Experimental study on multiple-input/multiple-output communication with time reversal in deep ocean

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Multiple-input/multiple-output (MIMO) communication using adaptive time reversal is examined by comparing orthogonal frequency division multiplexing (OFDM) with simulated MIMO test signals by synthesizing experimental data in deep ocean. The experiment was carried out in a 1,100-m-depth area at a range of 10 km with a bandwidth of 500 +/- 50 Hz. Although time variance is not included in analysis of OFDM, it is impossible to increase the numbers of MIMO channels with OFDM. On the other hand, with adaptive time reversal, it is possible to achieve 8 x 20 and 6 x 20 MIMO communication with binary phase shift keying (BPSK) and quadrature phase shift keying (QPSK), respectively, in spite of time variance and input signal-to-noise ratio (SNR) degradation due to synthesized signals. Thus, it is demonstrated that adaptive time reversal shows a much better performance than OFDM in MIMO underwater acoustic communication.

1. Introduction

Achieving reliable or high-rate communication in underwater acoustic channels is still a challenging problem owing to the limited bandwidth, very long time spread, and large Doppler effect. For km-order transmission, the available bandwidth is limited to from 10 to 20 kHz at most by the transducer's capability, ambient noise in the low-frequency band, and large absorption loss in the high-frequency band. In underwater acoustic channels, numerous paths cause a very long time spread and intersymbol interference (ISI), whose duration sometimes reaches to over 100 symbols. The rate of the Doppler frequency shift due to source or receiver motion is very high because of the low propagation velocity of underwater acoustic waves. The effects of these distortions are several orders of magnitude higher than those in radio communication in air. To overcome these problems, time reversal is an effective method.[1-6] By time reversal, multipath signals are converged in time and space, so that the original transmitted signal is reconstructed with ISI removed. Additionally, after time reversal focusing, it is easy to compensate for the Doppler frequency shift. In our previous studies, the effectiveness of time reversal in multiple-input/single-output (MISO) and single-input/multiple-output (SIMO) communications has been investigated and demonstrated in at-sea experiments.[7-13)]

In the meantime, demand for multiuser communication or multiple-input-multiple-output (MIMO) communication has been rising for operation of multiple autonomous underwater vehicles (AUVs) or high-rate communication networks. In multiuser or MIMO communication, multiple sources transmit different information-bearing signals simultaneously to increase the amount of information to be transferred. These signals have to be separated on the receiver side, that is, space division multiplexing (SDM). Time reversal is also a promising solution to realize such communication by achieving SDM based on its spatial focusing.[14-17] In previous experimental studies, the performance of multiuser communication with adaptive time reversal was investigated, and it was clarified that adaptive time reversal is very effective especially when sources are very close.[11-12] In Ref. 13, adaptive time reversal was first applied to MIMO communication and it was confirmed that four-channel multiplexing with binary phase shift keying (BPSK) was possible.

On the other hand, in radio communication in air, orthogonal frequency division multiplexing (OFDM) is commonly used, and in the research field of underwater acoustic communication there are many reports in the literature about MIMO or multiuser communication with OFDM.[18-28] However, OFDM is weak against the time variance of channel responses or non-uniform Doppler shifts, and the peak-to-average power ratio (PAPR) of OFDM signals is high. Thus, it has many disadvantages in underwater acoustic communication even in cases of SIMO or single-user communication. Additionally, the capability of SDM methods in OFDM to separate interfering signals from multiple sources is expected to be inferior to that of adaptive time reversal.

In this paper, on the basis of experimental data, the performance of adaptive time reversal for MIMO communication is analyzed in comparison with that of OFDM by investigating how many channels can be multiplexed, which has not been analyzed in our previous study[13]. As a result, it is demonstrated that it is possible to increase the number of source channels up to eight with BPSK and six with quadrature phase shift keying (QPSK) in the case of using adaptive time reversal. In the meantime, it was impossible to increase the number of channels to more than two in the case of using OFDM. Thus, it is proved that adaptive time reversal is very effective for MIMO communication as well as for multiuser communication.

2. Experimental methods

An at-sea experiment was carried out in the inner part of Suruga Bay, at a water depth of 1,100 m, using a source with a frequency band from 450 to 550 Hz and a twenty-channel receiver array. The source was suspended from R/V Kaiyo with its depth changed in stages and different information-bearing signals were transmitted at each depth. These signals were recorded at the receiver array and, after recovering, synthesized to generate test signals to simulate MIMO communication. The number of synthesized signals corresponds to the number of channels of the source array. Thus, it is possible to clarify how many channels can be multiplexed by changing the number of signals.

The transmitted signals were modulated with BPSK and QPSK at a symbol rate of 100 symbols/s. In every packet, a linear frequency modulation (LFM) chirp from 450 to 550 Hz was transmitted as a probe signal for time reversal processing. The composition of OFDM signals is explained later in Sect. 3.2.

Measurements were executed twice for 2 days. In the first measurement, the source depth was changed from 595 to 955 m at intervals of approximately 20 m. In the second measurement, it was changed from 525 to 955 m at intervals of approximately 10 m. The receiver array was moored at a range of 10 km away from the point of the suspended source. The receiver aperture spanned a depth from 848 to 962 m with an element spacing of 6 m. The sound speed profiles at the experiment site and the arrangement of source and receiver arrays are shown in Fig. 1. These profiles were measured at 10:30 (blue solid line) and 17:30 (dashed-dotted line) on the first day, near the point of the receiver array and the suspended source, respectively. Thus, it can be supposed that there was no significant change in the sound speed profile during these measurements. Additionally, if the sound speed profiles had been changed during measurements at each depth of the suspended source, such differences in time would be included in differences of channel responses from different source depths, and they would not affect the performance analysis of MIMO communication.

It is known that acoustic waves propagate by refraction depending on the sound speed profile and repeated reflection on the surface and seafloor. According to the sound speed profile shown in Fig. 1, more multipath waves are received in the case that the sources and receivers are deployed under a depth of approximately 600 m. The intention for such an arrangement of sources and receivers as shown in Fig. 1 was to analyze the performance of MIMO communication under more complex, richer multipath environments.

3. Theory for MIMO communication

3.1 Adaptive time reversal for SDM

For MIMO communication, multiple information-bearing signals are transmitted simultaneously from multiple sources (source array) to multiply the amount of information to be transferred. This is a natural way to increase the data transmission speed under various limitations in underwater acoustic channels, as mentioned above. Such multiple signals have to be discriminated on the receiver array side, that is, SDM. Time reversal is expected to be a promising method to realize this. This is because it is easy to extend time reversal focusing to multiple targets and, additionally, by adaptive time reversal it is possible to suppress interferences from other sources, which is called co-channel interference (CCI), without degrading signals from an intended source, as will be explained later.

MISO and SIMO communications with time reversal applied are called active and passive time reversal communications, respectively.[1,3] In MISO communication with active time reversal, a probe signal is transmitted from a source, the received signals are time-reversed and modulated with information symbols on the array side, and transmitted from the array. Thus, time reversal signals are actually transmitted. On the other hand, in SIMO communication with passive time reversal, a probe signal and an information-bearing signal are transmitted consecutively from a source, and these received signals are cross-correlated at a receiver array following summation over channels. Thus, time reversal focusing is virtually implemented in signal processing. In MIMO communication, there are two methods to realize SDM; in one, that the source array side knows the channel responses from each source to each receiver and transmitted signals are generated to suppress CCI in advance on the basis of the knowledge of the channel responses. In the other, just-modulated signals are transmitted and CCI is removed somehow on the receiver side. Thus, active time reversal MIMO corresponds to the former while passive time reversal MIMO corresponds to the latter. Usually, the latter method is used in MIMO communication on account of easier implementation in underwater acoustic communication. Thus, in this study, MIMO communication with passive time reversal is discussed, and the possibility of MIMO communication with active time reversal will be investigated in our future work.

In the rest of this subsection, how to introduce adaptive passive time reversal is explained briefly. As mentioned above, a probe signal and an information-bearing signal are transmitted in passive time reversal. Assuming that the channel response from the ith source to the jth receiver is $h_{ij}(t)$ and the original information-bearing signal transmitted from the ith source is $s_i(t)$, the received signal at the jth receiver is expressed as

$$r_j(t) = h_{ij}(t) * s_i(t), \tag{1}$$

where * indicates the convolution integral. Then, the passive time reversal process is expressed and deformed as

$$\sum_j h_{ij}(t) \otimes r_j(t) = \sum_j h_{ij}(t) \otimes \left(h_{ij}(t) * s_i(t) \right)$$
$$= \left(\sum_j h_{ij}(t) \otimes h_{ij}(t) \right) * s_i(t) \qquad (2)$$
$$= q(t) * s_i(t),$$

where $q(t)$ is called the q-function,[4] which is the summation over the receiver channels of the autocorrelation of channel responses. In the case of single-user or SIMO communication, if the effect of time reversal is sufficient, $q(t)$ is ideally close to the delta function,[29] so that the original signal $s_i(t)$ can be obtained without ISI.

However, for MIMO transmission, it is necessary to consider that signals from multiple sources interfere with each other, that is, CCI. Provided CCI is not strong, it is possible to discriminate such interfering signals only by passive time reversal. However, in order to increase the number of transmitting channels, a more effective method to suppress CCI is desired. For this purpose, adaptive time reversal is introduced in this study, which was proposed by Kim, and coworkers.[30,31] In adaptive time reversal, $h_{ij}(t)$ in Eq. (2) is replaced with an adaptive time-reversal probe signal. Supposing the expression of $h_{ij}(t)$ in the frequency domain is $H_{ij}(f)$, the adaptive time-reversal probe signal expressed in the frequency domain $w_{ij}(f)$ is given by

$$\mathbf{w}_i = \mathbf{R}^{-1}\mathbf{d}_i / \mathbf{d}_i^{\dagger}\mathbf{R}^{-1}\mathbf{d}_i , \qquad (3)$$

where

$$\mathbf{R} = \sum_k \mathbf{d}_k \mathbf{d}_k^{\dagger} + \sigma^2 \mathbf{I},$$

$$\mathbf{d}_k = \left[H_{k1}(f) \cdots H_{kM}(f) \right]^T ,$$

$$\mathbf{w}_i = \left[w_{i1}(f) \cdots w_{iM}(f) \right]^T ,$$

subject to the constraint that $\mathbf{w}_i^{\dagger}\mathbf{d}_i = 1$. Here, † denotes the complex conjugate transpose, M is the total number of receivers, and $\sigma^2\mathbf{I}$ is a small diagonal loading for a matrix inversion with an identity matrix **I**. Using adaptive time reversal, the signal from the ith source is preserved while signals from other sources are suppressed, that is, null focusing is generated at interfering source points.[12] After adaptive time-reversal processing, a single-channel decision feedback equalizer (DFE) is appended to remove residual ISI, similarly to previous studies.[7-12]

3.2 MIMO communication with OFDM

As mentioned above, OFDM is widely used for multiuser or MIMO communication. Thus, in this study, the performance of MIMO communication with adaptive time reversal is compared with that of OFDM. As a method of MIMO communication, zero-forcing OFDM (ZF-OFDM) is used in this study as a standard basic method.[32] In ZF-OFDM, the channel response $H_{ij}(f)$ is estimated using a pilot symbol and the ZF detector is calculated using

$$\boldsymbol{W} = (\boldsymbol{H}^{\dagger}\boldsymbol{H})^{-1}\boldsymbol{H}^{\dagger}, \tag{4}$$

where the element in the ith row and jth column in the matrix $\boldsymbol{H}$ is $H_{ij}(f)$. Following the pilot symbol, an information-bearing symbol is transmitted, and its received signal is divided by this ZF detector at each subcarrier frequency in the frequency domain. If this technique works ideally, both CCI and ISI are suppressed, so that SDM can be realized.

As it is known as intercarrier interference (ICI), since OFDM modulation/demodulation is based on fast Fourier transform (FFT), it is very weak against time variance. Thus, in this study, an OFDM test signal is composed as follows. As mentioned above, in the beginning of every packet, an LFM chirp signal is transmitted. From this LFM chirp signal, channel responses of two packets transmitted consecutively from the same source depth are obtained, and these two consecutive channel responses are convoluted, one with a pilot symbol and, the other with an information symbol of OFDM. Thus, the time variance during the OFDM symbol length is not included and only the performance of ZF-OFDM in suppressing CCI is evaluated. In the meantime, in the case of adaptive time reversal, raw signals are analyzed so that the time variance is included as distortion as well as CCI and ISI. Then, the method of comparison in this analysis is unfair, being disadvantageous to adaptive time reversal and advantageous to OFDM.

4. Results and discussion

As explained above, MIMO test signals are generated by synthesizing the received signals from sources at different depths in postprocessing. The number of signal-synthesizing source channels is changed from two to eight in the case of BPSK and from two to six in the case of QPSK.

Figure 2 shows the result when the number of source channels is four in the case of BPSK and the interval of the source depth is 20 m. Signals from the four adjacent depths are synthesized by shifting them one by one. In this figure, the four points connected with dotted lines indicate the output signal-to-noise ratio (SNR) at each source depth of such a signal-synthesizing four-channel source array. The source transmitted signals twice at each depth; thus, two results are plotted for each source depth in this figure. It is confirmed that the performance of adaptive time reversal is not dependent on source depth. On the other hand, in the case of OFDM, it is impossible to achieve error-free demodulation in all the results. In the results when the source depth is approximately 850 or 900 m, phase estimation fails. Thus, the output SNRs are markedly deteriorated in these results.

In Fig. 3, the average bit error rates (BERs) and output SNRs at each source channel are shown with increasing number of signal-synthesizing source channels in the case of BPSK in order to investigate how many channels can be demodulated. In this and the following figures, the results obtained at the source depth intervals of 10 and 20 m are indicated as "ATR 10m" and "ATR 20m" in the case of adaptive time reversal and "OFDM 10m" and "OFDM 20m" in the case of OFDM, respectively. As shown in Fig. 3(a), bit errors with adaptive time reversal are seldom generated, while bit errors with OFDM are more frequently observed even in the case of a few channels and increase considerably. Since the received signals are synthesized, noise is also added with increasing number of signal-synthesizing channels. This is the reason why the output SNRs are degraded in steps in all the results shown in Fig. 3(b). In spite of such degradation, adaptive time reversal achieves signal multiplexing up to eight channels, which provides an aggregate data rate of 800 bps. In Fig. 4, demodulated symbols with eight channels, whose source depths are from 735 to 875 m at intervals of 20 m, are shown on a constellation map in both cases of adaptive time reversal and OFDM.

In Fig. 5, the average BERs and output SNRs in the case of QPSK are shown similarly to in Fig. 3. In Fig. 5(a), it is shown that OFDM with bit errors starts to occur even with a small number of source channels and demodulation is not successful. In Fig. 6, demodulated symbols with six channels, whose source depths are from 615 to 715 m at intervals of 20 m, are shown similarly to in Fig. 4, to show the performance when adaptive time reversal reaches the maximum aggregate data rate of 1,200 bps.

It should be noted again that the time variance during each packet is not considered in the cases of OFDM in this analysis. However, because time variance actually exists, it is anticipated that the performance of OFDM will deteriorate further in practical use. On the other hand, without increasing the noise level due to synthesis, the performance of adaptive time reversal may not be degraded with increasing number of source channels so that it is expected to achieve MIMO communication with a larger number of channels. For reference, no significant differences are observed between results with the source array intervals of 10 and 20 m. However, it is necessary to investigate the effect of the source array interval in more detail because a smaller source array is preferred in practical use. As shown in a previous study, even when sources are close to each other, adaptive time reversal is effective. Thus, it is expected to be advantageous in a dense source array.

5. Conclusions

In this study, adaptive time reversal is applied to MIMO communication, and its performance is discussed in comparison with OFDM, based on experimental data in deep ocean. Although the time variance is not included in the case of OFDM, the performance of adaptive time reversal for SDM is much better than that of OFDM. In the analysis of the effect of increasing the number of source channels, multiplexing with up to eight and six channels is achieved using adaptive time reversal with BPSK and QPSK, respectively.

As our future work, we will investigate why the performance of SDM with OFDM is much poorer than that of adaptive time reversal. Moreover, at-sea experiments with real source arrays in more complex environments will be carried out for practical use.

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Figure Captions

Fig. 1. (Color online) At-sea experimental setup. Left panel: sound velocity profiles near the source and receiver arrays, indicated as Tx and Rx, respectively. Right panel: source and receiver array arrangements.

Fig. 2. Output SNRs of each channel when signals from four channels are synthesized in the case of BPSK.

Fig. 3. (Color online) (a) Average BERs and (b) output SNRs in the case of BPSK with increasing number of signal-synthesizing channels.

Fig. 4. Demodulated symbols on constellation map with (a) adaptive time reversal and (b) OFDM, in the case of eight-channel source array with BPSK.

Fig. 5. (Color online) (a) Average BERs and (b) output SNRs in the case of QPSK with increasing number of signal-synthesizing channels.

Fig. 6. Demodulated symbols on constellation map with (a) adaptive time reversal and (b) OFDM, in the case of six-channel source array with QPSK.

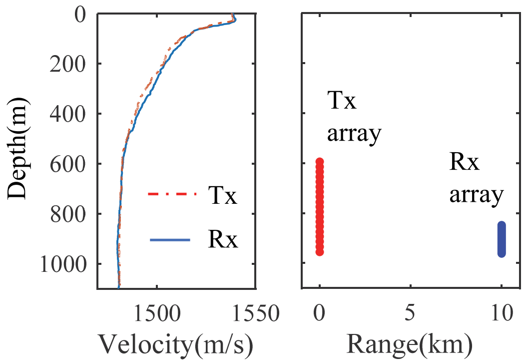
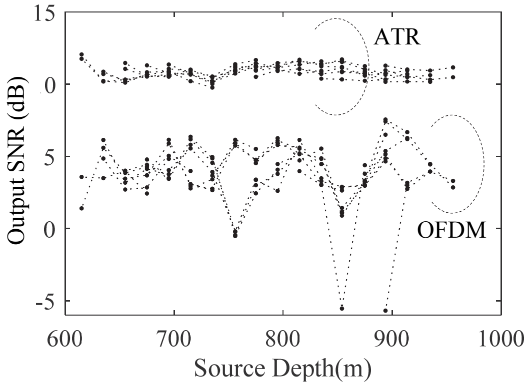


Fig. 1. (Color Online)


15
10
5
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-5
600
700
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Output SNR (dB)
Source Depth(m)
ATR
OFDM

Fig. 2.

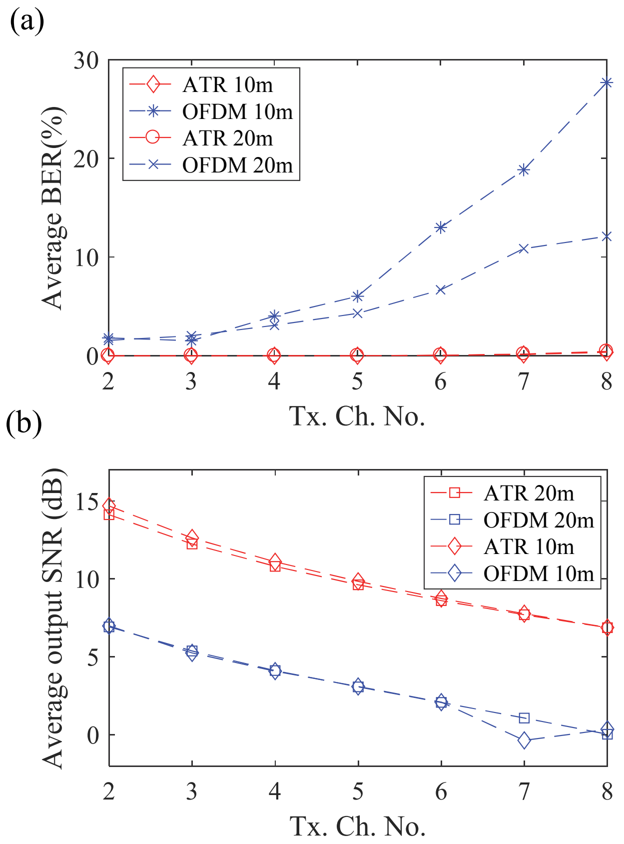
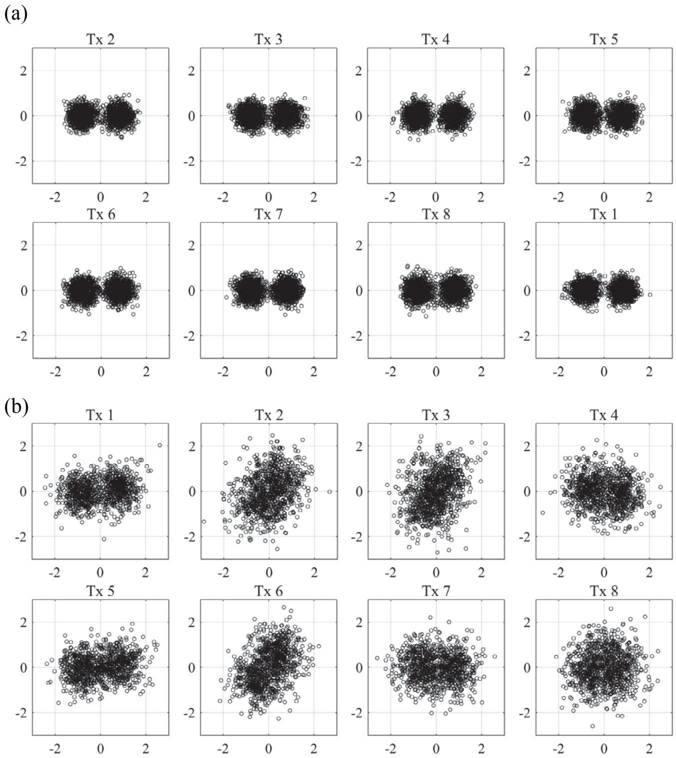


Fig. 3. (Color Online)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(b)
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Fig. 4.

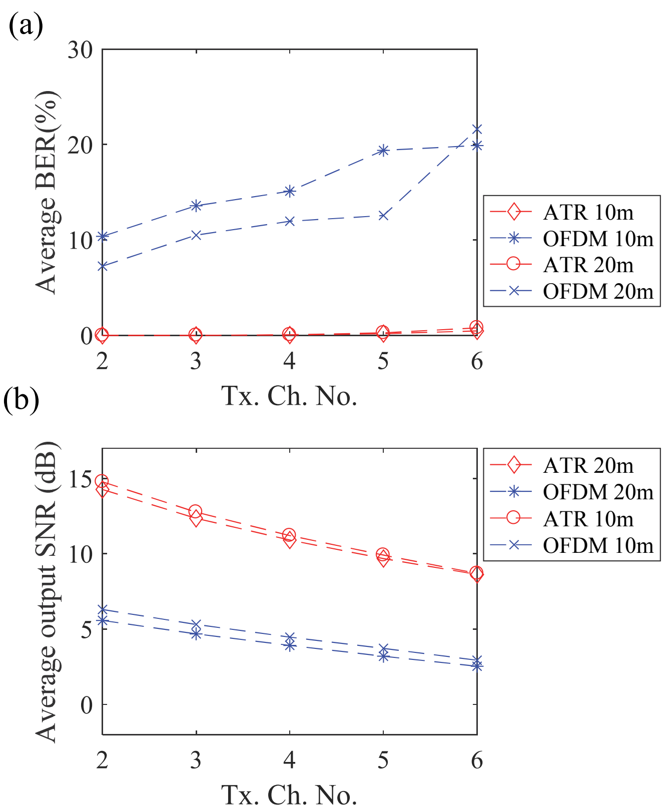

Fig. 5. (Color Online)

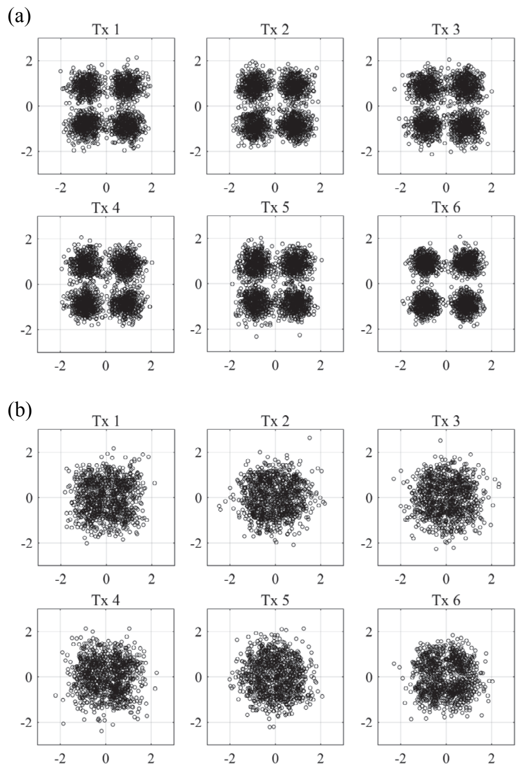

Fig. 6.