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Short communication

Time reversal MFSK acoustic communication in underwater channel with large multipath spread

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ABSTRACT

It has been recognized that, compared with coherent acoustic communication, Multiple Frequency Shift Keying (MFSK) underwater acoustic communication offers the advantages of low complexity, easy-implementation and channel tolerance, but it is subject to significant performance degradation caused by inter-symbol interference (ISI) when the multipath spread is larger than symbol duration. The time reversal is capable of effectively suppressing the channel multipath by the means of temporal-spatial focusing, which has been widely examined and applied in coherent underwater acoustic communication systems. However, there is a lack of investigations to incorporate the time reversal with MFSK communication. In this paper, we report a multi-channel time reversal MFSK receiver, in which the channel estimate is initially obtained and periodically updated by matched filtering of the sync preamble, meanwhile, down-conversion is adopted to reduce computational complexity. The performance of the proposed receiver is evaluated in a shallow water channel with severe multipath spread, in terms of bit error rate (BER) and robustness upon time variations.

1. Introduction

In view of numerous studies in high bandwidth efficiency coherent acoustic communication technologies such as QPSK(Zhou et al., 2017), OFDM(Gomes and Barroso, 2004) and MIMO(Zhou et al., 2014), MFSK acoustic communication is still drawing extensive attention from various practical fields due to its low implementation complexity as well as robustness in the presence of severe time-frequency selective fading channels.

However, an inherent drawback of the classical MFSK is that it cannot solve the multipath induced inter-symbol interference (ISI) when the multipath spread is larger than the symbol duration. Traditional solutions including adding protection interval or increasing symbol duration are adopted to ensure that the multipath component of the previous symbol does not overlap with the new following symbol, both of which unfortunately lead to additional overhead. Moreover, frequency selective fading caused by the multipath components that spanning inside the range of symbol width poses another difficulty to the MFSK systems, as the non-coherent demodulation totally relies on the comparison of energy associated with each modulated frequencies to obtain correct detection. Until now, the most general method to circumvent the above problem is to adopt different error correction coding, such as the Non-Binary LDPC code in (Fan et al., 2014), Turbo code in (Yue et al., 2012) and convolutional code in (Green and Rice, 2000), to correct the errors caused by ISI and frequency selective fading (Edelmann et al., 2002; Mousavi et al. (2016),Stojanovic, 2005) while retaining the advantages of MFSK.

To develop a channel-tolerant acoustic communication approach, M.D.Green and J.A.Rice (Green and Rice, 2000) proposed to incorporate frequency hopping (FH) with MFSK to overcome the problem caused by multipath. However, the date rate of the FH-MFSK is low as the spread spectrum (Green and Rice, 2000) nature of FH means low efficiency of bandwidth utilization.

In (Yang and Yang, 2003) it was reported that different lengths of multipath delays have a significant effect on the bit error rate (BER) of FSK underwater communication, multi-channel beamforming as well as the spatial diversity combining is adopted to improve the BER performance. Moreover, (Yang and Yang, 2006) found that MFSK BER performance using an incoherent receiver is determined by fading statistics of received signal amplitude, which exhibits a non-Rayleigh behavior and may be modeled as a K-distribution.

X.J. Shu et al. (Shu et al., 2016) investigated the Chaotic modulation MFSK (CMFSK) to improve the security for confidential applications. However, (Shu et al., 2016) also pointed out that, in terms of the BER

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performance under multipath distortion the CMFSK is equivalent to conventional digital modulations.

Being recognized as a promising underwater acoustic (UWA) channel matching technology (Zhang and Dong, 2013; Song et al., 2008), passive time reversal is capable of overcoming the impairment of multipath by the means of temporal-spatial focusing. Implementation of multi-channel time reversal (TR) processing is generally equivalent to first obtain the multi-channel probes that carried the information of UWA channels and then perform time reversal with the received signal of each channel, output of which are finally summed up to enable temporal spatial compressing of multipath (Silva and Jesus, 2002). Currently, due to its easily coupling with channel equalizer (Jamshidi and Moezzi, 2015a), ISI cancellation algorithm (Jamshidi, 2011; Jamshidi and Moezzi, 2015b) and channel estimator in coherent receiver structure, there have been substantial investigations of time reversal in coherent underwater acoustic communication, such as those applying the time reversal in OFDM(Liu and Yang, 2012; Zhou et al., 2015a,b), QPSK(Xi et al., 2015; Duan and Zheng, 2015) and MIMO-PSK(Zhang et al., 2016). It is quite interesting to point out that, until now few literature has been reported to incorporate the time reversal with MFSK acoustic communication, although both of which are recognized as low complexity and easy implementation.

In this letter we report our work to apply the time reversal method in the MFSK communication to address the difficulties caused by ISI in the presence of severe multipath spread. With down-conversion, a multi-channel time reversal MFSK receiver is proposed, which adopts the sync preamble as channel probe. Finally, the performance of the proposed method is verified by the sea trial experiment performed in shallow sea channel with large multipath spread, based on which the comparison are made to demonstrate the practical effectiveness of time reversal MFSK.

2. Brief introduction of time reversal and MFSK

2.1. Multi-channel time reversal (Zhou et al., 2014)

For multi-channel time reversal system, under the assumption that the impulse response of the ith channel $h_i(t)$ remains static within the period, the signal received by the ith channel is

$$s_{ir}(t) = s(t) \otimes h_i(t) + n_i(t) \tag{1}$$

where $s_{ir}(t)$ is received signal, $s(t)$ is source signal, $n_i(t)$ is local interference noise, the symbol $\otimes$represents convolution operation. Thus the time reversal processing at the ith channel can be expressed as:

$$\begin{aligned} r_i(t) &= s_{ir}(t) \otimes h_i^{'}(-t) = [s(t) \otimes h_i(t) + n_i(t)] \otimes h_i^{'}(-t) \\ &= s(t) \otimes h_i(t) \otimes h_i^{'}(-t) + n_i(t) \otimes h_i^{'}(-t) \\ &= s(t) \otimes h_i(t) \otimes h_i^{'}(-t) + n_i(t) \otimes h_i^{'}(-t) \end{aligned} \tag{2}$$

Where $h_i^{'}(-t)$ is time reverse of the channel response obtained by various estimation methods such as MMSE or LS (Chitre et al., 2008). For the multi-channel time reversal, time reversal output of each channel is summed up to explore spatial diversity of the multipath structure.

$$\begin{aligned} s'(t) &= \sum_{i=1}^{n} r_i(t) \\ &= s(t) \otimes \sum_{i=1}^{n} \left[h_i(t) \otimes h_i^{'}(-t)\right] + \sum\nolimits_{i=1}^{n} n_i(t) \otimes h_i^{'}(-t) \approx s(t) + nn(t) \end{aligned} \tag{3}$$

where $q(t) = \sum_{i=1}^{n} [h_i(t) \otimes h_i^{'}(-t)]$ defined as q function (Song et al., 2007) is the autocorrelations of the channel response summed over all channels, which approaches to an ideal delta-t impulse response with an increasing number of receivers (Song and Badiey, 2012), $nn(t)$ is the total noise term. Therefore, after the multi-channel time reversal processing, multipath is effectively temporally-spatially focused to suppress the ISI.

2.2. The proposed TR MFSK receiver

Demodulation of MFSK is generally performed with fast Fourier transforms (FFTs) and then energy measurement of each FFT bins. Namely, using M = 16 implies that each MFSK symbols contains 16 FFT bins. To reduce the computational complexity, the FFTs demodulation can also be performed after the front-end processing of down conversion and down resampling (Yang, 2005).

The structure of the proposed multi-channel time reversal MFSK receiver is shown in Fig. 1. As Fig. 1 indicates, after the down-conversion and down-resampling, the matched filtering output of the sync preamble is used as the measured channel response for time reversal processing. Time reversal output of each channel is summed up for the final MFSK demodulation to yield temporal-spatial multipath suppression. Note that, compared with contemporary coherent time reversal receiver, the time reversal MFSK directly adopts the error-correction coding to address the residual ISI and fading, thus avoid the need to place an equalizer after the time reversal processing (Song and Badiey, 2012; Yang, 2005).

In terms of the computational complexity, while the core processing of classic MFSK demodulation is FFT calculation that only need (P/2) $\log_2$P multiplications for P point operation, it is straightforward that convolution operation of time reversal processor can also be implemented in the form of FFT-multiplication-IFFT. Meanwhile, the adoption of down-conversion and down-resampling leads to further saving of calculation burden. Thus, compared to that of classic MFSK receiver, the increasing of complexity in time reversal receiver is still tolerable for practical application.

3. The experiment

3.1. Experimental configuration

The experimental field data was collected at Wuyuan Bay, Xiamen, China, which is a semi-enclosed bay (shown in Fig. 2(c)) with an average depth of about 10 m. The MFSK signal was transmitted from a transducer at a depth of 2 m with a source level of about 185 dB re 1 μPa at 1 m. The transmitted signal was received by a four-element broadband receiver array, that covering 2–8 m of the water column with an element spacing of 2 m. Both the transducer and four-element receiver are produced by the China Shipbuilding Industry Corporation (CSIC), with the model of T16k and RA16k respectively. The distance of receiver and source is 1000 m as shown in Fig. 2(a). The sound speed profile is provided in Fig. 2(b) with a sea state of slight wind.

The parameters of the MFSK modulation and time reversal demodulation are provided in Table 1 with the frame structure illustrated in Fig. 3. The received signals are collected for off-line demodulation processing in PC. For the purpose of evaluation and comparison, the performance of the MFSK demodulation adopting the multi-channel time reversal is compared with that of the classical MFSK demodulation. To facilitate further performance enhancement, convolution coding and interleaving is also adopted to mitigate the residual ISI and fading. The estimated bulk Doppler was −2 Hz. Note that, as the purpose of experiment is to evaluate

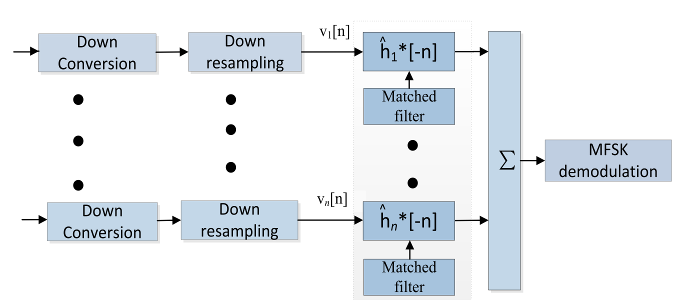
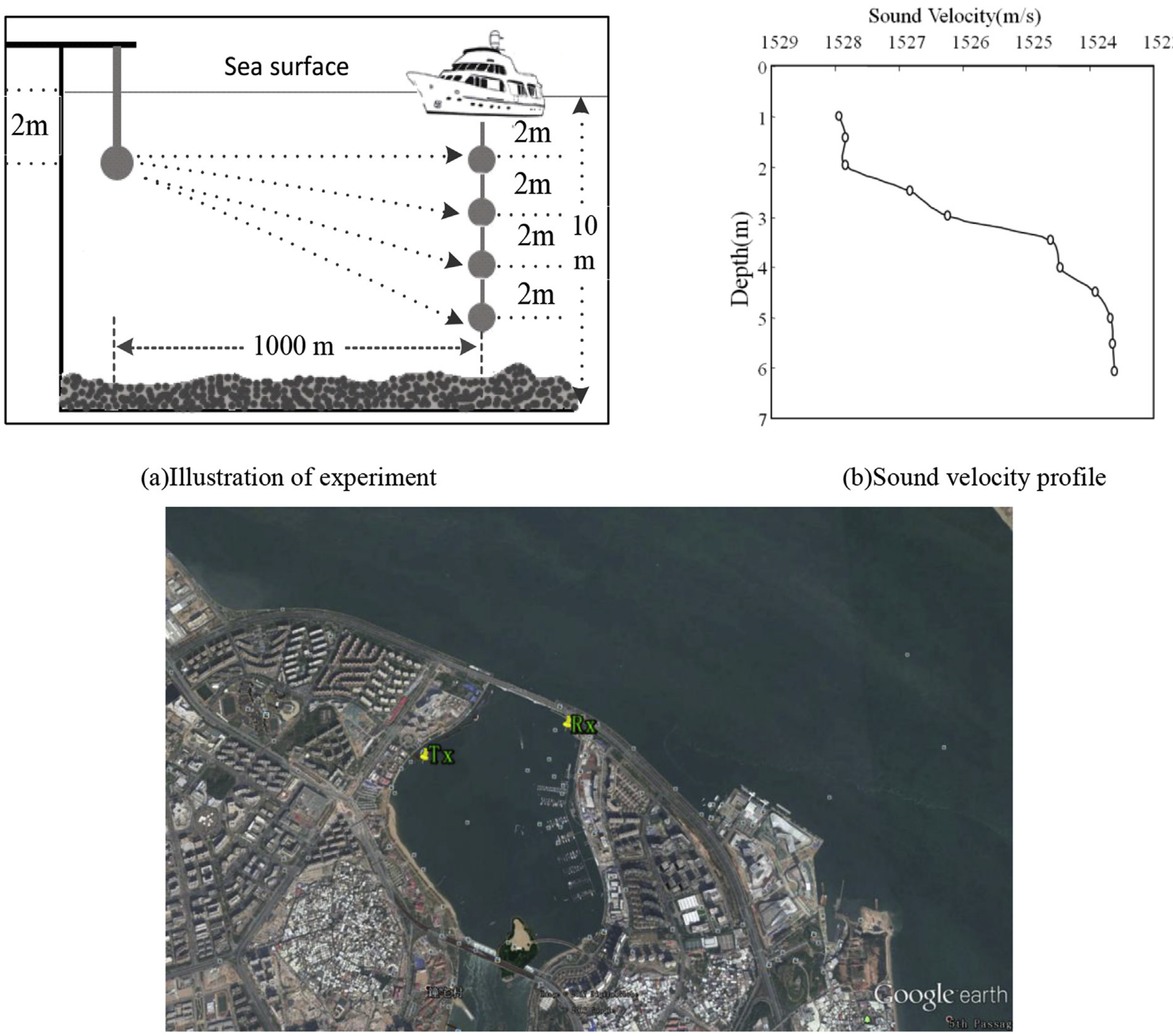


Fig. 1. Illustration of the TR MFSK receiver.



(a)Illustration of experiment

(b)Sound velocity profile

(c) Map of Wuyuan bay

Fig. 2. Setup of the experiment.

Table 1
MFSK modulation and demodulation parameters.

Parameter	value
M-ary of MFSK	M = 16
Symbol duration	13.65 ms
Bandwidth	13 kHz–18 kHz
Sync preamble	LFM signal, width:17.7 ms; bandwidth: 13 kHz–18 kHz
Length of guard time after sync preamble	50 ms
Period of channel estimate updating	Never updating; 3 frames; 1 frames
Peak bit rate	293 bps
Length of time reversal processor	1 024
The original sampling rate	75ksps
Down resampling rate	18.75ksps
Point of FFTs	256
error-correction coding	(2,1,7) Convolution code, (7,4) Interleaving code
Bits per frame	768bits
Number of frames	11

the performance of time reversal at the presence of time variation and multipath, no any Doppler correction method such as resampling is adopted in MFSK demodulation.

Sync signal (213ms)	Guard interval (213ms)	Probe signal (17.7ms)	Guard interval (50ms)	Data block (4128ms)

Fig. 3. The format of signal frame.

Shown in Fig. 4 is the channel response of four channels obtained by matched filtering of the LFM sync preamble. It is evident that the multipath spans a range of approximate 24 ms, which produces severe ISI as the duration of MFSK symbol is 13.65 ms. The large multipath spread of the experimental channel is caused by the boundary reflections inside the semi-enclosed bay. Meanwhile, from Fig. 4 it can be observed that different channel associated with element at different depth exhibits various multipath structure, which indicates the potential for exploring spatial diversity by the means of multichannel time reversal. The q function of the multi-channel time reversal is provided in Fig. 5, from which one may see the apparent effect of temporal-spatial multipath compression achieve by the multi-channel time reversal.

3.2. Experimental results and discussion

A clip of transmitted signal, received signal, as well as the associated signal at each step of the demodulation is provided in Fig. 6 in the form of

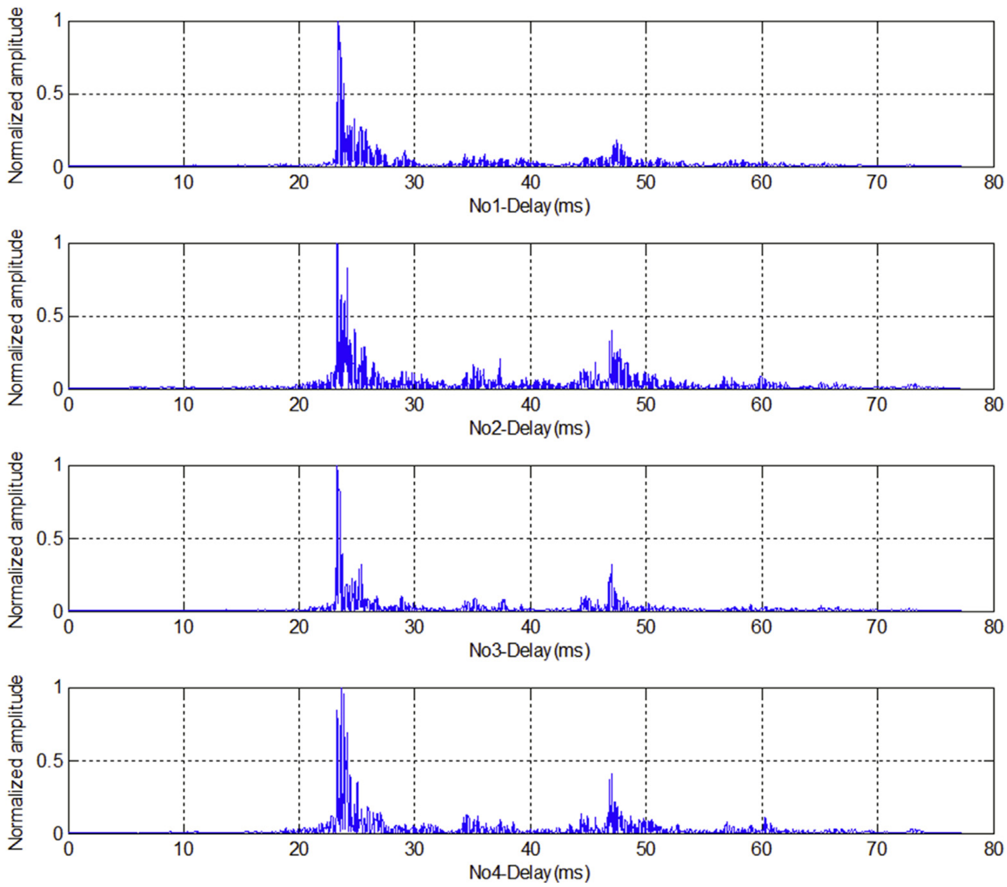


Fig. 4. Channel responses associated with 4 receiving elements.

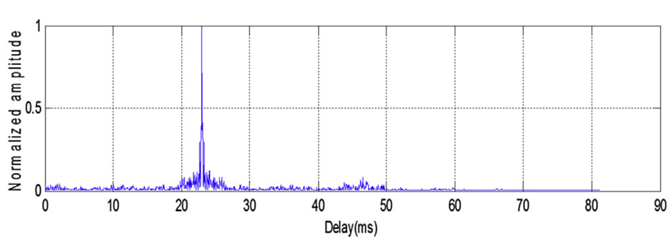


Fig. 5. q function of the multichannel time reversal.

waveform and associated spectrum. As indicated by Fig. 6(a)(f), there are two MFSK symbols that associated with two different frequencies in the clip of transmitted signal. After multipath propagation in shallow water channel, for received signal these two symbols exhibit substantial frequency selective fading as shown in time domain of Fig. 6(b) and spectrum of Fig. 6(g) respectively. Thus error demodulation may be produced for FFT bins that experience significant fading. In Fig. 6(c) and (d), the receiving MFSK symbols after down conversion and down resampling are shown, which is designed to reduce computational complexity but unfortunately fails to address the fading caused by multipath. Fig. 6(e)(f) provided the waveform and spectrum of this clip after time reversal processing respectively, which exhibit that the amplitude fading caused by multipath is effectively mitigated.

Fig. 7 provides the BER curve with and without time reversal. Note that, channel estimate updating period is one frame for the time reversal receiver associated with the BER curves in Fig. 7, namely, time reversal processing of each frame is performed with the channel response obtained by receiving sync preamble of the frame itself. It can be observed from Fig. 7 that the time reversal receiver outperforms the classic MFSK receiver in BER. To be specific, for the fourth frame, while the classic MFSK receiver corresponds to an original bit error rate (BER) of 0.1938 and a BER of 0.1042 with encoding, the original BER and the encoding BER of the time reversal MFSK receiver is 0.0103 and 0 respectively.

The reason of the BER performance comparison is that there exist serious ISI as the multipath spread of the experimental channel significantly exceeds the symbol duration. As a result, in the presence of high original BER caused by ISI, even the employment of error-correction encoding fails to improve the performance, as indicated by the BER after the 5th frame. By effectively suppressing the multipath, it is no surprising that the time reversal MFSK receiver yield significant performance improvement. Moreover, it is observable from Fig. 7 that the BER of MFSK receiver without TR exhibits an obviously rising trend with the increasing of frame number, due to the impact of uncompensated Doppler. This negative trend is also alleviated by the time reversal processing as shown in Fig. 7. Previously similar results have been reported (Song, 2013) in time reversal coherent acoustic communication system, indicating the Doppler mitigation capability of time reversal.

A basic assumption of the time reversal is that the channel needs to remain static to ensure the effectiveness, which is extremely difficult, if not impossible, to stand for practical UWA channels. It may lead to considerable performance degradation for the time reversal coherent acoustic communication system (Rouseff et al., 2009), as the channel sensitivity coming from both the phase and magnitude variations of channel. Periodically updating of the channel estimate based on training sequence or previously detected symbols is adopted to guarantee the performance of coherent time reversal (Zhou et al., 2015a,b), which will unfortunately cause additional overhead or error propagation.

Different from the coherent communication systems, because the non-coherent demodulation avoids the impact of phase fluctuation, time reversal MFSK receiver is expected to offer better robustness upon the channel variations. To evaluate the impact of channel variations on time reversal MFSK, the performance of the time reversal MFSK receiver that

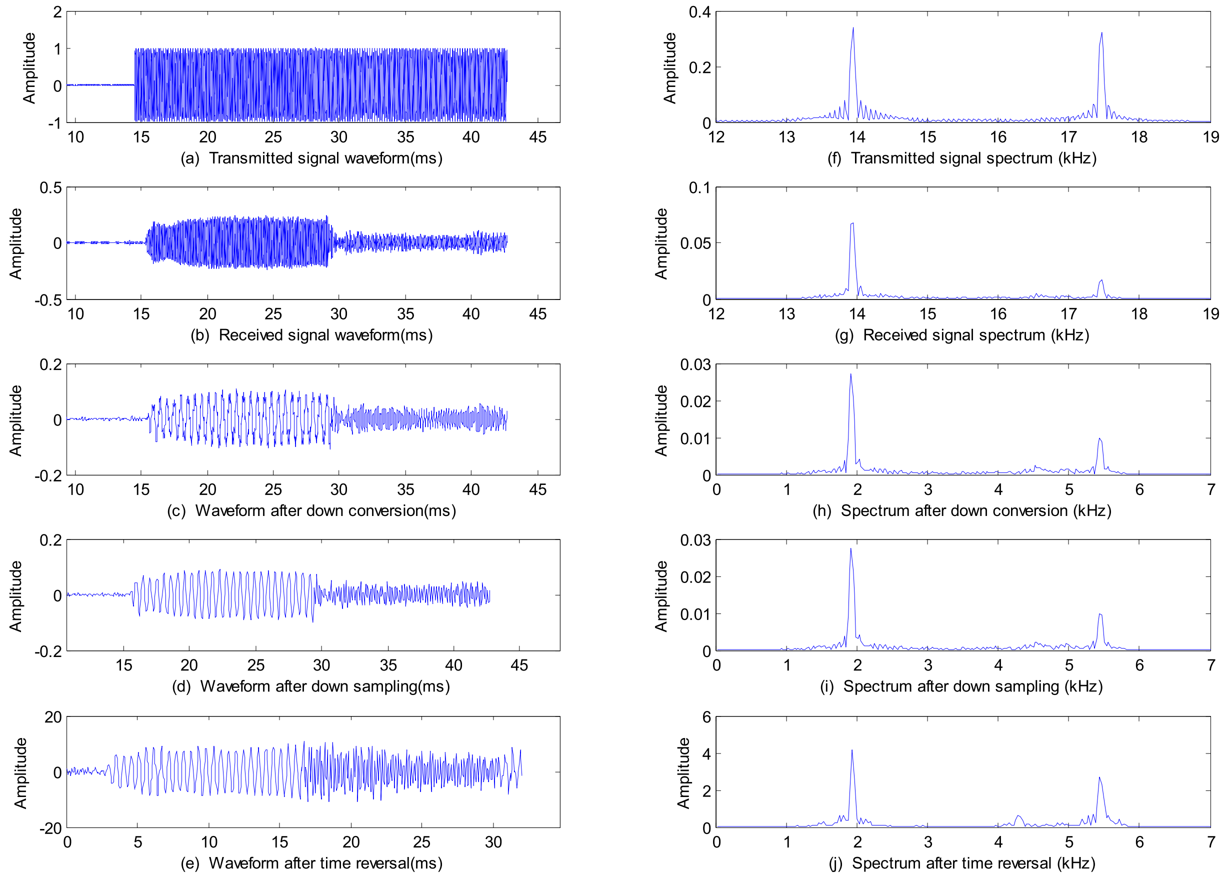


Fig. 6. Signal waveform and associated spectrum in each step of the demodulation.

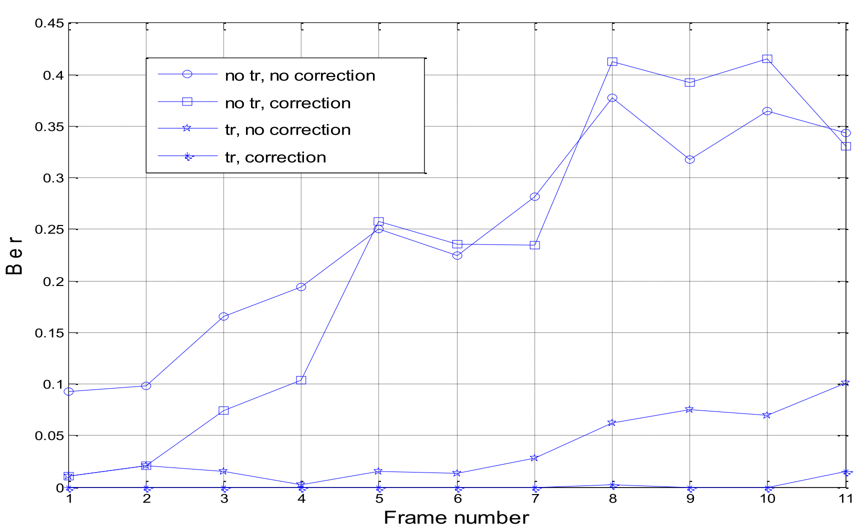


Fig. 7. BER with and without time reversal and correction coding.

does not update the channel estimate, updates the channel estimate every three frames, updates the channel estimate every frame is compared respectively. It can be seen from the original BER curves in Fig. 8 that, the performance degradation caused by time variation of UWA channel is noticeable, with the receiver updating the channel estimate more frequently corresponding to a lower original BER. Specifically, for the tenth frame of data, while no updating lead to an original BER of 0.06977, channel estimate updating every three frame, and that updating per frame yield an original BER of 0.03876 and 0.007752 respectively. Moreover, it can be observed that, for time reversal MFSK receiver, the sensitivity to channel variations is still acceptable for applications in practical environment, as the time varying channel in a time scale of minute (i.e., 11 frames) does not cause intolerable impairment for time reversal MFSK communication.

4. Conclusion

While the MFSK is recognized as a robust way for underwater acoustic communication, it is unfortunately subject to tremendous performance degradation at the presence of large multipath spread. In this letter we

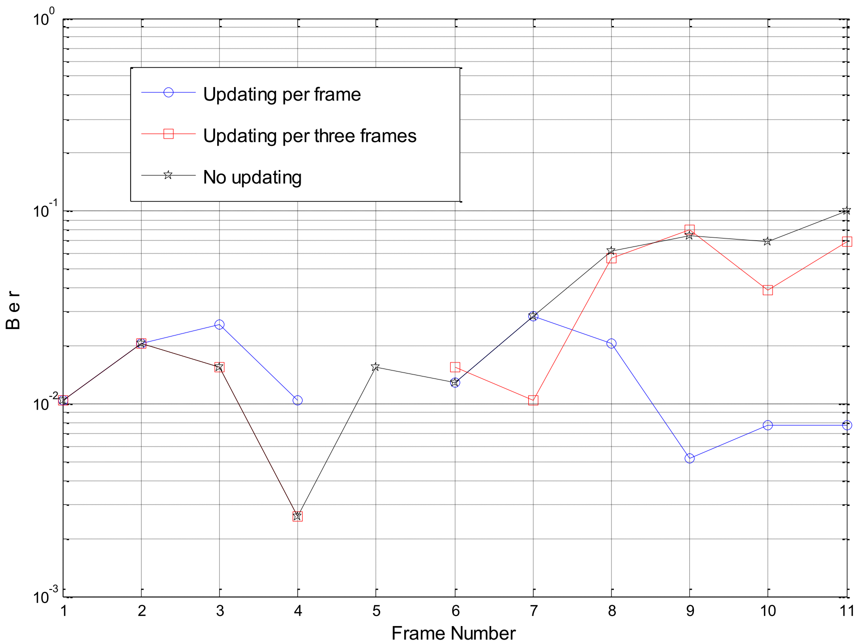


Fig. 8. Original BER with different probe updating period.

reported a time reversal MFSK receiver to mitigate the ISI caused by severe multipath. Avoiding the need of equalizer, the multi-channel time reversal processor is incorporated with the classic MFSK receiver to yield enhanced performance. The experimental results performed in a shallow water channel are investigated to evaluate the effectiveness of time reversal on MFSK demodulation.

As the experimental shallow water channel exhibit adverse multipath spread as well as time variation, it is no surprise that the conventional MFSK receiver experience significant performance degradation. While the effectiveness of multi-channel time reversal in mitigating the multipath has been verified by previous investigation based on coherent UWA systems, the results obtained in this paper reveal the capability of time reversal in enhancing the MFSK receiver.

Specifically, BER comparison between time reversal and classic MFSK receiver quantitatively show that the time reversal is capable of improving the performance of MFSK in the presence of adverse multipath spread. The q function of the multi-channel time reversal as well as the temporal-spectra behavior during the MFSK demodulation is also provided to clarify the reason behind the performance improvement. Meanwhile, by the means of down conversion and down resampling the low implementation complexity advantage of MFSK can be retained in time reversal receiver.

Moreover, the benefit that the time reversal MFSK receiver is capable of avoiding the Doppler correction was also noticed, which is consistent with previous investigation in coherent system. Furthermore, quantitative evaluation with different updating period of channel estimate reveals that, time reversal MFSK receiver has the potential of being applied in typical time varying channel.

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References

Chitre, M., Shahabudeen, S., Stojanovic, M., 2008. Underwater acoustic communications and networking: recent advances and future challenges. Mar. Technol. Soc. J. 42 (1), 103–116.

Duan, W., Zheng, Y.R., 2015. Bidirectional Soft-decision Feedback Equalization for Robust MIMO Underwater Acoustic Communications. Oceans - St. John's. IEEE, pp. 1–6.

Edelmann, G.F., Akal, T., Hodgkiss, W.S., Kim, S., Kuperman, W.A., Song, H.C., 2002. An initial demonstration of underwater acoustic communication using time reversal. IEEE J. Ocean. Eng. 27 (3), 602–609.

Fan, W.W., Li, B., Zhang, Y.W., Sun, D.J., 2014. Research of FH-MFSK underwater acoustic communication based on non-Binary LDPC codes. In: Applied Mechanics and Materials, vol. 519. Trans Tech Publications, pp. 945–952.

Gomes, J., Barroso, V., 2004, July. Time-reversed OFDM communication in underwater channels. In: Signal Processing Advances in Wireless Communications, 2004 IEEE 5th Workshop on. IEEE, pp. 626–630.

Green, M.D., Rice, J.A., 2000. Channel-tolerant FH-MFSK acoustic signaling for undersea communications and networks. IEEE J. Ocean. Eng. 25 (1), 28–39.

Jamshidi, A., 2011. Direct sequence spread spectrum point-to-point communication scheme in underwater acoustic sparse channels. IET Commun. 5 (4), 456–466.

Jamshidi, A., Moezzi, S., 2015a. On the practical aspects of joint passive phase conjugation and equalization in underwater communication systems. Majlesi J. Telecommun. Devices 4 (2), 71–77.

Jamshidi, A., Moezzi, S., 2015b. Experiential assessment of iteratively residual interference elimination in the passive phase conjugation for acoustic underwater communications. Ocean Eng. 105, 287–294.

Liu, Z., Yang, T.C., 2012. On the design of cyclic prefix length for time-reversed OFDM. IEEE Trans. Wireless Commun. 11 (10), 3723–3733.

Mousavi, M.R., Karimi, M., Jamshidi, A., 2016. Probability distribution of acoustic scattering from slightly rough sea surface. Ocean Eng. 112, 134–144.

Rouseff, D., Badiey, M., Song, A., 2009. Effect of reflected and refracted signals on coherent underwater acoustic communication: results from the kauai experiment (kauaiex 2003). J. Acoust. Soc. Am. 126 (5), 2359–2366.

Shu, X., Wang, H., Yang, X., Wang, J., 2016. Chaotic modulations and performance analysis for digital underwater acoustic communications. Appl. Acoust. 105, 200–208.

Silva, A.J., Jesus, S.M., 2002, October. Underwater communications using virtual time reversal in a variable geometry channel. In: OCEANS'02 MTS/IEEE, vol. 4. IEEE, pp. 2416–2421.

Song, A., Badiey, M., Song, H.C., Hodgkiss, W.S., Porter, M.B., the KauaiEx Group, 2008. Impact of ocean variability on coherent underwater acoustic communications during the Kauai experiment (KauaiEx). J. Acoust. Soc. Am. 123 (2), 856–865.

Song, A., Badiey, M., 2012. Time reversal multiple-input/multiple-output acoustic communication enhanced by parallel interference cancellation. J. Acoust. Soc. Am. 131 (1), 281–291.

Song, H., 2013. Time reversal communication with a mobile source. J. Acoust. Soc. Am. 132 (4), 2623–2626.

Song, H., Hodgkiss, W.S., Kuperman, W.A., Akal, T., Stevenson, M., 2007. Multiuser communications using passive time reversal. IEEE J. Ocean. Eng. 32 (4), 915–926.

Stojanovic, M., 2005. Retrofocusing techniques for high rate acoustic communications. J. Acoust. Soc. Am. 117 (3), 1173–1185.

Xi, J., Yan, S., Xu, L., Tian, J., 2015. Bidirectional blind equalization based on the constant modulus and subspace-based algorithms. In: IEEE International Conference on Signal Processing, Communications and Computing. IEEE, pp. 1–5.

Yang, T.C., 2005. Correlation-based decision-feedback equalizer for underwater acoustic communications. IEEE J. Ocean. Eng. 30 (4), 865–880.

Yang, W.B., Yang, T.C., 2003. High-frequency underwater acoustic communications using FH-FSK signaling in a reverberant shallow water environment. J. Acoust. Soc. Am. 114 (4), 2407.
Yang, W.B., Yang, T.C., 2006. M-ary frequency-shift-keying bit error rate analysis for a high-frequency underwater acoustic fading channel. J. Acoust. Soc. Am. 119 (5), 3398.
Yue, L., Yang, X.L., Wang, M.Z., Fan, S.H., 2012, October. Performance of turbo coded FH/MFSK in shallow water acoustic channel. In: Signal Processing (ICSP), 2012 IEEE 11th International Conference on, vol. 2. IEEE, pp. 1401–1405.
Zhou, Y.H., Jiang, W.H., Tong, F., Zhang, G.Q., 2017. Exploiting joint sparsity for underwater acoustic MIMO communications. Appl. Acoust. 116, 357–363.
Zhou, Y.H., Tong, F., Zeng, K., Chen, Y.G., 2014. Selective Time Reversal Receiver for Shallow Water Acoustic MIMO Communications. Oceans. IEEE, pp. 1–6.
Zhang, G., Dong, H., 2013. Underwater communications in time-varying sparse channels using passive-phase conjugation. Appl. Acoust. 74 (3), 421–424.
Zhou, Y., Jiang, W., Chen, L., Tong, F., 2015a. Underwater acoustic speech communication using time reversal and time-frequency differential ofdm methods. J. Appl. Acoust. 34 (4), 283–290.
Zhang, L., Han, J., Huang, J., Zhang, Q., 2016. Iterative Channel Estimation and Equalization for Underwater Acoustic MIMO SFBC OFDM Communication. Ocean Acoustics. IEEE, pp. 1–6.
Zhou, Y., Cao, X., Yanyi, W.U., Tong, F., 2015b. Spread spectrum underwater acoustic communication based on passive time reversal in time varying channels. J. Appl. Acoust. 34 (6), 509–515.