RAKE RECEIVER WITH INTERFERENCE CANCELLATION FOR AN UNDERWATER ACOUSTIC MODEM

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Abstract: *To achieve reliable communication in underwater acoustic (UWA) channels, UWA modems must deal with both multipath propagation and Doppler distortions. Doppler estimation/compensation, channel estimation and equalization are essential for UWA modem design. In this paper, a new Rake receiver with interference cancellation (IC) is proposed to improve detection performance. The conventional Rake receiver provides maximal ratio combining of multipath components. However, the intersymbol interference due to the multipath components is not addressed, which can significantly degrade the receiver performance at high data rates. With multipath interference cancellation, the proposed Rake-IC algorithm can significantly improve the receiver performance. The Rake-IC algorithm is integrated into a UWA modem operating at high data rates. The single-carrier transmission with superimposed data and pilot symbols is considered. The channel estimation and multipath combining are implemented in the frequency domain. Turbo iterations are used in the receiver to improve its performance. The performance of the UWA modem with the Rake-IC algorithm is investigated and compared with that of the conventional Rake receiver and linear equalizer in numerical and lake experiments. Frame error rate (FER) is used for the performance evaluation. For numerical simulations, effective data rates of 2 kbps and 3 kbps are considered. At a FER of 0.01, the Rake-IC receiver achieves an SNR (signal-to-noise ratio) gain of 9 dB compared with the linear equalizer at both data rates, while the conventional Rake receiver cannot provide reliable detection within the SNR range we considered. Results from lake experiments also demonstrate high detection performance of the UWA modem with the proposed Rake-IC algorithm, in comparison with the conventional Rake receiver and linear equalizer.*

Keywords: *Channel equalization, Interference cancellation, Low-complexity, Rake receiver, Underwater acoustic modem*

1. INTRODUCTION

In underwater acoustic (UWA) communications, the transmitted signal experiences severe multipath and Doppler distortions [1] [2]. Doppler estimation and correction, channel estimation and equalization are the main techniques used in UWA modems for data demodulation. Many algorithms have been proposed for Doppler estimation and correction in the receiver [3] [4] [5]. In the modem presented in this paper, Doppler estimation and correction are performed in two steps. At the first step, the cross-ambiguity function (CAF) is used to obtain an initial Doppler estimate [2] [3]. Fine Doppler estimation is then carried out based on the dichotomous frequency estimation [6]. The channel estimation in the modem is performed in the frequency domain using a sparse basis expansion model [7], which is of low-complexity and accurate enough to provide reliable demodulation of the data packet. Channel equalization can be done in the frequency domain using a Rake receiver. However, the performance of the Rake receiver can be limited as it ignores the intersymbol interference (ISI) due to the multipath propagation.

To deal with the multipath interference, spread-spectrum signals are often used, which do not allow a high spectral efficiency to be achieved for communication. In [8], a receiver was proposed with interference cancellation. The receiver processing comprises three stages: linear equalization, interference reconstruction and interference cancellation. Simulation results showed that the performance of the receiver was improved by performing the interference reconstruction and cancellation. In this paper, we propose a new filtering algorithm with multipath interference cancellation (IC). The key idea is to remove the interference from other multipath signal components based on the channel estimate before the maximal ratio combining. The proposed Rake-IC algorithm works in the frequency domain. Turbo iterations are exploited in the baseband processing to improve the channel estimation and equalization accuracy. It is worth mentioning that the application of the proposed receiver is not limited in UWA communication systems, it can be used in any communication systems operating in rich multipath environments.

The performance of the UWA modem with the Rake-IC algorithm is investigated through numerical simulations and lake trials. Frame error rate (FER) is used as the evaluation metric. Both simulation and experimental results indicate that the demodulation performance of the UWA modem can be significantly improved by using the Rake-IC algorithm compared to both a conventional Rake receiver and linear equalizer. The Rake-IC receiver allows the use of a higher data rate and requires a smaller number of turbo iterations to be used.

2. GENERAL STRUCTURE OF THE TRANSMITTER AND RECEIVER

In this section, the transmitter and receiver structures are briefly described.

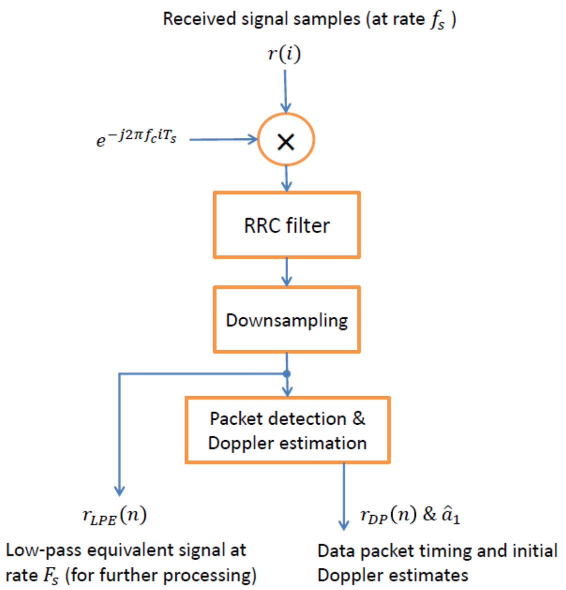

Figure 1: Front-end processing. Sample indices i and n denote samples at sampling rates f_s and F_s, respectively.

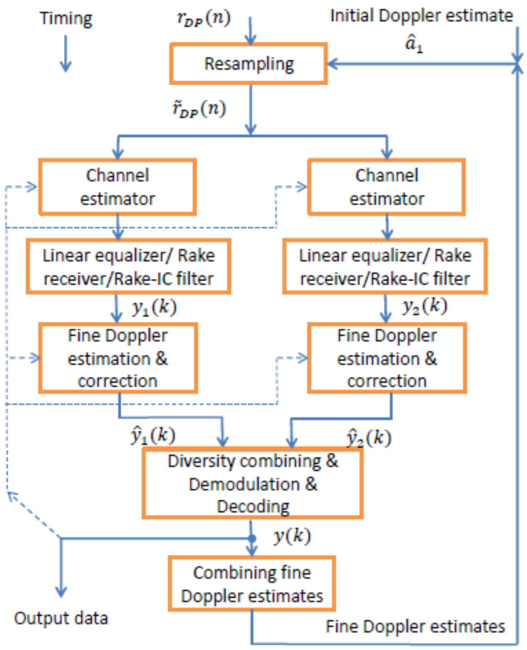

Figure 2: Baseband processing[7]. Sample index k denotes baseband samples.

At the transmitter, a superimposed pilot and data packet structure is used, with pilot symbols $p(k)$ in the real part and data symbols $d(k)$ in the imaginary part: $D(k) = p(k) + jd(k)$, where $p(k), d(k) \in \{-1,1\}$. The data symbols are encoded by a rate 1/2 or rate 1/3 convolutional code and interleaved. For the transmitter data, single-carrier modulation is considered. The superimposed pilot and data symbols are pulse-shape filtered and up-sampled by a root raised-cosine (RRC) filter with a roll-off factor of 0.2. After pulse-shaping, the signal is up-converted to the carrier frequency.

The receiver contains two parts, the front-end processing and the baseband processing. In the front-end (see Fig. 1), the received signal $r(i)$ is downshifted, low-pass filtered and down-sampled to a rate $F_s = 2F_d$, where F_d is the baseband sampling rate. The low-pass equivalent signal $r_{LPE}(n)$ is then used for packet timing detection and an initial Doppler estimation using the cross-ambiguity function [2]. The detected data packet in baseband is denoted as $r_{DP}(n)$.

As shown in Fig. 2, the baseband signal $r_{DP}(n)$ is then resampled based on the initial Doppler estimate $\hat{a}_1$. The Doppler corrected signal is split into two branches for further processing, including channel estimation and equalization, fine Doppler estimation and correction and demodulation. A sparse frequency-domain channel estimator is used [7]. The channel equalization can be performed by a linear equalizer or a conventional Rake receiver. It will be shown in Section 4 and 5 that the modem performance can be significantly improved by using the proposed Rake-IC filter. The fine Doppler estimation is done based on the dichotomous frequency estimation [6] and then the estimate is used for resampling in the next iteration. Tentative data estimates are used in further iterations to improve the channel estimation and demodulation performance. More details on the receiver structure can be found in [7].

3. RAKE RECEIVER WITH INTERFERENCE CANCELLATION

A conventional Rake receiver provides the maximal ratio combining for signal components propagated over various multipaths [9]. The frequency response of the conventional Rake receiver can be expressed as: $H_R(\omega) = \widehat{H}_c^*(\omega)$, where $\widehat{H}_c(\omega)$ is the estimate of the channel frequency response. The output of the Rake receiver will be: $C_R(\omega) = H_R(\omega)X(\omega)$, where $X(\omega)$ is the spectrum of the baseband received signal. However, such a receiver ignores the ISI due to the multipath propagation, which significantly degrades the detection performance in systems with a high spectral efficiency.

A linear equalizer can be used to reduce the ISI due to the multipaths. The frequency response of the equalizer $H_e(\omega)$ can be computed as:

$$H_e(\omega) = \frac{\widehat{H}_c^*(\omega)}{\left|\widehat{H}_c^*(\omega)\right|^2 + \varepsilon},$$

where ε is a regularization parameter. The performance of the linear equalizer is limited when the noise level is high. To further improve the demodulation performance, a Rake filter with interference cancellation in the frequency domain is proposed. Both the conventional Rake receiver and the linear equalizer will be used as benchmarks for performance comparison.

The idea of the proposed algorithm is to remove the interference from multipath components before maximal ratio combining. The spectrum of the baseband received signal $X(\omega)$ can be represented by:

$$X(\omega) = P(\omega)H_c(\omega), \quad \omega \in [-\pi F_d, \dots, \pi F_d],$$

where $P(\omega)$ is the spectrum of the transmitted signal. The frequency response $H_c(\omega)$ can be represented as a linear combination of basis functions $\Phi_m(\omega)$ with expansion coefficients c_m:

$$H_c(\omega) = \sum_{m=1}^{M} c_m \Phi_m(\omega),$$

where M is the number of multipath signal components in the channel, c_m is the mth channel coefficient and $\Phi_m(\omega) = e^{-j\omega\tau_m}$ is the mth basis function (complex exponential).

For maximal ratio combining, the frequency-domain equalizer output can be written as:

$$C_{MRC}(\omega) = \sum_{n=1}^{M} c_n^* \, \Phi_n^*(\omega) X_n(\omega),$$

where $X_n(\omega)$ is the spectrum of the nth multipath signal component. An estimate $\hat{X}_n(\omega)$ of $X_n(\omega)$ can be obtained as:

$$\hat{X}_n(\omega) = X(\omega) - \sum_{m=1,\, m\neq n}^{M} \hat{P}(\omega)\hat{c}_m\Phi_m(\omega),$$

where $\hat{c}_m$ is an estimate of the mth channel coefficient. For the first turbo iteration, the fast Fourier transform (FFT) of the pilot signal is used as $\hat{P}(\omega)$, for further turbo iterations, the FFT of the combined signal (pilot and data estimate) is used. The output of the Rake-IC filter can be further written as:

$$\hat{C}_{MRC}(\omega) = \sum_{n=1}^{M} \hat{X}_n(\omega)\hat{c}_n^*\Phi_n^*(\omega) = \sum_{n=1}^{M}\left[X(\omega) - \sum_{m=1,\, m\neq n}^{M} \hat{P}(\omega)\hat{c}_m\Phi_m(\omega)\right]\hat{c}_n^*\Phi_n^*$$

$$= X(\omega)\sum_{n=1}^{M}\hat{c}_n^*\Phi_n^* - \sum_{n=1}^{M}\sum_{m=1}^{M}\hat{P}(\omega)\hat{c}_m\hat{c}_n^*\Phi_m(\omega)\Phi_n^*(\omega) + \sum_{n=1}^{M}\hat{P}(\omega)\hat{c}_n\hat{c}_n^*|\Phi_n(\omega)|^2$$

$$= X(\omega)\hat{H}^*(\omega) - \hat{P}(\omega)\left|\hat{H}(\omega)\right|^2 + \hat{P}(\omega)\sum_{n=1}^{M}|\hat{c}_n|^2|\Phi_n(\omega)|^2$$

$$= \hat{H}^*(\omega)\left[X(\omega) - \hat{P}(\omega)\hat{H}(\omega)\right] + \hat{P}(\omega)\sum_{n=1}^{M}|\hat{c}_n|^2.$$

The time-domain output can be obtained by taking the inverse FFT of $\hat{C}_{MRC}$.

4. SIMULATION RESULTS

In this section, we present the numerical simulation results.

The UWA channel is modelled as a linear system with a static multipath channel structure followed by a time Doppler compression. The channel power delay profile is uniform over the discrete delays [1, 11, 43, 91, 100]/$2F_d$. The channel coefficients are randomly generated and normalized at each simulation trial. The time Doppler compression is defined by a velocity v and an acceleration a between the transmitter and receiver. For each simulation, v is randomly generated from a uniform distribution within [-1, 1] m/s, and a is randomly generated from a uniform distribution within [-0.5, 0.5] $\mathrm{m/s^2}$.

In total, 2000 simulation trials are run. The transmitted signal is of 32 kHz carrier frequency with a frequency bandwidth of 6 kHz. In each simulation trial, one data packet is transmitted. Convolutional codes of rate 1/2 or rate 1/3 are used for encoding. With a rate 1/3 code, each data packet contains 600 encoded data symbols with superimposed pilot symbols.

Fig. 3 shows the FER performance of the modem in the simulated channels. The FER is computed as the ratio of the number of data packets detected with error to the total number of transmitted data packets. Five turbo iterations are used. It can be seen that the Rake-IC receiver significantly improves the FER performance compared to the case of using the linear equalizer. For a FER of 0.01, an SNR gain of about 9 dB is achieved by using the Rake-IC receiver at both code rates. Even with a rate 1/2 code, the Rake-IC filter still provides better performance than that of the linear equalizer with the lower data rate.

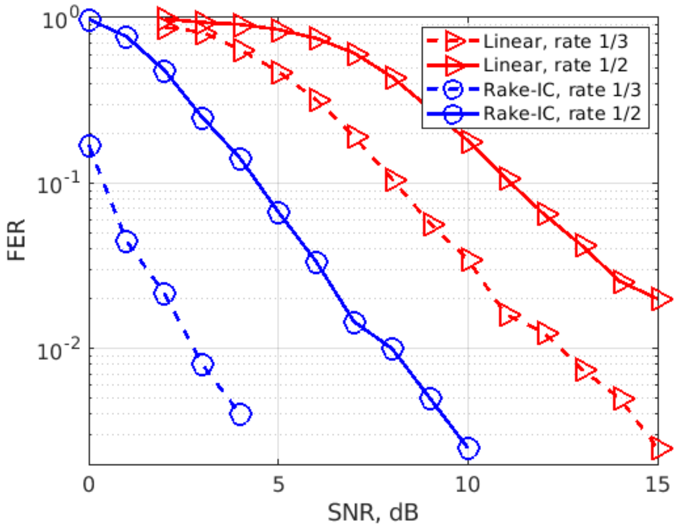

Figure 3: FER performance in simulations.

5. LAKE EXPERIMENT

In this section, the performance of the proposed Rake-IC receiver is evaluated in lake trials. The projector and hydrophone positions remain static during the experiment. The maximum depth of the experiment site is around 8 m. The projector (Tx) and hydrophone (Rx) are placed at a depth of 2 m and 50 m distance apart.

During the experiment, pseudo-random BPSK modulated data packets are transmitted. The transmitted signals are of 24 kHz, 32 kHz or 48 kHz carrier frequency with 6 kHz bandwidth. The duration of each data packet is 100 ms. We use a code rate of 1/3. In total, 100 data packets are transmitted in each experiment. A plot of the baseband received signal with background noise is shown in Fig. 4.

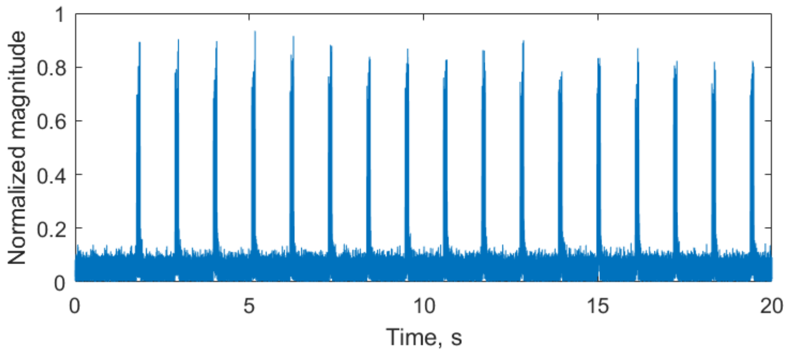

Figure 4: Baseband received signal (first 20 seconds) in the lake experiment at 32 kHz carrier frequency.

An example of the channel impulse response estimate in the lake experiment is shown in Fig. 5. The channel delay spread is around 13 ms.

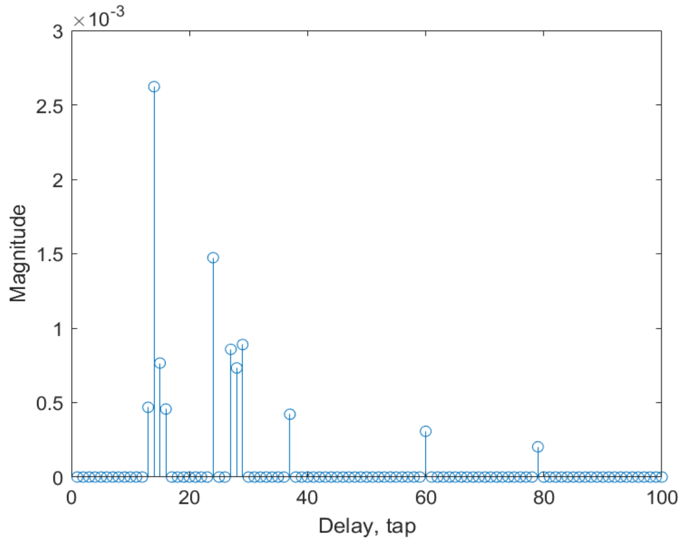

Figure 5: Impulse response in a lake experiment with 32 kHz carrier frequency.

Table 1: BER and FER performance in lake experiments

		BER			FER		
	iteration	24 kHz	32 kHz	48 kHz	24 kHz	32 kHz	48 kHz
Linear equalizer	1	0.2889	0.1627	0.3422	1	0.96	1
	2	0.0071	0.0006	0.0065	0.25	0.03	0.25
	5	0.0005	0	0.0005	0.02	0	0.04
Rake-IC filter	1	0.0183	0	0.0364	0.35	0	0.54
	2	0	0	0.0021	0	0	0.03
	5	0	0	0.0002	0	0	0.01

The BER and FER performance of the modem in three lake experiments are summarized in Table. 1. Both the linear equalizer and the conventional Rake receiver are considered for performance comparison. Five turbo iterations have been applied for the baseband processing. It can be seen that the demodulation performance improves as the number of iterations increases with both equalizers. The performance of the Rake-IC receiver outperforms the linear equalizer in all experiments. For the 32 kHz carrier frequency, the Rake-IC receiver provides error-free detection with a single iteration. The performance of the conventional Rake receiver is omitted here as it is much worse compared to the other two. For the 32 kHz signal, the best BER and FER performance achieved by the conventional Rake receiver is 0.01 and 0.25, respectively. It can be seen that the best detection performance is obtained when transmitting a signal of 32 kHz carrier frequency, and the performance degrades at 48 kHz carrier frequency. This is related to the optimal operating frequency range of the transducer we used in the experiments.

6. CONCLUSION

In this paper, a Rake-IC algorithm with interference cancellation is proposed and incorporated into a UWA modem. The Rake-IC receiver is implemented in the frequency domain. The performance of the Rake-IC receiver is investigated and compared with that of a conventional Rake receiver and a linear equalizer in numerical simulations and lake trials. The experimental results indicate that the Rake-IC receiver can significantly improve the demodulation performance compared to other receivers and it allows us to operate with a higher data rate in UWA communications.

7. ACKNOWLEDGEMENT

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