An Improved Demodulation Scheme for FH-MFSK Underwater Acoustic Communications

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***Abstract*—Underwater acoustic communications are required for controlling and networking a variety of underwater or sea surface objects. Due to the unique characteristics of the underwater acoustic channel, e.g., complicated multipath propagation, selective frequency fading, extreme Doppler effect and heavy ambient noise, FH-MFSK techniques play a vital role in robust underwater acoustic communication, especially in shallow water. However, based on detecting the frequency of the receiving signals, the demodulation scheme for FH-MFSK may be sensitive to the frequency shifting caused by underwater Doppler shifts. This paper focuses on how to design the frequency demodulation scheme and to improve the performance of underwater FH-MFSK acoustic communication system. By using an original Double-Line Interpolation algorithm with Hanning window, we propose a demodulation scheme to enhance the tolerance of the Doppler shift and improve the detection rate. Simulations and demodulation performance were tested. Experimental results show a promising future for FH-MFSK demodulation in underwater acoustic communication system.**

Keywords-underwater acoustic communication; interpolation algorithm; demodulation scheme; frequency hopping; FSK; FFT;

I. Introduction

Underwater acoustic communications are required for controlling and networking a variety of underwater or sea surface objects (e.g., AUVs, UUVs, submarines, underwater sensors and buoys, etc). Therefore, they are of growing research interests recently [1-3]. Though a number of new techniques have been presented, such as time reversal techniques [4], MIMO-OFDM [5], etc, FH-MFSK (Frequency-Hopping Multi-carrier Frequency Shift Keying) is still being considered as one of the most reliable modulation techniques in shallow water acoustic communications [2]. By using frequency-hopping techniques, FH-MFSK is able to overcome the inter symbol interference (ISI) caused by multipath spreads, especially in shallow water [3]. As a result, FH-MFSK is widely used in present commercial acoustic modems for its robustness. However, the demodulation for FSK system is usually based by detecting the frequency information of the signals. Thus, FH-MFSK may be very sensitive to the frequency shifting caused by underwater Doppler effect. In this paper, we propose an improved demodulation scheme for underwater FH-MFSK acoustic communications, which enhances the tolerance to unpredictable frequency shifting in shallow water.

Current underwater FH-MFSK demodulation schemes, based on FFT algorithm, are usually inevitable to the fence effect [6] and sensitive to the Doppler shift, because of the truncation and discreteness in signal collection. Nevertheless, the underwater acoustic channel, in which the sound speed is five orders of magnitude lower than the light speed, is more vulnerable to the uncertainty in the Doppler effect. In order to obtain higher performance in such severe circumstances, we investigate interpolation methods and propose a improved solution which used a Double-Line Interpolation (DLI) algorithm for underwater acoustic communication. We focus on designing the demodulation scheme for underwater FH-MFSK system. The proposed demodulation scheme uses an original double-line interpolation algorithm with Hanning window, and is able to improve the tolerance of the Doppler shift and the successful detection rate.

The rest of the paper is organized as follows. In Session II, the frequency resolution problem is reviewed and interpolation approach are introduced. Session III presents a double-line interpolation algorithm and a demodulation scheme for underwater FH-MFSK system. In Session IV, simulations are made and the performance of our demodulation scheme is assessed. Finally, the conclusion is drawn in Session V.

II. Frequency Resolution and Interpolation

Due to unique characteristics of the underwater acoustic channel, such as multipath propagation, selective frequency fading, Doppler spreads and heavy ambient noise, the available bandwidth of underwater acoustic systems is extremely limited. For example, the frequency bandwidth used in mid-distance underwater acoustic communications may range from 10 kHz to 15 kHz [3]. To apply FH-MFSK techniques with such a narrow frequency bandwidth, high frequency resolution should be achieved. In this session, we review the frequency resolution problem occurred in the FFT based demodulation, then interpolation approach is introduced to solve this problem.

A. Frequency Resolution

Generally, in an underwater communication system, digital single-frequency modulated signals are represented as

$$s(n) = A\cos(2\pi f_c nT + \theta_0)\ , \qquad (1)$$

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where f_c is the frequency of the carrier and T is the of sampling period, whose inverse is the sampling frequency

$$f_s = {}^{1}\!/_{T}\,. \tag{2}$$

Then, the Fourier transform is used to convert $s(n)$ from time domain to frequency domain through

$$S(n) = \frac{A\sin[\pi(n+f_cT)]}{2\sin[\pi(n-f_cT)/N]} \cdot e^{j[\theta_0 - \frac{N-1}{N}(n-f_cT)\pi]}, \tag{3}$$

where N is the length of FFT samples.

Here, frequency resolution problems may occur, known as the fence effect (Fig. 1) which is caused by the relationship of frequency resolution Δf, the sampling frequency f_s and the length of the FFT samples N, as expressed in(4). We found that frequency resolution was one major factor directly affecting the performance of FFT based demodulation systems, especially for narrow bandwidth and Doppler spreads effected underwater FH-MFSK communications.

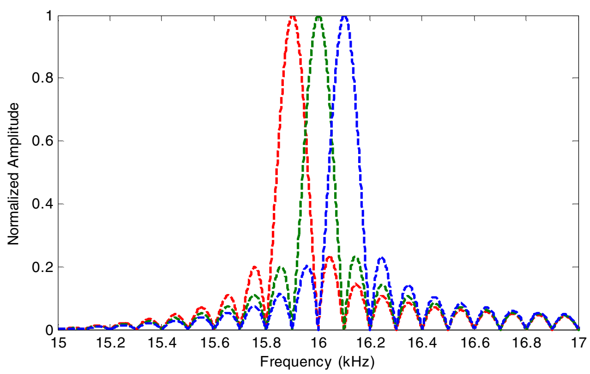

Figure 1. The fence effect and frequency resolution problem

$$\Delta f = {}^{f_s}\!/_{N} \tag{4}$$

Common approach to solve the problem are usually based on (4), by reducing the sampling rate f_s or increasing the number of samples N. A variety of methods for improving the frequency resolution of FFT has been proposed, such as prolonging the length of the signal, zero padding [6] and resampling techniques [7]. However, these methods are able to improve the resolution effectively, but extra computational complexity would also be added to demodulation systems, which will add the cost of the underwater acoustic devices.

B. Interpolation Approach

Literature [8] shows that interpolation can be investigated to estimate the frequency of real peak with other spectrum we have known in FFT results. For demodulation, the information we concerned most in the FFT results is the index (or position) of the peak. As a result, the interpolation enable to estimate the real peak of the FFT results. In other words, the interpolation is a good optional approach to indirectly improve the frequency resolution of demodulation systems.

Due to the fence effect, the index should be slightly offset to calculate the real peak frequency. The optimized peak frequency is expressed by

$$f_o = \left(i \pm |\delta|\right)\Delta f\,, \tag{5}$$

where i is the index of the peak.

Using interpolation to make estimation of a real peak frequency is of simplicity and low computational complexity. Moreover, it can be easily added to any demodulation system without complicated programming. Thus, it is quite suitable for real-time underwater acoustic system.

The selection of the interpolation function is essential and will directly affect system performance. Though many interpolation algorithms have been proposed for increasing the resolution of peak frequency of FFT, the Double-Spectrum Interpolation (DSI) is still the most important algorithm. DSI algorithm is simple but can achieve very high accurate in frequency estimation. The frequency estimation is given by

$$f_o = \left(i \pm \left| \frac{a_1}{a_0 + a_1} \right| \right) \cdot \Delta f\,, \tag{6}$$

where a_0 and a_1 are the power value of the peak and its higher neighbour. More details of DSI can be seen in literature [8].

III. Double Line Interpolation and Demodulation Scheme

Our research found that the double-spectrum interpolation algorithm might not perform as well as expected in a real underwater MFSK demodulation system. Thus, in this session we proposed a new interpolation method and an improved demodulation scheme for underwater acoustic FH-MFSK system.

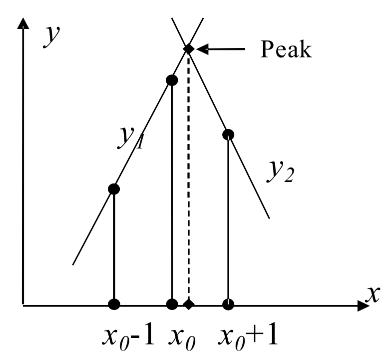

Figure 2. The model of the Double-Line Interpolation (DLI)

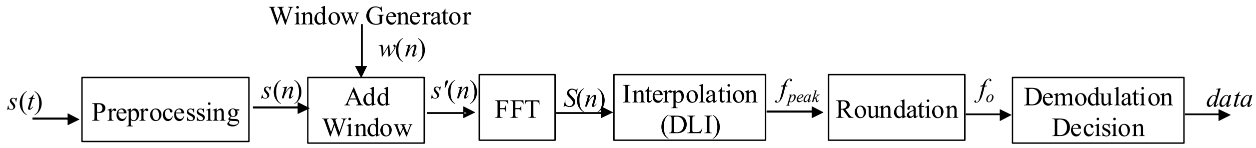

Figure 3. The structure of the proposed FH-MFSK demodulation scheme

In order to match our demodulation system better, we developed an interpolation algorithm, namely Double-Line Interpolation (DLI) algorithm.

The model of the DLI is illustrated in Fig. 2. The estimation of the peak was made by two oblique lines that depend on the peak and its two neighbour points. One line passes the peak of the spectrum and its lower neighbour point; the other line is decided by the higher neighbour and share the opposite slope of the first line we made.

As depicted in Fig. 2, two line equations can be defined and with the three points, the following equations can be obtained:

$$\begin{cases} y-y_1=k\left(x-\left(x_0-1\right)\right) \\ y-y_2=-k\left(x-\left(x_0+1\right)\right) \\ y-y_0=k\left(x_0-i\right) \\ y-y_0=-k\left(x_0-i\right) \end{cases} . \tag{7}$$

Then, by solving these four equations, we can derive (8) for the peak estimation.

$$x_{peak}=x_0+\frac{y_2-y_1}{2\cdot\left(y_0-\min\left(y_1,y_2\right)\right)} \tag{8}$$

With the information of the left and right of the peak in spectrum used, DLI is capable to compensate the left and right offset. Consequently, it may work better in overcoming the uncertainty of the underwater Doppler shifts.

The structure of the underwater FH-MFSK demodulation system using DLI algorithm, which is able to achieve higher performance, is shown in Fig. 3. The whole demodulation process is as follows:

a) Preprocessing: After receiving the acoustic signal $s(t)$ from the transducer, it will be amplified filtered and converted into digital signal $s(n)$;

b) Add Window: Hanning window is generated and added to $s(n)$, by which may reduce the leakage of spectrum power, then output signal was $s'(n)$;

c) Fourier Transform: Calculate the FFT results of $s'(n)$, and get the output signal $S(n)$;

d) Interpolation: Search the index of the peak of $S(n)$, i, and the necessary amplitude values, a_0, a_1 and a_2. Then, estimated peak index was given by applying interpolation algorithm in (8). Finally, calculate the estimated peak frequency f_{peak}. The optimized peak frequency is calculated by

$$f_{peak}=\left(i+\frac{a_2-a_1}{2\cdot\left(a_0-\min\left(a_1,a_2\right)\right)}\right)\frac{f_s}{N}, \tag{9}$$

where f_s is the receiving sampling frequency and N is the length of FFT window.

e) Roundation: Round f_{peak} to the nearest frequency in the frequency pattern by using

$$f_o=\mathrm{int}\left(f_{peak}\cdot M\right)/M, \tag{10}$$

where M is the number of carriers in MFSK, and *int*() is the function to round a number to the nearest integer.

f) Demodulation Decision: Interpret f_o to binary data with the frequency hoping pattern used in modulation system.

Here are the considerations for our demodulation scheme. First, in our demodulation scheme, the spectrum leakage is reduced by added Hanning window before FFT calculation. Second, the proposed double-line interpolation based FFT demodulation method enable underwater acoustic frequency modulation system to achieve higher frequency resolution. Third, the interpolation and rounding process together contribute to less vulnerability to the Doppler effect. Finally, this demodulation scheme is simple and practical, high in operation speed and stability for the peak frequency optimizing. Consequently, the final decision of the demodulation allows the Doppler shift to the maximum extent, and improve the successful demodulation rate of underwater acoustic communication systems.

IV. SIMULATIONS AND RESULT

Simulations were conducted to verify the demodulation scheme in Session III for underwater acoustic FH-MFSK. The performance of DSI and DLI based algorithm were compared in this session.

The simulation was carried out in NI LabVIEW [9]. The modulation we used in the test was FH-4FSK, with central frequency f_c = 15 kHz, the sampling frequency f_s = 50 kHz and the sampling length N = 256. The frequency resolution was approximate 0.2 kHz. In order to compare the interpolation algorithm and the effects of the added window, five cases of

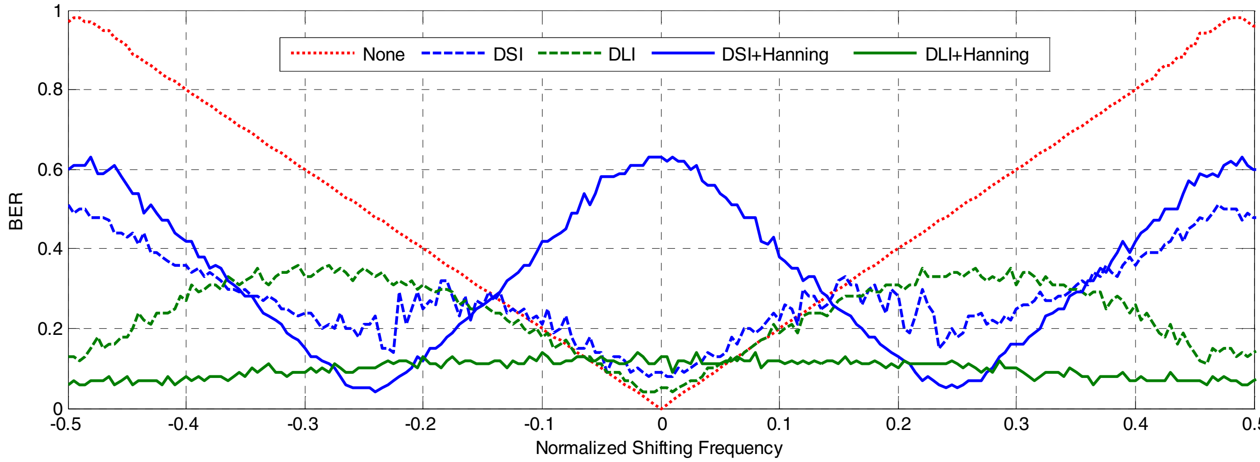

Figure 4. Comparisons of the performance of different demodulation scheme: no interpolation, double-spectrum interpolation, double-line interpolation, double-spectrum interpolation with Hanning window, and double-line interpolation with Hanning window. The frequency shifting in this figure is normalized to the frequency resolution Δf.

demodulation tests had been made. They were non-interpolation, double-spectrum interpolation with/without Hanning window, double line interpolation with/without Hanning window, respectively. Different frequency shifts were taking into consideration. The comparative performance of the simulations was drawn in Fig. 4. These conclusion might be made from the result:

1) The demodulation without interpolation may have poor ability regarding to the severe frequency shifting;

2) The double spectrum interpolation enables to reduce the interference caused by Doppler effect, but it becomes unstable when adding Hanning window;

3) The double line interpolation is able to overcome the frequency shift. Furthermore, it achieves much higher accurate when Hanning is added before the FFT algorithm.

V. CONCLUSION

In this paper, we focused on FH-MFSK demodulation for underwater acoustic communications, which was able to tolerate the Doppler shift and improve the detection rate. An improved demodulation solution was proposed for FFT based FH-MFSK underwater acoustic communications, which reduced the influence of the Doppler shifting and achieved higher performance. The double line interpolation was used in the scheme. Simulations were conducted and the demodulation performance was tested. Result showed a promising future for underwater FH-MFSK demodulation.

This work is of great significances in practical underwater FH-MFSK acoustic communications for two reasons: 1) Unlike other methods based on the relationship of resolution, sampling frequency and sampling number, the demodulation scheme we proposed doesn't add extra computational complexity to the system, so is more suitable for underwater systems; 2) The scheme enable to avoid the errors caused by frequency shifting and it's more possible to demodulate the data correctly in the underwater acoustic communication system.

Further research will focus on the Doppler effect in mobile underwater acoustic communications. In addition, more interpolation algorithms will be tested and taken into action in FH-MFSK underwater acoustic communications.

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