Image Transmission with Joint Time Reversal and OFDM in Underwater Acoustic Environment

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Abstract. The development of technology and applications in the underwater acoustic field are a challenge for researchers. The OFDM system is an interesting research topic to date because of its high-rate and high-quality wireless capabilities. In a multipath environment, OFDM can reduce the effect of multipath fading by converting frequency selective channel to a flat sub-channels parallel collection of frequency. Time reversal with its spatial and temporal focal properties is a technique that can be relied upon in reducing channel fading and intersymbol interference which causes distortion in the received signal. In this paper, we present a study of transmitting images in underwater acoustic environments using a combined time reversal and OFDM (TR-OFDM) technique. The estimation technique based on the MMSE algorithm is used in the image restoration process. The simulation results show that transmitting image with the TR-OFDM system has superior performance compared to traditional OFDM system. With BPSK modulation and MMSE estimation technique, the BER obtained by TR-OFDM is \(10^{-3}\) at SNR 8.2 dB. Modulation schemes such as M-PSK and M-QAM are also presented in this paper. BPSK modulation is proven to have the best performance on SNR 20 dB with zero resulting error.

1. Introduction
Currently, underwater wireless communication is a rapidly growing research field. The development of reliable communication for underwater acoustic communication (UAC) is a challenge for researchers since it involves complex multipath, absorption, and also ambient noise variable. Because of its high spectrum efficiency, resistance ability to frequency selective fading, low computational in modulation/demodulation and channel equalization OFDM becomes a robust method for communication [1]-[2]. By inserting a cyclic prefix (CP)/ postfix, OFDM can eliminate inter-symbol interference (ISI) and inter-carrier interference (ICI). Due to the extremely low underwater sound speed (1500 m / sec), then at the same time, the spread of delay on the underwater acoustic channel takes tens or even hundreds of milliseconds. Therefore, a reliable system is needed that can overcome this problem. Although OFDM can eliminate ICI with the addition of CP, frequency selective fading is the problem that often faced in the underwater acoustic communication system.

Time reversal (TR) or phase conjugation is a technique considered in UAC due to its ability in signal focusing at the specified point in a waveguide. In TR, the distorted signal is compressed in the time domain and multipath energy is collected to increase SNR. The use of arrays on transmitters/receivers is then proposed in TRM [3].
Passive Time Reversal (PTR) has been successfully tested at sea and has been extensively applied to underwater acoustic communications. PTR performance has been validated by experiments in a lake using single carrier BPSK and QPSK [4], [5], [6]. Venkatesh et al. in [7] studied the combination of time reversal mirrors (TRM) and OFDM with Wiener filter formulation is used in channel estimation and in the experiment the author used multiple transmitters and a single receiver. In [8] the author compares the performance of channel estimation with LS and MMSE algorithms for image transmission in underwater acoustic channel using OFDM technique, and the results prove that MMSE has superior performance than LS estimation.

Previous studies have also shown the remarkable performance of time reversal and OFDM system in UAC. With the advantages of TR and OFDM, the two techniques are combined (TR-OFDM) for image transmission in this paper. TR-OFDM system performance is evaluated through simulation. The MMSE algorithm is applied as a channel estimation method to obtain the restored image. The multipath UAC are represented using a geometry-based model to show the performance of the system in an environment with a varying number of ISI taps. Modulation scheme applications such as M-PSK and M-QAM have also been observed to influence the quality of communication systems. In addition to being presented in a visual image that is restored to the receiver, the TR-OFDM system performance is also analysed based on the bit-error-rate (BER).

2. Underwater Acoustic Communication

In the underwater acoustic channel, the signal sent from the transmitter goes to the receiver through several paths. Multiple travel paths between transmitter and receiver arrive due to the acoustic waves are reflected at the surface and bottom boundaries of the acoustic channel. Multipath emerges because of acoustic wave reflections from the surface, bottom or any obstacle as well as acoustic wave refractions. The acoustic signals transmitted can be classified into two groups: direct path and multipath, and the multipath signals are grouped into four types: trajectories derived from the reflections of sea surface and sea surface (SS), trajectories caused by reflections of sea surface and sea bottom (SB), reflections of the sea bottom and sea surface (BS), and reflections from the sea bottom and the sea bottom (BB). The entire path is the result of reflection from the beginning of the signal propagation to the end before reaching the receiver. The receiver can thus get the signals arriving on different paths, each signal is delayed according to the channel geometry. The underwater acoustic channel in this paper is represented using a geometry-based channel model as shown in Figure 1. The model represents a shallow underwater channel by using environmental and geometric parameters. The model uses the impulse response of the channel by weighting according to the attenuation due to reflection and absorption [9].

![Figure 1. Underwater channel model: Z_t, transmitted height above the bottom; Z_r: receiver height above the bottom; L: horizontal distance between the transmitter and receiver](image)

The impulse response of a multipath channel can be modelled by the weighted sum of delayed delta functions:

\[ h(t) = \sum_{i=1}^{L} a_i \delta(t - \tau_i) \]  

(1)

where \( a_i \) denotes the attenuation coefficient, \( \tau_i \) is the time delay of the i-th path, \( \delta \) is a Dirac delta function, while \( L \) is the total number of the multipath in underwater acoustic channel.
3. System Model for TR-OFDM Communication

The following is a signal model for TR-OFDM communication with the concept of TR equivalency:

\[ q(t) = h(t) \ast h(-t) \]  \hspace{1cm} (2)

where \( h(t) \) is the impulse response of the actual UAC and \( h(-t) \) is the time-reversed impulse response \( h(t) \) in the time domain. The multipath in UAC can be characterized by using signal model proposed in [10] to be applied for the TR-OFDM communication. Figure 2 represents the process of the TR-OFDM communication which is developed with a simple TR for pre-processing OFDM signals. When compared with OFDM systems, there is a TR-filter in TR-OFDM system. This TR filter functions as a spatiotemporal match filtering [11]. The duration of the symbol of the transmitted OFDM signal is denoted by \( T_s \) and the number of subcarriers is denoted by \( K \), then the OFDM signal transmitted after subcarrier modulation can be represented as follows:

\[ s(t) = \sum_{k=0}^{K-1} d_k e^{j2\pi f_k(t-t_s)}, \quad t_s < t < t_s + T_s \]  \hspace{1cm} (3)

where \( f_k \) denotes the k-th subcarrier frequency and \( d_k \) is a complex number of k-th subcarrier. In TR-OFDM, OFDM signals must be pre-processed with the TR filter first, so the formula is as follows:

\[ s^{TR-OFDM}(t) = s(t) \ast h(-t) \]  \hspace{1cm} (4)

where * is the linear convolution operator. TR-OFDM signals that have gone through a multipath underwater acoustic channel will be captured by the receiver with the following formula:

\[ y^{TR-OFDM}(t) = s^{TR-OFDM}(t) \ast h(t) + n(t) = s(t) \ast h(-t) \ast h(t) + n(t) \]  \hspace{1cm} (XX)

\[ = s(t) \ast q(t) + n(t) \]  \hspace{1cm} (5)

In equation (5), \( n(t) \) represents white Gaussian noise. If we substitute equation (1) into equation (5), we will get the following equation:

\[ y^{TR-OFDM}(t) = s(t) \ast \left[ \sum_{i=1}^{L} \alpha_i^2 \delta(t) + \sum_{i=1}^{L} \sum_{j \neq i} \alpha_i \alpha_j \delta(t + \tau_i - \tau_j) \right] + n(t) \]  \hspace{1cm} (6)

We can see in formula (6) that the first term \( \sum_{i=1}^{L} \alpha_i^2 \delta(t) \) shows the spike of TR focusing which has the highest amplitude and the term \( \sum_{i=1}^{L} \sum_{j \neq i} \alpha_i \alpha_j \delta(t + \tau_i - \tau_j) \) shows TR focusing side lobes derived from the TR signals propagation.

Figure 2. TR-OFDM transmission system block diagram

4. Simulation Results

The designed TR-OFDM system performance was evaluated through a simulation. A series of communication processes through an underwater acoustic channel was done to send information in the form of an image with a size of 256 x 256 pixels. The geometry-based channel model was developed based on the real towing tank conditions which had dimensions of 200 m x 12 m x 6 m.

4.1 Multipath Channel Model

The channel model is assumed as shown in Figure 1. The distance between the transmitter and the receiver was 100 m and the height of the receiver is calculated from the bottom of the pool was 3 m.
The channel had uniform depth \((h)\) and constant sound speed \((c)\) of 1500 m/sec. The water condition is relatively calm and there was no relative motion between the transmitter and receiver. The multipath channel was assumed to be stationary and the channel response was applied to simulate the underwater acoustic channel. The channel response can be represented as in Figure 3. To compare system performance in a multipath environment, the simulation used a number of varying ISI taps: 5, 9 and 21 taps.

4.2 Image Transmission in Multipath Environment

In this simulation transmitting image with OFDM that used 52 subcarriers and 16 subcarrier pilot symbols where the OFDM specification was used can be seen in Table 1. The process started with the conversion of images into a series of binary data on the transmitter. Then, the modulation process was carried out and continued with IFFT to get subcarrier orthogonality with each other.

![Figure 3. The underwater acoustic channel response](image)

| Table 1. Simulation parameter |
|-----------------------------|
| Parameter                  | Specification |
| FFT size                   | 64            |
| No. of used subcarrier     | 52            |
| Cyclic prefix              | 16            |
| Frequency carrier          | 10 kHz        |
| Channel model              | multipath     |
| Constellation              | BPSK,QPSK,16QAM |

![Figure 4a. Original image](image)  
![Figure 4b. Restored image using OFDM with SNR=5 dB.](image)  
![Figure 4c. Restored image using TR-OFDM with SNR=5 dB.](image)

A cyclic prefix was inserted as guard time to avoid ISI. Information in the form of a grayscale image was a jpg file that was sent using BPSK modulation. After going through a multipath channel, the image was restored in the receiver using the MMSE equalization technique. Ambient noise is Gaussian distributed and spectrally white.

The result of image restoration on the 5 dB SNR is shown in Figure 4b and 4c that compared to the original image (Figure 4a). Using the MMSE equalization algorithm, the transmission image using the
TR-OFDM system shows better image quality than OFDM. To get the detailed results of the TR-OFDM system performance, the simulations are presented in the SNR with a range from -2 dB to 20 dB as shown in Figure 5.

![Figure 5. BER comparison of TR-OFDM and OFDM](image)

![Figure 6. BER comparison of number of taps](image)

### Table 2. Simulation results of M-PSK and M-QAM.

| SNR (dB) | BPSK  | QPSK  | 16-QAM |
|----------|-------|-------|--------|
| 5        | 0.033 | 0.17  | 0.29   |
| 10       | 0.00015 | 0.025 | 0.16   |
| 15       | 0.000019 | 0.0047 | 0.078  |
| 20       | 0     | 0.0034 | 0.053  |

![Figure 7a. Received constellation of BPSK at SNR = 5 dB](image)

![Figure 7b. Received constellation of BPSK at SNR = 10 dB](image)

![Figure 7c. Received constellation of BPSK at SNR = 20 dB](image)

The BER curve proves that TR-OFDM has a superior performance compared to OFDM. To achieve the BER value of $10^{-2}$, TR-OFDM requires an SNR value of 6.2 dB, while OFDM requires SNR value of around 15 dB.

The multipath condition also affects the TR-OFDM performance. In underwater environment with sparse multipath, TR-OFDM performance is better than in rich multipath environment, because of its impact on the emergence of severe ISI. This result can be seen in Figure 6. By using the BPSK modulation scheme, the BER value obtained on 5 taps is far better than the number of taps above it. There is a difference of 10 dB of the SNR value between TR-OFDM at 5 taps and 9 taps for a BER value of 0.03, and at SNR 6 dB there is a difference of 0.6 in BER value with TR-OFDM at 21 taps.

Besides BPSK modulation, the TR-OFDM system performance was also tested with QPSK and 16-QAM modulation schemes. The simulation results in Table 2 showed that at SNR 20 dB BPSK modulation worked perfectly by generating an error value equal to zero. Meanwhile, in QPSK modulation, the BER value was 0.053 and the BER value in the 16-QAM modulation was 0.053. Among the three modulation schemes, the best performance of TR-OFDM was obtained using BPSK.
modulation. Simulations were run on channel condition with a number of taps of 5. BPSK constellations received at SNR 5 dB, 10 dB, and 20 dB are shown in Figure 7a, 7b, and 7c respectively.

5. Conclusion

Image transmission using the TR-OFDM communication system has been presented in this paper. By using BPSK modulation and MMSE estimation method the simulation result shows that TR-OFDM performance is superior to OFDM. At 8.2 dB SNR the BER obtained by TR-OFDM reaches $10^{-3}$, while OFDM at SNR 15 dB has a constant value at $10^{-2}$. The results of image restoration with TR-OFDM have better quality than OFDM. In the condition where the number of taps on the ISI is 5 taps, the performance of the TR-OFDM system works well, but at the number of taps at 9 and 21 taps, the performance of TR-OFDM has decreased to 0.1 at SNR 20 dB. With BPSK modulation, TR-OFDM system performance gets zero error value at SNR 20 dB. When compared with the QPSK and 16-QAM modulation schemes, the worst BER value obtained in the 16-QAM modulation scheme is 0.053 at SNR 20 dB. The next research is to investigate the effect of environmental noise on TR-OFDM performance by measuring the real environment in East Surabaya.

6. References

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