Research Article

Optimizing of Iterative Turbo Equalizer for Underwater Sensor Communication

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We present an iterative turbo equalization to cope with intersymbol interference induced by reflection of sea level and sea bottom for underwater sensor communication channel. Iterative turbo equalizer consists of inner codes and outer codes; we employ decision feedback equalizer as an outer code and turbo codes as an inner code. Equalizer and decoder are connected through the interleaving and deinterleaving that update each other’s information repeatedly. At the receiver side, we resort to powerful turbo equalization algorithms that iteratively exchange probabilistic information between inner decoder and outer decoder, thereby reducing the error rates significantly. Furthermore, we expand iterative turbo equalizer techniques for single-input-single-output (SISO) system to multiple-input-multiple-output (MIMO) system in order to increase data rates for underwater sensor communication channel. Based on experimental channel response, we confirmed that the performance is improved as iteration number is increased. The performance is improved by 3.5 [dB] compared to noniteration for SISO channel and by 1 [dB] for MIMO channel, respectively. We also decided that optimal iterations are 3. Very important for a successful decoding is the channel estimation, which is also discussed.

1. Introduction

The excessive multipath encountered in underwater sensor communication (USC) channel is creating intersymbol interference (ISI), which is limiting factor to achieve a high data rate and bit error rate (BER) performance. Various different methods to cope with multipath situation have been developed. In addition to ISI, cochannel interference (CoI) is also occurred resulting from the use of multiple transmitters in UW communication. Removal of both CoI and ISI is a challenging problem in view of difficult channel conditions. The optimal detector is a maximum likelihood detector (MLD), which can be realized, for example, by the soft Viterbi algorithm. Due to the length of the impulse response in the UW channel, the number of states in the decoder will be increased. One well-proven method to counteract ISI is the decision feedback equalized (DFE), which has been used in many UW communication links [1, 2]. However, the use of DFE has difficulties when a multipath with a number of arrivals has equal strength or low SNR [3]. The other way to cope with ISI, iterative equalizer which constitutes an outer loop is used in the receiver. An inner loop consists of iterative decoder. The assembly utilizes the error correcting power of the iterative codes to get an efficient equalizer [4, 5]. Based on iterative turbo equalization technique for single-input-single-output (SISO) channel, this paper expands it to the multiple-input-multiple-output (MIMO) channel for increasing data rates and capacity gains [6].

In this paper, we study iterative coding-based equalization for single-carrier USC channel. Among the iterative coding schemes, turbo codes and LDPC codes are dominant channel coding schemes in recent studies [7–9]. This paper decides that turbo coding scheme is optimal for underwater communications system in aspect to performance, packet size, and underwater environments. As an outer code, DFE is used in the paper. As an inner code, the turbo codes are used. In MIMO system, space-time trellis codes (STTCs) were employed as an inner code. In receiver side, BCJR algorithm is used for STTC decoding in order to improve BER performance by increasing iterations. This paper gives basic theory of iterative turbo equalization for SISO and MIMO systems; a description of our system and the result of some sea
trials were conducted in the East Sea with an iterative turbo equalizer.

2. Iterative Turbo Equalizer for USC Channel in the SISO System

Iterative turbo equalizer has better performance than the general equalizer. However, because of using a MAP (maximum a posteriori) algorithm, it has the disadvantage of complexity by increasing exponentially as the length of the channel impulse response [7]. For this reason, a low-complexity linear equalizer or DFE is used in order to reduce the complexity. In this paper, we consider turbo equalizer with DFE. The baseband model of turbo equalizer is shown in Figure 1.

Figure 1 shows iterative linear equalizer; that is, decision feedback equalizer is used, which constitutes an outer code of the receiver. An inner code consists of the turbo codes. The information to be transmitted was encoded by a rate of 1/3 turbo code with identical recursive encoders having the duobinary generator polynomial with 16 states [8]. The interleavers are designed for good properties in a turbo code and were taken from [10]. The receiver of turbo equalizer interleavers are designed for good properties in a turbo code.

An acoustic transducer was towed at 100[m] below the ocean. The source signal has 3.8[kHz] to 8[kHz] band. The water depth was approximately 200[m]. An acoustic transducer was towed at 100[m] below the ocean. The source signal has 3.8[kHz] to 8[kHz] band. The water depth was approximately 200[m]. An acoustic transducer was towed at 100[m] below the ocean. The source signal has 3.8[kHz] to 8[kHz] band. The water depth was approximately 200[m].

where $sgn[\cdot]$ is a signum function defined by

$$sgn \{ x \} = \begin{cases} -1, & \text{when } x < 0, \\ 0, & \text{when } x = 0, \\ +1, & \text{when } x > 0, \end{cases}$$

and $e_i[k]$ is the Sato error given by

$$e_s[k] = L^I_c[k] y[k] - \gamma sgn \{ L^I_c[k] \},$$

where $\gamma$ is a constant value. The value of $L^D_c$ after interleaving is computed as $L^I_c - L^I_c$ and then input turbo decoder. The estimated extrinsic value of $L^D_c$ at decoder output is given by

$$L^D_c = \log \frac{P(x = +1)}{P(x = -1)}.$$
3. Application to MIMO
Underwater Communication

MIMO technique is being studied in underwater communications because of increasing the data rates. MIMO communication systems employ multiple sensors at the transmitter and receiver sides. They can yield significantly increased data rates and improved link reliability without additional bandwidth. Representative method is space-time trellis codes (STTCs). In this paper, we propose turbo equalization models for MIMO system in the USC channel employing STTC and turbo codes. We will show how much coding gain can be achieved for increasing number of iterations.
3.1. System Model for MIMO Underwater Communication. Consider an $N \times M$ MIMO communication system equipped with $N$ transmit transducers and $M$ receives transducers. The individual data streams of each transmitter are symbol aligned and are sent simultaneously. The data streams of each transmitter consist of successive data packages. The data packages start with a training sequence which is followed by the payload sequence. Figure 4 shows the proposed $N \times M$ MIMO system structure based on turbo equalization.

The source bits are encoded by STTC encoder and interleaved then mapped to QPSK symbols. After the signals have been received by the receive array, the process consists of estimating the channel impulse response in training or decision mode and detecting the symbols by using the estimated channel impulse response. For increasing data rate and diversity gain according to using MIMO technique in underwater channel environment, exact channel estimation is necessarily. After channel estimation and symbol detection have been done, significant performance improvement iterative turbo equalization BCJR algorithm [11] for STTC decoding, deinterleaving, and turbo decoding is performed. As shown in Figure 1, the baseband equivalent signal received at the $m$th hydrophone can be expressed in the discrete-time domain form as

$$ r_m(k) = H \sum_{n=1}^{N} \sum_{l=0}^{L} h_{n,m}(k,l) s_n(k-l) e^{j \theta_{n,m}(k)} + v_m(k), \quad (8) $$

where $k$ is the time index, $s_n(k)$ is the transmitted data symbol or training symbol from $n$th transducer, and $h_{n,m}(k,l)$ is the channel impulse response of the frequency-selective, time-varying fading channel with length $L + 1$ between $n$th transducer and $m$th hydrophone. $v_m(k)$ means an additive white Gaussian noise. The phase term $\theta_{n,m}(k)$ means the frequency or timing synchronization error, but we do not consider this in this paper. The measurement vector $r_m$ at the $m$th hydrophone can be written as

$$ r_m = \sum_{n=1}^{N} S_n h_{n,m} + v_m, \quad (9) $$

For $m = 1, \ldots, M$, where

$$ r_m = [r_m(1), \ldots, r_m(K)]^T, $$

$$ h_{n,m} = [h_{n,m}(1), \ldots, h_{n,m}(L + 1)]^T, \quad (10) $$

$K$ is a length of the training sequence:

$$ S_n = \begin{bmatrix} s_n(1) & 0 & \cdots & 0 \\ s_n(2) & s_n(1) & \cdots & \vdots \\ \vdots & \vdots & \ddots & \vdots \\ s_n(K) & s_n(K-1) & \cdots & s_n(K-L) \end{bmatrix}, \quad (11) $$

where $S_n$ contains the $n$th training sequence and $v_m$ is the additive noise vector. Equation (II) can be rewritten as

$$ r_m = Sh_m + v_m, \quad (12) $$

where $S = [S_1, \ldots, S_N]$ and $h_m = [h_{1,m}^T \cdots h_{N,m}^T]^T$.

The channel estimation problem is to estimate $h_m$ from the measurement $r_m$ and known $S$ as shown in (12). Existing techniques for sparse channel estimation can be categorized roughly into two types [12]. The first type is approximation schemes that solve the nonlinear optimization problem of minimizing the squared residual prediction error as a function of the gain and the delay location of all the dominant taps. The second type chooses some important taps of the sampled channel impulse response. Among the explicit sparse channel estimation techniques are the $L_p$-norm regularized method and greedy algorithms such as the matching pursuit (MP) algorithm. In this paper, we use the sparse channel estimation with dominant tap detection by using $L_1$-norm minimization. $L_1$-norm minimization is used for method of estimate $h_m$ as the following equation:

$$ h_m = \arg \min \|S\|_1 \text{ subject to } |r_m - Sh_m| < \epsilon. \quad (13) $$

Then, the values of the channel responses are clipped as follows:

$$ h_{n,m}(l) = \begin{cases} \text{nonzero,} & \text{if } h_{n,m}(l) > \text{threshold,} \\
\text{zero,} & \text{else.} \end{cases} \quad (14) $$

This dominant tap detection is performed that if the estimated value $h_{n,m}(l)$ is bigger than particular value, it would have nonzero value and the residuals will have zero value. The value $h_m$ is the channel information corresponding to the estimated nonzero tap. In this paper, we use the zero forcing equalizer for ISI cancellation.

3.2. MIMO Turbo Equalization and Results. In MIMO turbo equalization, two codes are concatenated in the serial fashion. The inner codes are turbo codes with 16 states described in Section 2, and outer codes are STTCs with optimal generator polynomial described in [13]. Normally, the candidates of outer codes are space-time block codes (STBCs) and STTCs. Representative method of STBCs is V-BLAST (Vertical-Bell Labs Layered Space-Time) [14, 15]. This system obtained diversity or spatial multiplexing effect. The MLD is optimal and fully exploits the available diversity. However, STBCs for MIMO turbo equalization cannot obtain coding gain even if increasing number of iteration. This is the reason that the outputs of STBCs are not soft type symbols. The types of input symbols and output symbols must be soft symbols in order to improve performance by increasing number of iterations [16]. At the receiver, we resort to powerful turbo equalization algorithms that iteratively exchange probabilistic information between inner decoder and outer decoder, thereby reducing the error rates significantly. Therefore, we adopt STTCs which are introduced by Roy et al. in 2007 [17]. These codes are described by a trellis structured. We used BCJR algorithm which is soft-based Viterbi algorithm as a STTC decoder. The symbols of outer decoder are then subtracted from the input and interleaved. The interleaved symbols are canceled a posteriori from the proceeding received symbol. Interleaving helps receiver convergence. To confirm the performance improvement of the iterative turbo equalization for MIMO system, the simulation was conducted. Underwater communication is difficult to maintain the reliability because it is
affected by temperature, depth, and geometry. The channels for simulation were generated by Bellhop model, and the sound speed profile that was measured via sea trials was used. We considered $2 \times 2$ MIMO system. Figures 5(a)–5(d) are channel impulse responses between the transmitters and receivers. As expected, numerous reflections can be observed due to surface and bottom. The range between sources and receivers is 1 [km], and the water depth is 200 [m]. The transmitters’ and receivers’ depths are 110 [m] and 117 [m]. The carrier frequency is 12 [kHz], and the sampling frequency is 192 [kHz]. The preamble signal was modulated by BPSK with data rate of 0.5 [kbps]. Source data were modulated by QPSK with data rate of 2 [kbps]. The underwater channel characterization for multipath environment is measured using 2000 [symbols] of PN code symbols. Figure 6 shows the BER curves using the iterative turbo equalization for MIMO system in USC channel based on Figure 4. In Figure 6, curve A shows only zero forcing (ZF) equalizer and curve B shows STTCs which are added after ZF equalizer. Curve B obtains coding gains of 10 [dB] compared to curve A. The importance of measuring the gains at same BER of $10^{-4}$ is illustrated by curves C and D.
The same as SISO system, we also confirmed that the coding gain of 1 dB can be achieved compared to noniteration.

4. Conclusions

In this paper, we proposed receiver structure based on an iterative turbo equalization to cope with intersymbol interference and multipath errors underwater sensor communication channel. Iterative turbo equalizer consists of inner codes and outer codes; we employ decision feedback equalizer as an outer code and turbo codes as an inner code.

We simulated the performance of the iterative turbo equalizer using the channel response data with distance of 5 km and data rate of 1 Kbps which are obtained by experiment in the Eastern coast of Korea. In simulation results, we confirmed that the performance is the best as iteration number is increased. The BER performance is improved by 3.5 dB compared to noniteration. We also decided that optimal iteration numbers are three. We expand iterative turbo equalizer technique to MIMO system in order to increase data rates for underwater sensor communication channel. We also confirmed that the decoding gain of 1 dB can be achieved compared to noniteration.

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