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Acoustic MIMO Communications in a Very Shallow Water Channel

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Abstract: Underwater acoustic channels pose a great difficulty for the development of high speed communication due to highly limited band-width as well as hostile multipath interference. Enlightened by rapid progress of multiple-input multiple-output (MIMO) technologies in wireless communication scenarios, MIMO systems offer a potential solution by enabling multiple spatially parallel communication channels to improve communication performance as well as capacity. For MIMO acoustic communications, deep sea channels offer substantial spatial diversity among multiple channels that can be exploited to address simultaneous multipath and co-channel interference. At the same time, there are increasing requirements for high speed underwater communication in very shallow water area (for example, a depth less than 10 m). In this paper, a space-time multichannel adaptive receiver consisting of multiple decision feedback equalizers (DFE) is adopted as the receiver for a very shallow water MIMO acoustic communication system. The performance of multichannel DFE receivers with relatively small number of receiving elements are analyzed and compared with that of the multichannel time reversal receiver to evaluate the impact of limited spatial diversity on multi-channel equalization and time reversal processing. The results of sea trials in a very shallow water channel are presented to demonstrate the feasibility of very shallow water MIMO acoustic communication.

Keywords: underwater acoustic; underwater acoustic communication; multiple-input multiple-output (MIMO); decision feedback equalizer (DFE); very shallow water; multi-channel; time reversal

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1 Introduction

There is rapidly increasing R&D interest in high data rate underwater acoustic communication systems in the fields of oceanic exploitation, underwater construction, oceanography research, and national defense (Chitre *et al*., 2008). Features of underwater acoustic channels (Li and Preisig, 2007; Rouseff *et al*., 2009), such as narrow bandwidth, serious multipath, Doppler spread, and background noise are recognized as key limitations for R&D of high data rate underwater acoustic communications (Song *et al*., 2008; Cotter and Rao, 2002; Wu *et al*., 2013; Stojanovic, 2008, Zeng *et al*., 2010).

Enlightened by significant success of multiple-input multiple-output (MIMO) technology in wireless communication fields, significant data rate increases can be achieved under acoustic channels by simultaneously transmitting multiple data streams from a bank of transmitters. Previous investigation and experiments have indicated that, MIMO systems are capable of using multiple spatially parallel underwater communication channels to improve communication performance including capacity (Song *et al*., 2007; Ling *et al*., 2014; Tao *et al*., 2010).

Multichannel decision feedback equalizer (DFE) receivers and time reversal receivers are widely investigated in the research community as coherent receivers for MIMO acoustic communication. A space-time equalizer consisting of multiple DFE equalizers is adopted as the coherent receiver for MIMO acoustic communications (Flynn *et al*., 2004; Song and Ritcey, 1996). In (Song *et al*., 2011; Yang, 2005), a low complexity time reversal receiver is proposed by combination of multiple time reversal processors and single channel equalizers. In (Zhou *et al*., 2014), a time reversal receiver and a space-time receiver are jointly adopted as a selective time reversal receiver to facilitate low complexity implementation and selective focusing of channel with a long delay spread.

However, most investigations on MIMO acoustic communication are carried out in underwater acoustic channels with a large depth (>100 m) (Song *et al*., 2006), which offers substantial spatial diversity for exploitation as well as enabling the deployment of large receiving arrays (number of element>10). Given increasing high speed communication requirements in very shallow water such harbors, bridges, and coastal facilities, the feasibility and performance of MIMO technology in very shallow channels, i.e., with a depth of smaller than 10 m, is worth further analysis and validation.

This paper presents the implementation and performance evaluation of a multichannel DFE receiver for very shallow acoustic MIMO communication, so as to accommodate the limited spatial diversity in a very shallow water channel.

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Considering the extreme shallow water depth, that excludes the deployment of a large receiving vertical array, a small size receiver array, with only 2, 3 and 4 elements, is analyzed and compared to evaluate the impact of spatial diversity on the performance of multi-channel equalizer and the mutichannel time reversal receivers. At the same time, the capabilities of two types of receiver, to suppress multipath interference and co-channel interference of MIMO channel, with small number of receivers and small size DFE, are investigated.

2 MIMO model and receiver structure

2.1 System model of MIMO acoustic communication

The classic model of a MIMO acoustic communication system with N transmitters and M receivers can be written as (Song *et al*., 2011; Ling *et al*., 2014):

$$\boldsymbol{y}_m(k)=\sum_{n=1}^{N}\sum_{l=0}^{L-1}\boldsymbol{s}_n(k-l)\boldsymbol{h}_{n,m}(k,l)+\boldsymbol{z}_m(k) \tag{1}$$

where, $\boldsymbol{y}_m(k)$ and $\boldsymbol{z}_m(k)$ are the receiving signal and additive noise at the mth receiver, respectively. $\boldsymbol{s}_n(k)$ and $\boldsymbol{h}_{n,m}(k,l)$ are the transmitting signal of the nth transmitter and the channel impulse response between n-mth couple, respectively. k is time index for observation time, l is time index for time delay, L is the time delay dimension of the channel impulse response. Under the assumption the channel remains stable in P samples, Eq. (1) can be expressed as:

$$\boldsymbol{y_m}=\sum_{n=1}^{N}\boldsymbol{A}_n\boldsymbol{h}_{n,m}+\boldsymbol{z}_m \tag{2}$$

where the P row-L column matrix $\boldsymbol{A_n}$ is:

$$\boldsymbol{A}_n=\begin{bmatrix} s_n(k+L) & s_n(k+L-1) & \cdots & s_n(k+1) \\ s_n(k+L+1) & s_n(k+L) & \cdots & s_n(k+2) \\ \vdots & \vdots & \vdots & \vdots \\ s_n(k+L+P-1) & s_n(k+L+P-2) & \cdots & s_n(k+P) \end{bmatrix} \tag{3}$$

with:

$$\begin{aligned} \boldsymbol{y_m}&=[y_m(k+L)\quad y_m(k+L+1)\quad \cdots \quad y_m(k+L+P-1)]^{\mathrm{T}} \\ \boldsymbol{s_n}&=[s_n(k+L)\quad s_n(k+L-1)\quad \cdots \quad s_n(k+1)]^{\mathrm{T}} \\ \boldsymbol{h}_{n,m}&=[h_{n,m}(k,0)\quad h_{n,m}(k,1)\quad \cdots \quad h_{n,m}(k,L-1)]^{\mathrm{T}} \\ \boldsymbol{z}_m&=[z_m(k+L)\quad z_m(k+L+1)\quad \ldots \quad z_m(k+L+P-1)]^{\mathrm{T}} \end{aligned} \tag{4}$$

Eq. (2) can be further expressed as:

$$\boldsymbol{y}_m=\boldsymbol{A}\boldsymbol{h}_m+\boldsymbol{w}_m \tag{5}$$

where,

$$\boldsymbol{A}=[\boldsymbol{A}_1,\quad \boldsymbol{A}_2,\quad \cdots \quad \boldsymbol{A}_N] \quad \boldsymbol{h}_m=[\boldsymbol{h}_{1,m}\quad \boldsymbol{h}_{2,m}\quad \cdots \quad \boldsymbol{h}_{N,m}]^{\mathrm{T}}$$

The MIMO channel $\boldsymbol{h}$ can be estimated with least square (LS) or minimize mean square error (MMSE) method. For a multi-channel DFE receiver, the effects of underwater acoustic channels are addressed in the form of temporal-spatial equalization, which is updated by adaptive algorithms such as RLS and LMS to track the time variations of the acoustic channels. As the time reversal receiver generally needs a large number of receiving elements (>10) to achieve meaningful performance (Yang, 2005), the multi-channel DFE receiver is suitable for very shallow channels due to its tolerance of small size array with small number of elements.

2.2 The structure of multichannel DFE receiver

The classic multichannel DFE receiver for MIMO communication is illustrated in Fig.1 (Flynn *et al*., 2004; Zhou *et al*., 2014).

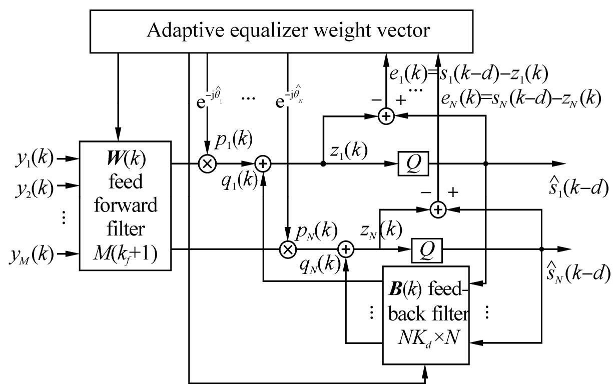


Fig. 1 Illustration of the multichannel DFE receiver

As shown in Fig. 1, the multi-channel DFE consists of N forward filters (FF) designed to recover N transmitting sequences, each of which is composed of MK_f-order FIR filters associated with M receivers. In Fig1, $\boldsymbol{W}(k)=[w_1(k)\quad w_2(k)\quad \cdots \quad w_N(k)]$ denotes $M(K_f+1)\times N$ coefficient matrix of N forward filters, where $w_n(k)$ corresponds to the nth ($1\le n\le N$) FF to recover the nth transmitting sequence, the carrier phase of which is compensated by the $\mathrm{e}^{-\mathrm{j}\theta_n}$ term driven with a second order phase lock loop (PLL). $p_n(k)$ is the output of the nth FF, expressed as:

$$p_n(k)=\boldsymbol{w}_n^{\mathrm{H}}(k)\tilde{\boldsymbol{y}}(k)\mathrm{e}^{-\mathrm{j}\theta_n} \tag{6}$$

where $\tilde{\boldsymbol{y}}(k)$ is $M(K_f+1)$ order input vector of the nth FF, expressed as:

$$\tilde{\boldsymbol{y}}(k)=[\boldsymbol{y}(k)\quad \boldsymbol{y}(k-1)\quad \cdots \quad \boldsymbol{y}(k-K_f)]^{\mathrm{T}} \tag{7}$$

where,

$$\boldsymbol{y}(k)=[y_1(k)\quad y_2(k)\quad \cdots \quad y_M(k)]$$

The feedback filter (FB) consists of a $NK_b\times N$ dimension vector $\boldsymbol{B}(k)=[\boldsymbol{b}_1(k) \quad \boldsymbol{b}_2(k) \quad \cdots \quad \boldsymbol{b}_N(k)]$, where K_b is the order of the FB filter, $\boldsymbol{b}_n(k)(1\le n\le N)$ is a NK_b dimension vector. Thus, output of the nth FB filter is:

$$\boldsymbol{q}_n(k)=\boldsymbol{b}_n^H(k)\hat{\boldsymbol{s}}(k-d) \tag{8}$$

where $\hat{\boldsymbol{s}}(k-d)=[\hat{s}_1(k-d) \quad \hat{s}_2(k-d) \quad \cdots \quad \hat{s}_N(k-d)]^{\mathrm{T}}$ is NK_b dimension input vector of the FB filter, i.e., previously detected bits, d is a constant for delay compensation. Thus, the nth $(1\le n\le N)$ layer variable vector $\boldsymbol{z}_n(k)$ produced by the FF and FB filter is written as：

$$\boldsymbol{z}_n(k)=\boldsymbol{p}_n(k)+\boldsymbol{q}_n(k) \tag{9}$$

The adaptive algorithms, such as RLS and LMS, can be used to update the DFE to accommodate time variations induced by channels. However, enough spatial diversity between multiple channels of the receiving array is recognized as a precondition for satisfactory performance of multi-channel equalization. This is easily realized for underwater acoustic channels with enough depth but may be difficult for very shallow channels. Thus, one of the key challenges for multi-channel DFE MIMO receivers in very shallow water is to achieve equalization in the presence of limited spatial diversity.

2.3 The structure of multichannel time reversal receiver

For the classic time reversal receiver, the channel responses obtained with the channel estimation algorithm are used to construct a multichannel time reversal receiver (Song *et al*., 2011; Yang, 2005) expressed as:

$$\begin{aligned}\hat{\boldsymbol{s}}_{\boldsymbol{n},\boldsymbol{m}} &= \boldsymbol{y}_{\boldsymbol{m}}\otimes\hat{\boldsymbol{h}}_{n,m}(-l)=\left[\boldsymbol{s}_n\otimes\hat{\boldsymbol{h}}_{n,m}(l)+\boldsymbol{z}_m\right]\otimes\hat{\boldsymbol{h}}_{n,m}(-l)=\\ &\boldsymbol{s}_n\otimes\hat{\boldsymbol{h}}_{n,m}(l)\otimes\hat{\boldsymbol{h}}_{n,m}(-l)+\boldsymbol{z}_m\otimes\hat{\boldsymbol{h}}_{n,m}(-l)\approx\\ &\boldsymbol{s}_n+\boldsymbol{z}_m\otimes\hat{\boldsymbol{h}}_{n,m}(-l)\end{aligned} \tag{10}$$

where $\boldsymbol{h}_{n,m}(-l)$ is the channel response obtained with channel estimation algorithms, such as LS algorithm or matching pursuit algorithm (MP) (Song *et al*., 2011). By summing output of multi-channel time reversal processors, spatial diversity can be achieved in the form of a multi-channel time reversal receiver as:

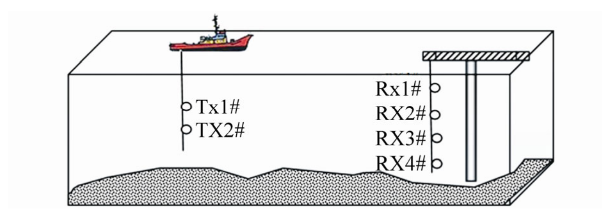
$$\hat{\boldsymbol{s}}_n=\sum_{m=1}^{M}\hat{\boldsymbol{s}}_{n,m} \tag{11}$$

By coupling multichannel time reversal with a single-channel adaptive DFE, the time reversal receiver is capable of improving the adaptability to time varying channels (Song *et al*., 2011; Yang, 2005). The purpose of the single-channel DFE is to address the residual ISI and accommodate the temporal variation of the physical channel. The principle of the single DFE matches a m DFE filter in the multichannel-DFE receiver. However, it is noted that the time reversal processor generally requires a vertical array with a large number (>10) to yield satisfactory spatial diversity (Yang, 2005).

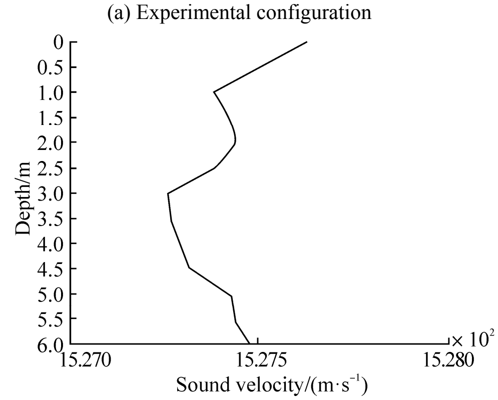
3 Experiment in a very shallow water channel

In this section, at-sea experiment results, in a very shallow water channel, are presented to evaluate the performance of the multichannel DFE MIMO receiver and the multichannel time reversal receiver. In the experiment configuration, with the same two transmitting sources, different number of receiving elements, i.e., 2TX-4RX, 2TX-3RX and 2TX-2RX, MIMO acoustic communication systems are adopted for the performance evaluation and comparison with respect to spatial diversity. The modulation format was quadrature phase-shift keying (QPSK) with a bit rate of 8 kilobits per second and a carrier frequency of 16 kHz. The bandwidth of the transducer coupling was 13–18 kHz. Original sampling rate of the received data is 96 ksps. Sampling interval of the baseband sequence is 1/2 of the symbol duration.

The MIMO acoustic communication experiment was carried out in a very shallow water acoustic channel at Wuyuan bay, Xiamen, China. The depth of the experiment area was about 6 m at the time of our MIMO communication experiment. The transmitting coupling was suspended to depth of 2 m and 4 m from a boat, with the 4-element receiving vertical array suspended to a depth range of 0.5–5.5 m with a spacing of 1.25 m at the pier (as shown in Fig. 2(a)), to produce multi-channel signals for 4-channel, 3-channel and 2-channel MIMO signal processing. The number of each MIMO transmitter (TX1, TX2) and each element of the vertical receiving array (RX1, RX2, RX3, RX4) are also marked in Fig. 2(a). The sound velocity gradient of the experiment channel is provided in Fig. 2(b). As the depth of the water is very small, variation of sound velocity along the vertical array is tiny. The distance between the transmitter and receiver is 1 000 m, corresponding to an SNR of 12 dB for receiving signals.



(a) Experimental configuration



(b) Sound velocity gradient

Fig. 2 Experimental configuration of MIMO acoustic communication system

The MIMO channel multipath response, with respect to time obtained during the experiment, is shown in Fig. 3, from which one can see that the very shallow water channels contain various multipath components. As the depth is very shallow, the response of all the MIMO channels generally exhibit a similar multipath pattern, corresponding to the very limited spatial diversity that can be exploited by the multi-channel equalizer.

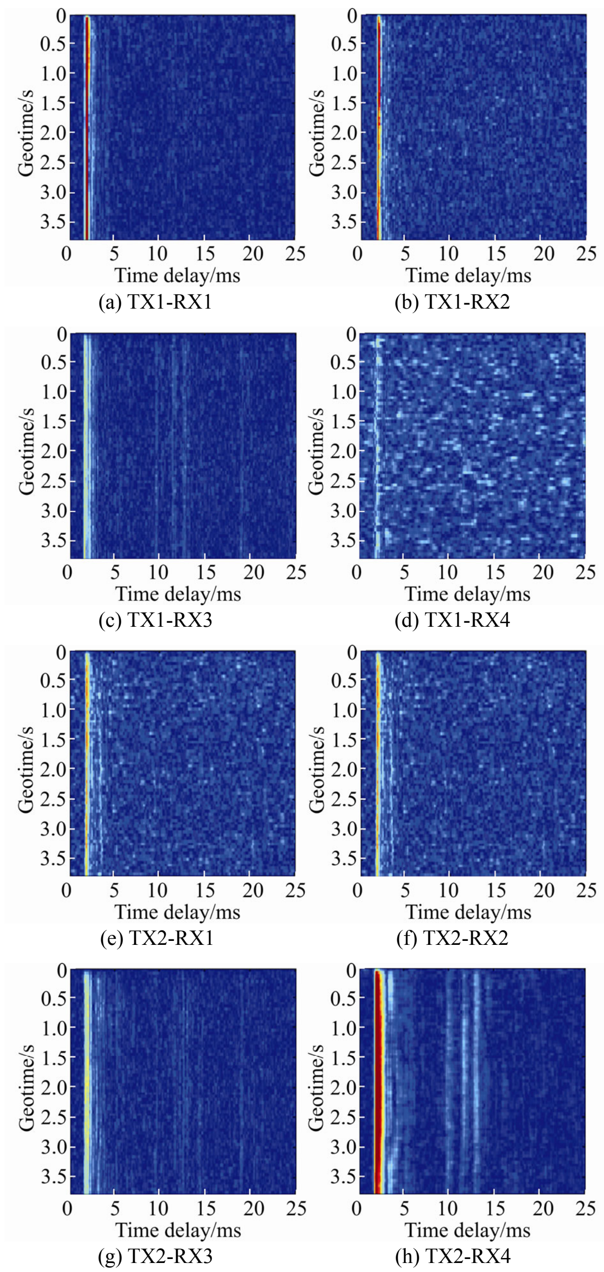


Fig. 3 Channel response with respect to time

In the MIMO communication signal processing, the multichannel DFE receiver andthe time reversal receiver, adopt 2 channels, 3 channels and 4 channels for multi-channel processing respectively.

For the multichannel DFE receiver, the adaptive DFE is updated with RLS algorithm. In the signal frame, the length of the training sequence is 500 to finish the training of RLS algorithm, after which the DFE receiver is adaptively updated with the decided output. For the purpose of communication performance evaluation, five packets, each of which contains 5 000 bits, are used for calculating the bit error rate (BER). The filter length of the RLS updating forward and backward is set as 24, 12, respectively, with an RLS forgetting factor of 0.998. The carrier phase is tracked with a second-order PLL (phase lock loop), embedded in the DFE, which is 0.000 3.

For the time reversal receiver, the length of the time reversal processor is the same with that of the channel estimator, set as 60. The matching pursuit algorithm (Song *et al*., 2011) is adopted for performing channel estimation. The single channel adaptive DFE following the multichannel time reversal processor is updated with RLS algorithm. The filter length of the RLS updating forward and backward is set as 24, 12 respectively, with the RLS forgetting factor of 0.998. The length of the RLS training sequence is 500. The carrier phase is tracked with a second-order PLL (phase lock loop) embedded in the DFE, the PLL factor is 0.000 3.

The constellation outputs corresponding to the MIMO multichannel DFE receiver as well as the time reversal receiver with different numbers of receiving elements are provided in Figs. 4 and 5 respectively, from which one may see that, while the 2-channel DFE receiver is capable of yielding preliminary equalization effects, the multichannel DFE receiver associated with a large number of elements achieves better separation. In comparison, with the same number of receiving elements, the time reversal receiver achieves worse performance compared to the multichannel DFE receiver does.

The BER results obtained by the two types of receivers with different channels are provided in Table 1. It indicates that, for BER of both TX1 and TX2 data, increasing the number of receiving elements contributes to improving the BER performance of both receivers, further validating the role of spatial diversity in multi-channel equalizer and time reversal. While the multi-channel DFE receiver with 2 channels achieves the BER, i.e., 0.06 for TX1 and 0.002 7 for TX2, the 2-channel time reversal receiver corresponds to the BER of 0.22 for TX1 and 0.013 7 for TX2, which is consistent with the result of the constellation plot.

In addition, the output SNRs of the two types of receiver with respect to the number of elements are presented in Table 2. As revealed by Table 2, both types of receivers with a large number of elements yield a higher output SNR than receivers with a small number of elements do. For the TX 2 case, the 2-channel, 3-channel as well as 4-channel DFE receiver and time reversal receiver produces an output SNR of 13.7 dB, 16.0 dB, 16.4 dB, and 12.2 dB, 12.5 dB, 13.7 dB respectively. Meanwhile, from the MIMO communication performance, as indicated by Figs. 4–5 and Tables 1–2, it is evident that the quality of MIMO channels from the 2nd transmitter is superior to that from the 1st transmitter.

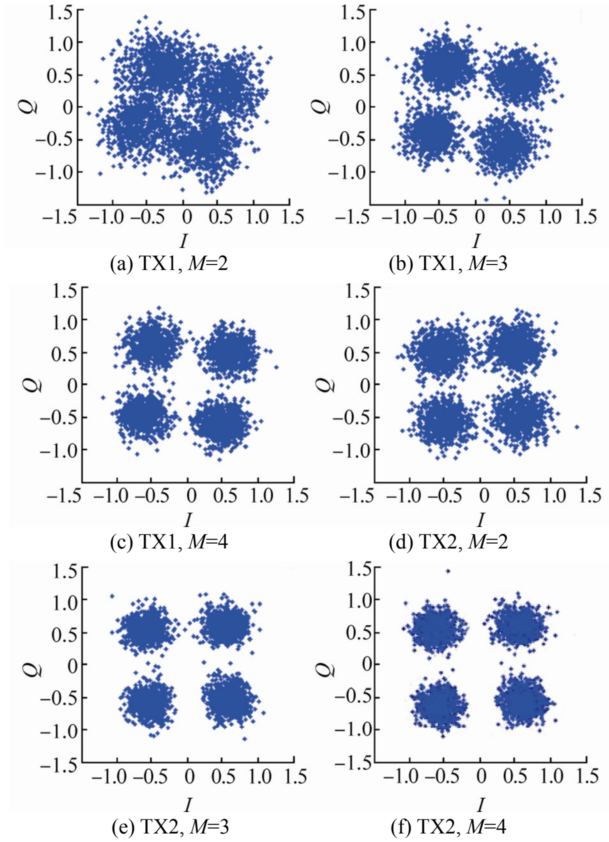


Fig. 4 Scatter plots of MIMO multichannel DFE receivers with different number of receiving elements

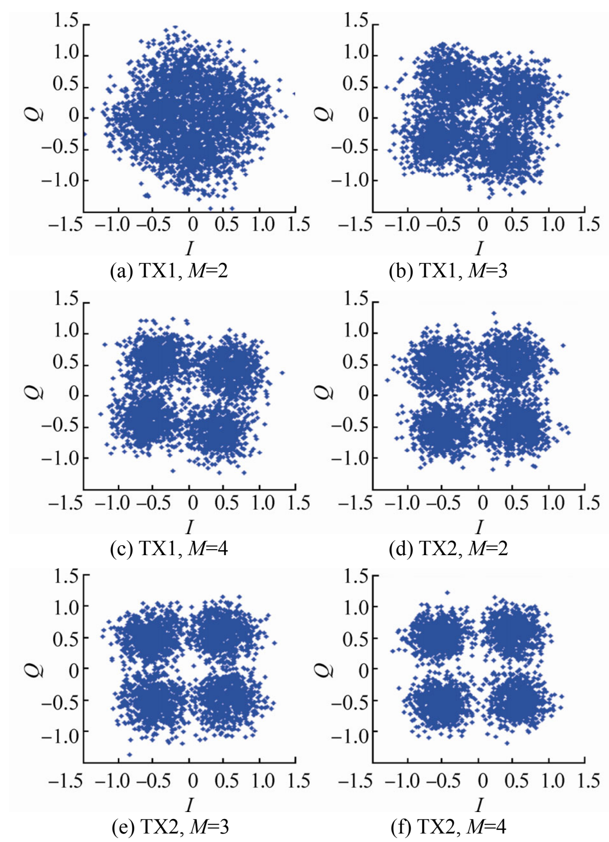


Fig. 5 Scatter plots of MIMO multichannel TR receivers with different number of receiving elements

The reason why DFE is better than TR in our experiment is that the time reversal receiver generally requires a large number of vertical elements (>10) to achieve spatial diversity (Yang, 2005). Unfortunately, the very shallow underwater acoustic channel excludes the deployment of a vertical array with large number of elements, thus limiting the performance of the TR receiver.

Table 1 The BER performance corresponding to different number of receiving elements

MIMO Receiver		TX1	TX2
M=2 (RX1,3)	multichannel DFE	0.06	0.002 7
	multichannel TR	0.22	0.013 7
M=3 (RX1,2,3)	multichannel DFE	0.007 3	0.001 0
	multichannel TR	0.044 0	0.009 7
M=4 (RX1,2,3,4)	multichannel DFE	0.001 7	0
	multichannel TR	0.016 3	0.002 3

Table 2 The output SNR of DFE receiver corresponding to different number of receiving elements dB

MIMO Receiver		TX1	TX2
M=2 (RX1,3)	multichannel DFE	9.7	13.7
	multichannel TR	6.4	12.2
M=3 (RX1,2,3)	multichannel DFE	12.8	16.0
	multichannel TR	10.5	12.5
M=4 (RX1,2,3,4)	multichannel DFE	14.3	16.4
	multichannel TR	11.9	13.7

4 Conclusions

In view of the requirement for high speed acoustic communication in very shallow water channels, a multichannel DFE MIMO receiver and a multichannel time reversal receiver are implemented and evaluated to verify the feasibility and performance of MIMO acoustic communication in very shallow water. The experiment results obtained in a real very shallow water channel are presented to show that the multichannel DFE receiver is capable of achieving MIMO communication with a relatively small number of channels (for example, 4 is enough for achieving satisfactory equalization effect in our investigation) given the presence of limited spatial diversity associated with very shallow water.

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