14th European Signal Processing Conference (EUSIPCO 2006), Florence, Italy, September 4-8, 2006, copyright by EURASIP

HYPOTHESIS-FEEDBACK EQUALIZATION FOR MULTICODE DIRECT-SEQUENCE SPREAD SPECTRUM UNDERWATER COMMUNICATIONS

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ABSTRACT

In this paper, multicode direct-sequence spread spectrum is considered to achieve high-speed data transmission in underwater acoustic channel, where extended multipath and rapid time-variability is encountered and the conventional RAKE receiver usually fails to function. To track and compensate the channel distortion, a decentralized hypothesis-feedback equalization (HFE) algorithm [1] which updates coefficients at chip rate is a promising method and has been used in multi-user underwater communication. But for multicode system, its performance is degraded by inter-channel interference (ICI). For this reason, a parallel interference cancellation hypothesis-feedback equalization (PIC-HFE) algorithm is proposed, which combines the capabilities of tracking the time-varying channel and suppressing the ICI. Simulation results proved that the proposed algorithm could significantly improve the performance of multicode system.

1. INTRODUCTION

Direct-sequence spread spectrum (DSSS) exhibits resistance to ISI and has the ability to achieve robust data link at low SNR, its application in underwater acoustic (UWA) channel has been studied extensively over the years [2][3][4]. However, limited by the available bandwidth of the channel, its transmission data rate is low. That is, this technique is not band efficient. One solution to this problem is multicode modulation, which has been developed for high-speed data transmission over wireless environments [5]. In this method, the incoming high-rate data stream is divided into a number of parallel low-rate bit streams as in multitone modulation. However, the low-rate bit streams are modulated with orthogonal sequences in order to separate the different sub-channels.

To use multicode scheme in UWA environment, two key problems must be solved. First, in multipath environment, the inter-channel interference (ICI) increases with the number of sub-channels. Second, duo to the rapidly time-varying characteristics of the UWA channel, the conventional RAKE receiver is not capable for the time-variability and the orthogonality among sub-channel codes is destroyed leading to seriously performance degradation of the receiver. Adaptive equalization methods can be employed to deal with this situation.

The first class of adaptive receivers is updated on symbol rate level. These receivers suffice for the majority of the radio applications [6]. However, in the rapidly time-varying environments where the channel changes over one symbol interval are not negligible, they may fail to converge and produce unreliable symbol decisions. So 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. But since the lack of reliable chip decisions, most of 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 [1], a decentralized hypothesis-feedback equalization (HFE) algorithm offers such a solution, which feedbacks hypothesized rather than the actual decisions. This method has been used in multi-user underwater communication, but for multicode system, its performance is degraded by inter-channel interference (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 section 2 the multicode system model is described and in section 3 the PIC-HFE algorithm is given. Then its performance is analyzed in section 4. Finally, conclusion is summarized in section 5.

2. MULTICODE SYSTEM MODEL

Fig.1 shows the transmitter and the receiver of the multicode modulation system that has been proposed in [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 $T = KT_b$. As a result of this increased symbol duration in each sub-channel the system performance becomes less sensitive to multipath delay spread. After that the symbols on each branch are multiplied by Walsh codes and then modulated using direct-sequence spread spectrum in order to separate different sub-channels and reduce the multipath interference.

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

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

where A is the sub-channel signal power, T_c is chip duration, $g(t)$ is the transmitter's impulse response, and

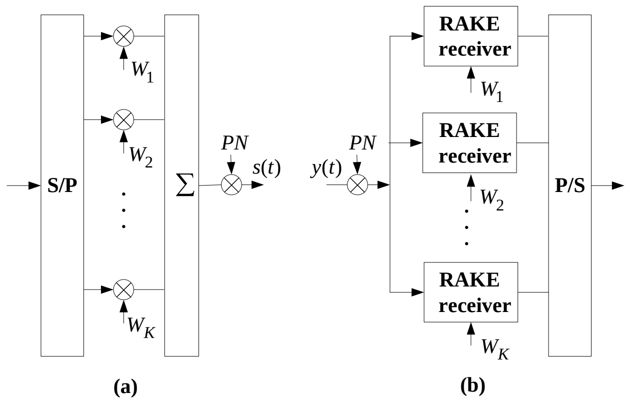


Fig.1. Multicode system model. (a) Transmitter, (b) Receiver.

$d_k(i)$ is the spread information sequence. Denoting the information symbol transmitted at time nT by $D_k(n)$, the spread sequence is given by

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

$$c_k(l) = W_k(l)PN(l) \quad (3)$$

where L is the processing gain, $c_k(l)$ is the k-th sub-channel's concatenated code including the Walch code $W_k(l)$ and common PN sequence $PN(l)$. The baseband transmitted signal is

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

Passing through the time-varying multipath channel, which complex lowpass equivalent impulse response is given by

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

where P is the number of paths, $\alpha_p(t)$ is the time varying complex-valued gain of the p-th propagation path, $\tau_p(t)$ is the corresponding path delay and $\theta(t)$ 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

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

$n(t)$ is the ambient noise of the underwater channel.

Note that each of the DS spread-spectrum modulated data streams passes through the same paths, which implies that the received delay characteristics will be same for all data streams. Therefore, it will make the receiver design less complex.

The original receiver [5] for the multicode modulation system consists of K RAKE receivers, shown in Fig. 1(b). However, in the rapidly time-varying multipath environment of underwater channel, it may fail to function. That is why PIC-HFE algorithm is proposed.

3. PIC-HFE ALGORITHM DESCRIPTION

The detailed description of a hypothesis-feedback equalization method for DSSS is presented in [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.2(a). In such a manner, it is possible to update the receiver parameters at the chip rate, which may be necessary for rapidly time-varying channels. This method operates in 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 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. But in this case the computational complexity will grow exponentially with the number of the sub-channels. In this paper, a suboptimum method called parallel interference cancellation hypothesis-feedback equalization (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 keeps linear with the number of the sub-channels.

The PIC-HFE algorithm operates iteratively to detect symbols. The structure of m stage iteration is shown in Fig.2(b), it executes the following steps:

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

$$\tilde{d}_{k,\pm}^{(m)}(nL + l) = \pm c_k(l), \quad l = 0,..., L-1 \quad (7)$$

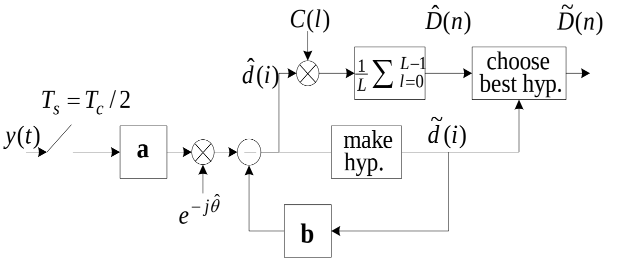
where superscript m is the iteration stage index.

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:

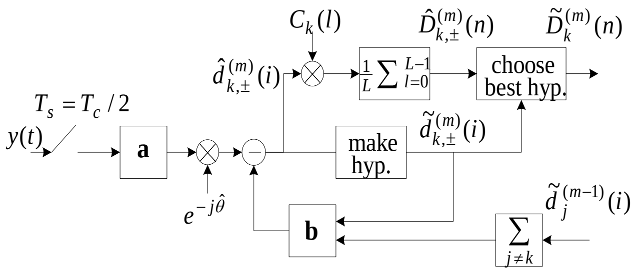
$$\hat{d}_{k,\pm}^{(m)}(i) = \mathbf{a}'_{\pm}(i)\mathbf{y}(i)e^{-j\hat{\theta}_{\pm}(i)} - \mathbf{b}'_{\pm}(i)\left\{\tilde{d}_{k,\pm}^{(m)}(i) + \sum_{\substack{j=1 \\ j\neq k}}^{K} \tilde{d}_j^{(m-1)}(i)\right\}$$

$$i = nL,..., nL + L - 1 \quad (8)$$

where $\mathbf{y}$ is the signal vector stored in the feedforward filter, $\mathbf{a}'$ and $\mathbf{b}'$ is the feedforward and feedback tap weight vector respectively, $\hat{\theta}$ is the phase estimate, $\tilde{d}_{k,\pm}^{(m)}$ is the current hypothesis spread sequence, $\tilde{d}_j^{(m-1)}$ is the ICI to be subtracted from the estimation. Note that, the decentralized algorithm is a special case of this presentation, supposed



(a)



(b)

Fig.2. The structure of hypothesis-feedback equalizer. (a) Decentralized HFE, (b) PIC-HFE (stage m).

$\tilde{d}_j^{(m-1)} = 0$ for all $j \neq k$, PIC-HFE is reduced to decentralized HFE.

In (8), the filter coefficients $\mathbf{a}'$ and $\mathbf{b}'$ are updated adaptively using an algorithm such as LMS or RLS, while the phase estimate $\hat{\theta}$ is updated jointly using a decision-directed phase-locked loop (PLL) [9]. After the adaptive equalization, the chip estimates are used for dispreading:

$$\hat{D}_{k,\pm}^{(m)}(n) = \frac{1}{L}\sum_{l=0}^{L-1} C_k(l)\hat{d}_{k,\pm}^{(m)}(nL+l) \qquad (9)$$

Then the final decision is to choose the hypothesized data symbol which results in the lower squared error:

$$Q_{k,\pm}^{(m)}(n) = \left|\pm 1 - \hat{D}_{k,\pm}^{(m)}(n)\right|^2 \qquad (10)$$

$$\tilde{D}_k^{(m)}(n) = \arg\min\left\{Q_{k,\pm}^{(m)}(n)\right\} \qquad (11)$$

Above process is operated for all sub-channels in parallel, and the winning hypotheses are passed to the next iteration. At last, 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

$$H = 2KM \qquad (12)$$

where M is the number of iteration stages. It can be seen that the complexity of PIC-HFE algorithm is a linear function of the number of sub-channels K.

4. SIMULATION RESULTS

In this section, we present some numerical results which illustrate the performance of the proposed PIC-HFE receiver compared with conventional RAKE receiver and decentralized HFE receiver in multicode system. A simulated underwater channel is used, which has a multipath including two paths of equal energy at the relative delays 0ms and 6 ms. The chip rate is 4kHz, the Doppler spread is set to 1.2Hz. Spread sequence of length 32 is used to modulate the data symbols at each sub-channel. And to achieve faster convergence and shorter training periods, we use the RLS algorithm for the equalizer lap weights update. The number of iteration stages need not to be large, $M = 2$ or 3 is usually sufficient for practical system.

Fig.3 illustrates the receiver performance measured by the receiver's output SNR per symbol with the number of sub-channels K, where output SNR is defined as:

$$\mathrm{SNR}_{\mathrm{out}} = 10\log\frac{\left|D(n)\right|^2}{\frac{1}{N}\sum_{n=1}^{N}\left|D(n)-\hat{D}(n)\right|^2} \qquad (13)$$

with N is the number of data symbols in a frame. The transmitter power is fixed and the receiver's input SNR is 5dB. 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. In contrast, both PIC-HFE and decentralized HFE can track the time-variability of the channel. But without the ability to suppress ICI, the decentralized HFE receiver outputs less SNR and gets unreliable more quickly than PIC-HFE.

Fig.4 gives 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, without Doppler tracking conventional RAKE is disabled at all input SNR, and by ICI cancellation, PIC-HFE receiver gains greater performance improvement than decentralized HFE receiver with the increase of input SNR. Simulation results demonstrate the advantage of PIC-HFE receiver in multicode system.

5. CONCLUSION

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

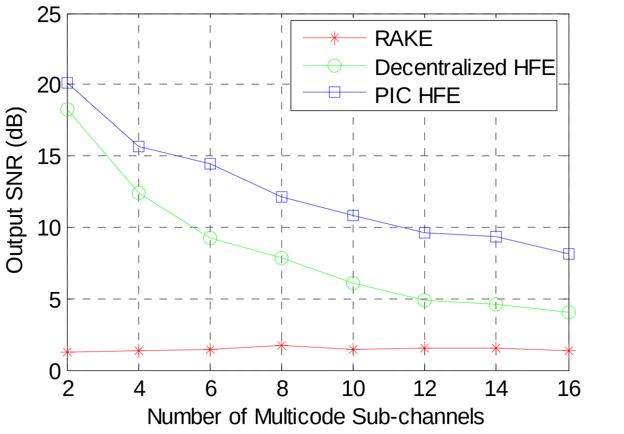


Fig.3. Output SNR versus the number of multicode sub-channels (input SNR = 5dB).

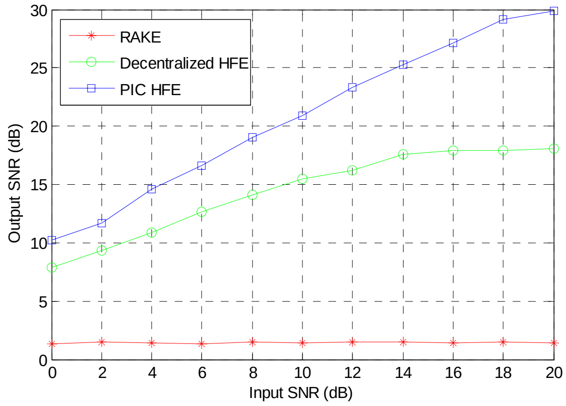


Fig.4. Output SNR versus input SNR (number of multicode sub-channels = 4).

REFERENCES

[1] M. Stojanovic, and L. Freitag, "Hypothesis-feedback equalization for direct-sequence spread-spectrum underwater communications," *IEEE OCEANS '2000*, Providence, RI, pp. 123-129, Sept. 2000.

[2] G. Loubet, V. Capellano, and R. Filipiak, "Underwater spread-spectrum communications," *IEEE OCEANS '97*, Halifax, NS, pp. 574-579, Oct. 1997.

[3] M. Stojanovic, J.G. Proarkis, J.A. Rice, and M.D. Green, "Spread spectrum underwater acoustic telemetry," *IEEE OCEANS '98*, Nice, pp. 650-654, Oct. 1998.

[4] E.M. Sozer, J.G. Proakis, R. Stojanovic, J.A. Rice, A. Benson, and M. Hatch, "Direct sequence spread spectrum based modem for under water acoustic communication and channel measurements," *IEEE OCEANS '99*, Seattle, WA, pp. 228-233, Sept. 1999.

[5] K.B. Letaief, J.C. Chuang, and R.D. Murch, "Multicode high-speed transmission for wireless mobile communication," *IEEE GLOBECOM '95*, pp. 1835-1839, Nov. 1995.

[6] P.B. Rapajic, and B.S. Vucetic, "Adaptive receiver structures for asynchronous CDMA systems," *IEEE J. Select. Areas Commun.*, pp. 685-697, May 1994.

[7] O. Prator, C. Unger, A. Zoch, and G.P. Fettweis, "Performance of adaptive chip equalization for the WCDMA downlink in fast changing environments," *IEEE Symposium on Spread Spectrum Techniques and Applications*, pp. 273-277, 2002.

[8] J.G. Proakis, *Digital Communications*, 4th ed., New York: McGraw Hill, 2001.

[9] M. Stojanovic, J. A. Catipovic, and J.G. Proakis, "Phase-coherent digital communications for underwater acoustic channels," *IEEE J. Oceanic Eng.*, pp. 100-111, Jan. 1994.