Research on MIMO Spread Spectrum Underwater Acoustic Communication Based on r-Combined Mapping

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Abstract. The complex underwater acoustic channel greatly limits the information transmission capacity of the underwater acoustic communication system, which seriously affects the performance of the underwater acoustic communication system. Therefore, robust and high quality underwater acoustic communication has been faced with severe challenges. This paper combines MIMO technology and spread spectrum technology to develop the MIMO spread spectrum underwater acoustic communication system based on r-combined mapping, which achieves a high information transmission rate and a high frequency band utilization by spatial multiplexing.

1. Introduction
Underwater acoustic channel is a complex channel with time varying and spatial variation[1], and it is also a random channel with serious multipath effect, which will cause some loss of sound waves energy during transmission[2]. These characteristics of underwater acoustic channel greatly limit the information transmission capacity of underwater acoustic communication system and seriously affect the performance of the system. Therefore, robust and high quality underwater acoustic communication has been faced with severe challenges.

The spread spectrum communication system has the character of strong anti-jamming ability and anti multipath capability. It has multiple access capability to work under the low SNR condition. However, it is an obvious disadvantage that the system’s transmission rate is too low in application. MIMO technology has been a new communication technology in recent years, which can make use of space resources to improve the system capacity without increasing the spectrum resources and the transducer transmission power[3][4]. In order to improve the quality of spread spectrum underwater acoustic communication, this paper will combine MIMO technology and spread spectrum technology to develop the MIMO spread spectrum underwater acoustic communication system.

The MIMO underwater acoustic communication system has a high transmission rate. However, in the same combination condition, the increase of transmission elements can lead to the decrease of the MIMO system performance. It is proposed to reduce the number of transmission transducers and reduce the number of devices by using the high-order combined spread spectrum based on the R-Complexity, which can achieve low error rate communication system. Then, it can further improve the communication rate of MIMO spread spectrum acoustic communication system.
2. MIMO spread spectrum underwater acoustic communication model based on r-combined mapping algorithm

2.1. Principle of r-combined mapping algorithm

The key in the MIMO spread spectrum underwater acoustic communication system is the coding mapping and inverse mapping process of the transmission information stream and the corresponding spreading sequence. In this paper, we will use the r-combined data mapping method in mathematics to perform coding mapping and inverse mapping. The theorem formula of r-combined mapping is shown in conclusion 1 and conclusion 2.

Conclusion 1: Any combination of r elements from n different elements, for a given combination number N (where the combination number is sorted based on the r-combination size), the combined elements \( a_i (1 \leq i \leq r) \) can be obtained from equation (2-1) [5]:

\[
\min_{[a_i]} C_{n-a_i}^{r-i+1} \leq C_n^r - N - \sum_{i=1}^{r-1} C_{n-a_i}^{r-i+1} \quad (2-1)
\]

Conclusion 2: Any combination of r elements from n different elements is superimposed, and when each element of the r combination is known, the combination number N based on the arrangement can be obtained from equation (2-2) [5]:

\[
N = a_r - a_{r-1} + \sum_{i=0}^{r-2} (C_{n-a_i}^{r-i} - C_{n+1-a_i}^{r-i}) \quad (2-2)
\]

Conclusion 1 is applied to the r-combination spread spectrum generator in the coding of the system, that is, the mapping process from the combined sequence number N (ie, the decimal information code) to the element serial number of the r-combination code; Conclusion 2 is applied to r-combined spread spectrum decoder in the decoding process of the system, that is, the inverse mapping process of the element sequence number of the r combined code to the combined sequence number N.

2.2. MIMO spread spectrum underwater acoustic communication
The model of MIMO spread spectrum underwater acoustic communication system based on r-combined mapping is shown in Fig. 1. Firstly, the specific position information of M sets mutually independent serial bit streams are generated according to the r-combined mapping algorithm. The spread spectrum sequences are selected from the corresponding spread spectrum atomic libraries according to the position information, superimposed and modulated. The transmit sequence is transmitted separately by M transducers.

At the receiving end, the received signal is demodulated. Time-reversed mirror signal processing is performed on each array element according to the channel estimation result[6]. Finally, the energy detector is used to perform search matching on each corresponding spread spectrum atomic library, and the r-combined inverse map is used to estimate the transmission information.

Among them, the pseudo-random code adopts the M_Walsh orthogonal combination sequence, which can satisfy the requirement of the r-combination algorithm for selecting a large number of spreading sequences. The orthogonal combination sequence has strict orthogonality and is generated by multiplying the Walsh sequence by another pseudo-random sequence. This feature ensures that the decoding process of the system of this system is not affected by other spreading codes. FIG. 2 shows the simulation of the correlation characteristics of the partially orthogonal combination sequence. The M_Walsh orthogonal combination sequence is composed of the Walsh sequence and the M sequence, and it still guarantees excellent autocorrelation and weak cross-correlation.

Fig. 2. Simulation of the correlation characteristics of the partially orthogonal combination sequence

In the mode of r-combination mapping using 32 select 5, the MIMO spread spectrum underwater acoustic communication system with m transmissions and n received array elements is simulated. Figure 3 shows the simulation results of two systems, including the use of 4 transmissions (1#, 2#,
4# array elements) 4 receptions, and 3 transmissions (1#, 2#, 3# array elements) 4 receptions. The system uses orthogonal combination spreading sequences with a period of 511. Each spreading symbol period maps 17 bits of information, and the average bit error rate of the system is counted.

The simulation results show that the system with 3 transmissions and 4 receptions has better performance than the system with 4 transmissions and 4 receptions. R-combined spread spectrum actually introduces channel interference, similar to multi-channel spread spectrum. The anti-interference performance of the system will decrease with the increase of the number of spreading sequences (the increase of the r-combination order and the increase of the transmitting unit). In practical applications, the number of spreading sequences in the system should not be too large. It can be seen that under ideal conditions the performance of the system with \( r_1 \) spreading sequences is

\[ 10 \log_{10}(r_1/r_2) \text{ dB} (r_1 > r_2) \]

worse than that of the system with \( r_2 \) spreading sequences.

Within a reasonable design range, the MIMO combined spread spectrum system can achieve higher frequency band utilization with fewer transmitting units, which is also very important for saving equipment costs.

![Fig. 3. Performance curve of MIMO spread spectrum underwater acoustic communication system (mSnP means 3 transmissions 4 receptions)](image)

3. Test and Verification

The communication coding mode, signal processing technology and underwater acoustic communication system proposed in this paper are tested by river experiment. Using the r-combined mapping algorithm and MIMO spread-spectrum underwater acoustic communication technology proposed in this paper, high-quality MIMO spread spectrum underwater acoustic communication based on r-combined mapping is successfully completed in the experiment. The feasibility of this coding mode and algorithm is verified.
FIG. 4 is a schematic diagram of a MIMO spread spectrum underwater acoustic communication test layout. The test site has a water depth of about 6 m, and the transmitting end uses a binary array transducer with a frequency band of 8-20 kHz. The two array elements are S1 and S2, respectively. The binary array transducer is placed horizontally at a position of about 3.5 m from the ice surface, and the array element spacing is 1 m. The receiving array is a binary array of hydrophones placed vertically, and the numbers are set from P1 and P2 from top to bottom. The upper array element is placed at a position of about 1.8 m from the ice surface, and the lower array element is about 2.3 m from the ice surface, and the array element spacing is 0.5 m. The communication distance of the transceiver is about 550 m.

The sampling rate of the system is 48 kHz, the frequency band is 10 kHz-14 kHz and the carrier frequency is 12 kHz. The spreading code adopts the orthogonal combination sequence with period 128. The LS algorithm is selected as the channel estimation algorithm. In each transmitting end, the system uses 32 spreading sequences to select 5 parallel spreading modes for parallel data transmission, and a total of 10 information sequences are transmitted in parallel in the transmitting array elements. The amount of data transmitted by each transmitter is 6800 bits, and a total of 13600 bits of data is transmitted. The transmission rate is about 531.25 bps.

FIG. 5. Received signals (a) array P1; (b) array P2

The received signals of array P1 and array P2 are shown in Figure 5. It can be seen that the signal-to-noise ratio of the receiving array is relatively low. This is because there are continuous and continuous different intensity noises in the filter at the receiving end, which forms a Low SNR.
environment. Due to the focusing effect of the time reversal mirror technology at the receiving end, the multi-path structure of each array element is obviously compressed, and the channel interference between the transmitting transducers is greatly compressed, and the advantages of the spread spectrum chips become very prominent in the subsequent decoding.

FIG. 6 shows the result of $2 \times 2$ MIMO spread spectrum received signal processing. Decoders solve the five peaks with the highest energy output peak. In each graph, the output peak is obvious. Among them, in FIG. 6, it can be seen that the five positions with the highest energy peak are 2, 9, 22, 26, and 28. So that the five spread spectrum parallel combination transmissions can be selected in the transmission information sequence. Then, the mapping is performed to the combined serial number, mapped to the combined serial number. The information decoding process is completed.

![FIG. 6. Results of MIMO spread spectrum received signal processing](image)

Since the inter-channel interference and the inter-symbol interference in the parallel transmission of the 10 sets of information sequences of the two array elements are strong, adding a time-reversal mirror based on the LS channel estimation can eliminate a large part of the channel interference and achieve low error transmission. MIMO spread spectrum underwater acoustic communication system. The use of MIMO high-order combined spread spectrum based on r-combined mapping algorithm reduces the number of transmitting transducers and reduces the complexity of the device. The experimental transmission rate reaches twice the transmission rate of the single-user r-combined spread spectrum system, which is 10 times the transmission rate of the single-user direct-spread system.

4. Conclusion
The MIMO spread spectrum underwater acoustic communication system based on the r-combined mapping algorithm achieves a high information transmission rate and a high frequency band utilization by spatial multiplexing, and has a large channel capacity. The excellent correlation characteristics of the spread spectrum code also provide guarantee for the stability of MIMO communication, and the addition of the late anti-interference technology also solves the effects of carrier phase hopping and multi-path extended interference of the underwater acoustic channel. In the test, the MIMO spread-spectrum underwater acoustic communication system with 2 transmissions and 2 receptions realized low error transmission of multiple transmission rates of 10 sets of data parallel transmission, completed high-quality MIMO spread spectrum underwater acoustic communication, and verified the coding mode and the feasibility of the algorithm.

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