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An improved hypothesis-feedback equalization algorithm for multicode direct-sequence spread-spectrum underwater communications

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Abstract In underwater acoustic communication, because the available bandwidth of the channel is severely limited, the direct-sequence spread-spectrum scheme can only be realized at low bit rates. To improve the transmission speed, a multicode spread-spectrum scheme is considered. However, in this case, due to the rapid time-variability of the underwater channel, and the influence of inter-symbol interference (ISI) and inter-channel interference (ICI), the conventional rake receiver may fail to function. The hypothesis-feedback equalization algorithm has been proposed for the direct-sequence spread-spectrum system [1]. By updating coefficients at chip rate and feeding back hypothesized chips, it can track time-variability and combat ISI effectively. However, for a multicode system, its performance will be degraded by ICI. An improved algorithm is proposed in this paper, which combines parallel interference cancellation (PIC) with hypothesis-feedback equalization (HFE), with the capabilities of tracking the time-varying channel and suppressing the ISI and ICI at the same time. Simulation results prove that the proposed algorithm can significantly improve the performance of a multicode system.

Keywords underwater communication, multicode spread spectrum, hypothesis-feedback equalization, parallel interference cancellation

1 Introduction

Direct-sequence spread spectrum (DSSS) exhibits resistance against inter-symbol interference (ISI) with the ability to

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achieve robust data link at low signal-to-noise ratio (SNR). Its application in underwater acoustic (UWA) channels has been studied extensively over the years [2–4]. However, limited by the available bandwidth of the underwater channel, its transmission data rate is very low. One solution to this problem is multicode modulation, which provides higher band efficiency and has been developed for high-speed data transmission within wireless environments [5]. In this method, the incoming high-rate data stream is divided into a number of parallel low-rate bit streams as those in multitone modulation. However, the low-rate bit streams are modulated with orthogonal sequences rather than orthogonal carriers in order to separate the different sub-channels.

To use the multicode scheme in the UWA environment, two key problems must be solved. First, multi-path produces ISI and inter-channel interference (ICI). Second, the rapid time-varying characteristics of the UWA channel. Due to these factors, the conventional rake receiver is not capable of dealing with the time-variability, and the orthogonality among sub-channel codes is destroyed, which will lead to serious performance degradation of the receiver.

Adaptive equalization methods can be employed to deal with this situation. Its structure groups fall into two categories: symbol equalizers and chip equalizers. The first class of adaptive receivers is updated at symbol rate level. These receivers suffice the majority of the radio applications [6]. However, in the rapid time-varying environments where the channel changes over one symbol interval, which are not negligible, they may fail to converge and produce reliable symbol decisions. Therefore, another class of receivers is designed, which adapts its coefficients at chip rate and thus is capable of tracking the channel with large Doppler shift and spread [7]. These chip equalizers invert the channel and restore the orthogonality of the sub-channel sequences destroyed by the multipath transmission. Because of the lack of reliable chip decisions, most chip equalizers are linear and preclude feedback taps, which may lead to noise enhancement [8]. This fact motivates the search for a detection strategy that provides reliable chip decisions before despreading has taken place. In

Ref. [1], a decentralized hypothesis-feedback equalization (HFE) algorithm offers such a solution, which feedbacks the hypothesized rather than the actual decisions. This method has been used in multi-user underwater communication, but for a multicode system, its performance will be degraded by ICI.

In this paper, an improved parallel interference cancellation hypothesis-feedback equalization (PIC-HFE) algorithm is proposed for multicode communication. Simulation demonstrates that PIC-HFE outperforms the decentralized HFE with the enhanced ability to suppress ICI.

In Sect. 2 the multicode system model is described and in Sect. 3 the PIC-HFE algorithm is given. Then its performance is analyzed in Sect. 4. Finally, the conclusions are summarized in Sect. 5.

2 Multicode system model

Figure 1 shows the transmitter and the receiver of the multicode modulation system that has been proposed in Ref. [5]. In this system, the incoming high-rate data bits with duration T_b are serial-to-parallel converted into K low-rate bit streams with symbol duration $T = KT_b$. After that, the symbols on each branch are multiplied by Walsh codes and then modulated via using direct-sequence spread-spectrum in order to separate different sub-channels and reduce the multi-path interference.

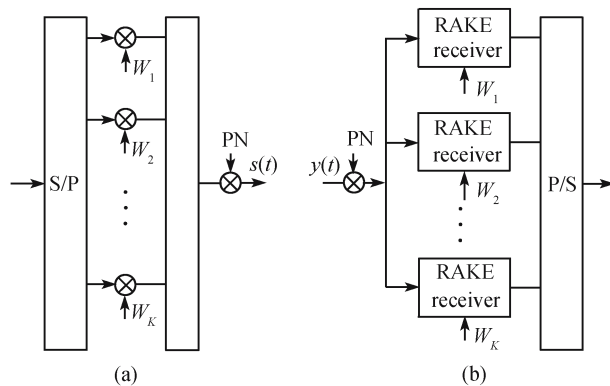


Fig. 1 Multicode system model
(a) Transmitter; (b) receiver

The transmitted signal on the k th sub-channel can be represented as

$$u_k(t) = \sum_i \sqrt{2A} d_k(i) g(t - iT_c) \quad (1)$$

Where A is the sub-channel signal power, T_c is chip duration, $g(t)$ is the transmitter's impulse response, and $d_k(i)$ is the spread information sequence. Denoting the information symbol transmitted at time nT by $D_k(n)$, the spread sequence is given by

$$d_k(i) = D_k(n) c_k(l), \quad i = nL + l, \quad l = 0, 1, \dots, L-1 \quad (2)$$

$$c_k(l) = W_k(l) \text{PN}(l) \quad (3)$$

Where L is the processing gain, $c_k(l)$ is the k th sub-channel's concatenated code including the Walsh code $W_k(l)$ and common PN sequence $\text{PN}(l)$. The baseband transmitted signal is

$$s(t) = \sum_{k=1}^K u_k(t) \quad (4)$$

Passing $s(t)$ through the time-varying multi-path channel, whose complex lowpass equivalent impulse response is given by

$$h(t) = \sum_{p=1}^P \beta_p \delta(t - \tau_p) e^{j\theta} \quad (5)$$

where P is the number of paths, β_p is the time varying complex-valued gain of the p th propagation path, τ_p is the corresponding path delay and θ is additional phase distortion that may arise due to motion or offset of the local carrier. Then, the received signal, denoted as $y(t)$, can be expressed as

$$y(t) = \sum_{k=1}^K \sum_{p=1}^P \beta_p u_k(t - \tau_p) e^{j\theta} + n(t) \quad (6)$$

where $n(t)$ is the channel noise.

The original receiver [5] for the multicode modulation system consists of K rake receivers, shown in Fig. 1(b). It coherently demodulates the received signal to recover K sub-channel bits respectively. Figure 2 shows the structure of the sub-channel rake receiver which consists of P taps aligned with the accurate time arrival of the paths. Ignoring the effect of the channel noise, and then the correlator's output of the p th tap of the k th sub-channel is [9]

$$\begin{aligned} Z_k^p(n) &= T\sqrt{2A}\beta_p \hat{\beta}_p D_k(n) + T\sqrt{2A} \sum_{\substack{p'=1 \\ p' \neq p}}^P \beta_{p'} \hat{\beta}_p X_{k,k}^{p'}(n) \\ &\quad + T\sqrt{2A} \sum_{\substack{k'=1 \\ k' \neq k}}^K \sum_{p'=1}^P \beta_{p'} \hat{\beta}_p X_{k,k}^{p'}(n) \\ &= E_k^p(n) + F_k^p(n) + I_k^p(n) \end{aligned} \quad (7)$$

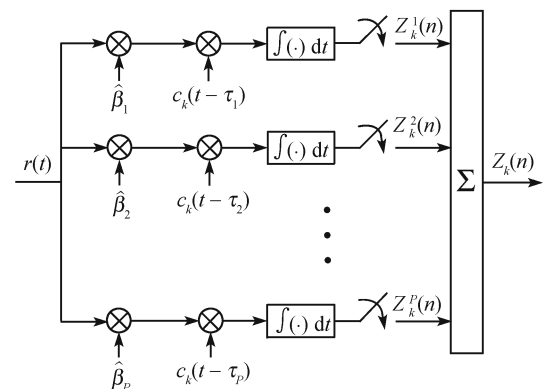


Fig. 2 The structure of the k th sub-channel's rake receiver

where $\hat{\beta}_p$ represents the weight of the p th tap and the estimate of β_p , $X'_{k,k'}(n)$ is defined as

$$X'_{k,k'}(n) = \frac{1}{T} [D_k(n-1+q)R_{k,k'}(\Delta+qT) + D_k(n+q)\hat{R}_{k,k'}(\Delta+qT)] \quad (8)$$

$\Delta = \tau_{p'} - \tau_p, j = 0$ or 1 for $\Delta \geq 0$ or $\Delta < 0$ respectively, and

$$R_{k,k'}(\tau) = \int_0^\tau c_{k'}(t-\tau)c_k(t)dt$$

$$\hat{R}_{k,k'}(\tau) = \int_\tau^T c_{k'}(t-\tau)c_k(t)dt$$

Therefore, the total output of the k th sub-channel's rake receiver is

$$Z_k(n) = \sum_{p=1}^P E_k^p(n) + \sum_{p=1}^P F_k^p(n) + \sum_{p=1}^P I_k^p(n)$$

$$= E_k(n) + F_k(n) + I_k(n) \quad (9)$$

where $E_k(n)$ is the correlator's output of the n th bit of the k th sub-channel, F_k and I_k are the corresponding ISI and ICI terms, respectively. Therefore, in the rapid time-varying multi-path environment of the underwater channel, the conventional rake receiver may fail to function. That is why the PIC-HFE algorithm is proposed.

3 PIC-HFE algorithm description

The detailed description of a hypothesis-feedback equalization method for DSSS is presented in Ref. [1]. It is based on hypothesizing the value of the data symbol as $+1$ or -1 in the case of binary modulation. For each hypothesis, an adaptive chip-rate decision feedback equalization is performed. Data detection is performed by choosing the hypothesis with lower mean squared error (MSE) at the end of each bit interval. At the same time, the receiver parameters corresponding to the winning hypothesis are retained for use in the next bit interval, which consists of a number of chip intervals equal to the processing gain. The hypothesis-feedback equalization structure is shown in Fig. 3(a). In such a manner, it is possible to update the receiver parameters at the chip rate, which may be necessary for rapid time-varying channels. This method operates in a decentralized way and can be employed by multicode system receiver directly. However, without taking ICI into account, the symbol detection performance is degraded. The optimum hypothesis-feedback equalization in the multicode system is to hypothesize all 2^k possible combinations of the data symbol at K sub-channels and then choose one with the minimum MSE. In this case, however, the computational complexity will grow exponentially with the number of the sub-channels. In this paper, a suboptimum method called PIC-HFE is proposed, which combines parallel interference cancellation with the hypothesis-feedback equalization. The PIC-HFE algorithm can improve the performance of

multicode system significantly and the computational complexity stays linear with the number of the sub-channels.

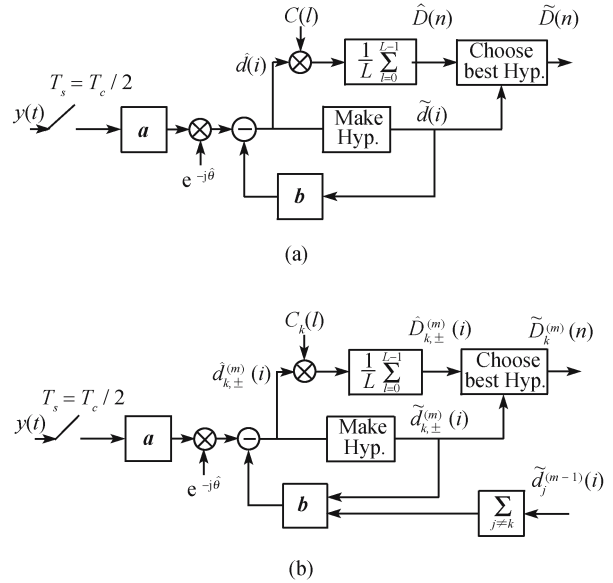


Fig. 3 The structure of hypothesis-feedback equalizer
(a) Decentralized HFE; (b) PIC-HFE (stage m)

The PIC-HFE algorithm operates iteratively to detect symbols. The structure of m stage iteration is shown in Fig. 3(b). It executes the following steps:

At first, hypotheses are made for the transmitted information symbol. For BPSK, the two hypotheses for the n th bit of sub-channel k are

$$\tilde{d}_{k,\pm}^{(m)}(nL+l) = \pm c_k(l), \quad l = 0, 1, \dots, L-1 \quad (10)$$

where superscript m is the iteration stage index, $\tilde{d}_{k,\pm}^{(m)}$ is the chip sequence corresponding to the hypothesized bit $+1$ or -1 .

Secondly, for each hypothesis, the corresponding chips and previous stage detection results of other sub-channels are fed back to produce an estimate of the current chip

$$\hat{d}_{k,\pm}^{(m)}(i) = \mathbf{a}'_{\pm}(i)\mathbf{y}(i)e^{-j\hat{\theta}_{\pm}(i)} - \mathbf{b}'_{\pm}(i) \left[\tilde{d}_{k,\pm}^{(m)}(i) + \sum_{j=1, j \neq k}^K \tilde{d}_j^{(m-1)}(i) \right]$$

$$i = nL, nL+1, \dots, nL+L-1 \quad (11)$$

where the \mathbf{a}' and \mathbf{b}' are the feedforward and feedback tap weight vector, respectively, \mathbf{y} is the signal vector stored in the feedforward filter, $\hat{\theta}_{\pm}$ is the phase estimate, $\tilde{d}_{k,\pm}^{(m)}$ is the current hypothesis spread sequence, and $\tilde{d}_j^{(m-1)}$ is the ICI to be subtracted from the estimation. What is noteworthy, suppose $\tilde{d}_j^{(m-1)} = 0$ for all $j \neq k$, PIC-HFE is then reduced to the decentralized HFE proposed in Ref. [1].

After the adaptive equalization, the chip estimates are used for despreading

$$\hat{D}_{k,\pm}^{(m)}(n) = \frac{1}{L} \sum_{l=0}^{L-1} c_k(l) \hat{d}_{k,\pm}^{(m)}(nL+l) \quad (12)$$

Then the final decision is to choose the hypothesized data symbol, which results in the following squared error

$$Q_{k,\pm}^{(m)}(n) = |\pm 1 - \hat{D}_{k,\pm}^{(m)}(n)|^2 \quad (13)$$

$$\tilde{D}_k^{(m)}(n) = \arg \min_{+1,-1} \{Q_{k,\pm}^{(m)}(n)\} \quad (14)$$

The process above is operated for all sub-channels in parallel, and the winning sub-channel hypotheses are passed to the next iteration. Finally, filter coefficients and phase estimates corresponding to the final winning hypotheses are retained for the next symbol interval.

The number of hypotheses of PIC-HFE algorithm is

$$H = 2KM \quad (15)$$

where M is the number of iteration stages. It is a linear function of the number of sub-channels K .

4 Simulation results

In this section, we present some numerical results that illustrate the performance of the proposed PIC-HFE receiver compared with the conventional rake receiver and decentralized HFE receiver in a multicode system. A simulated underwater channel is used, which has a multi-path including two paths of equal energy at the relative delays 0 ms and 6 ms. The chip rate is 4 kHz, and the Doppler spread is set to 1.2 Hz. Spread sequence of length 32 is used to modulate the data symbols at each sub-channel.

Figure 4 illustrates the receiver performance measured by the receiver's output SNR with the number of sub-channels K . The transmitter power is fixed and the receiver's input SNR is 5 dB. Although the conventional rake receiver locates taps at accurate time arrival of the paths, it still fails to function even at small K and no obvious processing gain is obtained during despreading. The performance degradation is considered mainly due to Doppler spread. By contrast,

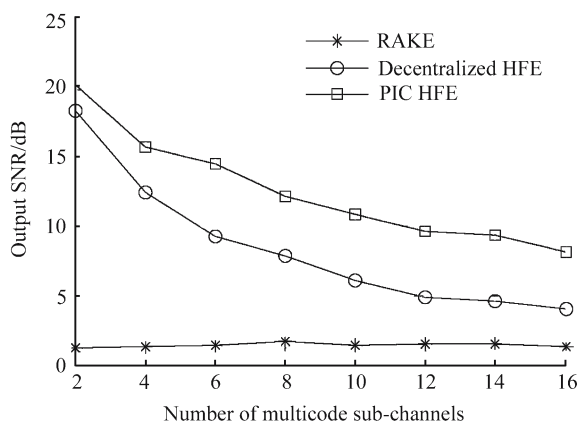


Fig. 4 Output SNR versus the number of multi-code sub-channels (input SNR = 5 dB)

both PIC-HFE and decentralized HFE can track the time-variability of the channel. However, without the ability to suppress ICI, the decentralized HFE receiver outputs less SNR and encounters unreliability more quickly than PIC-HFE.

Figure 5 shows the receiver's output SNR per symbol with different receiver's input SNR. K is set to be 4. Also, it can be seen that conventional rake is disabled at all input SNR and PIC-HFE receiver gains greater performance improvement than decentralized HFE receiver with the increase of input SNR. Simulation results demonstrate the advantages of the PIC-HFE receiver in a multicode system.

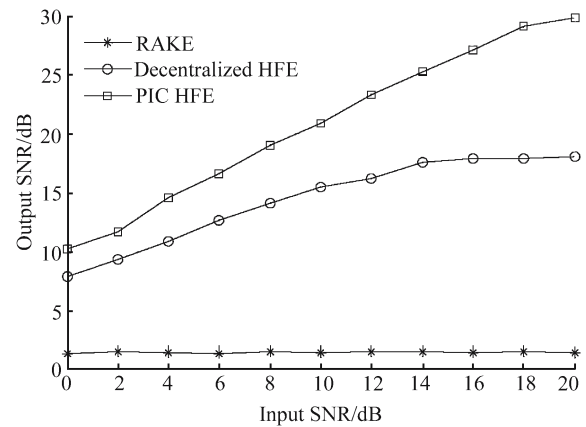


Fig. 5 Output SNR versus input SNR (number of multi-code sub-channels = 4)

5 Conclusion

In this paper, a PIC-HFE receiver is proposed for the multi-code direct-sequence spread-spectrum system, which can be used in high-speed underwater acoustic communication. The receiver adapts the tap coefficients at the chip rate, so it is capable of tracking the rapid time-variability of the channel. Furthermore, with parallel interference cancellation, ICI can be suppressed effectively. The computational complexity of PIC-HFE stays linear with the number of the sub-channels. Simulation results demonstrate that PIC-HFE outperforms the conventional rake receiver and the decentralized HFE in a multicode system.

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