Underwater Acoustic Channel Estimation Based on Signal Cancellation

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Abstract. Aiming at the requirement of underwater information security transmission, the security of encryption key generation and distribution in underwater acoustic communication is concerned. Key generation technology based on underwater acoustic channel (UAC) estimation can improve the security and real-time generation of encryption keys. In this paper, the idea of estimating the multipath structure of UAC is to retrieve the arrival signal by acquiring the parameters of larger energy Eigen-ray from real arrival signal, and to eliminate the arrival signal of larger energy Eigen-ray path from the real signal through signal cancellation, so as to eliminate the influence of side lobes of larger energy signal to arrival signals of other Eigen-ray path, to improve the estimation performance of multipath structure in underwater acoustic channel. The simulation and experimental results show that the improved algorithm can estimate the multipath structure of underwater acoustic channel more accurately and provide support for the subsequent underwater information security transmission.

Keywords: Underwater acoustic channel · Matched filtering · Parameters inversion · Signal cancellation · Channel correction

1 Introduction

Ocean channel is a time-varying and space-varying random channel, which can be regarded as a time-varying random filter to transform the signal waveform. If the observation or processing time is not too long, the acoustic channel can be described by a time-invariant filter. Match filter (MF) is the most basic detection algorithm based on matched filtering. MF is the optimal detector under Gaussian white noise, and is one of the classical underwater acoustic signal detection algorithms. Matched filters are also commonly used in underwater acoustic channel estimation.

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In non-stationary environment, the optimal decision threshold of MF will fluctuate with the change of signal-to-noise ratio, which seriously affects the detection performance of MF. In order to solve this problem, Conte and Lops in 1995 normalized the matched output using the received data and obtained the normalized matched filter. At the same time, the covariance matrix of background noise was obtained using the auxiliary data without targets. Then the matrix was substituted into MF to obtain the adaptive normalized matched filter [1]. In 2002, Abraham first introduced the cumulative sum detection algorithm PT into underwater acoustic signal processing, and then adaptively accumulated the square output value of the normalized matcher to detect. PT algorithm takes full account of the multipath effect of the channel and shows good detection performance [2]. Yin Jingwei of Harbin University of Engineering has studied the underwater acoustic channel estimation based on FRFT. Without Doppler frequency offset, the accuracy of the matched filtering algorithm is higher [3]. Li Jun of Dalian Naval Ship College adopts matched filtering technology to estimate the time delay structure of underwater acoustic multipath channel, and the estimation effect of single-frequency pulse and frequency modulation pulse signal is compared [4, 5]. But the above method does not solve the problem of underwater acoustic channel structure estimation when the time delay between channels is smaller than the pulse width. Chen Xing et al., Chengdu Institute of Information Engineering, proposed a clean algorithm based on matched filter to improve the range resolution of multi-target recognition. The simulation results are effective [6], but the correction of the estimated target strength and time delay estimation error is not considered.

In view of the above problems, this paper introduces signal cancellation algorithm into the field of underwater acoustic channel multipath structure estimation, improves the time delay resolution of underwater acoustic channel multipath structure estimation, and proposes an error compensation algorithm for underwater acoustic channel multipath structure estimation to correct the estimated underwater acoustic channel multipath structure. The simulation and experimental results show that the proposed algorithm can improve the time delay resolution of underwater acoustic channel multipath structure estimation. The proposed channel estimation algorithm can estimate the multipath structure of underwater acoustic channel more accurately.

2 Channel Estimation Principle Based on Matched Filter

MF is an optimal linear filter. Its criterion is that the output signal-to-noise ratio (SNR) is the largest, and it is often used in communication, detection and other systems [7, 8]. When the input signal of a linear time invariant filter is a known signal and the noise is an additive stationary noise, the matched filter can maximize the output power signal-to-noise ratio under a certain input power signal-to-noise ratio, which is a filter matching the input signal.

For the input signal s(t), the impulse response function of the matched filter is:

$$h(t) = ks * (t_0 - t) \tag{1}$$

Among them, k is an arbitrary constant.

Formula (1) shows that the impulse response of the matched filter is the mirror of input signal s(t), but there is only one delay time t_0.

Suppose there are p eigen rays, the underwater acoustic multipath channel is considered to have p path. The impulse response of underwater acoustic multipath channel can be obtained as follows:

$$\mathrm{h(t)} = \sum\nolimits_{i=1}^{p} a_i p(t - \tau_i) \tag{2}$$

If the transmitting signal is s(t), the received signal after propagation through underwater acoustic channel is as follows:

$$\mathrm{x(t)} = \mathrm{s(t)} * \mathrm{h(t)} = a_1 s(t - \tau_1) + \ldots + a_i s(t - \tau_i) \tag{3}$$

The estimation of underwater acoustic channel multipath structure is to obtain a_i and τ_i, which can be estimated by matched filtering.

Figure 1 is schematic block diagram of matched filtering.

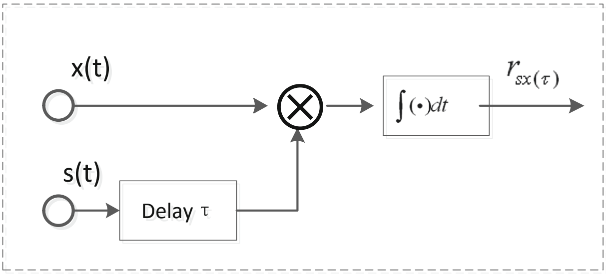

Fig. 1. Schematic block diagram of matched filtering

If the noise of the marine environment is n(t), the actual received signal is $x_i(t) = x(t) + n(t)$, s(t) is local copied signal, and the output of the matched filter is:

$$r_{x_1t}(\tau) = \int_{-\infty}^{\infty} [x(t) + n(t)]s(t - \tau)dt = r_{xs}(\tau) + r_{ns}(\tau) \tag{4}$$

If the noise n(t) is not correlated with the signal s(t) and the mean value of the noise is zero, then there is $r_{x_1t}(\tau) = r_{xs}(\tau)$, the output signal modulus $\left|r_{x_1t}(\tau)\right|$ of matched filter will form a series of peaks in the corresponding correlation domain, and the corresponding peak position of each multipath signal will be delayed τ_i relative to the direct sound. The estimation of multipath structure of UAC can be realized by extracting the larger peak parameters among $\left|r_{x_1t}(\tau)\right|$.

3 Improved Channel Estimation Algorithms Based on Signal Cancellation

3.1 Zero-Setting Algorithm for Peak Region

Zero-setting algorithm for peak region represents the signal zero-setting process within a certain width of the peak value in the process of extracting underwater acoustic channel structure after LFM matched filtering. When the LFM signal is received, the received LFM signal is processed with the local copy LFM signal to obtain the matched filtering signal after pulse compression; the peak value and location information of the maximum energy peak are extracted, and the data in the pulse width of LFM after matched filtering around the peak value is set to zero; the peak threshold and the number of routes are set. Two parameters are used to search the output of the matched filter, and the estimation of the multipath structure of UAC is obtained.

3.2 Signal Cancellation Algorithms

Signal cancellation algorithm is a recursive idea. Firstly, the received LFM signal is processed by matched filtering to obtain the matched filtering signal after pulse compression. Then, the matched filtering signal is processed to detect the parameters such as amplitude and time at the maximum peak value, and the arrival time-domain form of the signal is inverted by the obtained maximum energy signal parameters, and matched. The ideal matched filter signal is obtained by filtering. In the real arrival signal, the estimated high energy signal is eliminated, the side lobe of the high energy peak is eliminated, and the weak intensity multipath peak is revealed. The appropriate threshold is set, and the above two steps are repeated to achieve all the effective eigenvalues. The parameter information is extracted to estimate the multipath structure of UAC.

3.3 Improved Algorithm Based on Signal Cancellation

The peak area zero-setting algorithm based on signal cancellation does not consider the masking problem of weak energy multipath peaks in the pulse width range of strong energy multipath peaks, but removes the arrival signal of strong energy sound lines through the method of zero-setting in the pulse width range, which is easy to cause the loss or distortion of multipath structure of underwater acoustic channel; signal cancellation algorithm considers the masking problem of weak energy multipath peaks in the pulse width range of strong energy multipath peaks, and eliminates the arrival signal of strong energy sound lines by inversion signal cancellation method, which has no effect on weak energy peaks. However, the algorithm does not consider that when the peak interval is less than the pulse width, the adjacent pulses have both the peak value and the location of the estimated peak. It has a certain impact on the accuracy of underwater acoustic channel multipath structure estimation.

Therefore, based on the signal cancellation algorithm, this paper proposes an error compensation algorithm for underwater acoustic channel multipath structure estimation, which fine-tunes the estimated multipath delay and amplitude of underwater acoustic channel, and then matches the corrected results with the underwater acoustic multipath channel obtained by matched filtering to determine the optimal corrected value. Finally, more accurate information of multipath structure parameters of underwater acoustic channel is obtained.

The implementation process of the proposed algorithm is as follows:

(1) The received LFM signal is processed by matched filtering to obtain the matched filtering signal after pulse compression.

(2) The signal after matched filtering is processed to detect parameters such as amplitude and time at the maximum peak.
(3) The time-domain form of arrival of the signal is retrieved by using the parameters of the maximum energy signal, and the retrieved signal is removed from the received signal by using the signal cancellation algorithm.
(4) In the signal arrived in real environment, the estimated high energy signal is eliminated, and the sidelobe of the high energy correlation peak is eliminated, while the weak energy peaks by other paths are revealed.
(5) Setting appropriate threshold and repeating (2)-(4) so as to extract the parameter information of all effective eigenvalues and obtain the estimation of the multipath structure of underwater acoustic channel.
(6) To obtain the multi-path structure of underwater acoustic channel, the local signal of underwater acoustic channel is reconstructed by traversing the preset amplitude and time-delay transformations, and the optimal solution is found by matching the actual impulse response signal of underwater acoustic channel in the corresponding region.

4 An Improved Algorithm Model Based on Signal Cancellation

The underwater acoustic channel estimation algorithm proposed in this paper is based on signal cancellation. Firstly, the impulse response of UAC is obtained by matched filtering algorithm. Then, the impulse response of UAC is estimated by signal cancellation algorithm. Finally, the obtained UAC multipath structure is modified.

Figure 2 shows the flow chart of the improved algorithm based on signal cancellation.

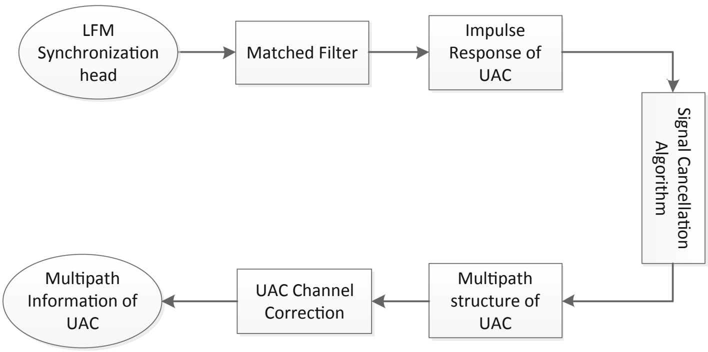

Fig. 2. Flow chart of improved algorithm based on signal cancellation

Figure 3 is flow chart of signal cancellation algorithm.

Because the expression of each eigen-ray's arrival signal in impulse response of UAC after matched filtering is influenced by the adjacent eigen-ray's arrival signal, the correlation waveform of high-energy eigen-ray's arrival signal has greater influence on

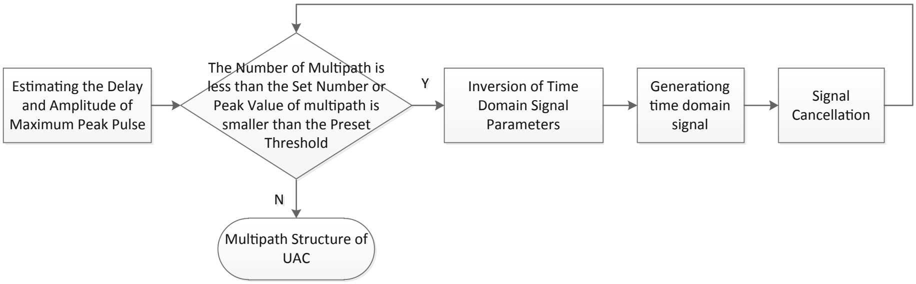

Fig. 3. Flow chart of signal cancellation algorithm

the correlation waveform of low-energy eigen-ray's arrival signal, so it can be eliminated by processing larger peak multipath first.

Figure 4 is flow chart of underwater acoustic multipath correction algorithm.

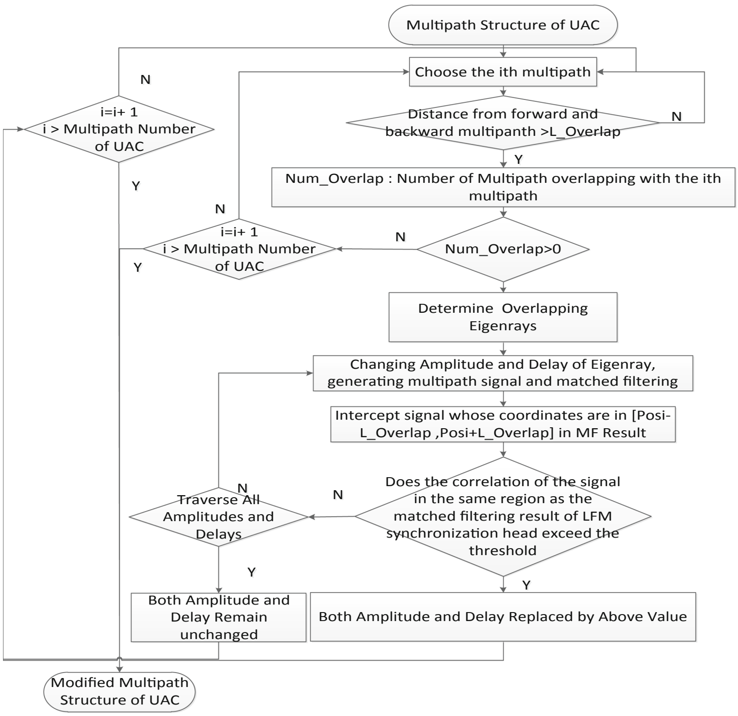

Fig. 4. Flow chart of multipath correction algorithm for UAC

In the correction stage of underwater acoustic channel, because the error of the amplitude and delay of some multipath is mainly affected by noise and the arrival signal of the two eigenvalues that close to it, the improved algorithm calculating the space between the estimated eigen ray with two other eigen rays that close to it to judge whether the two eigen rays have overlapping areas with the estimated eigen ray. The predict impulse response signal of underwater acoustic channel is reconstructed by traversing the preset amplitude and time-delay transformations, and matched with the actual impulse response signal of underwater acoustic channel in the corresponding region to find the optimal amplitudes and delay times.

5 Simulation of Multipath Structure Estimation for UAC

Table 1 shows LFM simulation signal parameters.

Table 1. Summary of LFM simulation signal parameters

Parameters	Bandwidth/kHz	Duration/s
Value	5	1, 0.5, 0.05

Table 2 shows the simulation channel multipath parameters.

Table 2. Summary of multipath parameters of underwater acoustic channel

UAC		Eigen rays					
		1	2	3	4	5	6
A	Amplitude	3.58	2.40	1.70	1.38	0.95	−0.2
	Time delay/ms	1.50	2.30	6.20	8.00	5.05	5.0
B	Amplitude	3.80	2.40	1.70	1.35	0.88	−0.2
	Time delay/ms	0.40	2.80	7.80	8.40	5.10	2.0

There are two groups of underwater acoustic multipath channels, all of multipath delay intervals of the first group data are larger than pulse width of LFM signal after matched filtering, and the multipath delay intervals of the second group data has one eigen rays smaller than t pulse width of LFM signal after matched filtering; the noise is Gauss white noise; the Monte Carlo statistical method is used to analyze underwater acoustic signals. The statistics of channel amplitude estimation error, underwater acoustic channel delay estimation error and underwater acoustic channel multipath number error are carried out; the number of statistics is 100.

Figure 5 is schematic diagram of the transmission signal.

The synchronization signal in Fig. 5 is used to synchronize the received signal; the detected signal is LFM signal with different time lengths (each group of LFM signals has the same time duration); after synchronization, the LFM detection signal in the data segment is used to estimate the multipath structure of UAC. The number, amplitude and time delay of the multipath sound lines are used as statistics of the performance of UAC multipath structure estimation.

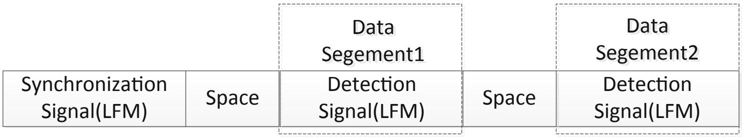

Fig. 5. Composition diagram of transmission signal

Figure 6 is a comparison of the performance of zero-setting algorithm, signal cancellation algorithm and the proposed algorithm for underwater acoustic channel estimation when all of the multipath delay intervals are larger than the matched output pulse width of LFM signal after matched filtering.

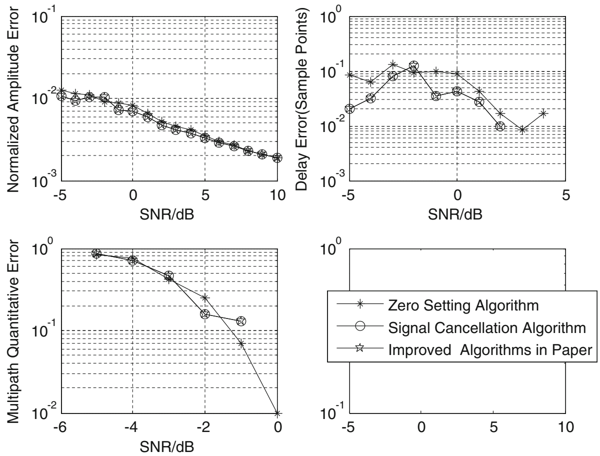

Fig. 6. Performance comparison of underwater acoustic channel estimation algorithm

From Fig. 7, it can be seen that when all of multipath delay intervals of UAC are greater than pulse width of LFM signal after matched filtering, the performance of zero-setting algorithm is similar to that of the proposed algorithm by comparing the amplitude error, delay error and multipath number error of UAC estimation.

Figure 7 shows the performance comparison of zero-setting algorithm, signal cancellation algorithm and the underwater acoustic channel estimation algorithm proposed in this paper when one of multipath delay intervals is less than pulse width of LFM signal after matched filtering.

From Fig. 7, we can see that when one of multipath delay intervals of UAC is less than pulse width of LFM signal after matched filtering, the performance of the proposed algorithm is better than that of zero-setting algorithm; the estimation results are more accurate compared with the signal cancellation algorithm.

Figure 8 is the performance of underwater acoustic channel estimation for LFM signals with different duration.

From Fig. 8, it can be seen that the performance of UAC multipath structure estimation increases with the increase of SNR when the duration of LFM signal is constant, and

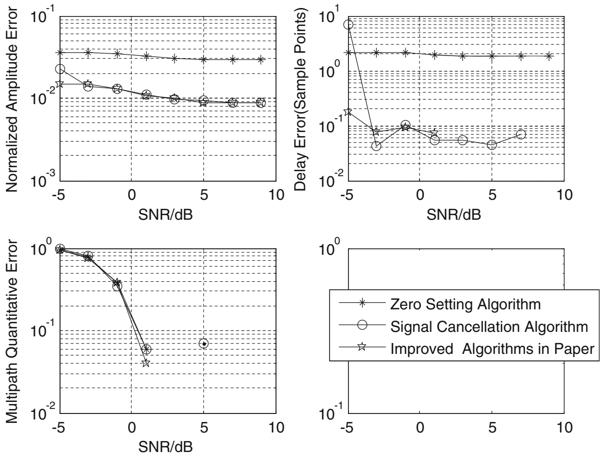

Fig. 7. Performance comparison of underwater acoustic channel estimation algorithms

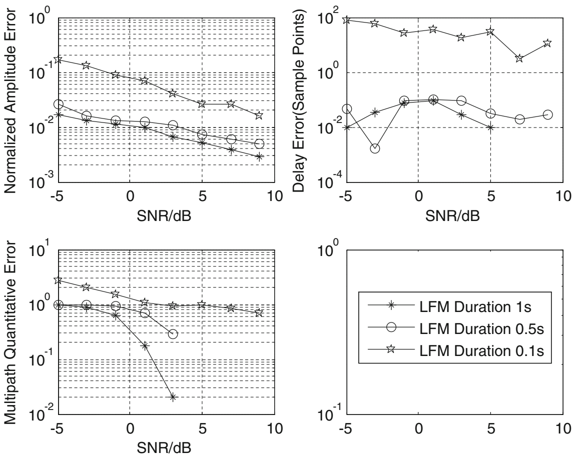

Fig. 8. The relationship between underwater acoustic channel estimation performance and signal duration

the performance of underwater acoustic channel multipath structure estimation increases with the increase of the time of LFM signal when the SNR is constant.

6 Data Analysis of Lake Test

In order to test the actual performance of the improved algorithm based on signal cancelling, channel-free estimation algorithm, zero-setting algorithm, signal cancellation algorithm and the algorithm proposed in this paper are used to process the lake test data. Among them, channel-free estimation algorithm means that no channel equalization processing of received signal directly carries out despread and demodulation operations for information recovery. Because the multi-path structure of underwater acoustic channel on Lake is unknown, the estimated multi-path structure of underwater acoustic channel will be used to balance the multi-path effect of information demodulation, and the estimation effect of underwater acoustic channel structure will be evaluated by transmitting the bit error rate of recovery information of DSSS signal.

Table 3 shows LFM detection signal parameters.

Table 3. Summary of LFM detection signal parameters

Parameters	Bandwidth/kHz	Duration/s
Value	5	1, 0.5, 0.1, 0.05

Table 4 shows the DSSS signal parameters.

Table 4. DSSS signal parameters

Parameters	Value
fc/kHz	8
Modulation Style	BPSK
fs/kHz	96
Ts/ms	12.6
m Sequence Length	63

Figure 9 is schematic diagram of the transmission signal composition.

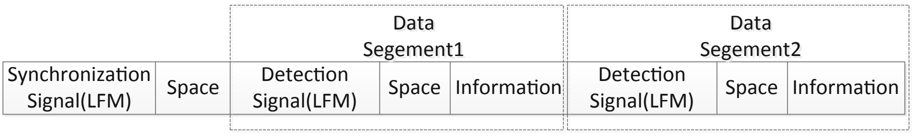

Fig. 9. Composition diagram of transmission signal

The synchronization signal in Fig. 9 is used to synchronize the transmitted signal; the detected signal is LFM signal with different duration (each group of LFM signals has the same duration); the information segment is DSSS modulated information, which consist of 6 segments that has 420 bits.

Test conditions: the water depth is 20 m, the transducer is placed 3 m underwater and the hydrophone is placed 3 m underwater, they are 50 m apart.

Figure 10 is received underwater acoustic signals.

By synchronizing the received signals in Fig. 10, each data segment is extracted. The LFM detection signal in the data segment is used to estimate the multipath structure of

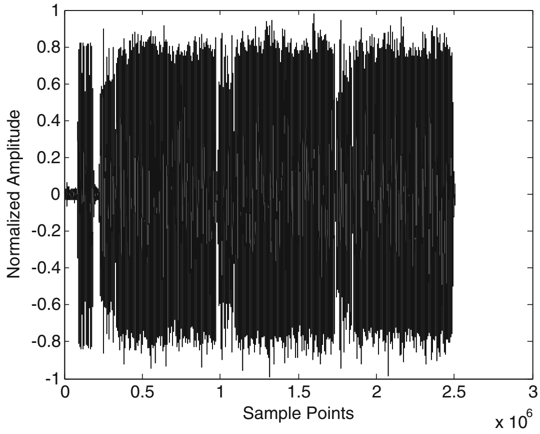

Fig. 10. Received underwater acoustic signals

UAC, and the estimated underwater acoustic channel structure is used to equalize the information in the data segment. Finally, the transmitted information is recovered and the bit error rate (BER) is calculated.

Figure 11 is correlation comparison of channel estimation results for different algorithms.

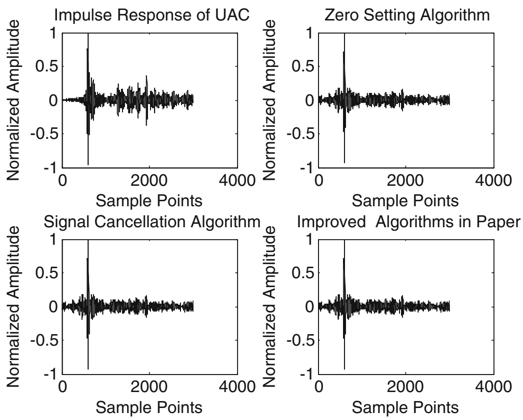

Fig. 11. Correlation comparisons of channel estimation results for different algorithms

Figure 11 shows that when the channel estimation results are used to equalize the underwater acoustic channel influence of LFM synchronization head, the peak value of the correlation results is sharper and its energy is more concentrated. But it is difficult to draw a conclusion from the correlation results of zero-setting algorithm, signal cancellation algorithm and the proposed algorithm in this paper.

Figure 12 is comparisons of the performance of underwater acoustic channel structure estimation with different UAC estimation algorithms.

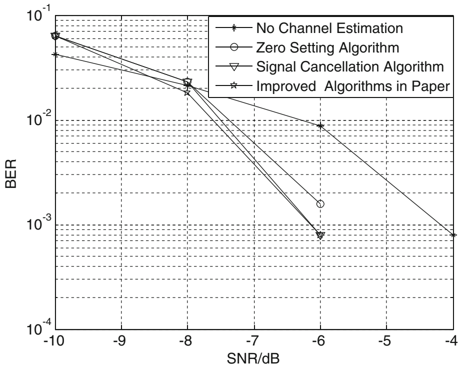

Fig. 12. Performance comparison of different UAC estimation algorithms

The performance comparison of different underwater acoustic channel structure estimates with LFM duration of 0.5 s is shown in Fig. 12. Figure 12 shows that when the SNR condition is good (the SNR in the figure is greater than −8 dB), the BER is higher without channel estimation, and the performance of cancellation algorithm is slightly better than that of zero-setting algorithm; the performance of the proposed algorithm in the paper is the best.

Figure 13 shows the influence of LFM duration for the structure estimation performance of UAC.

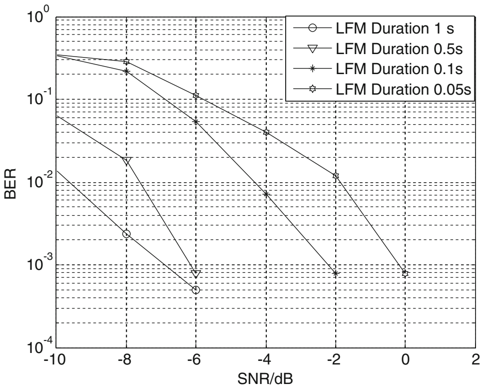

Fig. 13. Effect of different LFM durations on estimation performance

Figure 13 shows that the estimation performance of the proposed underwater acoustic channel structure estimation algorithm improves with the increase of LFM signal duration.

7 Conclusions

The performance of zero-setting algorithm is better on the premise that there is only one eigen ray in the pulse width of LFM signal after matched filtering. In the actual underwater acoustic environment, there will be overlapping results of multiple eigen ray signals, so the estimation results are not ideal. The performance of signal cancellation algorithm is better than the zero-setting algorithm. However, it does not consider the influence of adjacent eigen rays on the estimation, so the accuracy of channel multipath structure estimation decreases. The channel estimation algorithm proposed in this paper uses the principle of signal cancellation to remove the energy multipath signal, eliminating the masking effect of the side lobe of the high energy multipath signal for the low energy multipath signal, and improving the performance of low energy multipath signal. Then, we improve the estimation accuracy of multipath structure of UAC by modifying the multipath structure of UAC. The simulation and experimental results show the effectiveness of the improved algorithm proposed in this paper. Because the above research does not consider the computational complexity in practical application, we will further optimize the above modified algorithm in the later stage in order to achieve the goal of real-time channel estimation.

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