = Q \left( \frac{E^2 \{Z(n)\}}{E\{n_{i0}^2\} + E\{n_{i1}^2\} + E\{n_{i2}^2\}} \right) \\
= Q \left( \frac{N_s E_p \sum_{i=0}^{L-1} \alpha_i^2}{N_s E_p \sum_{i=0}^{L-1} \alpha_i^2 + \frac{N_s^2 W T_f}{2}} \right) .
\]

Substituting \( N_s E_p = E_b \) into (24) and doing some math operations, we obtain the BER expression of the ADTR autocorrelation receiver denoted with every bit energy:
\[
P_e^{ADTR} = Q \left( \frac{E_r \sum_{i=0}^{L-1} \alpha_i^2}{N_0} \right) .
\]

In order to facilitate the writing, do the following variable substitution:
\[
E_r = E_b \sum_{i=0}^{L-1} \alpha_i^2 ,
\]
\[
\beta = WT_f/2.
\]

Define signal to noise ratio (SNR) at the receiver:
\[
SNR = \frac{E_r}{N_0} .
\]

Substituting (26), (27) and (28) into (11) and (25) respectively, we obtain that
\[
P_e^{DTR} = Q \left( \frac{SNR}{\sqrt{SNR + \frac{\beta}{N_s}}} \right) ,
\]
\[
P_e^{ADTR} = Q \left( \frac{SNR}{\sqrt{SNR + \frac{\beta}{N_s}}} \right) .
\]

Equation (29) and (30) show that \( P_e^{DTR} \) and \( P_e^{ADTR} \) have the same denominator. Then if we want to compare \( P_e^{DTR} \) and \( P_e^{ADTR} \), we only need to compare their numerators according to the property of \( Q \) function. In order to conventionally compare them, we list the two noise term of their numerators in Table I.

<table>
<thead>
<tr>
<th>Type of receiver</th>
<th>DTR</th>
<th>ADTR</th>
</tr>
</thead>
<tbody>
<tr>
<td>Noise term1</td>
<td>SNR</td>
<td>SNR</td>
</tr>
<tr>
<td>Noise term2</td>
<td>( N_s \beta )</td>
<td>( \beta / N_s )</td>
</tr>
</tbody>
</table>

Table I shows that the DTR receiver has the same first as the ADTR receiver, but its second term is \( N_s^2 \) times of the second term of the ADTR receiver. Therefore the BER performance of the ADTR receiver presented in this paper is significantly better than the DTR autocorrelation receiver under the condition that system parameters of the DTR system are same as the ADTR system. In addition, the performance of ADTR receiver becomes much better when \( N_s \) increases. Theoretical analysis results show that the proposed ADTR averages the reference signal and the received signal respectively, the impact of noise on the receiver performance is reduced and the BER performance of the receiver is improved. This makes BER performance of the ADTR receiver significantly better than the DTR receiver.

IV. SIMULATION RESULTS AND ANALYSIS

To better verify that the proposed ADTR receiver performance, the BER performance of the DTR and ADTR autocorrelation receiver are simulated over typical UWB multipath channel model CM1 recommended by IEEE802.15.3a. Channel CM1 is the line of sight (LOS) and the distance between receiver and transmitter is 2m. The channel time resolution is 2ns, the observation time is 100ns and root-mean squared (RMS) delay spread is \( \tau_{rms} = 5.1212ns \). Frame time \( T_f = 10ns \) and integral time of correlator \( T_r = 10ns \). The second derivation of Gaussian pulse is adopted as UWB monopulse, whose time field expression is...
where $\tau_m=0.2\text{ns}$ denotes pulse-shaping factor and $T_p=0.5\text{ns}$. The waveform of the second derivation of Gaussian pulse with normalized amplitude in time domain is shown in Fig.3. Fig.4 shows the BER performances of the DTR and ADTR receivers with $N_s=3$.

It can be seen that compared with DTR receiver, BER of ADTR correlation receiver is improved evidently when $N_s=3$ from Fig.4. When BER = $10^{-4}$, the ADTR receiver has about 1.1dB SNR improvement than the DTR receiver. This verifies that the ADTR receiver can improve the system BER performance efficiently. Fig.5 gives the BER performances of the DTR and ADTR receivers with $N_s=6$.

Fig.5 shows that compared with Fig.4, the improvement of the ADTR receiver performance is more evident as the $N_s$ increases. When BER=$10^{-4}$, the ADTR receiver has about 2.1dB SNR improvement than the DTR receiver. These results certify that the ADTR receiver proposed in this paper averages the received signals in every frame of the previous symbol interval and the current symbol interval to construct the new reference signal and the new received signal respectively. This reduces the impact of noise on the performance of the receiver. BER performance of the receiver is improved evidently.

This paper presents an ADTR UWB autocorrelation receiver, which averages the received signals within every frame of the previous symbol period and the current symbol period to construct the new reference signal and the new received signal respectively, then correlates with each other to recover the transmitted symbol. This receiver keeps useful signal constant and reduces the impact of noise on the performance of the receiver at the same time. Then its BER performance is improved obviously. Theoretical BER performance of the ADTR receiver is analyzed and its BER expression is derived. Theoretical analysis and simulation results show that the ADTR receiver BER performance is significantly better than DTR receiver and compared with the DTR receiver, greater $N_s$ becomes, more obviously the performance is improved under the conditions of the same system parameters. Increasing $N_s$ will reduce the transmission rate. Thus, we need consider transmission rate and BER performance simultaneously to choose the value of $N_s$ in practical applications.

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