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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.

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

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

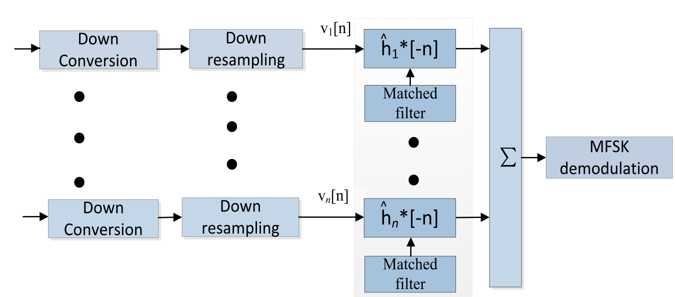

Fig. 1. Illustration of the TR MFSK receiver.