Non-Data-Aided Weighted Non-Coherent Receiver for IR-UWB PPM Signals

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This letter proposes an energy-detection-based non-data-aided weighted non-coherent receiver (NDA-WNCR) scheme for impulse radio ultra-wideband (IR-UWB) pulse-position modulated signals. Compared to the conventional WNCR, the optimal weights of the proposed NDA-WNCR are tremendously simplified as the maximum eigenvector of the IR-UWB signal energy sample autocorrelation matrix. The NDA-WNCR serves to blindly obtain the optimal weights and entirely circumvent the transmission of training symbols or channel estimation in practice. Analysis and simulation results verify that the bit error rate (BER) performance of the NDA-WNCR closely approaches the ideal BER of the conventional WNCRs.

Keywords: Energy detection, non-data aided, weighted non-coherent receiver, impulse radio, ultra-wideband.

I. Introduction

In recent years, weighted non-coherent receivers (WNCR) have been motivated for impulse radio ultra-wideband (IR-UWB) with simple circuitry [1]-[4]. Requiring no local template waveform generation and operating at the sub-Nyquist sampling rate, WNCR considerably facilitates system implementation and achieves cost-efficient devices.

In [1], weighted energy detection techniques were developed for IR-UWB systems with on-off keying modulation. The optimal weights and threshold were derived by maximizing the deflection coefficient of the symbol decision statistic. Based on [1], Wu and others [2] proposed a similar weighted symbol decision strategy for pulse position modulation (PPM) signals, where the optimal threshold-setting was intrinsically evaded. Although the WNCRs in [1] and [2] significantly outperformed the conventional NCR (CNCR) in alleviating the aggregated noise effect, they were only feasible when the channel state information (CSI) and the noise power density are known *a priori*. In a more general signal model, D'Amico and others [3] verified the derivations of [1] and [2] and presented a pilot-symbol-aided optimal weight estimation method which offered the best possible performance at the cost of an efficiency penalty in low data-rate applications incurred by transmission of training symbols. These drawbacks imply a desideratum for a rather different weighting approach when the channel becomes severely time varying. Some other works on detecting the IR-UWB PPM signal include [4], where the compressed likelihood ratio test demanded an all-digital front-end design and a prohibitively high sampling rate, and thus involved a significant complexity from the ADC and back-end computation point of view.

In order to circumvent the practical barriers in estimating the nuisance parameters of the CSI and the noise, the main goal of this letter is to formulate a non-data-aided WNCR (NDA-WNCR) scheme for the IR-UWB PPM signals. The NDA-WNCR has a threefold merit in practice: It is a completely blind WNCR scheme yielding no system overhead for obtaining the optimal weights. Demanding no *a priori* knowledge of the noise, it is immune to the noise power uncertainty effects. It possesses almost the same bit error rate (BER) performance as that of the WNCR, which is achieved under the condition that the *a priori* CSI is ideally known.

II. System Model

Let the received IR-UWB PPM signal be represented as

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$$y(t)=\sum_{i=-\infty}^{\infty} c_i \sum_{j=0}^{N_f-1} \varpi_{\mathrm{mp}}(t-iT_\mathrm{s}-jT_\mathrm{f}-d_iT_\Delta-\tau)+v(t), \quad (1)$$

where i, j, T_f, and T_s denote the symbol index, frame index, frame duration, and symbol interval, respectively. Each symbol is comprised of N_f frames, T_Δ is the PPM time shift, and τ is the coarsely synchronized timing offset between the transmitter and the receiver. The pulse-position symbols are restricted to $d_i \in \{0,1\}$, and the sequence $c_i \in \{-1,1\}$ accounts for the polarity randomization code introduced to smooth the signal spectrum. The effective multipath pulse is $\varpi_{\mathrm{mp}}(t)=\sqrt{E_\mathrm{b}/N_\mathrm{f}}\sum_{l=1}^{L_{\mathrm{mp}}}\alpha_l\varpi_l(t-\tau_l)$, where $\varpi_l(t)$ is the received UWB pulse at the l-th tap with unit energy, E_b is the symbol energy, α_l and τ_l are respectively the fading coefficients and delays of the multipath components, and $\sum_{l=1}^{L_{\mathrm{mp}}}\alpha_l^2=1$. When the pre-filter bandwidth W is sufficiently large, the additive white Gaussian noise (AWGN) is denoted by $v(t)$, with zero-mean and double-sided power spectral density $N_0/2$.

For simplicity, we omit the symbol subscript i hereinafter. In the WNCR scheme, each T_f is partitioned into $2K$ sub-intervals with equal length T_b. An integrate-and-dump square-law device operates to collect the received signal energy samples within the j-th frame as

$$y_{k,j}^{(m)}=\int_{(j-1/(m+1))T_\mathrm{f}+(k-1)T_\mathrm{b}}^{(j-1/(m+1))T_\mathrm{f}+kT_\mathrm{b}}\left|y(t)\right|^2 dt,\ \ m\in\{0,1\}, \quad (2)$$

where $k\in\{1,2,\cdots,K\}$, $j\in\{0,1,\cdots,N_\mathrm{f}-1\}$, and the $K\times N_\mathrm{f}$ aggregate received signal energy sample matrix is $\mathbf{Y}^{(m)}=[\mathbf{y}_0^{(m)},\mathbf{y}_1^{(m)},\cdots,\mathbf{y}_{N_\mathrm{f}-1}^{(m)}]$ with entry $[\mathbf{Y}^{(m)}]_{kj}=y_{k,j}^{(m)}$.

If we suppose $\boldsymbol{\omega}=[\omega_1,\omega_2,\cdots,\omega_K]^T$ is the target combining weight vector for the current symbol statistic of the WNCR, we can easily obtain the weighted symbol decision statistic by

$$\begin{aligned} Z_{\mathrm{WNCR}} &= tr(\boldsymbol{\Omega}^T\mathbf{Y}^{(0)})-tr(\boldsymbol{\Omega}^T\mathbf{Y}^{(1)}) \\ &=\sum_{j=0}^{N_\mathrm{f}-1}\boldsymbol{\omega}^T(\mathbf{y}_i^{(0)}-\mathbf{y}_j^{(1)})\gtrless 0 \begin{smallmatrix}\nearrow \hat{d}=0,\\ \searrow \hat{d}=1,\end{smallmatrix} \end{aligned} \quad (3)$$

where $\boldsymbol{\Omega}=\boldsymbol{\omega}\otimes\mathbf{1}_{N_\mathrm{f}}^T$ (Kronecker product), $\mathbf{1}_{N_\mathrm{f}}$ is a column vector of N_f ones, $\hat{d}$ is the demodulated symbol, and $tr(.)$ is the trace of a matrix. If $\forall k,j,[\boldsymbol{\Omega}]_{kj}=1$, Z_{WNCR} is reduced to the non-weighted CNCR symbol statistic, Z_{CNCR}.

According to the central limit theorem, when the time-bandwidth product $N_\mathrm{f}T_\mathrm{b}W$ is asymptotically large, Z_{WNCR} follows the Gaussian distribution [5]

$$Z_{\mathrm{WNCR}}\sim\begin{cases}\mathcal{N}(tr(\boldsymbol{\Omega}^T\boldsymbol{\Theta}),\ \ tr(\boldsymbol{\Omega}^T\mathbf{R}\boldsymbol{\Omega})),\ d=0,\\ \mathcal{N}(-tr(\boldsymbol{\Omega}^T\boldsymbol{\Theta}),\ \ tr(\boldsymbol{\Omega}^T\mathbf{R}\boldsymbol{\Omega})),\ d=1,\end{cases} \quad (4)$$

where

$$\begin{cases}\boldsymbol{\Theta}=E\left[\left|\tilde{\mathbf{Y}}\right|\right]=E\left[\left|\mathbf{Y}^{(0)}-\mathbf{Y}^{(1)}\right|\right],\\ \mathbf{R}=E\left[(\tilde{\mathbf{Y}}-\boldsymbol{\Theta})(\tilde{\mathbf{Y}}-\boldsymbol{\Theta})^T\right],\end{cases} \quad (5)$$

are the aggregate IR-UWB signal energy sample matrix and the covariance matrix of Z_{WNCR}, respectively.

By applying the BER minimization criterion [2], [3], the unnormalized optimal weights are obtained as

$$\boldsymbol{\Omega}_{\mathrm{WNCR}}^{(\mathrm{opt})}=\mathbf{R}^{-1}\boldsymbol{\Theta}, \quad (6)$$

and the corresponding BER performance of the WNCR is

$$P_{\mathrm{Err},1}=Q\left(\frac{tr\left(\left(\boldsymbol{\Omega}_{\mathrm{WNCR}}^{(\mathrm{opt})}\right)^T\boldsymbol{\Theta}\right)}{\sqrt{tr\left(\left(\boldsymbol{\Omega}_{\mathrm{WNCR}}^{(\mathrm{opt})}\right)^T\mathbf{R}\boldsymbol{\Omega}_{\mathrm{WNCR}}^{(\mathrm{opt})}\right)}}\right), \quad (7)$$

where $Q(x)=\int_x^{+\infty}\exp(-t^2/2)dt/\sqrt{2\pi}$. Note that when the optimal weights $\boldsymbol{\Omega}_{\mathrm{WNCR}}^{(\mathrm{opt})}$ in (6) are readily available in a slow varying or quasi-static channel environment, $P_{\mathrm{Err},1}$ gives the lowest BER performance bound of the WNCR.

III. Non-Data-Aided WNCR

1. Optimal Weights of the NDA-WNCR

In this section, we develop the NDA-WNCR. If $\mathbf{Y}^{(m)}$ contains the IR-UWB PPM signal component, then the statistically averaged signal-to-noise ratio (SNR) of the weighted symbol statistic Z_{WNCR} can be represented as

$$\gamma(\boldsymbol{\Omega})=\sqrt{\frac{T_\mathrm{b}W}{2}}\frac{tr(\boldsymbol{\Omega}^T\boldsymbol{\Theta})}{\sqrt{tr(\boldsymbol{\Omega}^T\boldsymbol{\Sigma}_0\boldsymbol{\Omega})}}, \quad (8)$$

where $\boldsymbol{\Sigma}_0=N_0^2T_\mathrm{b}W\mathbf{I}_K$, and $\mathbf{I}_K$ is a $K\times K$ identity matrix.

We realize that maximizing $\gamma(\boldsymbol{\Omega})$ in (8) is equivalent to maximizing $\Gamma(\boldsymbol{\Omega})=\gamma^2(\boldsymbol{\Omega})$, which is represented as

$$\Gamma(\boldsymbol{\Omega})\triangleq\alpha_1\frac{tr(\boldsymbol{\Omega}^T\mathbf{R}_\theta\boldsymbol{\Omega})}{tr(\boldsymbol{\Omega}^T\boldsymbol{\Sigma}_0\boldsymbol{\Omega})},\quad \alpha_1=\frac{T_\mathrm{b}W}{2}, \quad (9)$$

where $\mathbf{R}_\theta=E[(\mathbf{Y}^{(0)}-\mathbf{Y}^{(1)})(\mathbf{Y}^{(0)}-\mathbf{Y}^{(1)})^T]$ is the average autocorrelation matrix corresponding to the IR-UWB PPM signal energy matrix $\boldsymbol{\Theta}$.

Consequently, the optimal weights can be defined as

$$\begin{aligned}\boldsymbol{\Omega}_{\mathrm{NDA}}^{(\mathrm{opt})} &= \underset{tr(\boldsymbol{\Omega}^T\boldsymbol{\Omega})=N_\mathrm{f}}{\arg\max}\ \alpha_1\frac{tr(\boldsymbol{\Omega}^T\mathbf{R}_\theta\boldsymbol{\Omega})}{tr(\boldsymbol{\Omega}^T\boldsymbol{\Sigma}_0\boldsymbol{\Omega})}\\ &=\underset{\boldsymbol{\beta}^T\boldsymbol{\beta}=1,\ \boldsymbol{\Omega}=\boldsymbol{\beta}\otimes\mathbf{1}_{N_\mathrm{f}}^T}{\arg\max}\ \alpha_1N_\mathrm{f}\frac{\boldsymbol{\beta}^T\breve{\mathbf{R}}_\theta\boldsymbol{\beta}}{\boldsymbol{\beta}^T\boldsymbol{\beta}}\\ &=\underset{\boldsymbol{\beta}^T\boldsymbol{\beta}=1,\ \boldsymbol{\Omega}=\boldsymbol{\beta}\otimes\mathbf{1}_{N_\mathrm{f}}^T}{\arg\max}\ \alpha_1\alpha_2N_\mathrm{f}\frac{\boldsymbol{\beta}^T\mathbf{R}_\theta\boldsymbol{\beta}}{\boldsymbol{\beta}^T\boldsymbol{\beta}},\end{aligned} \quad (10)$$

where $\breve{\mathbf{R}}_\theta = \mathbf{C}^{-1}\mathbf{R}_\theta\mathbf{C}^{-T} = \boldsymbol{\Sigma}_0^{-1}\mathbf{R}_\theta = (N_0^2 T_\mathrm{b} W)^{-1}\mathbf{R}_\theta = \alpha_2\mathbf{R}_\theta$, $\boldsymbol{\beta} = \mathbf{C}^T\boldsymbol{\omega}$, and $\mathbf{C}$ is the Cholesky decomposition of $\boldsymbol{\Sigma}_0$, that is $\boldsymbol{\Sigma}_0 = \mathbf{C}\mathbf{C}^T$. The constraint of $tr(\boldsymbol{\Omega}^T\boldsymbol{\Omega}) = N_\mathrm{f}$ is set on the basis that $\Gamma(\boldsymbol{\Omega}) = \Gamma(\boldsymbol{\Omega}')$ for $\boldsymbol{\Omega}' = c\boldsymbol{\Omega}$, $\forall c \neq 0$.

Using the scalar Lagrange multiplier $\lambda_{\mathrm{Lag}} \in \mathcal{R}$, we obtain

$$\Gamma(\boldsymbol{\beta}) = \boldsymbol{\beta}^T\mathbf{R}_\theta\boldsymbol{\beta} + \lambda_{\mathrm{Lag}}(\boldsymbol{\beta}^T\boldsymbol{\beta} - 1), \tag{11}$$

where by taking the derivative of $\Gamma(\boldsymbol{\beta})$ with respect to $\boldsymbol{\beta}$, that is $\partial\Gamma(\boldsymbol{\beta})/\partial\boldsymbol{\beta} = 0$, we can easily find the optimal weight vector $\boldsymbol{\beta}_{\mathrm{opt}} = eig_{\max}(\mathbf{R}_\theta)/\| eig_{\max}(\mathbf{R}_\theta)\|_2$ ($\|\cdot\|_2$ denotes the Euclidean norm) as the maximum eigenvector of $\mathbf{R}_\theta$, corresponding to the largest eigenvalue of $\mathbf{R}_\theta$.

Finally, we obtain the weighted symbol decision statistic of the NDA-WNCR as

$$\begin{aligned} Z_{\mathrm{NDA}} &= tr((\boldsymbol{\Omega}_{\mathrm{NDA}}^{(\mathrm{opt})})^T\mathbf{Y}^{(0)}) - tr((\boldsymbol{\Omega}_{\mathrm{NDA}}^{(\mathrm{opt})})^T\mathbf{Y}^{(1)}) \\ &= \sum_{j=0}^{N_\mathrm{f}-1}\boldsymbol{\beta}_{\mathrm{opt}}(\mathbf{Y}^{(0)} - \mathbf{Y}^{(1)}) \gtrless 0 \begin{array}{l} \nearrow \hat{d} = 0, \\ \searrow \hat{d} = 1, \end{array} \end{aligned} \tag{12}$$

where $\boldsymbol{\Omega}_{\mathrm{NDA}}^{(\mathrm{opt})} = \boldsymbol{\beta}_{\mathrm{opt}} \otimes \mathbf{1}_{N_\mathrm{f}}^T$. Note that without any system overhead symbol, it is quite challenging to obtain accurate estimation of $\mathbf{R}_\theta$, because, in practice, the receiver is subject to stringently limited number of received signal energy samples for obtaining $\mathbf{R}_\theta$.

Similar to Z_{WNCR}, Z_{NDA} also complies with normal distribution:

$$Z_{\mathrm{NDA}} \sim \begin{cases} \mathcal{N}(tr((\boldsymbol{\Omega}_{\mathrm{NDA}}^{(\mathrm{opt})})^T\boldsymbol{\Theta}), tr((\boldsymbol{\Omega}_{\mathrm{NDA}}^{(\mathrm{opt})})^T\mathbf{R}\boldsymbol{\Omega}_{\mathrm{NDA}}^{(\mathrm{opt})})), & d=0, \\ \mathcal{N}(-tr((\boldsymbol{\Omega}_{\mathrm{NDA}}^{(\mathrm{opt})})^T\boldsymbol{\Theta}), tr((\boldsymbol{\Omega}_{\mathrm{NDA}}^{(\mathrm{opt})})^T\mathbf{R}\boldsymbol{\Omega}_{\mathrm{NDA}}^{(\mathrm{opt})})), & d=1, \end{cases} \tag{13}$$

and hence the BER performance of the NDA-WNCR is

$$P_{\mathrm{Err},2} = Q\left(\frac{tr((\boldsymbol{\Omega}_{\mathrm{NDA}}^{(\mathrm{opt})})^T\boldsymbol{\Theta})}{\sqrt{tr((\boldsymbol{\Omega}_{\mathrm{NDA}}^{(\mathrm{opt})})^T\mathbf{R}\boldsymbol{\Omega}_{\mathrm{NDA}}^{(\mathrm{opt})})}}\right). \tag{14}$$

2. Implementation of the NDA-WNCR

It is extremely challenging to acquire the IR-UWB PPM signal energy sample matrix $\boldsymbol{\Theta}$ in the absence of pilot symbols or *a priori* knowledge of the channel and the noise. Compared to $\boldsymbol{\Omega}_{\mathrm{WNCR}}^{(\mathrm{opt})}$ in (6), the derived optimal weights of the NDA-WNCR is significantly relaxed to solely rely on $\mathbf{R}_\theta$. This simplification substantially diminishes the difficulty to estimate the energy sample matrix $\boldsymbol{\Theta}$ and the covariance matrix $\mathbf{R}$ and greatly facilitates the weight-setting process.

Based on the records of the recently received symbol statistics, we propose a simple arithmetical averaging strategy for estimating $\mathbf{R}_\theta$ in practice:

$$\begin{aligned} \hat{\mathbf{R}}_\theta^{(i)} &= \frac{1}{N_\mathrm{f}L}\sum_{i'=i-L+1}^{i}\sum_{j=0}^{N_\mathrm{f}-1}(\mathbf{y}_{i',j}^{(0)} - \mathbf{y}_{i',j}^{(1)})(\mathbf{y}_{i',j}^{(0)} - \mathbf{y}_{i',j}^{(1)})^T \\ &\approx \eta\hat{\mathbf{R}}_\theta^{(i-1)} + \sum_{j=0}^{N_\mathrm{f}-1}\frac{(\mathbf{y}_{i,j}^{(0)} - \mathbf{y}_{i,j}^{(1)})(\mathbf{y}_{i,j}^{(0)} - \mathbf{y}_{i,j}^{(1)})^T}{N_\mathrm{f}}, \end{aligned} \tag{15}$$

where i is the time index of the current symbol statistic, $\mathbf{y}_{i',j}^{(m)}$ is the received signal energy sample vector of the j-th frame in the i'-th symbol, $\eta = N_\mathrm{f}(L-1)/N_\mathrm{f}L$, and L is the number of the most recently received symbols. Based on the estimated $\mathbf{R}_\theta$, that is, $\hat{\mathbf{R}}_\theta^{(i)}$, the corresponding estimation of $\boldsymbol{\beta}_{\mathrm{opt}}$ can be easily obtained with a low-complexity singular-value decomposition computation, which is proportional to $\mathcal{O}(K^3)$. Note that the receiver needs a minimum number of L symbols before the demodulation operation begins. This can be easily achieved through the system synchronization operations.

IV. Simulations

Monte-Carlo computer simulations are carried out to verify the BER performance of the proposed NDA-WNCR scheme and make comparisons with the performance of the CNCR and WNCR. The transmitted UWB monocycle pulse is of Gaussian shape with pulse width of 1 ns. The other simulation parameters are fixed as T_f= 120 ns, W=5 GHz, T_b=5 ns, N_f=1, and K=12.

Figure 1 gives the BER performance of the NDA-WNCR in two IEEE802.15.3a channel model (CM) environments; namely, CM 1 and CM 3. Compared to the WNCR, for which

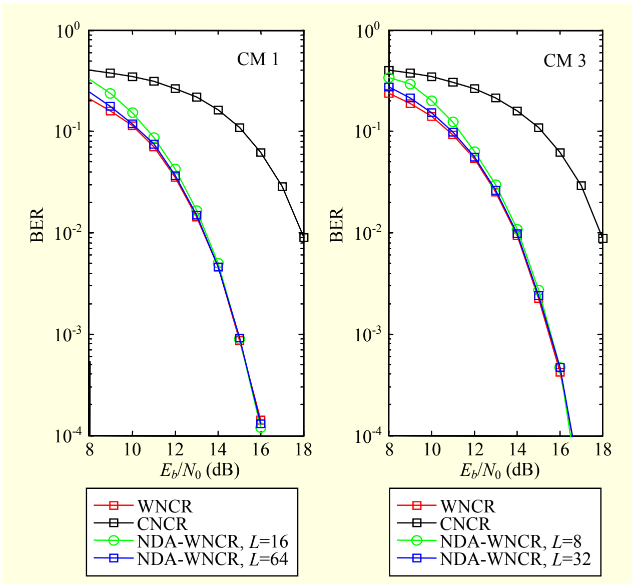

Fig. 1. BER performance of NDA-WNCR in CM 1 and CM 3.

the CSI knowledge is known prior to the symbol decision, the BER performance of the NDA-WNCR closely approaches that of the WNCR when the number of reference symbols (the most recently received symbols) is increased or when the SNR is becoming larger. This result validates the effectiveness of the NDA-WNCR weighting vectors.

V. Conclusion

A novel NDA-WNCR is proposed for IR-UWB PPM signals. The NDA-WNCR serves as a blind reception scheme operating on the received IR-UWB PPM signal energy sample autocorrelation matrix only. It is capable of obtaining the optimal weights without requiring any system overheads and eventually achieving almost the same BER performance as the ideal WNCR.

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