Variable Tap-Length Multiuser Detector for Underwater Acoustic Communication

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Abstract. In this paper, we propose a variable tap-length multiuser detector (VT-MUD) for multiuser underwater acoustic communications. The proposed scheme adopts interleave-division multiple access (IDMA) and dynamically adjusts tap-length based on the accumulated squared error (ASE) to achieve a good balance between performance and complexity. Simulation results demonstrate that the proposed scheme can converge to the optimum tap-length and achieve better bit error rate (BER) performance than traditional fixed tap-length multiuser detector (FT-MUD).

Keywords: Underwater acoustic communications · Interleave-division multiple access · Multiuser detector · Variable tap-length

1 Introduction

Underwater acoustic communication has become an important research hotspot for commercial and military applications. However, with the characteristics of limited bandwidth, enormous propagation delays and serious multipath effect, the underwater acoustic channel (UAC) brings great difficulties and challenges to reliable communications [1–3]. Furthermore, multiple-access interference (MAI) will exist in real underwater acoustic communication network because multiple users are present simultaneously in both time and frequency. To mitigate these effects, effective multiuser detection (MUD) scheme must be employed.

Interleave-division multiple access (IDMA) is considered as a special case of code-division multiple access (CDMA), which inherits many advantages from CDMA

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and further improves performance and spectral efficiency with low computational complexity [4–6]. With the above characteristics, MUD schemes based on IDMA for underwater acoustic networks become the focus of studies in recent years. Two types' iterative receivers, employing adaptive decision feedback equalization (DFE) and conventional soft Rake for downlink multi-user underwater communications have been studied in [7]. It proved that the MUD strategy using DFE has performance improvements compared with Rake IDMA receiver. In order to remove MAI and ISI, two chip-level DFE-IDMA and DFE-CDMA receivers that utilize chip-level adaptive DFE are proposed in [8]. In [9], adaptive, chip-level, centralized decision feedback equalizer has been used to remove MAI and inter-symbol interference (ISI) for uplink IDMA shallow-water acoustic channels. The studies in [7–9] all employ fixed tap-length multiuser detection (FT-MUD). Unfortunately, the performance and computational complexity of the system are highly influenced by the tap-length of the filter. With too few taps, the system may not achieve well performance; in contrast, using too many taps, besides wasting computations, may increase the steady-state MSE [10]. There are no rules which can predict the optimal tap-length to obtain optimal performance of system for a specific UAC. Furthermore, for UAC, the optimum tap-length is likely to change with time. Hence, the existing FT-MUD strategies cannot accommodate to complicated UAC.

According to the above observations, a variable tap-length multiuser detector (VT-MUD) for underwater acoustic communication is presented based on IDMA in this paper. The proposed detector employs tap-length update algorithm that adaptively adjusts the number of taps for both complexity reduction and performance improvement.

2 System Model

Consider a typical multiuser underwater acoustic communication system with K simultaneous users, as shown in Fig. 1. Assume that IDMA is adopted. Spreader (repetition encoder) is same for all users and user-specific interleavers are used to distinguish users. The information bits $\mathbf{b}_k = [b_k(1), b_k(2), \cdots, b_k(N_b)]^T$ of the kth user are generated randomly, where N_b is the information bits frame length. The user's bits are spread by a simple repetitive scrambling sequence generating $\mathbf{c}_k = [c_k(1), c_k(2), \cdots, c_k(N)]^T$, where $N = N_b L_s$ is total number of chips, L_s represents the length

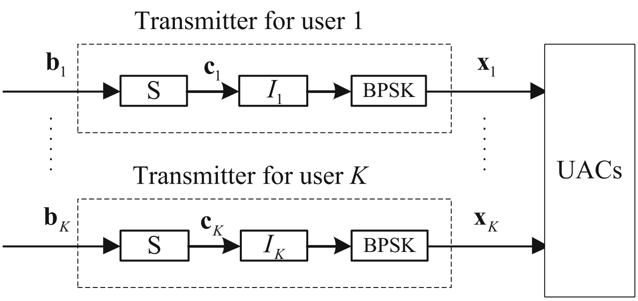

Fig. 1. Transmission system

of spreading sequence. Then the output of spreader is permuted by user-specific interleaver $I_k[\cdot]$. Finally, the output of $I_k[\cdot]$ is mapped to binary phase shift keying (BPSK) symbol

$$\mathbf{x}_k = [x_k(1), x_k(2), \cdots, x_k(N)]^T \tag{1}$$

The received signal after transmission on the underwater acoustic channels (UACs), can be written as

$$r(n) = \sum_{k=1}^{K} \sqrt{P_k} h_k(n) * x_k(n) + v(n) \tag{2}$$

where P_k is transmitted signal power of the kth user, $h_k(n)$ is underwater acoustic channel impulse response from the kth user to destination, which can be obtained by BELLHOP model [11]. $v(n)$ represents sample of the additive white Gaussian noise with zero mean and variance σ^2.

3 Variable Tap-Length Multiuser Detector

The proposed VT-MUD receiver after the acquisition stage is depicted in Fig. 2. MAI and ISI have been mitigated by jointly employing variable tap-length adaptive equalization and multiuser detection.

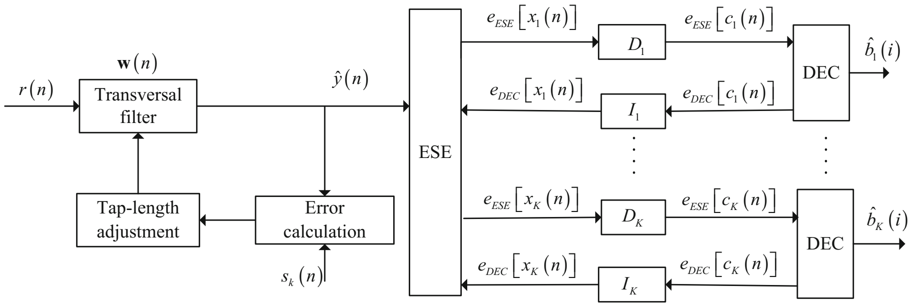

Fig. 2. The structure of VT-MUD

The VT-MUD scheme estimates the optimal tap-length by tap-length update algorithm and generates the estimation $\hat{y}(n)$ of the received signal. The key thought of tap-length adjustment is employing segmented equalization. Assuming that a M taps FIR filter is divided into L concatenated subfilters of P taps each ($M = LP$). Each part of the segmented equalization generates an estimate $\hat{y}_m(n)(1 \leq m \leq L)$ of the received data as

$$\hat{y}_m(n) = \mathbf{w}_m(n)\mathbf{u}(n) \tag{3}$$

where $\mathbf{w}_m(n)$ is the tap-weight vectors of the filter, which is determined iteratively employing normalized least mean square (NLMS) algorithm [12] as

$$\mathbf{w}_m(n+1) = \mathbf{w}_m(n) + \frac{\mu}{\delta + \mathbf{u}^T(n)\mathbf{u}(n)} e_m(n)\mathbf{u}(n) \tag{4}$$

where μ $(0<\mu<2)$ is the step size factor, δ is a small correcting value to avoid numerical instabilities. $\mathbf{u}(n)$ is the observation vector

$$\mathbf{u}(n) = [r(n), r(n-1), \cdots r(n-l+1)] \tag{5}$$

where l is the tap-length of current moment. The corresponding error signal $e_m(n)$ for each segment is

$$e_m(n) = |s_k(n) - \hat{y}_m(n)| \tag{6}$$

where $s_k(n)$ is known training sequence. $e_m(n)$ can be used to compute mean square error (MSE) as

$$MSE_m(n) = E\left[|s_k(n) - \hat{y}_m(n)|^2\right] = \frac{\sum_{i=1}^{n} e_m(i)^2}{n} \tag{7}$$

In order to simplify the calculation, the accumulated squared error (ASE) is used to evaluate the performance of different segments. The ASE can be computed as

$$A_m(n) = \sum_{i=1}^{n} |s_k(i) - \hat{y}_m(i)|^2 = \sum_{i=1}^{n} e_m^2(i) \tag{8}$$

The tap-length update algorithm mainly contains two steps. Assume that there are F active segments. Firstly, we compute the ASE of present and previous segment. Then, we compare the ASE level of present segment $A_F(n)$ with previous one $A_{F-1}(n)$. If $A_F(n)$ is much smaller than $A_{F-1}(n)$, extra P taps will be added to improve the equalization effect. In contrast, if $A_F(n)$ is insignificantly smaller (or even larger) than $A_{F-1}(n)$, P taps will be removed. The adaptive tap-length update algorithm can be modeled as follows

Step (i): Estimation of ASE for present and previous segment

$$A_F(n) = \sum_{i=1}^{n} \gamma^{n-i} |s_k(i) - \hat{y}_F(i)|^2 \tag{9}$$

$$A_{F-1}(n) = \sum_{i=1}^{n} \gamma^{n-i} |s_k(i) - \hat{y}_{F-1}(i)|^2 \tag{10}$$

Step (ii): Adjustment of tap-length

$$\text{if } A_F(n) \le \alpha_{up} A_{F-1}(n),\ \text{add } P \text{ taps} \tag{11}$$

$$\text{if } A_F(n) \ge \alpha_{down} A_{F-1}(n),\ \text{remove } P \text{ taps} \tag{12}$$

where γ is a forgetting factor ($\gamma \le 1$), α_{up} and α_{down} need to satisfy $0 < \alpha_{up}, \alpha_{down} \le 1$, $\alpha_{up} \le \alpha_{down}$. The length of equalizer will change frequently if α_{up} is close to α_{down}.

The received signals $r(n)$ go through the variable tap-length adaptive equalizer, hence, achieving estimated signal $\hat{y}(n)$, we can express the equalized output signal as

$$\hat{y}(n) = x_k(n) + \eta_k(n) \tag{13}$$

where $\eta_k(n)$ is residual distortion, consists of residual MAI and the noise signal $v_r(n)$. The equalized signal is further processed by using Elementary Signal Estimation (ESE) and *a posteriori* probability (APP) decoders (DECs) to recover user's data bits.

The ESE generates logarithmic likelihood ratio (LLR) which can be expressed as in [8] as

$$e_{ESE}[x_k(n)] = \frac{2\{\hat{y}(n) - E[\hat{y}(n)] + E[x_k(n)]\}}{Var[\hat{y}(n)] - Var[x_k(n)]} \quad \forall k, n \tag{14}$$

where $E[\cdot]$ and $Var[\cdot]$ are the mean and variance functions, respectively. The mean and the variance of $\hat{y}(n)$ and $x_k(n)$ in (14) can be computed as

$$E[\hat{y}(n)] = \sum_{k=1}^{K} E[x_k(n)], \forall n \tag{15}$$

$$Var[\hat{y}(n)] = \sum_{k=1}^{K} Var[x_k(n)] + \sigma_v^2, \forall n \tag{16}$$

$$E[x_k(n)] = \tanh\{e_{DEC}[x_k(n)]/2\}, \forall k, n \tag{17}$$

$$Var[x_k(n)] = 1 - \{E[x_k(n)]\}^2, \forall k, n \tag{18}$$

where $e_{DEC}[x_k(n)]$ which is generated by DEC is extrinsic LLR of $x_k(n)$. Because the noise $v_r(n)$ is not available, σ_v^2 can be estimated as

$$\hat{\sigma}_v^2 = \sigma_e^2 = E\left[|s_k(n) - \hat{y}(n)|^2\right] \tag{19}$$

The output of ESE $e_{ESE}[x_k(n)]$ is then de-interleaving to achieve the *a priori* information of the DEC, which can be given as

$$e_{\mathrm{ESE}}[c_k(n)] = D_k[e_{ESE}[x_k(n)]] \tag{20}$$

where $D_k[\cdot]$ represents de-interleaving function. Using the $e_{\text{ESE}}[c_k(n)]$ as input, the DEC adopts standard *a posteriori* probability (APP) decoding [13] to generate the *a posteriori* LLRs LLR_d_{APP}. After that the DEC generates the extrinsic LLR as

$$\begin{aligned} e_{\text{DEC}}[x_k(n)] &= I_k[e_{\text{DEC}}[c_k(n)]] \\ &= I_k[s(n) \cdot LLR\_d_{APP} - e_{\text{ESE}}[c_k(n)]] \end{aligned} \tag{21}$$

where $s(n)$ is spreading sequence. $e_{\text{DEC}}[x_k(n)]$ is used as *a priori* information in ESE for the next iteration. After several iterations, the output of DEC is hard decision to construct the user's data bits $\hat{b}_k(i)$.

4 Simulation Results

In this section, the feasibility of proposed VT-MUD scheme is confirmed and analyzed by simulation results, meanwhile, the performance in terms of BER and MSE is evaluated. The Bellhop model is utilized to simulate UAC. Signal carrier frequency is 12 kHz. Two active users have been considered. The distances between transmitter and receiver are 500 m and 700 m, respectively. And they are placed in the position of water depth 10 m. The wave height is set to 0.5 m. The information bits frame length is set to 1024. Each frame contains 768 bits as the training sequence. Random interleavers [4] are adopted to separate users. The same spreading sequence $\{+1, -1, +1, -1, +1, -1, +1, -1\}$ is adopted as repetition code for all users as in [8]. The iteration times of MUD is set as 10. The initial length of variable tap-length method is 15. The tap-length increment P is 15.

Firstly, we verify the effect of tap-length on system performance and obtain the optimal tap-length for a specific channel profile through simulation. In Figs. 3 and 4, 200 data packets are transmitted. Figure 3 shows the effects of tap-length on signal-to-interference-and-noise ratio (SINR) where signal-to-noise ratio (SNR) is fixed at

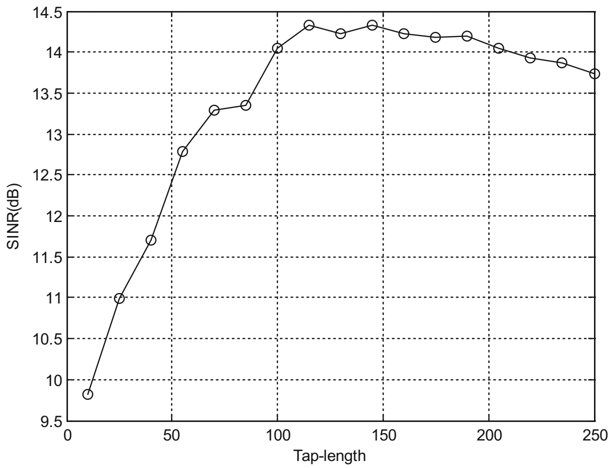

Fig. 3. The effects of tap-length on SINR at SNR = 15 dB

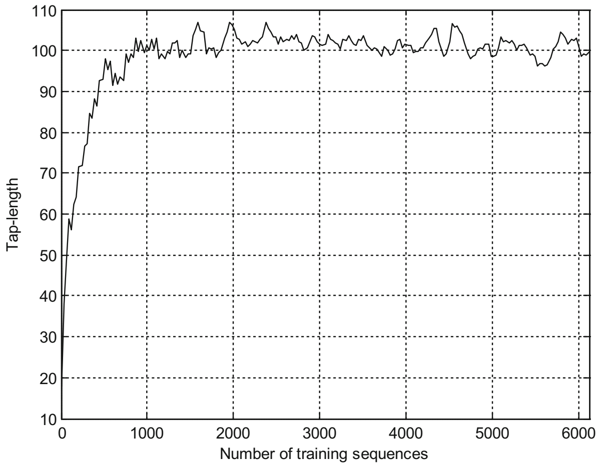

Fig. 4. Tap-length evolution for VT-MUD at SNR = 15 dB

15 dB. The output SINR is calculated according to [8]. As seen from the figure, the system cannot realize its full potential with few tap-length. In contrast, with too much tap-length, the SINR begins to deteriorate. It can be determined that the tap-length has significantly influence on the performance of the system. In this paper, considering the complexity, the optimal tap-length is defined as the minimum tap-length, which can let the system approximate the optimal SINR performance. It can be seen that the SINR is close to maximum when tap-length is set between 100 and 205. According to the definition of the optimum tap-length, we can identify the optimal tap-length in Fig. 3 is 100.

Then, we verify the feasibility of tap-length adjustment of the proposed detector. Figure 4 shows the automatic adjustment curve of tap-length in training mode. In (4), μ is set to 0.5, δ is set to 0.6. In (9) and (10), γ is set to 0.999. In (11) and (12), α_{up} is set to 0.998, α_{down} is set to 0.999. The channel in Fig. 4 is same as in Fig. 3. It is clear that the tap-length can eventually converge to the optimum value as in Fig. 3 as we expect.

Finally, we compare the BER performance and convergence performance of different schemes. A Monte-Carlo simulation is set up and 400 data packets are transmitted. Figure 5 shows the BER performance comparison between the proposed VT-MUD and existing FT-MUD scheme. As seen from the figure, VT-MUD can achieve better BER performance than existing FT-MUD scheme. At about BER = 10^{-3}, the proposed detector can achieve about 5 dB better than the FT-MUD. This is because there are no rules for FT-MUD to predict the optimal tap-length, while VT-MUD can converge to optimum tap-length. Convergence curves of two schemes has presented in Fig. 6. It is clear that the convergence rate of VT-MUD is close to FT-MUD, but VT-MUD can obtain lower MSE than FT-MUD. This is because tap-length is an important parameter on MSE performance, the tap-length can be adaptively adjusted by the VT-MUD.

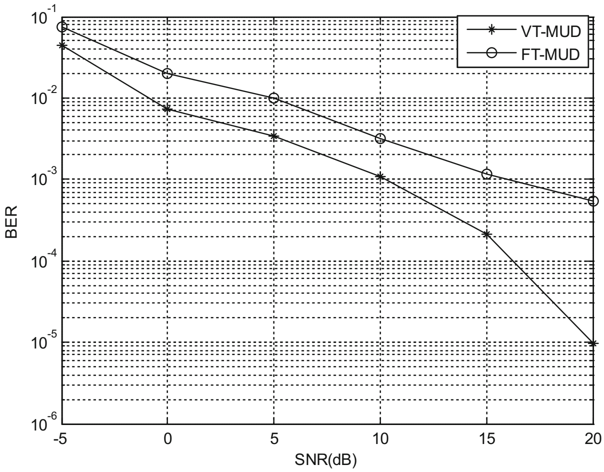

Fig. 5. BER performance comparison of proposed scheme and existing FT-MUD scheme

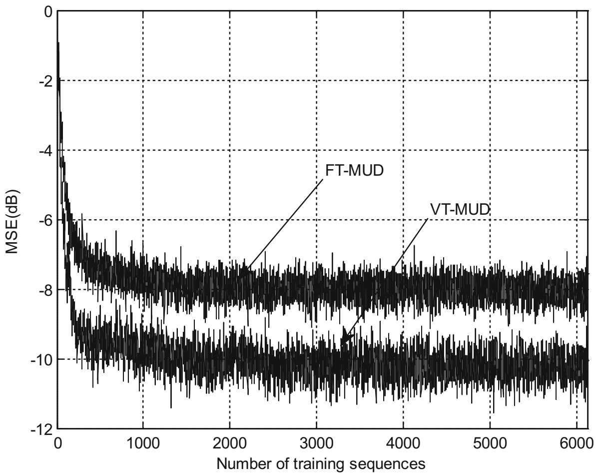

Fig. 6. MSE versus iteration number at SNR = 10 dB

5 Conclusion

In this paper, considering multiuser communication in UACs, we proposed a VT-MUD scheme. The proposed scheme utilizes adaptive tap-length update algorithm to converge to optimum tap-length with low computational complexity. The feasibility of proposed scheme has been confirmed and analyzed; meanwhile, the performances of the proposed VT-MUD and existing FT-MUD schemes have been compared. The results suggest remarkable performance improvements on VT-MUD as compared to FT-MUD.

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