Parallel Combinatory Spread Spectrum Underwater Acoustic Communication Technology

Shuping Han¹, Hangcheng Zhou¹* and Jianbo Liu¹
¹ Naval Submarine Academy, Qingdao, SHANDONG, 266199, China
*Corresponding author’s e-mail: 1210147512@qq.com

Abstract. In order to achieve stable and high-speed information transmission between underwater platforms, an underwater communication system based on parallel combinatorial mapping sequence spread spectrum is built. The stability, concealment, economy and engineering realization of the system are analyzed in depth. At last, the experiment of anechoic pool proves that the system can still maintain the stable transmission of information under the condition of low signal-to-noise ratio. Compared with direct spread spectrum communication, the system greatly improves the communication rate on the basis of maintaining the stability of communication.

1. Introduction
With the development of ocean exploration, the application of underwater acoustic communication technology is more and more extensive. Spread spectrum technology is widely used in the field of underwater acoustic communication due to its good anti-noise and anti-interference ability. But spread-spectrum communication rate is low, so this paper mainly studies the parallel combination principle and realization method of spread spectrum technology, its application in the field of underwater acoustic communication against doing an adaptive improvement, through the combination of mapping sequence spread spectrum method to build a stable parallel combination of the spread spectrum underwater acoustic communication system, and through the pool experiments on the performance of communication system is verified.

2. principle of parallel combined spread spectrum communication
In 1990, professor Jinkang ZHU from China University of Science and Technology proposed a soft spread spectrum communication mode -- parallel combined spread spectrum communication. [1] The data transmission capability and frequency band utilization ratio of this communication mode is significantly higher than that of ordinary spread spectrum communication, and it is suitable for use in frequency band limited environment (such as underwater acoustic channel). Underwater acoustic communication parallel combination of the spread spectrum communication is developed on the basis of M-ary spread spectrum communication with high information transmission ability of parallel communication mode. [2] This communication system chooses r spread spectrum codes and their respective phase polarity states from M spread spectrum codes, superimposes them first and then carries out carrier modulation. Thus, the information data k transmitted by the system is:

$$k = r + \left\lfloor \log_2 C'_M \right\rfloor$$
Where: \( \lfloor x \rfloor \) represents the integral part of \( x \). Obviously, the larger \( M \) and \( r \), the more information data. Set the \( k \) bit information data to be sent by the sending end as \( d_1, d_2, \ldots, d_k \). The information sequence is fed into a data-spread sequence mapper, and the transmitted signal can be expressed as:

\[
s(t) = \sqrt{2P} \sum_{j=1}^{r} q_j P\eta(t) \cot(\omega t + \phi)
\]

In gaussian white noise channel, the received signal can be expressed as

\[
R(t) = s(t - \tau) + n(t) + J(t)
\]

Where, \( \tau \) is communication transmission delay; \( N(t) \) is gaussian white noise, and its bilateral power spectral density is \( N_0/2 \). \( J(t) \) is the interference signal.

In the receiving end, \( M \) demodulators can be used to decompose the received signal after the carrier wave. Respectively, using the local spread spectrum sequence \( P\eta_i(t) \) for expansion processing. In the case that the carrier frequency and spread spectrum sequence have been precisely synchronized, the output of the channel \( i \) spread spectrum demodulator can be expressed as

\[
Z_i(t) = P\sum_{j=1}^{r} q_j P\eta(t)P\eta_i(t) + n_i(t) + J_i(t) \quad (i = 1, 2, \ldots, M)
\]

Because of the orthogonality of the spread spectrum sequence, the demodulator output is

\[
Z_i(t) = \begin{cases} 
q_j P\eta + n_j(t) + J_j(t), & i = i_j \\
n_i(t) + J_i(t), & i \neq i_j
\end{cases}
\]

According to the output results of \( M \) demodulators, we select the spread spectrum sequence corresponding to \( R \) correlated outputs with large absolute value and its sequence phase polarity as the combined sequence of transmitted signals, and then through the sequence-data inverse mapper, we can get the transmitted \( k \)-bit data. The communication rate of the parallel combined spread spectrum system can be expressed as

\[
R_b = \frac{k}{T_0} = \frac{\log_2 C^r_M + r}{T_0} \text{ (bit/s)}
\]

It can be seen that the communication rate is much higher than that of direct sequence spread spectrum (communication rate of \( R_b = 1/T_0 \) bit/s).\(^3\)

3. Selection of technical parameters of parallel combined spread spectrum system

With the increase of parallel channel, multichannel signal superposition can lead to a significant increase of peak mean ratio, which is not conducive to the concealed demand of underwater military communication. And its interference is relatively increased under low signal-to-noise ratio, so data mapping and demodulation errors can easily occur, which is not conducive to the stability of the communication system. At the same time, with the increase of the number of the spread code sequence, the complexity of the receiver structure will be greatly increased, which is not conducive to the engineering implementation. Therefore, the selection of appropriate parallel path \( r \) and the number of spread code \( M \) is very important for the performance of the communication system. The following part mainly analyzes the system from four aspects of reliability, concealment, economy and engineering realization.

3.1 Reliability

Under the same SNR condition, the fewer parallel paths, the higher the reliability of the communication system. The simulation results show that if 16 spread spectrum codes are selected to transmit information in parallel and three channels, the BER of the system is higher when SNR is 4dB, and can reach 6*10^-4. With the increase of SNR, the bit error rate of the system decreases gradually. When SNR is greater than 2dB, no error occurs in the statistical range, that is, the bit error...
rate is less than $10^{-6}$ magnitude. It can be seen that the bit error rate is still at a high level under the condition of low signal-to-noise ratio, which is not conducive to the stability of underwater acoustic communication. When two parallel paths are used, when the signal-to-noise ratio is -10dB, there is no error code in the statistical range, which improves the stability of the communication system.

### 3.2 Concealment

In direct sequence spread spectrum system, spread spectrum signal has a wide frequency band. In the frequency domain, spread spectrum signal is evenly distributed, the power density of transmission signal is low, and the signal is immersed in white noise, making it difficult for the other side to find the signal, so spread spectrum communication is more concealed. However, with the superposition of parallel path signals, the peak-to-peak ratio will continue to increase, leading to the system's invisibility becoming worse and worse. Therefore, the number of parallel paths cannot be increased excessively.

### 3.3 Economy

#### 3.3.1 Communication rate

Through theoretical derivation, direct sequence spread spectrum communication rate is $R_b = 1/T$ bit/s, and the communication rate of parallel combined spread spectrum communication system is up to $R_b = (\log_2 C_M^r + r)/T(bit/s)$. Is $[\log_2 C_M^r + r]$ times of the direct sequence spread spectrum ([] is the downward integer). Thus it can be seen that the emergence of parallel paths will greatly improve the communication rate and guarantee the high efficiency of the communication system.

#### 3.3.2 Chip energy

As the number of parallel paths $r$ and the number of spread code $M$ changes, the energy $E$ required to transmit a single bit of information changes. In the case of no inter-code interference, it is assumed that the energy required for single-channel transmission is 1. Table 1 lists the relation between the parallel path $r$, the number of spread code $M$, and the number of transmitted bits $k$, and the energy required for the transmission of a single bit $E$.

| The number of $r$ | The number of orthogonal sequence $M$ | Combinatorial number NC | Bit number of Information $k$s | Total bit number $k$ | Chip energy |
|------------------|--------------------------------------|--------------------------|-------------------------------|---------------------|-------------|
| 2                | 7                                    | 21                       | 4                             | 6                   | 0.33        |
|                  | 9                                    | 36                       | 5                             | 7                   | 0.28        |
|                  | 12                                   | 66                       | 6                             | 8                   | 0.25        |
|                  | 17                                   | 136                      | 7                             | 9                   | 0.22        |
|                  | 24                                   | 176                      | 8                             | 10                  | 0.20        |
| 3                | 7                                    | 35                       | 5                             | 8                   | 0.38        |
|                  | 9                                    | 84                       | 6                             | 9                   | 0.33        |
|                  | 11                                   | 165                      | 7                             | 10                  | 0.30        |
|                  | 13                                   | 286                      | 8                             | 11                  | 0.27        |
|                  | 16                                   | 560                      | 9                             | 12                  | 0.25        |
|                  | 20                                   | 1140                     | 10                            | 13                  | 0.23        |

#### 3.4 Decoding complexity

With the increase of parallel channel and the number of spread code, the decoding complexity of the parallel channel increases continuously. From the perspective of engineering implementation, the number of parallel channels and the number of spread code cannot be increased indefinitely.
Considering reliability, concealment, economy and engineering realization, this communication system uses two parallel paths and 17 orthogonal Gold codes for parallel combination communication.

4. Parallel combination spread spectrum communication system simulation
In order to verify the effectiveness of the parallel combined spread spectrum underwater acoustic communication system established in this paper, the underwater acoustic communication experiment was carried out in the indoor anechoic pool. The test environment is shown in figure 1. In the experiment, a signal transmitter with a central frequency of 8kHz was adopted. The depth of both transmitting and receiving transducers was 5m, and the distance between transceiver and transmitter was 20m. Therefore, only the direct acoustic path and the reflected water path exist in the pool. The acoustic path is shown in figure 2. The speed of sound in the pool is 1497m/s.

![Figure 1. Schematic diagram of the experimental environment.](image1)

![Figure 2. Schematic diagram of sound ray path.](image2)

![Figure 3. Impulse Response of Anechoic Pool.](image3)

When the signal-to-noise ratio is -10db, the experimental results are as shown in figure 4 below (taking single channel information code as an example).
At the receiving end, the equalized signal is demodulated by QPSK first, and the demodulated binary sequence is correlated with the local spread spectrum code. Through the maximum decision, the spread spectrum sequence number corresponding to the maximum correlation peak and the sub-maximum correlation peak and its phase state are selected. Then, the transmitted information can be restored by demodulation based on data mapping. Taking the one way information demodulation as an example, its correlation is shown below.

As can be seen from Figure 6, the correlation despreading peaks of the two spread spectrum sequences are still in a high state when the signal-to-noise ratio is -10dB, and there is no error code in
the statistical range after many experiments, which fully guarantees the stability and reliability of the system.

At this point, the communication rate of the parallel combined spread spectrum communication system is:

\[
R_b = \frac{r + \log_2 C^r}{T} = \frac{2 + \log_2 C^2}{128 \times 0.5ms} \approx 284 \text{bit/s}
\]

Under the same conditions, the rate of general spread spectrum communication system is only 31.2 bit/s, through comparison, we can see that the parallel combined spread spectrum system greatly improves the communication rate of the system while ensuring the reliability of the system. Especially in the working environment of negative signal-to-noise ratio, its advantages of stability and concealment make it have broad application prospects in military communications.

References
[1] ZHU Jinkang, JIA Shun and WU Xiaohong, “Spread spectrum communication system and properties using mapping sequence,” Journal of China Institute of Communications, 1994, pp.63-68.
[2] Stojanovic M, Preisig J. “Underwater acoustic communication channels: Propagation models and statistical characterization,” IEEE Communications Magazine, vol.47, pp.84-89, 2009.
[3] YIN Jingwei, WANG Lei and ZHANG Xiao, “The application of parallel combinatory spread spectrum in underwater acoustic communication,” Journal of Harbin Engineering University, vol.31 No.7 pp.958-962, 2010.