Performance Simulation of Underwater Acoustic Spread Spectrum Communication Based on LDPC Code

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Abstract. As we all know, the underwater acoustic channel is a time-varying, space-changing, and frequency-varying fading channel with limited bandwidth and severe noise interference. This paper studies and analyzes the main factors restricting the transmission of underwater acoustic channels, and establishes an underwater acoustic multipath time-varying fading channel. The channel coding adopts Quasi-Cyclic Low-Density Parity-Check Codes (QC-LDPC), combined with spread spectrum technology and high-order modulation technology, and utilizes Log-likelihood Ratios Belief Propagation (LLR-BP) is decoded, the simulation results show that LDPC codes have stronger error correction capabilities in underwater acoustic spread spectrum communication systems, ensuring that the system can operate reliably under low SNR conditions.

1. Introduction

The ocean is rich in biological resources and strategic resources. All countries have accelerated the exploration and development of marine resources, and the demand for underwater communications is also increasing. Light waves and electromagnetic waves have severe attenuation and absorption underwater, and they cannot be transmitted over long distances in an underwater environment. Acoustic wave has become the main way to realize underwater wireless communication, but the underwater acoustic channel is complex and changeable. It has the characteristics of time-varying, frequency-varying, and space-varying [1], which greatly limits the long-distance, high-speed, and low-error of underwater acoustic signals. Rate of transmission [2].

In the underwater acoustic spread spectrum communication system: (1) Since the underwater acoustic channel is a random channel, it has the characteristics of high environmental noise, large propagation loss, narrow channel bandwidth, and serious multipath effect, which makes the received signal waveform serious. Distortion and distortion. (2) Using high-order modulation methods such as 64QAM, QPSK, improves the system transmission rate while reducing the Hamming distance between demodulated symbols, and results in an increase in the system's bit error rate and a decrease in communication efficiency.

Channel coding is an important way to reduce the bit error rate of spread spectrum communication systems. Low Density Parity Check Code (LDPC) Yes. The LDPC code and spread spectrum communication technology are combined to form an underwater acoustic communication system, and the spread spectrum communication technology is used to reduce the influence of frequency selective fading caused by the multipath delay expansion of the underwater acoustic channel on the system performance, and improve the concealment and concealment of the system and Anti-interference ability. The simulation results show that LDPC codes have stronger error correction capabilities than turbo codes, and can ensure reliable operation of the communication system under the condition of low signal-to-noise ratio.
2. Underwater acoustic channel model

2.1 Path loss
In the underwater acoustic channel, the path loss is a physical quantity related to the signal frequency and the propagation distance of the signal [3]:

\[ A(l \cdot f) = A_0 l^k a(f)^l. \]  (1)

In the above formula, \( A_0 \) is the normalized function, \( k \) is the propagation factor, \( a(f) \) is the absorption coefficient and its unit is dB. The absorption coefficient is generally determined by the actual situation, and it is calculated by the Thorp formula [4], the absorption coefficient and frequency The relationship is shown in Figure 2.

\[ a(f) = 0.11 \frac{f^2}{1+4f^2} + 44 \frac{f^2}{4100+f^2} + 2.75 \times 10^{-4} \cdot f^2 + 0.003. \]  (2)

The unit of frequency is kHz. Figure 2 shows the relationship between the absorption coefficient and the frequency. The absorption coefficient of the underwater acoustic channel increases as the frequency increases. In the case of a certain communication distance, the absorption coefficient limits the available bandwidth of the channel at high frequencies.

![Fig.1 the relationship between absorption coefficient and frequency.](image)

If multipath is considered, each path will act as a low-pass filter, and the transfer function will affect the amplitude of the signal. The transfer function of the channel can be expressed as [3]:

\[ H_p(f) = \frac{\Gamma_p}{\sqrt{A(l_p \cdot f)}}. \]  (3)

\[ \overline{H}(f) = \sum_p H_p(f)e^{-j2\pi f \tau_p}. \]  (4)

In the above formula, \( \Gamma_p \) represents the additional loss along the Pth path \((p=1,2,\ldots,p-1), l_p \) is the length of each path, and \( \tau_p \) is the delay on the p path.

2.2 Channel noise
Marine environmental noise can be approximately expressed as four kinds of noise: ship noise, marine turbulence noise, sea surface wave noise and thermal noise. The empirical formula gives the expression of the power spectral density of the four noises [4], and the unit of f is kHz.

\[ 10\log N_s(f) = 40 + 20(s - 0.5) + 26\log f - 60\log(f + 0.03). \]  (5)

\[ 10\log N_l(f) = 17 - 30\log f. \]  (6)

\[ 10\log N_w(f) = 50 + 7.5w^{1/2} + 20\log f - 40\log(f + 0.4). \]  (7)

\[ 10\log N_t(f) = -15 + 20\log f. \]  (8)
From the above formula, it can be found that different noises correspond to different frequencies. Ocean noise is approximately equal to the sum of the four types of noise. Figure 3 shows the noise power spectral density under different wind speeds and ship activity. It is found that the influence of noise on it decreases as the frequency increases, and environmental noise limits the bandwidth of the channel available at low frequencies.

Fig. 2 Marine environmental noise power spectral density

2.3 Channel model
According to the literature [5], the shallow water acoustic multipath time-varying fading channel as shown in Figure 4 is established, s(n) is the transmission sequence, and the sequence after passing through the underwater acoustic channel is y(n).

\[ y(n) = \sum_{i=1}^{L} h(i, n) * s(n-t_i) + g(n) \]  

(9)

\( g(n) \) is the additive noise of the underwater acoustic channel, \( h(i, n) (=1, 2, ..., L) \) is the sequence of multipath fading factors. Among them, it is the normalized path loss power \( p(i) \) and the unit power of the first path at time \( n \). The product of Rayleigh fading \( R(i, n) \), \( t_i \) is the delay on the corresponding path.

Fig.3 underwater acoustic channel model

3. QC-LDPC

3.1 QC-LDPC encoding
The performance of LDPC codes depends on the structure, and the performance of LDPC codes with different construction methods are very different, and the calculation complexity during encoding and decoding is also very different. Therefore, designing a code with simple calculation and excellent performance has become the focus of LDPC coding research work. One. The construction of the LDPC
code is mainly the construction of its check matrix $H$. The check matrix can be mainly divided into two types: structured check matrix and random check matrix. The random check matrix can be flexibly selected for parameters, but small loops are prone to appear. The structure of the random check matrix code is not fixed, and its structure is more complex than the structured check matrix, which is not conducive to implementation. The structured check matrix is generated through combination and algebra, which can avoid the generation of small loops, has a definite structure, has low coding complexity, and is easy to implement [6].

The QC-LDPC code is a structured LDPC code. It has excellent performance and simple coding structure and easy implementation of hardware circuits, which can greatly reduce the cost of hardware implementation.

The check matrix $H$ of a quasi-cyclic LDPC code consists of two parts:

$$H = \begin{bmatrix} A_{p \times m} & B_{p \times p} \end{bmatrix} \quad (10)$$

The size of sub-matrix $A$ is $p \times m$, and the size of $B$ is $p \times p$, and the $m \times p$ matrix $R$ is calculated:

$$R_{m \times p} = [B^{-1}_{p \times p} \cdot A_{p \times m}]^T \quad (11)$$

$R_{m \times p}$ is a quasi-circular structure matrix. The generator matrix $G$ can be obtained by $R_{m \times p}$:

$$G = \begin{bmatrix} p \times p \cdot I & R_{m \times p} \end{bmatrix} \quad (12)$$

In the above formula, $I_{p \times p}$ is the information bit, and $R_{m \times p}$ is the parity bit. Using its cyclic characteristic, a simple shift register is used to complete the encoding.

3.2 Decoding algorithm

Channel decoding can be divided into soft decision decoding and hard decision decoding. The hard decision decoding directly uses the hard decision value of the received signal, and the processing method is simple and easy to implement. The soft-decision decoding uses the waveform information output by the channel to calculate the probability that the accepted symbol is 1 and 0, respectively, for decoding. Compared with hard-decision decoding, soft-decision decoding has a gain of 2dB~3dB in performance, so soft-decision decoding has become a research hotspot.

The advantage of LDPC decoding lies in the introduction of iterative decoding. The most basic algorithm is Belief Propagation Algorithm (BP), which is a soft decision iterative decoding algorithm based on the probability domain. Such algorithms include: probability BP algorithm, The log-likelihood ratio confidence algorithm (Log-likelihood Ratios Belief Propagation, LLR-BP), minimum sum decoding algorithm (MSA), etc., the performance comparison of LDPC under different conditions is shown in Figure 5:

![Fig.4 performance comparison of LDPC codes under different conditions](image-url)
Figure 4(a) shows the performance comparison of different decoding schemes under Gaussian channel. Probabilistic BP algorithm is similar to LLR-BP algorithm decoding, but LLR-BP algorithm uses likelihood ratio to indicate that probability reduces multiplication operations and reduces The complexity of hardware implementation MSA algorithm performance is the worst. The performance comparison of LDPC under different iteration times under Gaussian channel is shown in Figure 4(b). As the number of iterations increases, its performance continues to improve, but the increase in the number of iterations increases the computational complexity and delay. Big. Therefore, the most suitable number of iterations should be selected according to actual needs during row decoding to achieve the optimization of performance.

4. Underwater acoustic spread spectrum communication system

4.1 Direct sequence spread spectrum

Direct-Sequence Spread-Spectrum (DS-SS) is to expand the information to be transmitted into a wider frequency band through the pseudo-random code sequence (PN), and the system obtains strong concealment and anti-interference capabilities. The receiving end uses the same pseudo-random sequence for despreading and recovers the original signal.

\[ x(t) = \sum_{n=0}^{\infty} x_n w_n (t-nL_x) \]  (13)

In the formula, \( w_n(t) \) is the gate function, only \( 1 \leq t \leq L_x \) is 1, \( L_x = 1/R_x \) is the symbol width, and \( x_n \) is the information code and the value is +1 or -1.

\[ p(t) = \sum_{n=0}^{\infty} p_n w_n (t-nL_p) \]  (14)

In the formula, \( L_p = 1/R_p \) is the chip width, \( p_n \) is the pseudo-random code with a value of 1 or -1, and \( w_n \) is the gate function.

The spread spectrum communication system is to add the information sequence \( x(t) \) and the pseudo-random sequence \( p(t) \) to the modulus of two to generate a spread-spectrum sequence with the same rate as the pseudo-random code rate, and then modulate to obtain a radio frequency signal. The random sequence despreads the spread spectrum, recovers the frequency band of \( a(t) \), and then restores the transmission information \( a(t) \) through demodulation.

4.2 System model

The communication system is shown in Figure 5. The source signal obtains the coded codeword through the LDPC encoder, the coded codeword is spread over a wide frequency band with a pseudo-random code sequence (PN), and the modulated signal is obtained by QPSK modulation. The signal passes through the underwater acoustic multipath established in 1.3 The fading channel is then despread and demodulated, and finally the data signal is restored through the LDPC decoder.
5. Simulation results and analysis

5.1 Parameter design
Using the underwater acoustic signal model designed in 1.3, using a carrier frequency of 10kHz, the rate of transmitting symbols is 5kBaud, and the parameters of each path are shown in Table 1.

| Path | Normalized amplitude attenuation | Path delay/ms |
|------|---------------------------------|--------------|
| 1    | 0.61                            | 0.06         |
| 2    | 0.92                            | 0.58         |
| 3    | 0.54                            | 0.73         |
| 4    | 0.42                            | 1.85         |
| 5    | 0.28                            | 2.13         |

Construct different channel coding methods to simulate the underwater acoustic communication system. The specific scheme is shown in Table 2:

| Program | Encoding | Spread spectrum method | Modulation |
|---------|----------|------------------------|------------|
| 1       | No coding| DSSS                   | QPSK       |
| 2       | Turbo    | DSSS                   | QPSK       |
| 3       | LDPC     | DSSS                   | QPSK       |

The LDPC coding method adopts a quasi-cyclic structure method, which makes the LDPC code have quasi-cyclic characteristics, and the coding complexity is low, which is convenient for hardware implementation and effectively avoids the generation of short loops. The code length is 1024, the code rate is 1/2, and the better performance LLR BP algorithm is used for decoding. The code length of the Turbo code is 1024, the code rate is 1/2, and the log-MAP algorithm is selected for decoding.

5.2 Result analysis
According to Figure 6, it can be seen that the underwater acoustic communication system using spread spectrum technology, when the code length and code rate are equal: (1) The performance of the system using channel coding is greater than that of the system without channel coding. The increase in amplitude has obvious advantages under the condition of low signal-to-noise ratio. (2) When the signal-to-noise ratio is the same, the LDPC code has better error correction performance than the Turbo code, and the communication system has a lower bit error rate.
In the underwater acoustic communication system, due to people's requirements for communication rate, high-order modulation methods are used to increase the communication rate of the system. However, the increase in communication rate causes the Hamming distance between codes to be shortened after demodulation, and the bit error rate also increases. The increase, the combination of channel coding technology and spread spectrum technology, on the one hand, enhances the ability of the system to resist multipath effects and interference, on the other hand, it improves the ability to deal with sudden or random errors, and adopts QC-LDPC encoding its coding structure Simple, the difficulty of hardware implementation is greatly reduced, and the cost is saved.

6. Conclusion
This paper studies and analyzes the main factors that limit the bandwidth and frequency of the underwater acoustic channel, and establishes a multi-path time-varying fading channel for underwater acoustics. Combining channel coding technology and spread spectrum technology, on the one hand, it enhances the system's ability to resist multipath effects and interference, and on the other hand, it improves the ability to deal with sudden or random errors. It also selects a simple structure and low coding complexity. The QC-LDPC code with a quasi-cyclic structure has stronger error correction capabilities than turbo codes in the simulation results, and can ensure reliable operation of the communication system under the condition of low signal-to-noise ratio.

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