Optimal Design of Modulation Parameters for Underwater Acoustic Communication

Hai-Peng Ren and Yang Zhao

***Abstract*—As the main way of underwater wireless communication, underwater acoustic communication is paid more and more attention in ocean research field in recent years. Compared with the free space wireless communication, the underwater acoustic communication suffers from the limits of the less available bandwidth, the more serious multipath effect and the even complex noise caused by the underwater acoustic channel. The communication scheme based on Phase Shift Keying (PSK) modulation and Time Reversal Mirror (TRM) equalization is considered to be a suitable one to achieve a reliable underwater acoustic communication. However, the scheme experiences a high Bit Error Rate (BER) due to the severe distortion of the received signals caused by the channel. To solve this problem, Carrier Waveform Inter-Displacement (CWID) modulation was proposed to use together with TRM equalization recently. The CWID modulation is based on Linear Frequency Modulation (LFM) PSK. The main idea of the CWID modulation is increasing the difference between the carrier waveforms of different symbols to reduce BER. The LFM carrier-waves with different frequency bands lead to different performance. Therefore it is important to find out the optimal frequency band of the carrier-waves to improve the performance of the communication. The Genetic Algorithm (GA) is introduced to search the optimal frequency band in this paper, due to its excellent performance in solving complicated optimization problems. Simulations were done to compare the performance of different modulation frequencies. The simulation results showed the superiority of the optimized CWID modulation method and the effectiveness of GA optimization.**

***Index Terms*—Carrier waveform inter-displacement, genetic algorithm, time reversal mirror, underwater acoustic communication.**

I. Introduction

As the development of marine research, a growing interest in underwater communication has been seen in the past three decades. The underwater wireless communication is considered to be a better way to achieve underwater communication due to its convenience and low cost. Since the radio waves are attenuated severely in the underwater communication channel, the acoustic waves are used as the carrier-waves in underwater wireless communication. The main challenges of the underwater acoustic communication system are obtaining higher Transmission Bit Rate (TBR) and lower BER under the constraints of the limited bandwidth, extended multipath, severe fading and rapid time variation in the communication channel [1]. The underwater acoustic channel is considered to be one of the most complicated communication channels [2]. The coherence communication method using PSK modulation and TRM equalization is recognized as a suitable underwater acoustic communication method [3]-[6], because LFM PSK modulation has a high frequency bandwidth efficiency, and the TRM equalization can resist the serious distortion caused by the underwater acoustic channel.

To improve the performance of the underwater acoustic communication system in sense of higher TBR and lower BER is the main work of the research. One way to increase the TBR is using the M-ary Phase Shift Keying (MPSK) modulation, but the BER will be increased at the same time due to the carrier-waveform difference between different symbols being weaker. To solve this problem, the CWID modulation, which increases a carrier waveform difference between different symbols, was proposed recently [7]. The frequency band of the LFM carrier-waves used in CWID modulation will affect the performance of the communication system. Therefore, it is important to find out the optimal frequency band of the LFM carrier-waves. Searching the optimal frequency band of the LFM carrier-waves is a multi-objective optimization problem. Higher TBR and lower BER are expected in this optimization problem. In this paper, GA, one of the Evolutionary Computation (EA) algorithms, is proposed to find out the optimal frequency band of the LFM carrier-waves. Simulations were done to compare the performance of different frequency band. The simulation results demonstrated that the proposed optimization method obtained a satisfied performance in the sense of higher TBR and lower BER.

This paper is organized as follows: Section 2 introduces the underwater acoustic communication system based on CWID modulation and TRM equalization; Section 3 gives the GA for searching the optimal frequency band; Section 4 gives the results of the optimization; Section 5 concludes the work.

II. Underwater Acoustic Communication System Based on CWID and TRM

The structure of the underwater acoustic communication system used in this paper is showed in Fig. 1. The system consists of source, transmitter, receiver and sink. The source (or the sink) generates (or receives) the messages. The transmitter modulates messages using CWID modulation and

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sends the modulated signals through communication channel. The receiver employs the Passive Time Reversal Mirror (PTRM) equalization and matched filter to demodulate the messages.

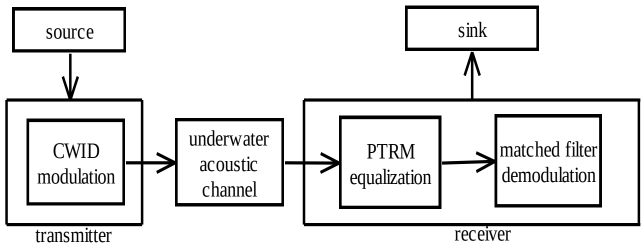

Fig. 1. Structure of the underwater acoustic communication system.

The principle of the wireless communication is that the transmitter modulates different binary codes (or symbols) into different carrier-waves. Then send the carrier-waves to the receiver through wireless channel. The receiver enables to demodulate the carrier-waves into the original binary codes (or symbols) correctly when it can distinguish one carrier-wave from others correctly. An error bit (or error symbol) will appear if it cannot do so.

The traditional PSK modulation represents the different symbols by using the different initial phases of a sinusoidal (or a LFM) carrier-wave [8]. In order to improve the TBR, MPSK is an option of modulation method in the communication. The difference between different carrier-waves will become weaker since the fixed 360 degrees difference will be divided into more pieces with less difference. Therefore, it is hard for the receiver to demodulate the carrier-waves correctly. This means that the less difference between different carrier-waves leads to a higher BER.

To solve this problem, CWID modulation was proposed in [7]. The main idea of the CWID modulation is finding a special position, the zero amplitude positions for LFM signals with zero degree initial phase, to divide the LFM carrier-waves into pieces of carrier signals and reorganize the order of the pieces of carrier signals to produce the new carrier-waves. For illustration, the carrier-waves of 4-CWID modulation are given in Fig. 2. Compared with the LFM QPSK, 4-CWID possesses much difference between different symbols.

PTRM, which can match the underwater acoustic channel automatically without any prior knowledge, is widely used to resist the severe distortion caused by the underwater acoustic channel in underwater acoustic communication systems [1], [3], [9].

Matched filter is used to demodulate the carrier-waves after equalization and to get transmitted massages. The filter stores the time reversed carrier-waves of all symbols as the reference. The carrier-waves after equalization are convoluted with each reference, one by one. The received carrier-wave will be decoded as the symbol represented by the reference, with which the convolution gets the maximum peak.

The simulation results in [7] demonstrate that the CWID modulation contributes to a lower BER under the same condition, compared to the conventional LFM QPSK modulation.

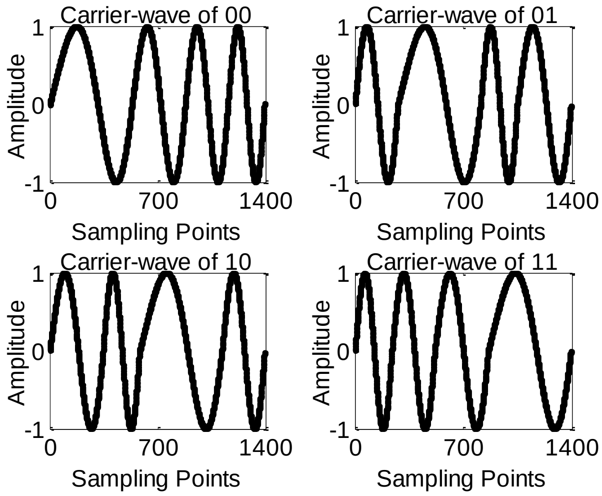

Fig. 2. 4-CWID carrier waveforms.

III. Finding Optimal Frequency Band Using GA

The different frequency band of the LFM carrier-waves may lead to a different performance of CWID modulation, so it is important to find out the optimal frequency band of the LFM carrier-waves to improve the performance in the sense of higher TBR and lower BER. GA is used to search the optimal frequency band of the LFM carrier-waves in this paper. GA is an optimization method that imitates the process of natural selection of the species and has been demonstrated to be an effective optimization method [10]. GA is easy to implement in computers and can operate without any prior knowledge for the mathematical model of the optimization problem, so it is widely used for solving complex optimization problems. In recent years, GA and its improved algorithms are proposed to solve optimization problems in the field of communication [11], [12]. The algorithm used in this paper is given as follows.

A. Variables to Be Optimized

The lower limit frequency and the upper limit frequency of the LFM carrier-waves are the two parameters to be optimized by GA in this paper. The range of the lower limit frequency we selected in this paper is 1-16 kHz, and the range of the upper limit frequency we selected in this paper is 17-32 kHz, due to the frequency band limit of the underwater acoustic channel [2] and the prior knowledge that the lower limit frequency (or the upper limit frequency) located in the range of 17-32 kHz (or 1-16 kHz) may lead to a poor communication performance.

B. Binary Encoding

The binary encoding method is used to encode the variables to be optimized. GA is a discrete algorithm, the resolution of the parameters to be optimized are 1 kHz, therefore, the length of the codes for both lower limit frequency binary codes and upper limit frequency binary codes are 4 bits. The 8 bits code will be divided into two 4-bits piece to decode. The decoding function is

$$f=\frac{B}{2^{N}-1}(f_{\max}-f_{\min})+f_{\min} \quad (1)$$

where B is the binary codes, N is the length of the binary codes, $f_{\max}$ and $f_{\min}$ are the maximum and minimum value of the parameters to be searched, respectively.

C. Fitness Function

The fitness represents how the individual match the objective. The fitness of each individual in GA is set as a function of TBR and BER, which is

$$F=T-B\cdot a \quad (2)$$

where F represents the fitness, T represents the TBR and B represents the BER for the parameters determined by the individuals. That means an individual with higher TBR and lower BER has a higher fitness. We can change the value of a (a>0) to fit the different applied conditions. In this paper, we set $a=10^5$. The optimization has two objects, higher TBR and lower BER, so the optimization problem in this paper is a multi-objective one. In (2), we convert the multi-objective optimization into single-objective one by giving the weight to the different objective.

D. Initial Population

The first step of GA is to create the initial population. The population size is fixed at 18 in this paper. The individuals of the initial population are generated randomly. In details, 8 random numbers belong to the range from 0 to 1 are created first. Then we turn the random numbers as 0, if it is smaller or equal to 0.5, else we turn it as 1. After the initial population are generated, we can get the decimal values of the lower limit frequency and the upper limit frequency by decoding the binary codes using (1).

E. Fitness Evaluation

As long as a new generation of population is created, the fitness of each individual will be evaluated. We calculate the fitness of each individual using (2). The TBR and BER in (2) are obtained through simulating the communication system using the parameters that the individual represented. All the simulations are operated in the same underwater acoustic channel. The underwater acoustic channel model in [13] is used, which includes the multipath effect, amplitude fading, noise and time variation effect. The multipath effect, amplitude fading and noise are the time-invariant parameters. The time-variant parameters are described using statistical method. In order to avoid the effect of the stochastic factor in the underwater acoustic channel, the 10 times simulation is done for each individual and the TBR and BER used to calculate the fitness are the average values of the 10 times simulation results.

F. Selection

Selection will be done subsequently. The principle of the selection is "survival of the fittest". That means the individual with higher fitness would generate more offspring. In this paper, the roulette method is used to reproduce the offspring. Selection can not create new individuals, but reproduce more existed individuals with higher fitness.

G. Crossover

The purpose of the crossover operation is to create new individuals from parents. The standard crossover rate is 0.5 in this paper. We choose a large standard crossover rate due to the optimization problem maybe a multi-peak one. A large standard crossover rate may contribute to avoid a local optimum. Before we do the crossover operation, we give each individual a random crossover rate, which belongs to the range from 0 to 1. Then we compare the crossover rate of each individual with the standard crossover rate. The individual will be selected to do crossover, when its crossover rate is smaller than the standard crossover rate. We exchange the binary codes between two random locations of the selected individuals.

H. Mutation

Mutation can create new individuals, and thus, contribute to find out the global optimum. In this paper, we set the standard mutation rate as 0.15, which is a larger one, also due to the possible multi-peak optimization. We give each bit of the individual a random mutation rate. The given random mutation rate belongs to the range from 0 to 1. We compare the mutation rate of each bit with the standard mutation rate, the bits with mutation rate smaller than the standard mutation rate will be mutated. We invert the bit to accomplish mutation.

I. Algorithm Stop Criterion

GA is an iterative algorithm. The flow chart of GA is showed in Fig. 3. The stop criterion is one of the followings: the optimal individuals are kept the same one in last three generations; the generation reaches 12. We select the two stop criterions since we can believe the fitness of the optimal individual is nearly stable when meets either of the two stop criterions. The optimal individual of the final population is the optimal frequency band of the LFM carrier-waves.

IV. Optimization Result

Simulations were done to search the optimal frequency band of the LFM carrier-waves in this paper. Fig. 4 shows the relationship between fitness of the optimal individual in each generation and the generation number. Fig. 5 shows the relationship between the average fitness of each generation and the generation number. The final optimal individual represents 2-29 kHz, namely, the optimal frequency band of the LFM carrier-waves is 2-29 kHz.

Fig. 6 shows the comparison of the fitness (i.e., TBR-BER*10^5) of the different methods under the different noise level. Methods in Fig. 6 include the conventional QPSK, the LFM QPSK, the 4-CWID [7], the optimized 4-CWID in this paper, and the method in [3]. It is clear that the CWID with the optimized parameters obtained in this paper has the best performance from the sense of higher TBR and lower BER.

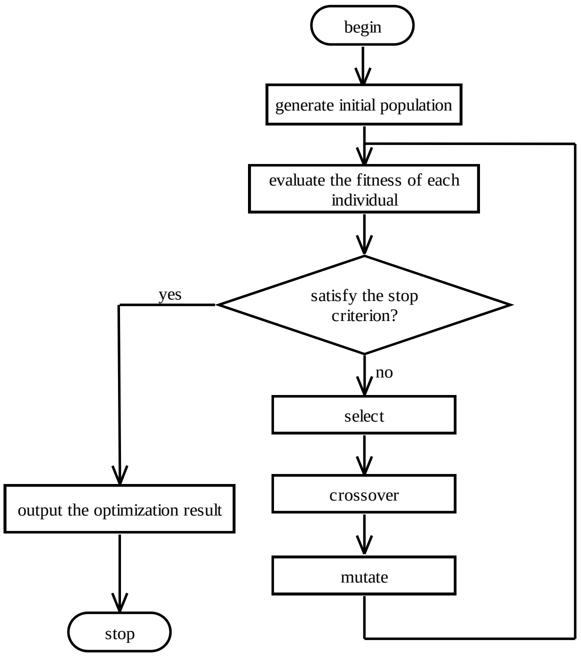

Fig. 3. Flow chart of GA.

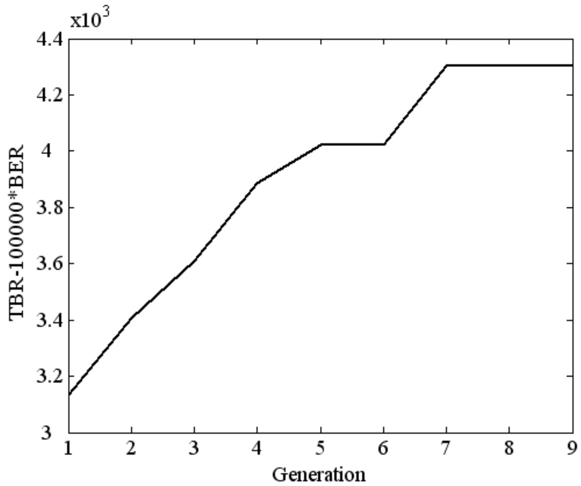

Fig. 4. Fitness of the optimal individual versus generation number.

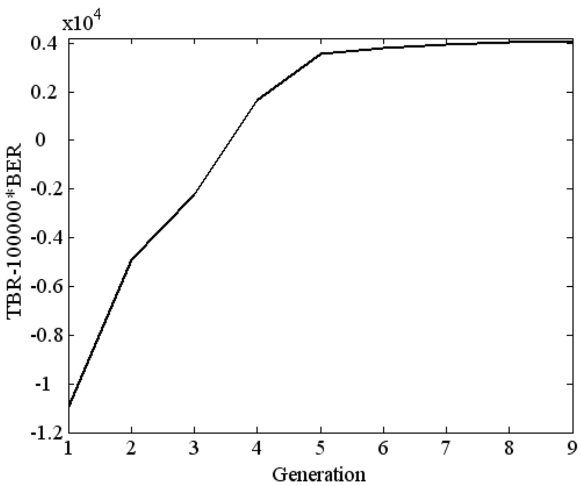

Fig. 5. Average fitness of the generation versus generation number.

V. Conclusions

Due to the severe distortion caused by the underwater acoustic channel, it is very difficult to implement the underwater acoustic communication in sense of higher TBR and lower BER. To solve this problem, the novel CWID modulation to increase the difference between different carrier waveforms is an effective way. What is the optimal parameter of the frequency band is an important factor to get better performance with the frame work of CWID modulation. We use GA to search the optimal frequency band for LFM carrier-waves to get better performance of the underwater acoustic communication in sense of higher TBR and lower BER. Comparison of the simulation results shows the superiority of the optimized parameters and the effectiveness of the GA optimization. In this paper, we set the resolution of the parameter as 1 Hz, which is not high. We can enlarge the bit length of the code to increase the resolution.

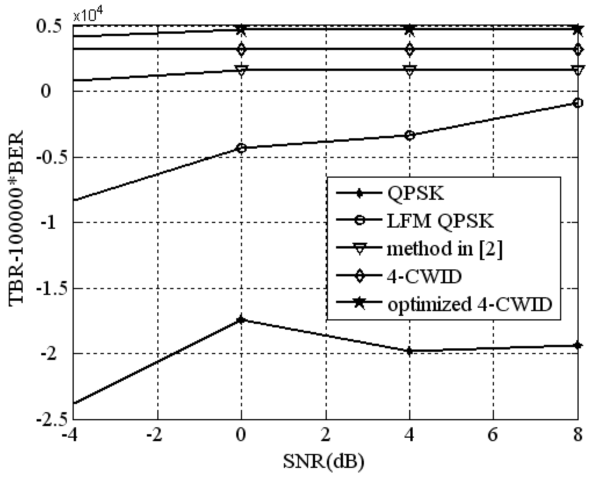

Fig. 6. Performance comparison of the different methods.

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