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Design and Implementation of Sensor Nodes Based on OFDM for Underwater Sensor Networks

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Abstract. Sensor node is a basic unit for the underwater sensor networks. Each sensor node has the following main functions, i.e., information acquisition, data processing, underwater acoustic communication, self-organizing network, etc. The sensor nodes are randomly deployed in the detection area for achieving omni bearing underwater information acquisition. However, the cost and the power consumption for the existing underwater sensor nodes are high. For solving these disadvantages, we design a kind of underwater sensor node that can be applied for the underwater communication channel with low cost and power consumption by fusing the Orthogonal Frequency Division Multiplexing (OFDM) technique and the Digital Signal Processing (DSP) technique.

Keywords: digital signal processing (DSP), orthogonal frequency division multiplexing (OFDM), sensor Nodes, underwater sensor networks

1 Introduction

71% of the earth is covered by ocean. The ocean has a great development potential owing to the expansive regional space and the abundant natural resources contained by it [1]. Underwater acoustic sensor networks have obtained a considerable attention to support aquatic applications, such as intrusion detection, military applications, pollution monitoring, marine animal protection, etc. [2-3]. The underwater sensor nodes are the important compositions for the underwater sensor network, which have a great effect on the researches of underwater sensor networks [4-9]. Underwater sensor node is a basic unit that possesses the functions, such as information acquisition, data processing, underwater communication and self-organizing network. The design and protocol optimization for the underwater sensor nodes are the important foundation for the development of the hardware experimental platform and the researches of the underwater sensor networks [10].

Three kinds of methods are usually utilized for the communication among the underwater sensor nodes, which are underwater electromagnetic wave, underwater optical communication and underwater acoustic communication [11]. Underwater electromagnetic wave and underwater optical communication cannot be utilized for the large-scale commercial stage owing to their insurmountable technical reasons. Recently, underwater acoustic communication technique is generally utilized for the data transmission among the underwater sensor nodes. Underwater acoustic channel is a communication channel with complicated frequency-dependent characteristic, time-dependent characteristic and space-dependent characteristic. The characteristics of the underwater acoustic communication severely impact the reliability and the stability of the underwater sensor nodes [12]. Orthogonal Frequency Division Multiplexing (OFDM) technique can solve the problem above owing to its advantages, such as anti-multipath effect, high frequency utilization rate and high transmission rate. OFDM technique is very suitable for the high-speed data transmission in the underwater acoustic channel with multipath propagation and Doppler frequency shift [13]. However, there exists some drawbacks in the existing underwater sensor nodes based on the OFDM technique, such as high cost and power consumption. For solving the drawbacks of the existing underwater sensor nodes, we design a new kind of underwater sensor network nodes that can be applied for the underwater acoustic channel while the cost and power consumption is low. Besides, the signal proceeding rate is high. The contributions of this paper can be summarized as follows.

(1)A hardware design scheme for the underwater sensor network node is proposed.

(2)A software design scheme for the implementation of the underwater sensor network node on the Digital Signal Processing (DSP) platform is presented.

(3)The performance of the designed underwater sensor networks node is tested by the experiments, from which the effectiveness of the designed underwater sensor networks node is verified. Besides, its superiority in terms of the bit error rate and the power consumption is shown.

The remainder of the paper is structured as follows: section 2 introduces the system model; section 3 describes the hardware design scheme for the underwater sensor nodes; section 4 presents the software design scheme on the DSP platform; section 5 tests the performance of the designed underwater sensor node; and section 6 concludes this paper.

2 System Model

Compared with the traditional Wireless Sensor Networks (WSNs), the underwater WSNs using underwater acoustic channel for communication have the following features: larger propagation delay, narrow frequency band, limited energy, multipath effect, Doppler effect and worse network connectivity. Underwater acoustic channel is a complicated communication channel owing to its features listed above. OFDM technique is suitable for the high-speed data transmission on the underwater acoustic channel. OFDM is a multi-carrier modulation technique. The main idea of OFDM technique can be summarized as follows. First, the serial data flows with high speed are transformed to parallel data flows. Then, the transformed parallel data flows are modulated and added to N orthogonal sub-channels with low speed. Finally, the parallel data flows are transmitted simultaneously. The data can be transmitted through multiple channels simultaneously by OFDM technique [14]. We first determine the structure of the data frame before confirming the detailed parameters for the OFDM communication. The frame consists of synchronal symbol and communication symbol. There are 5 communication symbols in one frame in our design, the structure of the data frame is shown in Fig. 1.

Synchronous Symbol	OFDM Symbol 1	OFDM Symbol 2	OFDM Symbol 3	OFDM Symbol 4	OFDM Symbol 5

Fig. 1. The structure of the data frame

The parameters, including guard interval, the number of subcarrier etc., also needs to be determined for the OFDM communication system. The parameters need to be decided according to the bandwidth, the multipath delay expansion and the required information transmission speed. The parameters of the OFDM are determined by the following steps: (1) determine the length of the cyclic prefix; (2) determine the length of symbol period; (3) determine the number of the subcarriers. The primary parameters utilized for the OFDM communication in our design are shown in Table 1.

Table 1. The primary parameters for the OFDM communication

Guard interval	128 (1.333ms)
Symbol length	1024 (10.666ms)
Sample frequency	96KHz
Bandwidth	24KHz-32KHz
The number of subcarriers	86
FFT/IFFT length	1024 (10.666ms)
The length of the synchronous symbol	10.666ms
Modulation	QPSK
Theoretical communication rate	2.539 Kbit/s

3 Hardware Design Scheme

The structure of the hardware design scheme for the underwater sensor node is shown in Fig. 2. The hardware system consists of Digital Signal Processing (DSP), audio converter, band-pass filter, signal amplifier, underwater acoustic transducer, power management circuit, lithium battery and so on. DSP is the processing corn of the hardware system. It controls the whole system, and processes the related algorithm of the OFDM communication. The underwater acoustic transducer is used for the transition between the acoustical signals and the electrical signals. The analog signals received by the underwater acoustic transducer need to be transformed to the analog signals with low noise and high amplitude by the band-pass filter and the signal amplifier in turn. Then, the transformed analog signals with low noise and high amplitude are converted to the digital signals by the A/D converter. On the other hand, the digital signals that need to be transmitted are firstly converted to the analog signals by the D/A convertor. Then, the converted analog signals are transmitted to the underwater acoustic transducer after being transformed by the power amplifier and the impedance matching circuit. The underwater sensor node can be acted as both a transmitter and a receiver. Hence, a transceiver needs to be deployed between the underwater acoustic transducer and the signal processing circuit. Lithium-ion battery pack is used for supplying electricity for our designed underwater sensor model, by which the power consumption can be reduced.

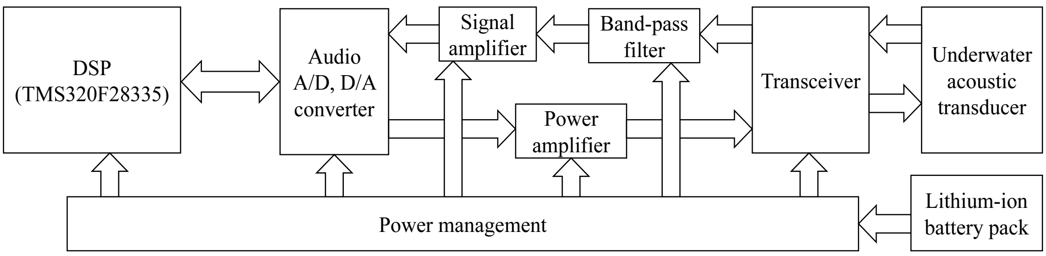

Fig. 2. The structure of the hardware design scheme for the underwater sensor node

For reducing the cost of the hardware for the underwater sensor node, the core control panel and the signal processing panel are separate in our design. The core control panel utilized in our design is TMS320F28335, which is a 4 layers panel. TM320F28335 is connected with the signal processing panel by the plug-in. The DSP core control panel consists of reset circuit, clock circuit, Joint Test Action Group (JTAG), electrical circuit, SARAM and ROM circuit. The MAX811S chip is utilized as the reset circuit. The crystal oscillator circuit supplied by the DSP is utilized as the clock circuit. Besides, a 30MHz crystal oscillator needs to be connected between the X1 pin and X2 pin of the DSP. The TPS73HD301 chip is utilized as the electrical circuit.

The TLV320AIC23B with low power consumption produced by TI company is utilized as the CODEC of the A/D and D/A converter. For the communication between TLV320AIC23B and DSP, the I2C communication protocol is utilized for the software control while the McBSP protocol is utilized for the digital audio data. The reason of choosing McBSP protocol is that the communication between the McBSP and the CUP, Direct Memory Access (DMA) is achieved by the peripheral bus in the DSP chip TMS320F28335. Besides, the received data by the McBSP interface can be directly enter the DMS controller, by which the resources of the CPU can be saved. The TLV320AIC23B is compatible with the I2C pattern and SPI pattern when designing the chip interface. I2C communication interface is utilized in our design. Besides, the TPA3100D2 produced by the TI company is utilized as the power amplifier in our design.

The programmable-gain amplifier circuit is utilized for solving the fading problem of the underwater acoustic signal, by which the faded signal can be amplified. It consists of VCA810 variable gain amplifier circuit, OPA690 high speed buffer circuit and the DC bias control unit in our design. The DC bias control unit consists of D/A converter and inverter. TLV5620 is utilized as the D/A converter, and connected with DSP chip by I2C bus. The gain of the VCA810 can satisfy the requirements of our design. The added OPA690 buffer circuit is utilized to avoid the signal oscillation problem produced by the programmable-gain amplifier when setting large gain. Meanwhile, the OPA690 also can be used to adjust secondary gain factor. The gain coverage of the designed programmable-gain amplifier can achieve -38dB-42dB. The input signal ripple does not exceed 1dB. In addition, the fluctuation of the gain in the band-pass is very small. Hence, the designed programmable-gain amplifier circuit can satisfy the signal amplification requirement for our designed hardware system.

The underwater acoustic transducer may receive heavily out-band noises owing to the complex environment of the underwater. The out-band noises need to be filtered for accurately demodulating the communication signals. Hence, we deign the filter circuit based on the analog active filter LTC562IG. The interior structure of the filter circuit is shown in Fig. 3, which contains an integrator and an operational amplifier. The value of the interior resistance and the capacitance for the integrator and the operational amplifier are 7958Ω and 100pF, respectively. The values of the resistance for the R2 and the RQ need to be set according to the practical situation according to the center frequency, the quality factor and the transfer function of the filter. We use $f0$, Q, $G(S)$ to denote the center frequency, the quality factor and the transfer function of the filter, respectively. The computational equations $f0$, Q and $G(S)$ of the are shown as follows.

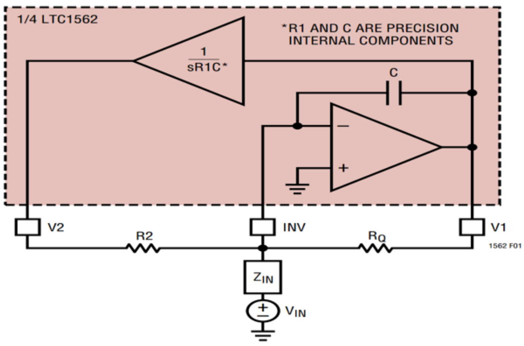

Fig. 3. The interior structure of the filter circuit

$$f0 = (200KHz)\left(\sqrt{\frac{7958}{R2}}\right). \quad \textbf{(1)}$$

$$Q = \frac{RQ}{R2\left(\frac{200KHz}{f0}\right)}. \quad \textbf{(2)}$$

$$G(S) = H_{BP} * \frac{s\left(\frac{w_0}{Q}\right)}{s^2 + s\left(\frac{w_0}{Q}\right) + w_0^2}. \quad \textbf{(3)}$$

where H_{BP} represents the DC gain of the filter circuit at the center frequency w_0, and $H_{BP} = R2/RIN$. From the equations above, we can see that the value of $f0$, Q and gain H are determined by the value of

$R2$ and RIN. The central frequency of the filter required in our designed system is 28KHz while the required -3dB bandwidth is 8KHz. Besides, the required cutoff frequency is 16KHz while the required out of band rejection is -21dB. Third-order filter can satisfy the above requirements. The value of the resistance and the capacitance related to the filter circuit can be obtained by the equations 1-3 according to the $f0$, Q and gain H. The schematic diagram of our designed filter circuit is shown in Fig. 4.

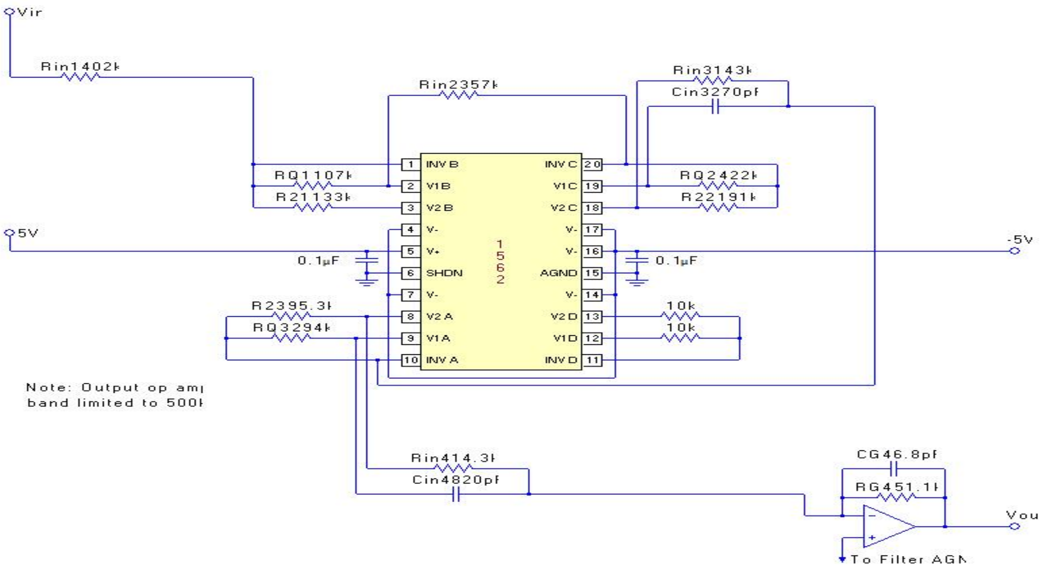

Fig. 4. The filter circuit

The DYW-28-G is utilized as the underwater acoustic transducer for the transition between acoustical signal and electrical signal in our designed hardware system. The performance of the DYW-28-G is tested by the experiments. The experiments contain amplitude-frequency characteristics, receiver sensitivity, etc. From the results of the experiment for the amplitude-frequency characteristics, we can see that the underwater acoustic transducer has better response to the out-of-band signals which are the interfering signals for the communication signal. Hence, the filter circuit is necessary. From the results of the experiment for the receiver sensitivity, we can see that the underwater channel is a fading channel with a larger multipath delay for the single band signals. Besides, the multipath delay increases with the increase of the experimental distance. The length of the multipath delay is influenced by many factors. Some of the key parameters for the OFDM communication given in the section 2 are obtained by these experiments.

4 Software Design Scheme

In this section, we introduce the software design scheme based on the hardware design scheme presented before for the underwater sensor node. The development environment is Code Composer Studio (CCS) 3.3. The flowchart of the software design scheme is shown in Fig. 5. At the beginning of the program, initialize the DSP, including the initialization of the system clock, PLL configuration, I/O ports, SCI UART, memory and so on. Then, initialize the AIC23, transceiver, programmable-gain amplifier circuit, etc. The initialization of the AIC23 includes sampling frequency, filter enable, gain and so on. Finally, configure the DMA controller and interrupt module. DSP determines whether to read the data or not by the interrupt module after the DMA controller is filled with the data transformed from the AIC23, by which the communication data can be transmitted and conducted in time. The software design works of the slave computer can be summarized as follows. 1) The implantation of the OFDM communication algorithm on the DSP, and the optimization of the programming. 2) The implantation of the data acquisition and the ping-ponging buffer. 3) The implantation of the UMMAC protocol and the channel allocation.

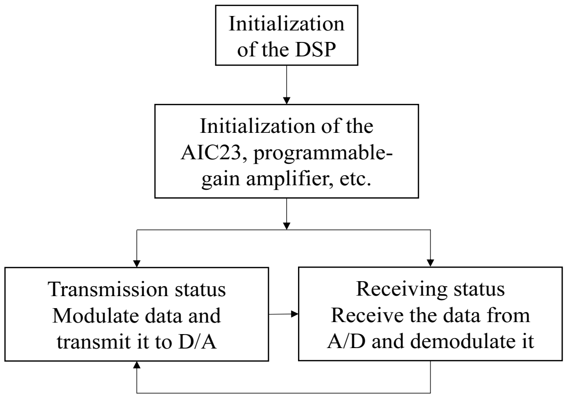

Fig. 5. The flowchart of the software design scheme

Fig. 6 shows the detailed process of the OFDM communication based on the DSP, which consists of the OFDM transmission process and the OFDM receiving process. The OFDM transmission process can be summarized as follows. The binary sequence to be transmitted is firstly divided into groups and frames. Then the QPSK symbol mapping is conducted. Symbol mapping means that each phase angle is mapped to the real part and imaginary part of the coding sequence, i.e. $X[n] = X_R[n] + jX_i[n]$, expressed by the normalized value. Then, adding zero at the forward and the backward of the mapped signals, and then Inverse Fast Fourier Transformation (IFFT) is conducted for extracting the real part $X_R[n]$ of the signal. Then, extracting the back 128 arrays as the cyclic prefix, and put them in the forward of the $X_R[n]$. Repeat the above process for obtaining the data that contains five symbols. Finally, add the synchronous signal at the front of the data. Hence, one data frame is generated. The communication signals are transmitted to the underwater acoustic channel after conducting by the A/D converter with oversampled. The oversampled can make the waves of the output analog signals smoother. The OFDM receiving process can be summarized as follows. First, find the starting point of the signal by the windowing power detector for the received signal. Then, the complete frame data is obtained after conducting the frame synchronization. Then, delete the cyclic prefix in the guard interval, and conduct the Fast Fourier Transformation (FFT). The frequency and phase of the signals are calculated after the FFT. Then, the phases and the binary sequences are obtained by de-mapping and decoding in turn. Finally, combine the data of the five symbols to obtain the complete data.

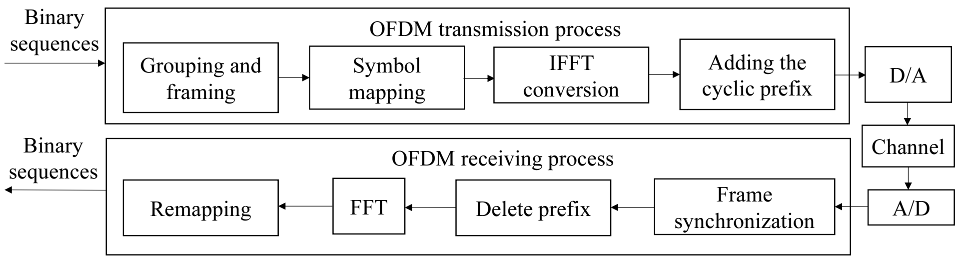

Fig. 6. The data process of the OFDM communication based on the DSP

First, we use C programming language to implement the requirements for the software design scheme. After achieving the functions, we optimize the programming by invoking the assembler language runtime library provided by the TI company. Table 2 shows the testing results of the time consumption for the key algorithm. From Table 2, we can see that the time consumption can be reduced by the assembler language.

In our designed system, DSP controller need to receive the data transmitted from the A/D converter incessantly when the underwater sensor node is in the receiving pattern. Meanwhile, the OFDM demodulation algorithm also needs to be conducted by the DSP controller. Hence, it is necessary to select an appropriate cache method for the DSP controller. The synchronous cache is utilized in our software design scheme. The ping-ponging structure is usually utilized to store data by the synchronous cache. In our design, we design DMA controller based on the source function library DSP2833x_DSM.c produced by TI. Table 3 shows the configured functions for the DMA controller.

Table 2. The testing results of the time consumption for the key algorithm

FFT		256 data	512 data	1024 data
C programming language	Clock period	341819	731468	1564048
	Time/ms	2.28	4.87	10.43
Assembly language	Clock period	16866	35145	73331
	Time/ms	0.11	0.23	0.49

Table 3. The configured functions for the DMA controller

```
void DMACHxAddrConfig (volatile Uint16 *DMA_Dest,volatile Uint16 *DMA_Source)
// Configure the destination address and source address of the data for the DMA controller
void DMACHxBurstConfig (Uint16 bsize,int16 srcbstep,int16 desbstep)
// Set the length of the frame and the source address offset in the frame.
void DMACHxWrapConfig (Uint16 srcbwsize,int16 srcwstep,Uint16 deswsize,int16 deswstep)
// Configure the total quantity of the source address offset and the destination address offset, reloaded source address and destination address.
DMACH1ModeConfig (DMA_SEQ1INT,PERINT_ENABLE,ONESHOT_DISABLE,CONT_DISABLE,
SYNC_DISABLE,SYNC_SRC,OVRFLOW_DISABLE,SIXTEEN_BIT,CHINT_END,CHINT_ENABLE);
// Configure trigger, trigger enable, ONESHOT enable, continuous model enable, peripheral synchronous enable, synchronization object selection, INTO enable, working mode selection, interrupt mode selection, interrupt enable.
```

The reloaded address will be set as the source address when the source address offset exceeds the configured total quantity of the offset. After correctly configuring the above functions, we only need to change the original address according to a certain order in the DMA interrupt. The key parameters for the ping-ponging cache are shown in Table 4. The cache addresses are corresponding to the PINGBuffer and PONGBuffer, respectively. When the buffer of the PING is full, the address of the destination will be point to the PONGBuffer, and change the flags. When the buffer of the PONG is full, the address of the destination will be point to PINGBuffer, and change the flags.

For verifying that the data can be correctly transmitted by the ping-ponging cache, we store the data in the ping-ponging cache in the interrupt. The sorted data is drawn by the drawing instrument and shown in Fig. 7. From Fig. 7, we can see that the designed ping-ponging cache can accomplish a series of data buffer, which verifies the correctness of the designed program for the ping-ponging cache.

Table 4. The key parameters for the ping-ponging cache

```
if (Buffer == PING){
        DmaRegs.CH1.DST_BEG_ADDR_SHADOW = (Uint32)&PONGBuffer[0];
        DmaRegs.CH1.DST_ADDR_SHADOW = (Uint32)&PONGBuffer[0];
        Buffer = PONG;/*handle the data of PING*/}
else{
        DmaRegs.CH1.DST_BEG_ADDR_SHADOW = (Uint32)&PINGBuffer[0];
        DmaRegs.CH1.DST_ADDR_SHADOW = (Uint32)&PINGBuffer[0];
        Buffer = PING;
        FirstTime = 0;/*handle the data of PONG*/
  }
```

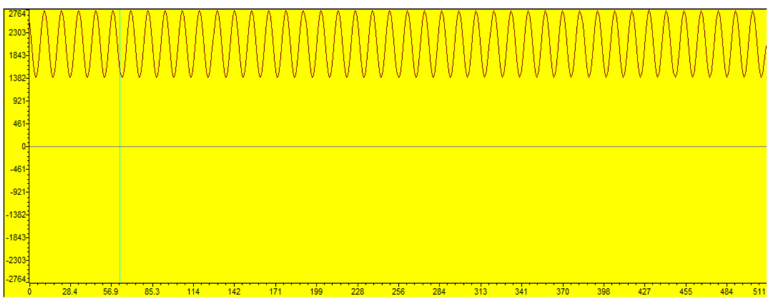

Fig. 7. The data for the ping-ponging cache

MAC protocols are used to allocate channels for the network nodes in the underwater sensor networks. Underwater Multi-channel MAC Protocol (UMMAC) protocol [15] which can be applied for the underwater communication network with long latency is utilized in our design. UMMAC protocol is a multi-channel MAC protocol based on the single transceiver. The communication handshaking process is divided into two phases by the UMMAC protocol. The first phase is the channel appointment and negotiation while the second phase is the data transmission. In the first phase, the transmitter and the receiver need to wait the prescribed time, and then send the appointment application on the pre-determined control channel for the channel negotiation. In the second phase, the transmitter and the receiver switch to the negotiated data channel for data communication. Once the appointment is successful, multiple packets are allowed to be sent between them.

5 Experiment

The performance experiments for our designed underwater acoustic node are shown in this section. The experiment environment is a pool. The length, width and the depth of the pool equal to 10m, 5m and 8m, respectively. We experiment the communication performance and the power consumption of the designed underwater acoustic node. The distance between the transmission node and the receiving node varies from 1m to 4m. The transmission node and the receiving node are put into a horizontal place where the depth of water is 0.4m.

The results of the experiment for the communication performance are shown in the Table 5. From Table 5, we can see that the average Bit Error Rate (BER) is 1.153% when the communication distance is 1m while it is 1.898% when the communication distance is 2m. The BER becomes high when the communication distance reaches 3m. The reason is that the power of the transmitter for the signal transmission is limited while the performance of the receiver for signal processing is not so good. Furthermore, the BER increases with the decrease of the Signal-to-Noise Ratio (SNR).

Table 5. The results of the experiment for the communication performance

Communication distance (m)	Bit error rate (%)
1	1.153
2	1.898
3	4.711
4	5.652

In addition, the power consumption of the underwater acoustic node is also experimented. We experiment it under the transmission model and the receiving model, respectively. The lithium-ion battery whose voltage equals to 12.6V is utilized to supply electricity for our designed underwater acoustic node. The capacity of the lithium-ion battery is 6800mah while its quantity of electric charge is 85.68W. The underwater sensor node can work for 3 hours 48 minutes under the transmission model while it can work for 51 hours under the receiving model in theory. The quantity of electric charge of the underwater sensor nodes is considered exhausted when the output voltage of the lithium-ion battery lower than 11.1V. The experiment results for the power consumption under the transmission model and the receiving model are shown in Fig. 8 and Fig. 9, respectively.

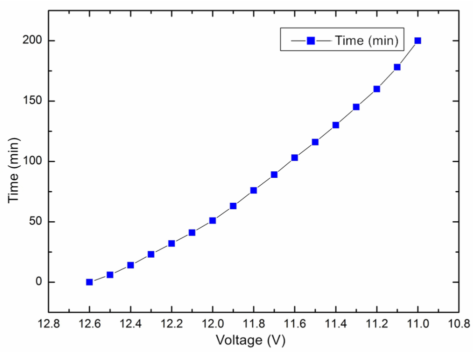

Fig. 8. Voltage vs. Time under the transmission model

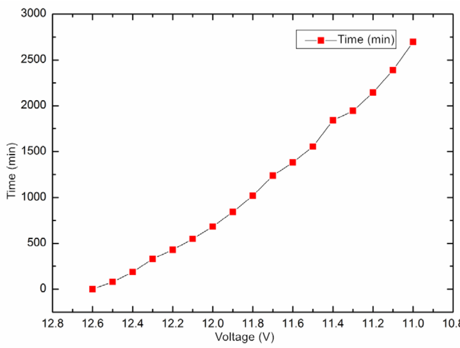

Fig. 9. Voltage vs. Time under the receiving model

From Fig. 8, we can see that the voltage of the battery reduced to 11.0V when the service hour is 202 minutes. Hence, the total service hours of the designed underwater sensor node are 3 hours 22 minutes under the transmission model, which is lower than the theoretical value. The reason is that there is still 10% of the state of charge for the battery while the voltage of the battery cannot satisfy the requirements of the underwater sensor node. Similarly, from Fig. 9, we can see that the total service hours of the designed underwater sensor node is 45 hours under the receiving model, which can accord with the theoretical analysis.

The comparison of the power consumption between our designed underwater sensor node and the land sensor node presented [16] is shown in Fig. 10. From Fig. 10, we can see that the power consumption of the underwater sensor node is much higher than that of land sensor node both under the transmission model and receiving model. Because the performance of the controller that the underwater sensor nodes utilize must be better than that used by the land sensor node owing to the complexity of the signal processing for the underwater communication. Hence, the power consumption of the controller for the underwater sensor node is higher.

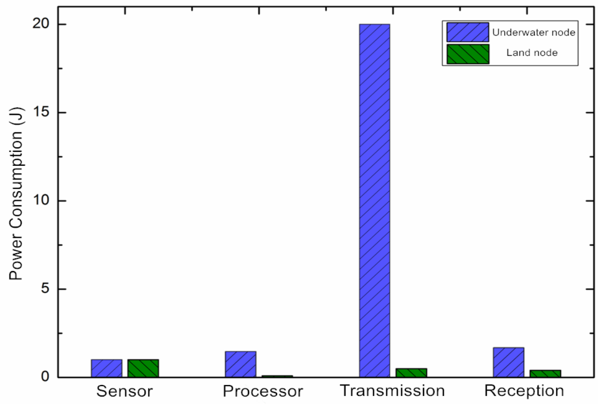

Fig. 10. Comparison of the power consumption between the underwater sensor node and the land sensor node

5 Conclusion

Many modulation modes cannot be well utilized in the underwater acoustic channel owing to the complicated features of the underwater acoustic communication. Orthogonal Frequency Division Multiplexing (OFDM) is adaptable for the underwater acoustic communication owing to its features, e.g., anti-multipath effect and high frequency utilization rate. Since the cost and the power consumption for the existing underwater sensor nodes based on the OFDM technique is high, we design a new kind of underwater sensor network nodes for reducing the cost and the power consumption in this paper. We designed the underwater sensor network node based on the OFDM and Digital Signal Processor (DSP). Moreover, we designed an underwater sensor network node model machine. Furthermore, the feasibility of the proposed model machine is verified by the experiments. The results of the experiments show that our proposed underwater sensor network node model machine can achieve high communication quality while the power consumption is low.

Acknowledgements

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