Study on time reverse mirror in underwater acoustic communication

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Time reversal mirror (TRM) can adaptively match the sound channel without any prior knowledge. In this paper, active TRM, passive TRM and virtual TRM which are all based on a single array element and the application of TRM in the underwater acoustic communication including single-user communication and multi-user communication are studied. Single sensor TRM which has time compression performance lacks array processing space gain, however, it can meet the requirements for underwater acoustic communication nodes being in the pursuit of simple structure and low power consumption. It is verified that TRM could focus multipath signal and achieve real-time adaptive channel equalization through computer simulation and test results, which could suppress the inter-symbol interference (ISI) and improve the signal-to-noise ratio (SNR).

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Introduction

It is indispensable for both military and civilian equipment to use high quality underwater acoustic communication technology, yet the complexity of the underwater acoustic channel seriously affects the performance of underwater acoustic communication system\cite{1}. Therefore, how to reduce and eliminate the underwater acoustic channel influence is particularly important in the underwater acoustic communication system. In recent years, TRM technology\cite{2}\cite{3} is a hot spot of research on underwater acoustic communication. On the basis of static sound field, it uses the transceiver reciprocity of the sound field’s transmission to achieve the compression in time and the focusing in space for the received time reversal signal\cite{4}\cite{5}.

The traditional TRM is composed of base array. Under the support of the ONR (Office of Naval Research), Professor Kuperman’s research team conducted many studies on it and published numerous papers, which promoted the application of the TRM in underwater acoustic communication. The first acoustic TRM shallow water experiment\cite{6} was done off the west coast of Italy in April 1996, this is the first time to validate the TRM technology through sea trials. From that until 2004, the experiment was conducted almost every year, and all of the trials made gratifying achievements. At present, any TRM introduced by a large amount of literature is based on array processing and needs to increase the amount of system operation so as to adaptively update channel\cite{7}-\cite{10}. It is too complicated to be used in underwater acoustic communication, which pursues simple nodes and low-power consumption. The literature\cite{11} analyzes the single-element TRM and focusing gain. Although single element TRM cannot get the spatial gain processed by the TRM, bringing sidelobe higher than array processing, it can still superimpose multi-path signals generated by the acoustic channel in the same time and in the same phase. It can also compress signals, eliminate inter-symbol interference and increase the signal-to-noise ratio at the same time. The literature\cite{12} proposed a single element virtual TRM technology, which greatly reduces the amount of system operation on the basis of realizing adaptive matching equilibrium channel. The literature\cite{13} put the single element TRM technology in UWA communication, achieving multi-user UWA communication and literature\cite{14} made single element TRM combined with UWA differential spread spectrum system, which markedly increased the system performance.

This paper first give a brief introduction about the single array element TRM, and then it proposes an application program of TRM technology used in single-user and multi-user water acoustic communication system. After that, combined with underwater acoustic spread-spectrum communication system, the paper gives the simulation and lake trial test results. As can be seen from the simulation, underwater acoustic communication system’s performance has been improved significantly by using TRM technology, which as well as makes high-quality underwater acoustic communication guaranteed.

Single Element Time Reversal Mirror

Single element time reversal mirror has an irreplaceable advantage in the pursuit of simple node and low-power underwater acoustic communication system. Single element time reversal mirror is constituted by a single element rather than the composition of the base array. Its greatest advantage is to simplify the complexity of the equipment of the time reversal mirror, which makes time reversal mirror technology used in underwater communication, especially applied to underwater network communication become more feasible.

Passive Time Reversal Mirror (PTRM)

Passive time reversal mirror was first proposed by Professor Dowling\cite{15} and PTRM first sea trial results in 2000 was shown in\cite{16}. There has been a lot of literature that research on PTRM and its application in underwater acoustic communication and they all required the waveform of the detecting code and the information code to be consistent, which makes PTRM in underwater acoustic communication limited. The passive time reversal proposed in\cite{17} broke this restriction, which means both waveform consistency is not necessary. Simply the spectrum and autocorrelation of detection code meet the followings: a) its frequency band could have a relatively complete coverage of the signal’s. b) It has good self-correlation, which means the correlation peak is sharp.

Figure 1 shows the block diagram of the passive time reversal mirror.
Signal \( s(t) \) will be sent after detection code \( p(t) \) at the transmitting end. The received time reversal detection signal and the received signal do convolution operation at the receiving end and then the result and local detection signal do convolution, which is the whole process of a single element passive time reversal mirror. The specific derivation see [18].

**Virtual Time Reversal Mirror (VTRM)**

Figure 2 shows a block diagram of a virtual time reversal mirror. Signal \( s(t) \) will be sent after detection code \( p(t) \) at the transmitting end, which is familiar to PTRM. Channel estimation will be first performed by using received detection signal and then we have time reversal channel \( h'(t) \). After the received signal and the time reversal channel doing convolution, the whole process of VTRM is completed. The specific derivations see [11].

**The application of single element TRM in UWC system**

Underwater acoustic channel system function is very sensitive to environmental parameters, the order of sensitivity were: The vertical position changes of the receiving point, changes in the thickness of the water layer, changes in the horizontal position, the changes in the speed of sound in water layer and so on. In multi-user underwater acoustic communication, the factors such as the horizontal distance and the vertical depth of each node, the sea and seabed ups and downs are different, which make the channel impulse response function between each node differ considerably, namely the cross-correlation of each node’s channel impulse response function is weaker. Therefore, taking advantage of the time reversal mirror the technology to focus expected user signal and to shield other multi-access interference, the space division multiple access technology based on time reversal mirror can be achieved. The multi-user communication system based on the virtual time reversal mirror is shown in Figure 3.
Single element virtual time reversal mirror and code division multiple access system in combination provides a single element virtual time reversal mirror code division multiple access (VTRM-CDMA) underwater acoustic communication system. At the receiving end, the synchronization code of each user can be used as a detection signal. By copying and other associated processing of the detection signal of each individual user, we can get each user’s estimated channel \( h_k'(t) \), then the time reversal channel is \( h_k'(-t) \), we can put the received signal and \( h_k'(-t) \) in convolution to get the final virtual time reversal mirror output focus signal.

**Simulation**

Model underwater acoustic channel with the channel simulation software, and underwater acoustic channel is shown in Figure 4 (a). We can select LFM signal as detection signal \( p(t) \), then deal the detection signal \( p(t) \) with single-array element passive time reversal mirror technology. The results can be seen in Figure 4 (b). Use the \( p(t) \) to estimate the channel, and we can get the estimated channel, which is shown in Figure 4 (c). The virtual time reversal channel which is constructed by the match of estimated channel and underwater acoustic channel can be seen in Figure 4 (d).

![Figure 4](image_url)

**FIGURE 4** channel impulse response and its time reversal channel

As we can see from Figure 4, both single-array element passive time reversal mirror and single-array element virtual time reversal mirror can match with underwater acoustic channel very well. Although there is still some sidelobe for the obtained time reversal channel, its amplitude is significantly lower than the main peak amplitude, which can inhibit the inter-symbol interference generated by the acoustic channel multi-path extension and have a good channel equalization effect.

Deal the cyclic shift spreading system with the channel which is shown in Figure 4 (a), the received waveform on receiving end can be seen in Figure 5 (a). The system is directly decoded by cyclic shift, and the decoding results are shown in Figure 5 (b).
As can be seen from Figure 5, the receiving end generates serious ISI because of the influence of underwater acoustic channel. Through cyclic shift matching and filtering, the multimodal is outputted but it can not be correctly decoded. Apply the single-array element passive time reversal mirror technology to cyclic shift spread spectrum systems, and we can get the receiver decoder effect diagram shown in Figure 6. It can be seen that the output of cyclic shift matched filter is an obvious single peak, and received signal can be correctly decoded.

**FIGURE 5** the decoding effect gram affected by underwater acoustic channel

**FIGURE 6** PTRM-CSK decoding result

**Conclusion**

Technicians always expect a simple structure and low power consumption when building underwater acoustic communication nodes as well as building underwater information network. However, underwater acoustic communication is usually seriously affected by the underwater acoustic channel. In order to reduce the complexity of the system and improve the efficiency and soundness of the communications, this article combines single element time reversal mirror and underwater acoustic communication system to make the time reversal mirror technology for underwater acoustic communication become more practical. This paper, which mainly introduces single element passive time reversal mirror and single element virtual time reversal mirror, analyzes the two technologies in combination with underwater acoustic communication. It also proposes a conclusion that single-user water acoustic communication is more suitable for single-element passive time reversal mirror and multi-user is more suitable for the virtual time reversal mirror.

The computer simulation results showed that although the time reversal mirror which constituted by a single sensor cannot get the processed spatial gain of time reversal array, the single element time reversal mirror can still superimpose multi-path signals generated by the acoustic channel in the same time and in the same phase. It can also compress signals, eliminate inter-symbol interference and increase the signal-to-noise ratio at the same time, therefore, it will be very promising for the single element time reversal mirror to be applied to the underwater acoustic communication.
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