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RESEARCH ARTICLE

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A novel auto-reference ultra-wideband receiver scheme

Abstract A new auto-reference (AR) transmit-receive scheme and a corresponding group decision algorithm on the generalized likelihood ratio testing (GLRT) principle is proposed in this paper to overcome the drawbacks of the power inefficiency and the high noise vulnerability in transmitted-reference (TR) ultra-wideband (UWB) systems. A partly overlapped detection window structure is introduced in which the decided data frames are regarded as the reference signal so that energy and time resources in the reference frame are saved and full-rate data transmission is achieved. Differential coding was utilized to solve the error propagation problem introduced by the overlapped detection windows. The group decision algorithm on the GLRT principle was utilized to estimate the correlation template through all data frames in detection windows and could offer better noise suppression. Simulation results reveal that the AR scheme with its decision algorithm outperforms the conventional and other modified TR schemes in generalized signal-to-noise ratio (SNR).

Keywords ultra-wideband (UWB), transmitted-reference (TR), auto-reference (AR), generalized likelihood ratio testing (GLRT)

1 Introduction

The ultra-wideband (UWB) technology, as a viable candidate for short-range high-speed radio services, has many merits, including low-power density carrier-free transmissions, ample multi-path diversity, and low-complexity baseband transceivers [1]. Because of the fine time-resolution of the subnanosecond pulses, the RAKE receiver was proposed to capture the multi-path signal energy [2]. However, to take full advantage of the available signal energy, tens or hundreds of correlation operations may be required. This is too complex and unrealistic in practice. Hence, suboptimal schemes such as the transmitted-reference (TR) and its differential scheme were proposed [3,4], which can perform successful multi-path energy capture and detection without requiring channel estimation. However, TR UWB has its own drawbacks such as consuming extra power and time resources to transmit reference signals, and employs noisy received signals as the reference signals for data detection that significantly degrades the bit error rate (BER) performance. A couple of methods have been presented to suppress the noise of the reference signal template [3−7]. Optimal and suboptimal receiver schemes have been presented [4], where a reference-data pulse pair structure was adopted. With the block-structured TR (BTR) system and the GLRT principle proposed in Ref. [5], conventional pulse pair structure was broken and communication resources such as power and time were saved. The noise is suppressed with the use of reference and data frames in an observation window simultaneously. In this paper, we design an auto-reference (AR) system on the basis of the generalized likelihood ratio testing (GLRT) principle without the reference frames in a block. Compared with the block-structured structure, our scheme with partly overlapped windows structure can save communication resources, and improve the bandwidth and the power efficiency of UWB systems. Simulation results for indoor multi-path channels reveal a significant performance improvement in terms of BER over the simple transmitted reference (STR) receiver.

This paper is organized as follows. In Sect. 2, we provide the conventional STR, BTR and our AR system model. The GLRT-based auto-reference receiver structure is derived. Section 3 gives numerical results for different detection window sizes of data modulated symbols. Concluding remarks are presented in Sect. 4.

2 System model

2.1 Conventional TR and block-structured TR schemes

In this paper, the case of single user is considered. The time-hopping or direct sequence modulation, which is used to reduce multi-user interference, is eliminated for simplicity without loss of generality.

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A single user UWB system employing antipodal signaling in an indoor multi-path channel is assumed. The ith received symbol of the STR system can be expressed by

$$r_{\mathrm{TR},i}(t) = \sum_{n=0}^{N_s-1} (p(t - iT_b - nT_f) + b_i p(t - iT_b - nT_f - T_d)) + \omega(t) \quad (1)$$

where $b_j \in \pm 1$ is the jth data symbol, $p(t) = h(t) * g(t)$ is the convolution of the transmitted pulse waveform $g(t)$ and the channel impulse response $h(t)$. $\omega(t)$ is AWGN with two-side spectral density $N_0/2$. N_s is the pulse repetition time in a symbol. T_b is the symbol interval and T_d is the distance of the pulses in a frame. T_f is the frame interval which is larger than the delay spread of the channel to avoid inter-symbol interference, i.e., $T_f > 2T_d > 2T_{\mathrm{md}}$, where T_{md} is the channel's maximum delay spread .

The nth received block-structured signal of Ref. [5] can be described by

$$r_{\mathrm{BTR},n}(t) = \sum_{j=1}^{N_r} p(t - (j-1)T_f - nT_m) + \sum_{i=1}^{N_d} b_{n,i} p(t - (i-1)T_f - N_r T_f - nT_m) + \omega(t) \quad (2)$$

where N_r is the number of reference pulses in a block and N_d is the number of data symbols. The pulse repetition time within one symbol equals to 1. T_m is the length of a block. During the signal block, the channel response is assumed time-invariant.

The symbol decision of Eq. (1) is given by

$$D_{\mathrm{TR},i} = \mathrm{sgn}\left(\sum_{n=0}^{N_s-1} \int_{nT_f+T_d}^{nT_f+T_d+T_{\mathrm{md}}} r_{\mathrm{TR},i}\left(t - T_d\right) r_{\mathrm{TR},i}(t)\mathrm{d}t \right) \quad (3)$$

For the BTR scheme, the GLRT principle was proposed in Ref. [5]. For simplicity, the block index n is omitted. The correlation template can be obtained by

$$\bar{p}_i = \frac{1}{N_r + N_d - 1}\left(\sum_{j=1}^{N_r} r_{r,j} + \sum_{j=1, j\neq i}^{N_d} r_{d,j} \tanh\left(\frac{r_{d,j}\bar{p}_i}{\sigma^2} \right) \right) \quad (4)$$

where $r_{r,i}$ and $r_{d,i}$ are the sampling vector of the ith received reference and data modulated frame, respectively. The decision variable of the ith symbol can be expressed by

$$D_{\mathrm{BTR},i} = \mathrm{sgn}(r_{d,i}{}^{\mathrm{T}}\bar{p}_i).$$

However, Eq. (4) is not the closed-form expression but just a recursive expression. The approximate solution based on the piecewise linear function and the matrix inverse was given but omitted here.

2.2 Auto-reference transceiver scheme

2.2.1 AR signal model

In the AR-UWB scheme, data pulses are transmitted successively and no extra reference pulse is needed in the data pulse stream except for a few pilot pulses when the link was established. The received signal can be expressed by

$$r_{\mathrm{AR}} = \sum_{i=-\infty}^{\infty} r_i = \sum_{i=-\infty}^{\infty} \sum_{n=0}^{N_s-1} b_i p\left(t - iT_b - nT_f\right) + \omega(t) \quad (5)$$

Because indoor UWB channel is slow time-variant and each symbol interval is small, the channel within the span of multiple symbols can be assumed time-invariant. Because the detection performance is irrespective of the location of the reference pulses [8], we let the current detection window partly overlap with the previous window and regard the decided symbol pulses at the end of the previous window as the reference pulses of the current window. In other words, the reference frames in the current detection window are substituted by the last N_r data frames in the previous window and successive N_d pulses are the new data pulses, as can be depicted in Fig. 1. N_r and N_d should satisfy $N_r \geqslant 1$, $N_d \geqslant 1$, and $N_r + N_d = N_w \leqslant N_c$, where N_c is the maximum number of frames within the channel coherence time, i.e. all those data modulated frames in one detection window will experience the same channel. N_w, N_r and N_d can be adjusted according to the coherence time of the channel and the complexity request of the receiver. The detection window structure is independent

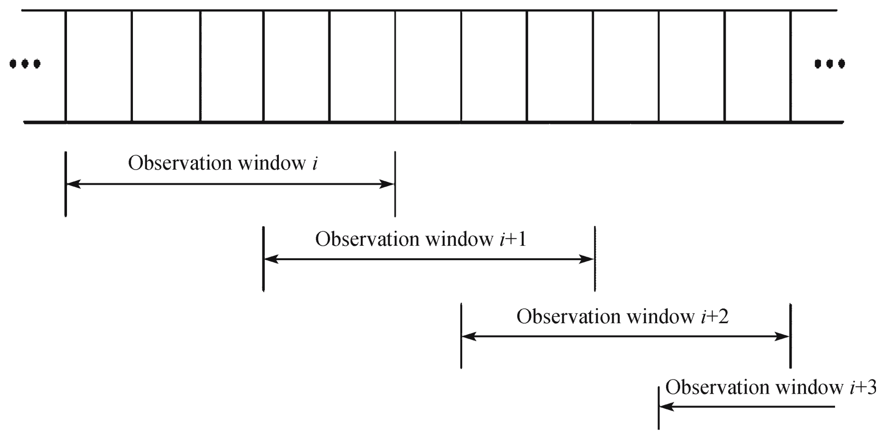

Fig. 1 Auto-reference receiver detection scheme

of the transmitter. Therefore, the current received signal in the detection window can be given by

$$\boldsymbol{r}=\begin{bmatrix}\bar{\boldsymbol{r}}_{r,1}\\ \vdots\\ \bar{\boldsymbol{r}}_{r,N_r}\\ \boldsymbol{r}_{d,1}\\ \vdots\\ \boldsymbol{r}_{d,N_d}\end{bmatrix}=\begin{bmatrix}\bar{b}_{r,1}\boldsymbol{p}\\ \vdots\\ \bar{b}_{r,N_r}\boldsymbol{p}\\ b_{d,1}\boldsymbol{p}\\ \vdots\\ b_{d,N_d}\boldsymbol{p}\end{bmatrix}+\begin{bmatrix}\bar{\omega}_{r,1}\\ \vdots\\ \bar{\omega}_{r,N_r}\\ \omega_{d,1}\\ \vdots\\ \omega_{d,N_d}\end{bmatrix} \tag{6}$$

where $\bar{\boldsymbol{r}}_{r,i}$ and $\bar{b}_i$ denote the ith referential data vector of the previous detection window and the ith estimate of referential data symbol, respectively; $\bar{\boldsymbol{\omega}}_{r,j}, \boldsymbol{\omega}_{d,i}$ denote the ith independent AWGN noise vector of the former data modulated frame and the current data modulated frame of length N respectively.

In order to reduce the complexity of detection and to compare with the BTR GLRT receiver, we suppose the simplest situation that $N_r = 1$ in the following discussion. Because the former data modulated frame acts as the reference frame, the referential data symbol estimation error will lead to unacceptable consecutive data block errors. For the purpose of eliminating error proliferation in the whole window, we introduce a differential encoder before the antipodal modulation. The information bit stream $C_i \in \{-1,1\}$ is passed through the differential encoder. The output encoded bit stream $b_i = b_{i-1}c_i$ is further sent to modulate the transmitted pulse data sequence, as shown in Fig. 2.

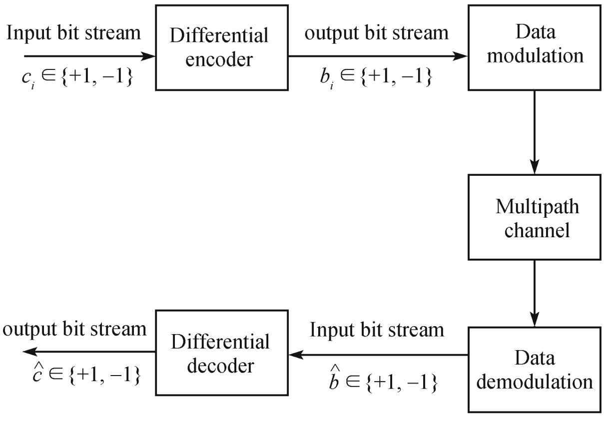

Fig. 2 Auto-reference system with differential encoder

2.2.2 Group detection algorithm

The coupled reference and data frames are transmitted in a conventional TR system, which can be extended from Eq. (2) by assuming $N_r = N_d = 1$, and the template signal is the reference frame

$$\hat{\boldsymbol{S}}_{\text{STR}} = \boldsymbol{r}_r \tag{7}$$

In the situation of multiple reference frames, the average transmitted reference (ATR) receiver provides a cleaner template signal by averaging the reference frames [4]

$$\hat{\boldsymbol{S}}_{\text{ATR}}=\frac{1}{N_r}\sum_{i=1}^{N_r}\boldsymbol{r}_{r,i} \tag{8}$$

The GLRT group detection algorithm was presented in Ref. [5] and it is easy to extend to our auto-reference system. When the data modulation b is drawn from {+1,–1} with probability 1/2, the GLRT estimate is applied to overlapped detection windows. When the ith symbol is to be detected, the other $N_d - 1$ symbols and the impulse response waveform vector $\boldsymbol{p}$ are all unknown parameters. Hence, the generalized likelihood ratio of symbol i can be obtained by

$$\begin{aligned} D_i &= \frac{\max\limits_{p:b_i=+1} P\left(r_{d,i} \mid b_i = +1\right)}{\max\limits_{p:b_i=-1} P\left(r_{d,i} \mid b_i = -1\right)} \\ &= \frac{P\left(r_{d,i} \mid \boldsymbol{p} = \bar{\boldsymbol{p}}_{(b_i=+1)}, b_i = +1\right)}{P\left(r_{d,i} \mid \boldsymbol{p} = \bar{\boldsymbol{p}}_{(b_i=-1)}, b_i = -1\right)} \end{aligned} \tag{9}$$

where $\max\limits_{p:b_i=\pm1} P(r_{d,i} \mid b_i = \pm 1)$ means the conditional probability and the maximum likelihood estimate $\boldsymbol{p}$ is given by the argument that maximizes the likelihood function $p_r\{r|\boldsymbol{p}\}$ over all $\boldsymbol{p}$ when $b_i = +1$ or $b_i = -1$ is true respectively. The conditional maximum likelihood estimate can be expressed by $\bar{\boldsymbol{p}}_{(b_i=+1)}$ and $\bar{\boldsymbol{p}}_{(b_i=-1)}$.

The symbol decision can be obtained by

$$\bar{b}_i = \operatorname{sgn}(D_i) \tag{10}$$

Substituting the Gaussian probability density function to Eq. (9), we can obtain the symbol decision

$$\begin{aligned} \bar{b}_i = \operatorname{sgn}\Big(&\boldsymbol{r}_{d,i}^{\mathrm{T}}\left(\bar{\boldsymbol{p}}_{(b_i=-1)} + \bar{\boldsymbol{p}}_{(b_i=+1)}\right) \\ &+ \frac{1}{2}\left(\left\|\bar{\boldsymbol{p}}_{(b_i=-1)}\right\|^2 - \left\|\bar{\boldsymbol{p}}_{(b_i=+1)}\right\|^2\right)\Big) \end{aligned} \tag{11}$$

Because $\bar{b}_{r,n}$ can be obtained from the previous window symbol decision and the received signal frames equate $\bar{r}_{r,n} = b_{r,n}\boldsymbol{p} + \bar{\omega}_{r,n}$, the first-step correlation template can be obtained by averaging

$$\hat{\boldsymbol{p}}=\frac{1}{N_r}\sum_{n=1}^{N_r}\bar{b}_{r,n}\bar{\boldsymbol{r}}_{r,n} \tag{12}$$

Through the correlation operation of the first-step template and the received data frames in the current detection window, we can attain the estimations of the parameters $b_{k(k\neq i)}$

$$\hat{b}_{k(k\neq i)} = \operatorname{sgn}\left(r_{d,k}\sum_{n=1}^{N_r}\bar{b}_{r,n}\bar{\boldsymbol{r}}_{r,n}\right) \tag{13}$$

With the estimation of $b_{k(k\neq i)}$ and the assumption $b_i = \pm 1$, the template estimate $\bar{\boldsymbol{p}}_{(b_i = \pm 1)}$ can be obtained by

$$\bar{\boldsymbol{p}}_{(b_i=\pm 1)} = \frac{1}{N_r + N_d}\left(\sum_{n=1}^{N_r} \bar{b}_{r,n}\bar{\boldsymbol{r}}_{r,n} + \sum_{k=1,k\neq i}^{N_d} \boldsymbol{r}_{d,k}\,\mathrm{sgn}\left(r_{d,k}\sum_{n=1}^{N_r}\bar{b}_{r,n}\bar{\boldsymbol{r}}_{r,n}\right) \pm \boldsymbol{r}_{d,i}\right) \tag{14}$$

Substituting Eq. (14) to Eq. (11), we can obtain the final decision of symbol i

$$\bar{b}_i = \mathrm{sgn}\left(\boldsymbol{r}_{d,i}^{\mathrm{T}}\bar{\boldsymbol{p}}^{(i)}\right) \tag{15}$$

where the final template

$$\bar{\boldsymbol{p}}^{(i)} = \frac{1}{N_r + N_d - 1}\left(\sum_{j=1}^{N_r} \bar{b}_j\bar{\boldsymbol{r}}_{r,j} + \sum_{j=1,j\pm i}^{N_d} \bar{\boldsymbol{r}}_{d,j}\,\mathrm{sgn}\left(\boldsymbol{r}_{d,j}\sum_{j=1}^{N_r}\bar{b}_{r,j}\bar{\boldsymbol{r}}_{r,j}\right)\right) \tag{16}$$

From Eq. (16) we can see that the template for symbol i is irrespective of the symbol i's received signal. Based on Eqs. (15) and (16), we can acquire all the symbol decisions sequentially. The decided symbols and their received frames can be utilized as the reference signal of the next detection window. After the decisions, the decided data are sent to a differential decoder

Once b_i is obtained, the original bit stream can be decoded from $c_i = b_{i-1}b_i$.

3 Simulation results and analysis

The theoretical analysis of STR was given in many references, which is omitted here. Because the correlation templates of AR and BTR schemes are both nonlinear functions of received signal, the BER performance is difficult to analyze and the closed-form expressions are not given here. Nevertheless, the modified Cramér-Rao bound (MCRB) Ref. [9] of the three schemes can be compared.

For the STR scheme, the template is the reference frame. It is easy to confirm that the variance of STR is equal to the noise variance σ^2. For the AR and BTR schemes, the template of each symbol is related to the other symbols in the current detection window. The MCRB which is looser than the CRB is given by Ref. [9]

$$M_{(p)} = \mathrm{DIAG}[\boldsymbol{F}_{M(p)}{}^{-1}] \tag{17}$$

where $\boldsymbol{F}_M$ is an $N \times N$ dimension modified Fisher information matrix of which elements are

$$[\boldsymbol{F}_{M(p)}]_{ij} = -E\left\{\frac{\partial^2 \ln P(\boldsymbol{r} \mid \boldsymbol{p}, b)}{\partial \boldsymbol{p}_i \partial \boldsymbol{p}_j}\right\} \tag{18}$$

We can obtain that the MCRBs of the template estimate of AR and BTR scheme are identical, i.e.

$$\mathrm{var}(p_i) \geqslant \frac{\sigma^2}{N_r + N_d} \tag{19}$$

The transmission efficiency of the STR, BTR and AR schemes are compared with the assumption of $N_s = 1$. Because the reference pulses and data pulses are always transmitted in pairs, the transmission efficiency β equates to 1/2 in the STR system. The transmission efficiency of BTR depends on the block structure. It can be expressed as

$$\beta = \frac{N_d}{N_r + N_d} \tag{20}$$

If $N_r = 1$ and $N_d = 10$, $\beta = 0.909$. While no extra reference pulses are inserted in the AR scheme, the data are transmitted in full rate and the transmission efficiency is always 1. That means the AR system can acquire the maximum transmission rate when N_s and T_f are the same as that of the STR and BTR system.

The performance of different TR systems is simulated and compared with our auto-reference scheme. The transmitted pulse waveforms are given by second derivative Gaussian function

$$p(t) = \left(1 - \frac{4\pi t^2}{\tau^2}\right)\mathrm{e}^{-2\pi\left(\frac{t}{\tau}\right)^2} \tag{21}$$

where τ is set to 0.7 ns. The UWB line-of-sight (LOS) indoor multi-path channel (CM1) proposed in "Channel modeling subcommittee report final" (http://grouper.ieee.org/groups/802/15, Nov. 2002, IEEE P802.15-02/368r5-SG3a) is adopted. The delayed components of the multi-path signal arrive in clusters and each cluster contains multiple rays. It is assumed that the arrival time of the cluster and the ray follows exponential rate laws with a cluster arrival rate of $\Lambda = 0.023\,3$ ns and a ray arrival rate of $\lambda = 2.5$/ns. The received signal amplitude is modeled as a Rayleigh random variable with a mean-squared value following a double exponential law with the inter-cluster signal level rate of decay given by $\Gamma = 7.1$ ns and the intra-cluster rate of decay given by $\gamma = 4.3$ ns. The frame time T_f and correlation integration time are both set to 40 ns, which are far more than the excess delay, and the energy of the multi-path components arriving after 40 ns can be neglected. Sampling period is set to 0.1 ns.

As described in Sect. 2, we assume that the length of the detection window is less than the coherence time of the channel. Therefore, during the detection window, the channel and the impulse response waveforms remain invariant. The number of referential signal frame N_r is set to 1 and the differential encoder is employed before data modulation, as depicted in Fig. 2. The BER versus generalized E_b/N_0 curves for the STR, the BTR GLRT receiver, and the AR receiver with different N_d, are utilized in Fig. 3. The consumed energy in the reference frame is considered and converted into effective E_b to form generalized E_b/N_0, where $N_0/2$ is the variance of noise. It can be seen that both the BTR and AR systems show significant performance improvements in comparison with STR. The gains grow with the increase of N_d. This is the reason why both schemes have utilized the information of the response waveform included in the other data frames. The increase of N_d means that more samples can be employed to estimate the impulse response waveform. Although the differential encoder introduces error propagation, the loss will be very small in high E_b/N_0. The gain of the AR receiver over the BTR receiver decreases with the increase of N_d because the performance gain over the BTR scheme mainly comes from the elimination of the reference pulses. Similar results can be found in Fig. 4.

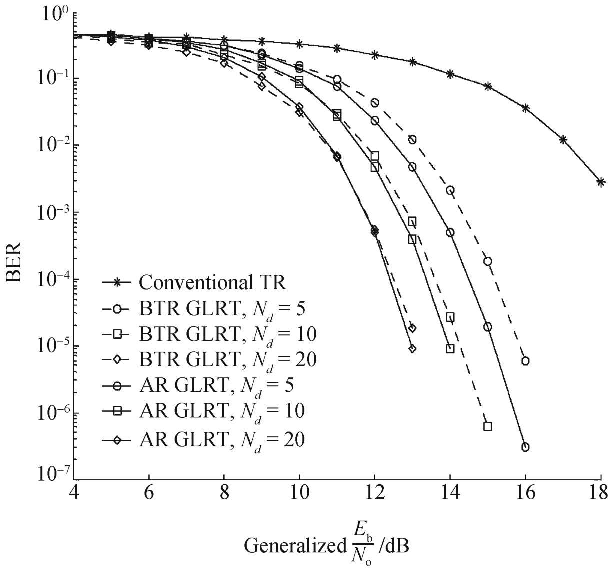

Fig. 3 The BER comparison of the TR and AR receivers with $N_r = 1$ and different $N_d = 5$, 10 and 20

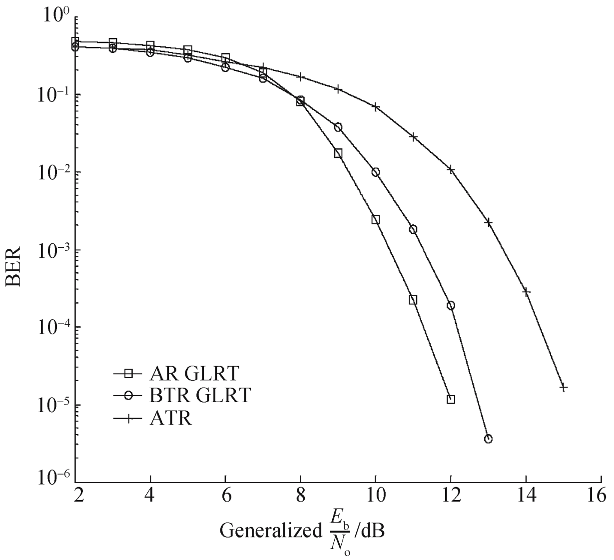

Fig. 4 The BER comparison of the ATR, BTR and AR receivers with $N_r = 5$ and $N_d = 16$

Figure 4 shows the BER performance of the STR, ATR, and AR schemes when $N_r = 5$ and $N_d = 16$, i.e. the length of the detection window N_w is still unchanged. We can find that the BER performance improves with the increase of the overlapped frames in one detection window, and the gain of the AR receiver over the BTR receiver increases at the same time.

4 Conclusions

An auto-reference system was presented in which data frames were transmitted consecutively and data symbols were detected in the overlapped detection windows. Data modulated frames in the tail of the previous detection window were utilized as the autocorrelation template of the next detection window. The simplest situation that one overlapped data frame was regarded as reference frame has been discussed and the differential encoder was introduced before the data modulation to overcome symbol estimate error proliferation. The parameters of the detection windows are flexible to adjust according to the channel coherence time in the receiver end and independent of transmitter ends. Simulation results have shown that the auto-reference system can achieve better BER performance than conventional TR and BTR GLRT schemes. It is obvious that the BER performance improves with the number of overlapped data frames and the length of detection windows while the complexity increases simultaneously. The tradeoff between the performance and the complexity should be considered. Nevertheless, the highest transmission efficiency was obtained via eliminating extra reference pulses.

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