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Communication between Spherical Underwater Robots Based on the Acoustic Communication Methods

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***Abstract* –This paper depicts an underwater acoustic communication system for Spherical Underwater Robots (SURs). The communication system will be integrated into the multiple SURs system to realize the communication between SURs and the cooperation of multi-SUR system. There are two main trial method adopted in this communication system, which are tamed spread spectrum and Frequency Hopping Multiple Access (FHMA) as well as Quadrature Phase Shift Keying-Code Division Multiple Access (QPSK-CDMA) method. The Micron Data Modem is employed as the communication module. The communication system consisted of channel encoding and decoding, spread spectrum modulation and demodulation, pairs of communication modules. The experiments results testify that the developed system is feasible and reliable to realize the underwater communication due to the low BER (Bit Error Ratio).**

Index Terms*– *Spherical Underwater Robots (SURs); Communication system; FHMA; QPSK-CDMA; Micron Data Modem;

I. INTRODUCTION

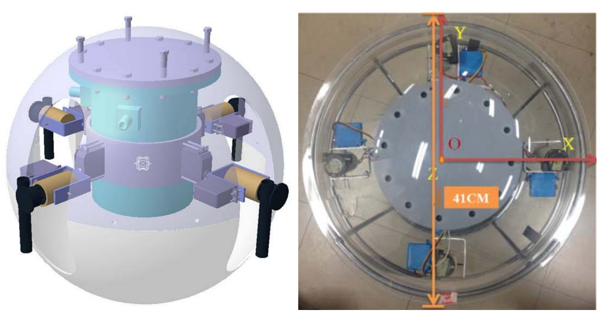
With the rapid expansion of the exploring and exploiting in the deep ocean, underwater robots technologies have also been promoted to a higher dimension. Since the vast space and complicated environment in ocean, it is very difficult for an individual underwater robot to fulfil tasks alone. For instance, the environmental monitoring on the vast region, the multi-point environmental factors parameter data acquisition, the cooperation of multi- threading missions, and the information sharing in long distance transmission. Multiple underwater vehicles system is one of the most important developmental directions. Therefore, we need the multi-underwater robot system to complete these tasks cooperatively in underwater environment. Then, it is obviously that an effective means of underwater communication system is the basic to realize the cooperation of the multi-underwater robot systems. Among various proposed underwater communication methods, the underwater acoustic communication is validated to be one of the most stable and feasible schemes in deep ocean.

Underwater Acoustic (UWA) communication can be established by transmission of acoustic waves. It is a rapidly growing field of research and engineering as the applications, which once were exclusively military, are extending into commercial field. Aiming at this pop research field, this paper concentrates on proposing underwater acoustic communication systems for multiple underwater vehicles.

Acoustic wave is not the only way for wireless transmission of signals underwater. However, the attenuation of radio wave transmitting through sea water is rather serious which results in the requirement of large antennae and high transmitter power. Optical wave does not suffer so much from serious attenuation, but they are affected by the scattering. Therefore, optical signal transmission requires high precision in pointing the narrow laser beams. While the laser technology is still being developing for practical use, acoustic wave becomes the only best solutions for communication underwater in practice at present [1]. However, compared with radio communication, the available frequency bandwidth of underwater acoustic communication is reduced by several orders of magnitude. Moreover, the low speed of sound results in large time delay among multipath signals caused by multipath propagation, as well as significant Doppler shifts. Usually, acoustic communication systems are not only limited by the noise, but also limited by the reverberation and time variability. Therefore, there are still some important problems that need to be solved in the research field of underwater acoustic communication. At present, the research on ensuring the reliability of underwater acoustic communication mainly focuses on four aspects, including the simulation and measure of the channel [2][3]; research on the use and algorithm of signal processor in the receiver [4][5]; diversity reception technique [6][7] and coding technique (compression coding and error correction coding) [8][9]. There are mainly two organizations that are engaged in the research of underwater acoustic communication network. In the USA, it is supported by Office of Naval Research, and the projects include AOSN (Autonomous Ocean Sampling Networks, 2003) and DADS (Deployable Autonomous Distributed System, 2005). The most famous is Sea web from 1998. It is a project to actualize monitoring underwater in a large range. In the year of 2004, the number of the nodes reached 40, the range is 100-1000km^2

and the rate is 800bit/s. In the Europe, it is supported by Marine Science and Technology Program. The projects include SWAN (Shallow Water Acoustic communication Network, 2006), ROBLINKS (Long Range Shallow Water Robust Acoustic Communication Links, 2004, Depth: 30m, Communication distance: 10km, Rate: 1kbit/s). The most famous is ACME (Acoustic Communication network for Monitoring of underwater Environment in coastal areas, 2004). There are 4 nods in the network and it can work 10m in depth underwater at the rate of 1kbit/s.

For the previous research, we have developed the first-generation Spherical Underwater Robot (SUR-I) which is actuated by three vectored water-jet thrusters for its propulsion system [10]-[15]. The processor element of the SUR-I is ARM module whose MPU was an ARM7TDMI core with a maximum 75 MHz of clock frequency. This PC control board had 32 MB of extended synchronous digital random-access memory (SDRAM) and 64 MB of NAND flash memory. For the more complex task, and the stronger handling capacity needed with the equipped various sensor subsystem, the second-generation Spherical Underwater Robot (SUR-II) is manufactured to be fit for this situation [16]-[21]. The TMS320f28335 processor is adopted as the main processor unit to replace the ARM for the processing capacity improvement. However, the SUR-II has the problem of the high energy consumption. Based on these reasons, the third-generation Spherical Underwater Robot (SUR-III) is developed. Fig.1 shows the prototype of the novel spherical underwater robot (SUR-III). The new structure of the robot takes four vectored water-jet thrusters as its propulsion system [22][23].



(a) Side view (b) Top view

Fig. 1. The prototype of the third-generation Spherical Underwater Robot

The organization of this paper is as follows. Related works is reviewed in section 1. Section 2 analyzes the underwater acoustic channel, which is a very important influencing factor in communication system. Section 3 describes the detailed design of the acoustic communication system based on CDMA and FHMA for multiple underwater vehicles. The development of an acoustic communication system for multiuser based on hardware platform is reported in section 4. Section 5 provides concluding remarks.

II. Analysis of Underwater Acoustic Channel

Channel is a very important component in communication system because its characteristics have great influence on the effect of communication. Therefore, underwater acoustic channel is analyzed at first, and a typical model of underwater acoustic channel used in this paper is given.

A. Characteristics of Underwater Acoustic Channel

Sound propagation underwater is primarily determined by noise, transmission loss, reverberation, and temporal and spatial variability of the underwater acoustic channel. Transmission loss and noise are the principal factors that determine the available frequency bandwidth, communication range and signal-to-noise ratio. Time-varying multipath affects the design and the processing of the signal, which usually imposes severe limitation on the performance of the system. Some major factors affecting communication in underwater acoustic channel are shown in Fig.2 [24].

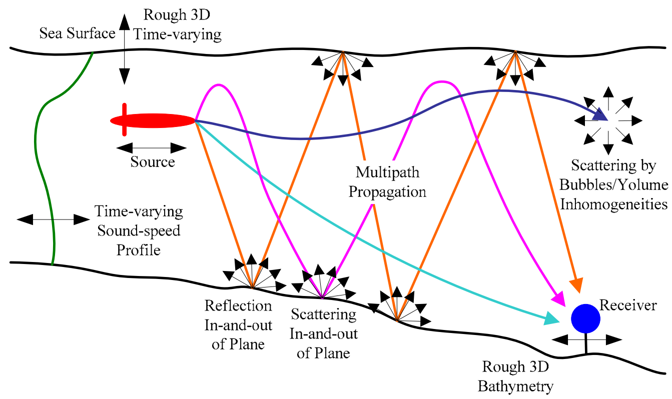


Fig.2 Some major factors affecting communication in underwater acoustic channel

Underwater acoustic channel is the most complex communication channel that we have known about. It brings many difficulties to underwater communication. Some main characteristics of underwater acoustic channel include limitation of frequency bandwidth, varying multipath, fast fading and high noise. The absorption and the diffusion of acoustic energy relate to transmission distance and frequency. That is to say transmission loss increases as transmission distance and frequency increase. This characteristic results in great attenuation of high frequency signal in long distance transmission. There are many noise sources in the ocean. Some typical noise sources are listed as the frequency rises: The effect of hydrostatic pressure caused by tide and wave; disturbance of earthquake; onflow; sailing ship; surface wave; thermal noise. For the frequency in the magnitude of ten kilohertz, a main noise source is surface wave. The high noise will cause the original signal difficult to recover.

Since the reflection of the surface and the floor of ocean as well as the existent of reflectors and scatter caused by the organisms, acoustic wave will reach the receiving part along several different paths after it is sent. This phenomenon is called multipath transmission. It’s a most important factor that affects the performance of underwater acoustic communication. Multipath transmission results in signal distortion (fast fading) and selective fading. The amplitude and the phase of the signal will change along with time and frequency which brings on errors in the receiving part. In order to solve the problem, equalization technique, diversity technique, spread spectrum technique and antenna array technique can be adopted.

B. Underwater Acoustic Channel Model

The underwater attenuation $A(l,f)$ can be expressed as:

$$A(l,f)=(\frac{l}{l_{ref}})^{\alpha}a(f)^{l} \quad (1)$$

where l is the distance between the transmitter and receiver; l_{ref} is a reference distance (typically 1 m); α is counterpart of the path loss coefficient in terrestrial radio, and it is used to model the propagation geometry. A practical value α=1.5 is usually adopted.

The factor $a(f)$ in equation (1) is the absorption loss that depends on the frequency *f*: it indicates the conversion between acoustic pressure and heat, and can be approximated by Thorp's formula. This dependence limits the available frequency bandwidth severely despite it is limited by the bandwidth of the transducer in practice. Within the limited frequency bandwidth, the signal is subject to multipath propagation, which is particularly obvious on horizontal channel. In shallow water, multipath occurs because of signal reflection from the surface and the bottom. In deep water, it occurs because of ray bending. The channel response varies in time, and also changes if the transmitter or the receiver moves.

Because underwater acoustic channel is very complex, it can't be represented by a precise simulation model. Generally speaking, underwater acoustic channel is a kind of slow time-varying coherent multipath channel. In the length of coherent time, it can be simplified as a coherent multipath channel, which only has multipath effect. In this paper, a typical model of acoustic ray is adopted to implement the simulation. The model is expressed as Fig.3.

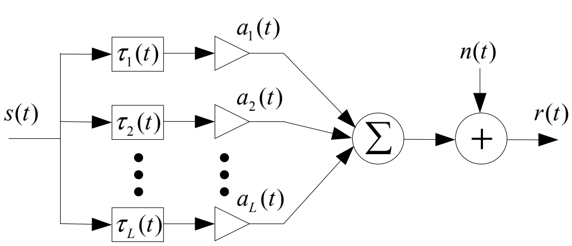


Fig.3 The model of time-varying multipath channel with additive white noise

When the input signal is $s(t)$, the output signal is:

$$r(t)=\sum_{k=1}^{L}a_k(t)s(t-\tau_k(t))+n(t) \quad (2)$$

where L is the number of multipath; $a_k(t)$ is the time-varying attenuation factor in the k_{th} transmission path; $\tau_k(t)$ is the delay; $n(t)$ is additive white noise. The typical model of underwater acoustic channel is given to implement the simulation.

III. ACOUSTIC COMMUNICATION SYSTEM

In order to implement communication simultaneously between multiple underwater vehicles in deep water, this section will propose an underwater acoustic communication system with two methods. The one is based on QPSK-CDMA with synchronization for multiple underwater vehicles; the other one is based on FHMA combined with tamed spread spectrum for multiple underwater robots.

A. QPSK-CDMA System

In the DS-CDMA system, original signal is linearly modulated using wideband PN code. It is convenient for spreading the frequency spectrum and is widely used in the communication field at present. If QPSK is adopted as the modulation method, it is called QPSK-CDMA.

QPSK is a phase modulation algorithm. In QPSK, the PN spread spectrum modulation technique in which two independent PN generators are used to produce two chipping streams which when multiplied by cos*2pfst* and sin*2pfst* functions are added to form the signal. QPSK uses four points on the constellation diagram, equispaced around a circle. The "Quad" in QPSK refers to four phases in which a carrier is sent in QPSK: 45, 135, 225, and 315 degrees, which is shown in Fig.4. With four phases, QPSK can encode two bits per symbol to minimize the BER-sometimes misperceived as twice the BER of BPSK.

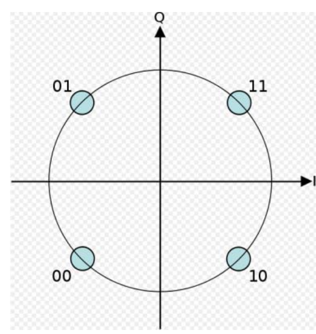


Fig.4 Constellation diagram for QPSK

The mathematical analysis shows that QPSK can be used either to double the data rate compared with a BPSK system while maintaining the same bandwidth of the signal, or to maintain the data rate of BPSK but halving the bandwidth needed. In this latter case, the BER of QPSK is exactly the same as the BER of BPSK-and deciding differently is a common confusion when considering or describing QPSK. Fig.5 shows the block diagram of QPSK-CDMA modulation. In this system, we define: $c_{In}^{(i)}$- PN code, inphase component; $c_{Qn}^{(i)}$ -PN code, orthogonal component. The transmission waveform of the i_{th} user in the system is

$$s_0^{(i)}(t)=A_0^{(i)}\cos(2\pi f_c t)\times\sum_n d_n^{(i)}c_{In}^{(i)}p_1(t-nT_c)$$
$$+A_0^{(i)}\sin(2\pi f_c t)\times\sum_n d_n^{(i)}c_{Qn}^{(i)}p_1(t-nT_c) \quad (3)$$

The signal received from User *i* is

$$s^{(i)}(t)=A^{(i)}\cos(2\pi f_c t+\varphi_i)\sum_n d_n^{(i)}c_{In}^{(i)}p_1(t-nT_c-\tau_i)$$

$$+A^{(i)}\sin(2\pi f_c t+\varphi_i)\sum_n d_n^{(i)} c_{Qn}^{(i)} p_1(t-nT_c-\tau_i) \tag{4}$$

The power of the received signal is $P^{(i)}=[A^{(i)}]^2$.

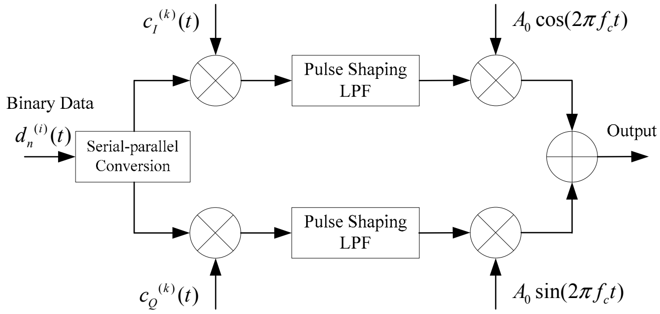


Fig.5 The block diagram of QPSK-CDMA modulation

The k_{th} CDMA receiver is operated as follows according to Fig.6:

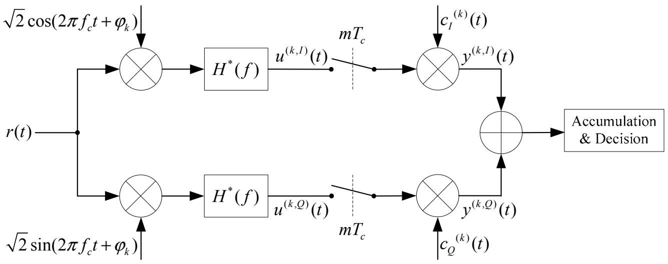


Fig.6 The process of QPSK-CDMA receiver

The input waveform is multiplied by the channel I coherent carrier $\cos(2\pi f_c t+\varphi_k)$ and the channel Q coherent carrier $\sin(2\pi f_c t+\varphi_k)$ of the k_{th} signal. The product of the two channels is low pass filtered, and matched filter is used for the pulse with shape specific. Sample the output of the low pass filters to recover the chips of channel I and channel Q. The chips are multiplied by the local synchronization PN code $c_{In}^{(i)}$ and $c_{Qn}^{(i)}$, the results are added to recovery the baseband data. The output of the channel I low pass filter in the k_{th} QPSK-CDMA receiver is

$$\begin{aligned} u^{(k,I)}(t) &\approx [r(t)\cdot\cos(2\pi f_c t+\varphi_k)]_{LP} \\ &= \frac{1}{2}A^{(k)}\sum_n d_n^{(k)} c_{In}^{(k)} p_2(t-nT_c)+\frac{1}{2}\sum_{i\neq k}A^{(i)}\sum_n d_n^{(k)}[c_{In}^{(i)}\cos(\varphi_i-\varphi_k) \\ &\quad +c_{Qn}^{(i)}\sin(\varphi_i-\varphi_k)]p_2(t-nT_c-\tau_{ik})+\frac{1}{\sqrt{2}}n_{LP}^{(i)}(t) \end{aligned} \tag{5}$$

where $p_2(t)$ is the output waveform after matched filtering of $p_1(t)$.The output of the channel Q low pass filter in the k_{th} QPSK-CDMA receiver is

$$\begin{aligned} u^{(k,Q)}(t) &\approx [r(t)\cdot\sin(2\pi f_c t+\varphi_k)]_{LP} \\ &= \frac{1}{2}A^{(k)}\sum_n d_n^{(k)} c_{Qn}^{(k)} p_2(t-nT_c)+\frac{1}{2}\sum_{i\neq k}A^{(i)}\sum_n d_n^{(i)}[c_{Qn}^{(i)}\cos(\varphi_i-\varphi_k) \\ &\quad -c_{In}^{(t)}\sin(\varphi_i-\varphi_k)]p_2(t-nT_c-\tau_{ik})+\frac{1}{\sqrt{2}}n_{LP}^{(Q)}(t) \end{aligned} \tag{6}$$

The output of the k_{th} QPSK CMMA receiver is the sampling result to the chips recovered by low pass filter, multiply the local synchronization PN code of the k_{th} channel I and channel Q separately and add them together:

$$y^{(k)}(mT_c)=u^{(k,I)}(mT_c)c_{Im}^{(k)}+u^{(k,Q)}(mT_c)c_{Qm}^{(k)}=u_m^{(k,I)}c_{Im}^{(k)}+u_m^{(k,Q)}c_{Qm}^{(k)}=y_m^{(k)} \tag{7}$$

Define $P^{(i)}=[A^{(i)}]^2$, we can obtain the final output of the receiver as follows:

$$\begin{aligned} y_m^{(k)} &= \frac{1}{2}\sqrt{P^{(k)}}\sum_n d_n^{(k)}[c_{In}^{(k)}c_{Im}^{(k)}+c_{Qn}^{(k)}c_{Qm}^{(k)}]p_2(mT_c-nT_c) \\ &\quad +\frac{1}{2}\sum_{i\neq k}\sqrt{P^{(k)}}\sum_n d_n^{(i)}\{[c_{In}^{(i)}c_{Im}^{(k)}+c_{Qn}^{(i)}c_{Qm}^{(k)}]\cos(\varphi_i-\varphi_k) \\ &\quad +[c_{Qn}^{(i)}c_{Im}^{(k)}-c_{In}^{(i)}c_{Qm}^{(k)}]\sin(\varphi_i-\varphi_k)\}p_2(mT_c-nT_c-\tau_{ik}) \\ &\quad +\frac{1}{\sqrt{2}}n_{LP}^{(I)}(mT_c)c_{Im}^{(k)}+\frac{1}{\sqrt{2}}n_{LP}^{(Q)}(mT_c)c_{Qm}^{(k)} \end{aligned} \tag{8}$$

B. FHMA System

Multiple accesses based on spread spectrum technique are necessary to implement communication between multi-user. However, the limitation of frequency bandwidth in underwater acoustic channel results in low rate of original data. In order to deal with the contradiction between the high data rate and the limitation of frequency bandwidth in underwater acoustic channel, another method is adopted for the underwater acoustic communication system, which is based on FHMA combined with tamed spread spectrum for multiple underwater robots.

Controlled by the PN code, the carrier frequency of FH system hops continually and randomly. Compared with DSSS, it has the characteristics of high utilization of the frequency band and solves the problem of near-far effect. They are very important in underwater acoustic communication system, especially in the condition of multiuser. Fig.7 shows the framework of frequency hopping communication system. In the transmitting part, the original signal modulates the carrier produced by the frequency synthesizer, which is controlled by the PN code. After one frequency hopping to another, it is very difficult to keep phase coherence. Therefore, FSK and ASK that can implement non-coherent detection are adopted as modulation method.

In the receiving part, the signal after processed by the amplifier will be sent into the mixer. In order to achieve despread spectrum of FH, the outputs of the frequency synthesizer should be identical with that in the transmitting part. That is to say, the synchronization of the PN codes in the two parts is necessary. Through mixing, the frequency of the signal will be fixed, which can be demodulated, and the signal is recovered finally. For the undesired signal, it doesn't know the hopping regularity, so the frequency is not correlated with the outputs of the frequency synthesizer in the receiving part. Thus, it can hardly bring on interference to the FH system.

Based on FH, we adopt FHMA to implement underwater acoustic communication simultaneously between multi-users.

In the FHMA system, the bandwidth is divided into several channels. The carrier frequency will continually hop along with the time instead of fixed to one channel. The hopping regularity is decided by the PN code of each user. The random hopping of the carrier frequency of each user results in the possibility of multiple accesses in a large frequency extent. In the receiving part, the same as FH, the PN code of each user should keep synchronous with that in the transmitting part. The key point in FHMA system is that the PN code of each user should be mutually orthogonal so as not to affect each other.

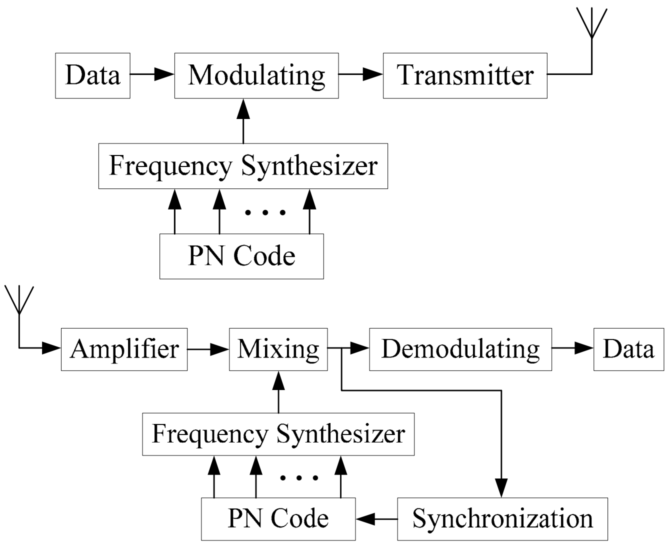


Fig.7 The framework of frequency hopping communication system

The data rate in the system was 650b/s, which fulfilled the requirement of the voice data transmission and the BER was 8.56×10^{-4} when the SNR was -14dB, which indicated that the transmission rate was raised and the communication reliability still kept good.

IV. Development of an Acoustic Communication System Hardware Platform

In order to verify if the systems proposed in the foregoing part are applicable in reality, this section proposed the development of a communication system of SUR-III for multiuser based on hardware platform. Micron Data Modem is employed as the communication module in the hardware platform of communication system.

A. Communication module-Micron Data Modem

The Tritech International Ltd Micron Data Modem provides a means of transferring data acoustically through water. Operation is point to point, between a pair of Micron Data Modems, at operational distances of up to 500m horizontally and 150m vertically at a data rate of 40 bits per second. Devices are addressed through a serial electrical interface, which may be controlled directly from a control board with a simple teletype (half-duplex) terminal program. The product of Tritech is illustrated in Fig.8.

Fig.8 Micron Data Modem for communication

The Micron Data Modem is integrated into the communication hardware platform as the communication module. The control system of the SUR-III is illustrated in Fig.9.

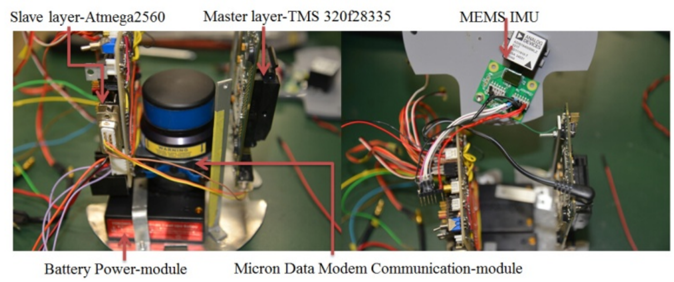
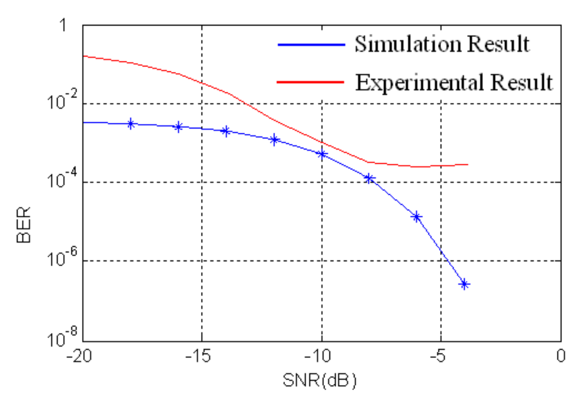


Fig.9 Prototype of the control system circuitry

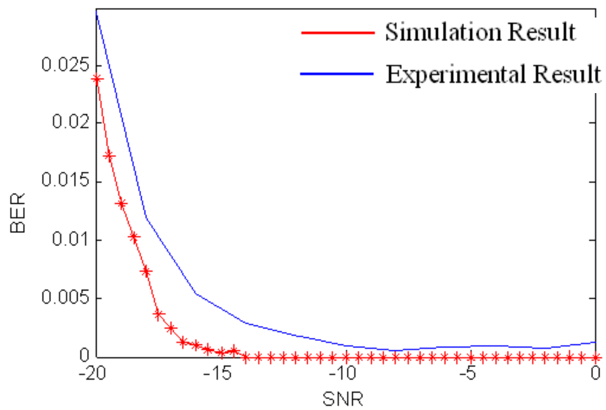
B. Experimental Results

The difficulties in underwater acoustic communication experiments lie on the ocean environment. For example, if we want to do the experiments in the depth of hundreds of meters or more in the ocean, underwater vehicles are needed to carry the equipments, which makes the expense rather large and the condition rather rigorous. Therefore, in this part, we will propose a scheme to implement the experiments in the laboratory for convenient.

Fig.10 shows the relationship between BER and SNR in the CDMA system and the FHMA system. The minimum value of BER in the CDMA system is 4.68×10^{-4} and the minimum value of BER in the FHMA system is 6.73×10^{-4}. It is obvious that the BERs in this hardware platform system are not as good as that in the simulation systems. Taking the experiment condition and the transmission rate into account, it is acceptable.



(a) In the CDMA system



(b) In the FHMA system

Fig.10 The relationship between BER and SNR

V. CONCLUSIONS

Two kinds of underwater acoustic communication systems for the SUR-III are proposed. One is based on CDMA which is designed to implement communication simultaneously between multiple underwater vehicles in deep water. Some key techniques such as spread spectrum and channel coding are adopted in order to ensure the communication reliability. The other is based on FHMA combined with tamed spread spectrum for multiple underwater vehicles which is designed to solve the contradiction between the high data rate and the limitation of frequency bandwidth in underwater acoustic channel. The results of the experiment proof that the transmission rate is raised and the communication reliability still keeps good. And the communication system developed can meet the quality we required. It is the feasible and stabile communication system which we can integrate into our SUR-III.

ACKNOWLEDGMENT

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