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Multi-Rate Base on OFDM in Underwater Sensor Networks

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Abstract: Underwater acoustic communication has the characteristics of multipath effect and frequency selectively attenuation. Aiming at these characteristics, this paper proposes a Multi-Rate model based on channel feature based on OFDM (Orthogonal Frequency Division Multiplexing) technology. With the frequency selectivity of underwater acoustic channel and the link distance, the optimal carrier frequency can be derived. The pilot in OFDM symbol can be used to attain the SNR of each sub-carrier, and the optimal modulation mechanism can be determined by the preset threshold. So we can get the maximal transmission rate under different link distances. This model addresses the problem of ISI (inter-symbol interference) caused by multipath in acoustic channel, and improves the throughput as well as transmission efficiency in underwater sensor networks. The simulation results show that under different link distances, the theoretical bandwidth can be obtained by the frequency selectivity of underwater acoustic channel, different sub-bands and modulation mechanisms can be obtained by channel estimation, and finally the maximal transmission rate can be acquired.

Keywords: Underwater acoustic sensor networks, Acoustic channel, Multi-rate, Orthogonal frequency division multiplexing, Channel estimation.

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1. Introduction

In recent years, UASNs (Underwater Acoustic Sensor Networks) have drawn broad attentions in scientific research, social services, and military applications and so on. UASNs can be widely applied in underwater target tracking and environment monitoring, etc [1, 2]. Compared with remote sensing methods, UASNs can provide real time in-situ information for shallow-water and deep-sea monitoring. However, unlike terrestrial wireless sensor networks, UASNs could not use electromagnetic wave as communication media due to its quick absorption in water. Therefore, acoustic signal is often used as a transport carrier in UASNs [3]. Underwater acoustic channel is a complex random channel with variable time-space-frequency parameters, low carrier frequency, long transmission delay, narrowband, strong noise, multipath interference, and many other transmission attenuation factors. Therefore, underwater acoustic communication becomes a highly challenging wireless communication area. The propagation speed of underwater acoustic signal (approximately 1500 m/s, with variation due to minor changes of pressure, temperature, and salinity of water) is five orders lower than electromagnetic wave propagation speed. Such high propagation delay will not only limit the interactive application, but also prolong the response time of communication.

At present, although the acoustic modem can elevate the data transmission rate to 10 Kbps, it cannot adaptively adjust the transmission rate to the distance and carrier frequency, and it also has some drawbacks in autonomous networks. In the non-uniform distributed deployment, UASNs with single carrier and fixed transmission rate can significantly enhance the efficiency of data transmission.

2. Related Work

Currently, in the research of multi rate technology, it is commonly implemented by different encodings and modulations. IEEE 802.11b [4] provides four rates of 1, 2, 5.5 and 11 Mbps, while IEEE 802.11a [5] provides eight rates of 6, 9, 12, 18, 24, 36, 48 and 54 Mbps. They support multiple rates in the physical layer, but in the MAC layer there are only definitions on different transmission rates for different types of frames (data frame, management frame and control frame), without regulations on how to select and change suitable transmission rate according to channel state for data frame. Literature [6] adopts the mechanism of variable lengths for spread spectrum to realize multi rates. Literature [7] uses grid encoding to realize multiple rates and multi-broadcast, the network nodes encode the received packets to reduce the redundant data.

As far as we know, in the area of UASNs, there are few literatures focused on the Multi-Rate and relevant technologies. Literature [8] considers the case when there are users with different needs on Quality of Service (QoS), some of them are rate-fixed and some are rate-variable, and presents a method of sub carrier allocation and power control for OFDM in case of multiple users and multiple rates.

This paper bases on the characteristics of UASNs, in order to solve the problem of multipath and Inter-Symbol Interference (ISI) in acoustic channel and realize high data transmission rate, it is planned to adopt OFDM. In the requirement of certain power and data bit error rate, the Signal to Noise Ratio (SNR) can be derived by channel estimation. Sub-carriers adopt different modulations according to the thresholds of SNR in different modulations. The practical maximal data transmission rate can be obtained by using the corresponding encoding and modulations of different subcarriers with the effective subcarriers.

3. Underwater Acoustic Model

3.1. Attenuations

In underwater acoustic channel, signal attenuation or path loss can be expressed as [9]:

$$A(l,f) = A_0 l^k \alpha(f)^l, \qquad (1)$$

where l is distance, f is signal frequency, A_0 is a constant, k is the diffusion factor, $A(l,f)$ is the absorption coefficient in dB. The acoustic signal is given:

$$10\log A(l,f)/A_0 = k\times 10\log l + l\times 10\log a(f) \qquad (2)$$

The first item is total diffusion loss, the second item is absorption loss. Diffusion factor k depends on the geometry of signal propagation. In general, k=2 in spherical diffusion, k=1 in cylinder diffusion and k=1.5 in experienced diffusion (it is similar in the case of radio channel and k is 2-4). The absorption coefficient is denoted by experienced value usually. The formula is given by Ainsile and McColm [10].

$$10\log\alpha(f) = A\frac{f_1 f^2}{f_1^2+f^2} + B\frac{f_2 f^2}{f_2^2+f^2} + Cf^2, \qquad (3)$$

where $a(f)$ is in dB/km and f is in kHz. S is the salt degree in permile, T is the temperature in °C, pH is the Potential of hydrogen of the sea.

$$f_1 = 0.78\left(S/35\right)^{1/2} e^{T/26}$$
$$f_2 = 42e^{T/17}$$
$$A = 0.106e^{(pH-8)/0.56}$$
$$B = 0.52\left(1+\frac{T}{43}\right)\left(\frac{S}{35}\right)e^{-z/6}$$
$$C = 0.00049e^{-\left(T/27+z/17\right)}$$

The commonly used experienced formula is:

$$\alpha = 0.036f^2 \qquad dB/km$$

3.2. Noise

The environmental noise can be modeled by these four aspects: tide turbulence, ship traffic, surface waves and thermal noise. Many environmental noises can be described as Gaussian distribution and continuous power spectrum density. The following formulas are used to denote the four noises by frequency function in unit of every μPa and every Hz as the frequency of kHz.

$$10\log N_t(f) = 17 - 30\log f$$
$$10\log N_s(f) = 40 + 20(s-0.5) + 26\log f - 60\log(f+0.03)$$
$$10\log N_w(f) = 50 + 7.5w^{1/2} + 20\log f - 40\log(f+0.4)$$
$$10\log N_{th}(f) = -15 + 20\log f$$

The tide turbulence only influences the very low frequency f < 10 Hz. When f = 10 Hz - 100 Hz, the dominant noise is ship traffic, if it is simulated as the influence factor of ship s, the value of s is 0 or 1 to represent the low activity or high activity. In 100 Hz –

1000 Hz (the primary frequency range for acoustic communication), the surface waves caused by wind is the main source of environmental noise. Finally, when f > 100 kHz, the main noise is thermal noise.

The overall p.s.d. of the ambient noise is $N(f)=Nt+Ns+Nw+Nth$. The noise decreases with frequency, thus limiting the useful acoustic bandwidth from below. In a certain frequency domain, the logarithm of noise power spectrum density can be used to denote linear attenuation, and can be replaced by this estimation formula.

$$10\log N(f) \approx N_1 - \eta \log f, \tag{4}$$

3.3. Signal to Noise Ratio and Optimal Frequency

The narrowband SNR is:

$$SNR(l,f) = \frac{P / A(l,f)}{N(f)\Delta f}, \tag{5}$$

where Δf is the bandwidth of received signal (centered as f_0).

Calculate the logarithm of Eq. 5 and can derive:

$$10\log SNR(l,f) = 10\log P - 10\log(N) - 10\log(A) - 10\log\Delta f \tag{6}$$

Substitute Eq. 1-4 into Eq. 5, set distance l as a constant, calculate d_{SNR}/d_f of Eq.4, we can have:

$$\frac{10}{SNR(l,f)\ln 10}\frac{dSNR}{df} = \frac{\eta}{f\ln 10} - A_0\times 10^3 \times l \times \frac{d[A\frac{f_1 f^2}{f_1^2+f^2} + B\frac{f_2 f^2}{f_2^2+f^2} + Cf^2]}{df} \tag{7}$$

When $d_{SNR}/df=0$, SNR is the smallest, Eq. 7 is transformed to solve the linear equation of higher degree with f.

3.4. Bandwidth

We define the 3 dB bandwidth $B(l)$ as that range of frequencies around $f_0(l)$ for which $SNR(l,f)>SNR(l,f_0(l))/2$, and it equal to:

$$SNR(l,f) > SNR(l,f_0(l))/2, \tag{8}$$

For every distance l, we begin by finding the optimal frequency $f_0(l)$, and setting the initial value of the constant k *and* $f_l(n)= f_0+$ k. We then proceed iteratively, increasing f in each step by a small value, until the condition (8) is satisfied. In particular, if $f_l(n)$ denotes the current value of f, for which SNR is still below the desired threshold, so the following operations are performed in the nth step:

(1) Determine $f_l(n)$ to derive the current $SNR(l,fl(n))$.

(2) Compare $SNR(n)$ and SNR_0. If $SNR(n)>1/2SNR_0$, increase k and continue the procedure, until $SNR(n+1)<1/2SNR_0$, then the $f_l(n)$ is the highest frequency.

(3) Calculate the lowest frequency using the same iteration, and the propagation is $B(l)=[f_{\min(l)}, f_{\max(l)}]$ centered at $f_0(l)$.

4. Multi-Rates Basing on OFDM

The basic idea of OFDM is to divide the available frequency band into many sub bands, high data flows are modulated on these sub bands and transmitted simultaneously. Therefore, the transmission rate of every sub band can be greatly decreased and the symbol period is extended, so the ISI is reduced. In the receiver, the sub bands are demodulated independently to derive multiple low-rate data flows. After parallel to serial transformation, higher-rate data flows are obtained.

When nodes distance is unchanged, from literature [9], the optimal carrier frequency and 3 dB bandwidth can be gained. Considering the practical available bandwidth of the devices, we can take the cross set between 3 db bandwidth and device bandwidth as the practical available bandwidth. After that, with different modulations and subcarrier numbers, there are several types of multi transmission rates technologies:

(1) Ignoring the practical channel status, using fixed modulations and changing subcarrier numbers to realize variable multi transmission rates.

(2) Ignoring the practical channel status, limiting the subcarrier number and using different modulations to realize multi transmission rates.

(3) Considering the practical channel status, using fixed modulations, removing some subcarriers with strong interference and changing subcarrier numbers to realize variable multi transmission rates.

(4) Considering the practical channel status, limiting the subcarrier number, adopting different modulations by different channel qualities to realize variable multi transmission rates.

(5) Considering the practical channel status, selecting different subcarrier numbers and modulations according to different channel qualities to realize variable multi transmission rates.

Comparatively, the last scheme is the optimal technology for variable multi-rates.

5. Multi-Rates Basing on Channel Estimation

The technique of adaption is to change modulations (constellation numbers), encoding ratio and transmission power to send more data and improve the efficiency of spectrum usage. Combining OFDM with adaption, the gain of system channel capacity can be enhanced and excellent system performance can be derived.

The multi-rates basing on channel estimation in this paper means that, with fixed power, we can choose maximized modulations which satisfy the requirement of BER to get the maximized channel capacity under the help of estimated SNR of subcarriers. The block diagram is shown in Fig. 1.

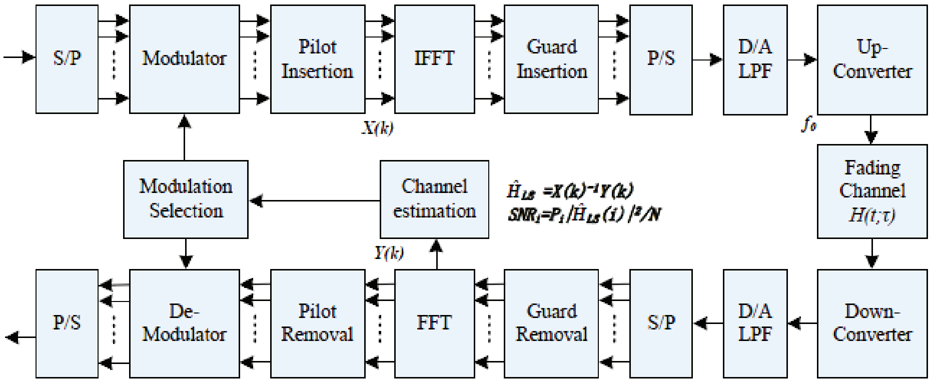


Fig. 1. The principle framework of OFDM system.

In order to achieve adaptive transmission, transmitter or receiver must have the effective knowledge of channel status. Channel status mainly denotes the SNR in the receiver. In this case, an adaptive policy should take the following steps:

(1) SNR threshold selection: the threshold is the least SNR satisfying the demand of BER, with given signal power and modulation.

(2) Channel parameters estimation: in order to select suitable transmission parameters in the next transmission slot, estimate the channel transfer function reliably and derive SNRs of all subcarrier channel.

(3) Adaptive parameters transfer: with the SNR and the threshold of subcarriers, nodes can choose suitable modulations and send this result to the transmitter. So the transmitter will adjust its modulations in the next transmission slot.

The threshold of SNR can be derived by experiments. From the relation between different BER and SNR when using different modulations in OFDM with a fixed transmission power. So a minimal SNR that satisfy the need of BER is found. Channel estimation can use the simple LS estimation. From the pilot data X and received demodulated signal Y, we can get $\hat{H}LS = X_{-1}Y$, then $SNR_i=P_i\,|\hat{H}LS(i)\,|2/N$.

The implementation process is as follows. First, by the link length and the attenuation model of acoustic signal, the optimal carrier frequency and 3db theoretical bandwidth is found. Combining with available bandwidth of device, the practical transmission bandwidth is derived. By the delay expand of channel, the intervals and frequency of sub bands is determined. Calculating the theoretical available subcarriers numbers, the transmitter send the pilot data at first, and the upper frequency conversion uses the optimal carrier frequency in light of different link distances. The receiver demodulates the pilot by FFT, gets the SNR of all subcarriers and selects reasonable modulations of subcarriers with comparison of thresholds. Then it sends the modulation parameters to the transmitter, the transmitter select effective subcarriers and the corresponding modulations basing on the feedback of receiver. By the effective subcarrier numbers, the encoding policy and modulations of subcarriers, and the practical available maximal data transmission rate is finally obtained.

6. Simulation and Analysis

6.1. Simulation Setup

In the same channel, we make comparisons on the bit error rate (BER) between the mechanism of Multi-Rates basing on channel estimation and that of fixed transmission rate. The simulation parameters are as follows. The device frequency range is 2 Hz - 200 kHz, the delay spread of underwater acoustic channel is 45 ms, the subcarrier interval is 5 Hz and the channel is Rayleigh attenuation model. The initialized modulations of all subcarriers are BPSK, and the encoding carrier adopts the rate of 3/4.

6.2. Simulation Result

(1) Relation between distance and optimal carrier frequency.

As demonstrated before, there is frequency selectivity in underwater acoustic channel. Fig. 2 is the illustration of the optimal carrier frequency with different distances in the Yellow Sea and the East Sea. It can be deduced that the carrier frequency is negatively proportional to distance. When the distance is less then 10 km, with the increase of distance, carrier frequency decreased significantly.

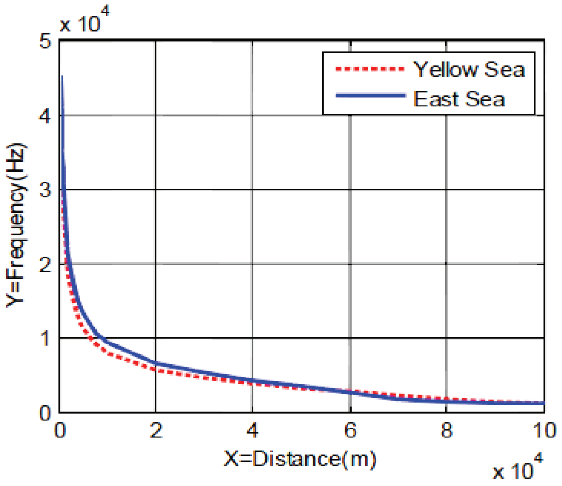


Fig. 2. Optimal carrier frequency with different distances.

(2) Relation between band and carrier frequency.

Fig. 3 shows the relation between band and carrier frequency, we can see that signal attenuation is negatively proportional to the distance. The frequency selectivity strengthens with longer distance, and the channel bandwidth is also negatively proportional to the distance. In short range transmission, the bandwidth is relatively wide. While the distance is around 5 km, the bandwidth sharply decreased. Apparently, single carrier transmission cannot obtain high transmission rate in this case.

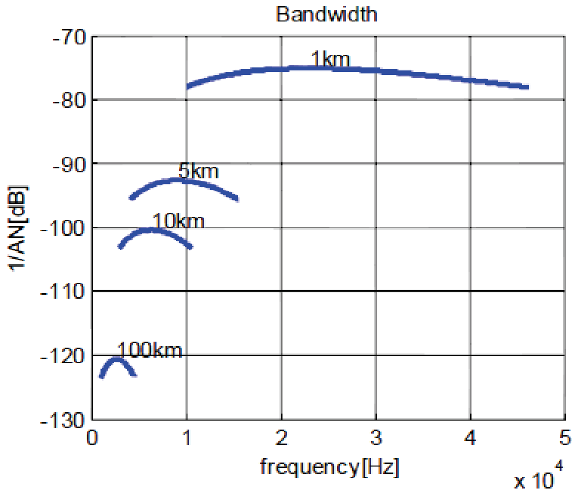


Fig. 3. Relation between bandwidth and distance.

(3) Relation between link maximal transmission rate and link length

Fig. 4 is the maximal transmission rate when link length is 1 km, 5 km and 10 km using QPSK. It is clear that the maximal transmission rate of channel is negatively proportional to the distance. With the increase of distance, the maximal transmission rate reduces gradually. This is because as link length increases, channel bandwidth decreases.

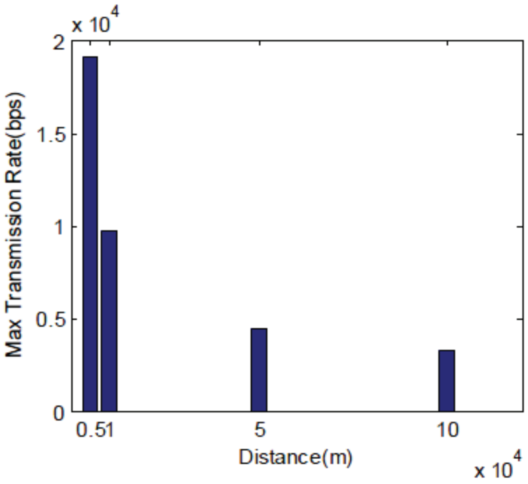


Fig. 4. Relation between maximal transmission rate and distance.

7. Experiment and Analysis

7.1. Experimental Design

The test system is shown in figure, which mainly consists of two sets of Universal Software Radio Peripheral (USRP) and two transducers (T218, D70). Basically USRPs are used as digital baseband and intermediate frequency of wireless communication systems, which can realize all waveform related processing, such as modulation and demodulation; digital up-conversion and digital down-conversion; sampling and interpolation, etc. The transmitter USRP performs source production, modulation, D/A conversion, and the electrical signal will be loaded to transducer after audio power amplifier. Transducer T218 is mainly to convert modulated signals into acoustic signal and through the underwater acoustic channel, transducer D70 will convert the received acoustic signal to electrical signals. Finally after signal amplification, the receiving terminal finishes corresponding A/D conversion, filtering and demodulation.

The configuration for the experiment contains four Cascaded Integrator Comb (CIC) to realize digital down converter (DDC). CIC filter is a high performance filter based on adder and delay apparatus, which is mainly used in spectrum formation and signal suppression for frequency outside the band.

Digital down converter (DDC) have two main functions as shown in Fig. 5. First, the signal from the intermediate frequency band is switched to baseband. Second, after the input signal (IF) multiplying the constant frequency (usually intermediate frequency) index signal, the resulting signal is complex and concentrated on zero frequency. If the factor N is adopted in signal sampling, the bandwidth of low frequency pass filter is [-Fs/N,Fs/N], then the sampler from [Fs, Fs] to[-Fs/N,Fs/N] will be removed. So actually, factor N can reduce the useful signal bandwidth.

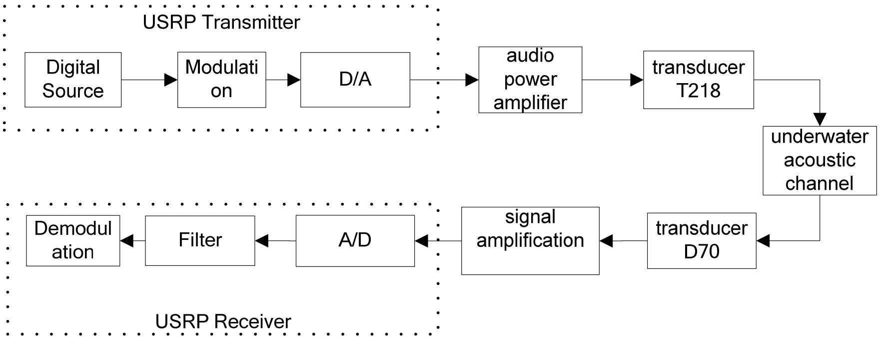


Fig. 5. Block diagram of the communication systems.

In practice, the extraction factor is used to set the OFDM signal bandwidth. USRP has four high-speed 12 AD converters with sampling rate of 64 m per second symbol. In theory, it can be used as a digital 32 M bandwidth. But practice bandwidth is 3 ~ 14 KHz or so, so reasonable extraction factor is needed to adjust the signal bandwidth. In addition, the range of AD converter is 2 V peak to peak values and the input is difference of fifty ohm, which is 10 mw power (10 dBm). Before ADCs there is a programmable gain amplifier (PGA) to amplify the input signal, so that in case of weak input signal, the whole range of ADCs cam still be used. The maximal PAG is 20 db. When the gain is zero the maximum input is difference of 2 V peak to peak value. When using 20 dB, only 0.2 V peak to peak value for differential input signal can achieve maximum range.

The following factors should be considered in the experiment:

(1) Bandwidth

Due to the characteristics of underwater acoustic channel, the impact of low frequency sound absorption and attenuation is weaker than that of high frequency band. In addition, the resonant frequency of the transducer T218 is 22 kHz, but in practice 22 kHz is the central frequency. The bandwidth of the transducer is [16 kHz, 30 kHz] and the optimal bandwidth is [21 kHz, 24 kHz]. In the experiment, the frequency is ranged in [16 kHz, 30 kHz] with consideration of the channel and equipment characteristics.

(2) Data rates

Data rate is mainly determined by symbol rate in OFDM, effective subcarrier number and modulation mode. In the experiment the lowest data rate is 960 bit/s and the highest is 14.4 kb/s.

(3) Modulation

Due to the high utilization rate, phase is extensively applied in underwater acoustic communication so that BPSK and QPSK are used here. Moreover, higher-order quadrature amplitude modulation (QAM) is also widely used way used in underwater acoustic communication system. However, by testing 16 QAM, 64 QAM and 256 QAM show high bandwidth utilization, but at the same time bring very high error rate. So in our test, QAM-8 is used with good communication quality.

Table 1 is system parameters under bandwidth of 1.3 kHz and 2.6 kHz, central frequency of 22 kHz and carrier interval of 5.08 Hz case; Table 2 shows the corresponding relations between each modulation mode and data rate after conversion; Table 3 is system parameters under bandwidth of 3.2 kHz and 6.4 kHz, central frequency of 22 kHz and carrier interval of 12.52 Hz; Table 4 shows the corresponding relations between each modulation mode and data rate corresponding relation after conversion.

Table 1. System parameters 1.

Subcarrier interval	5.08 Hz
Frequency band	20.7 kHz~23.3 kHz
Centre frequency	22 kHz
Number of subcarrier	256,512
Number of effective subcarrier	240,480
OFDM effective Symbol period	196.85 ms
Length of Cyclic Prefix	49.21 ms
OFDM Symbol period T’	246.06 ms
Modulation	BPSK, QPSK, 8QAM

Table 2. Modulation and data rate 1.

	BPSK	QPSK	8QAM
Number of effective subcarrier	240	240	240
Transmission rate	0.96 kb/s	1.92 kb/s	2.88 kb/s

Table 3. System parameters 2.

Subcarrier interval	12.52 Hz
Frequency band	18.9 kHz ~ 25.1 kHz
Centre frequency	22 kHz
Number of subcarrier	256, 12
Number of effective subcarrier	240, 480
OFDM Symbol period	99.84 ms
Length of Cyclic Prefix	19.96 ms
OFDM Symbol period T’	79.87 ms
Modulation	BPSK, QPSK, 8QAM

Table 4. Modulation and data rate 2.

	BPSK	QPSK	8QAM
Number of effective subcarrier	480	480	480
Transmission rate	4.8 kb/s	9.6 kb/s	14.4 kb/s

7.2. Experimental Results and Analysis

Fig. 6 is the comparison between different modulation mode and bit error rate with the 256 subcarriers while the effective subcarrier number is 480. According to the experimental results, when modulation mode is BPSK, channel transmission rate is 0.96 KB/s, and the communication rate is low, bit error rate is 0.001 or so. When the modulation order increases, data rate also becomes higher. When using 8 QAM modulations, the bit error rate is 0.0043.

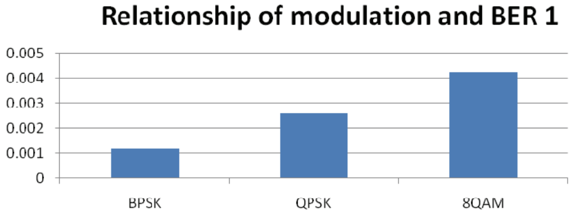


Fig. 6. Block diagram of the communication systems.

Fig. 7 is the comparison different modulation mode and bit error rate with 512 subcarriers between, while the effective subcarrier number is 480, the communication rate for BPSK, QPSK and 8QAM are 1.92 Kb/s, 3.84 Kb/s, 5.76 Kb/s respectively. We can get similar results from Fig. 6 and Fig. 7. Comparing the two figures, we can see that with the same BPSK modulation mode, when the subcarrier number and bandwidth increase, the communication rate and bit error rate also increase. And under 8 QAM modulation, the effects of bandwidth is more remarkable.

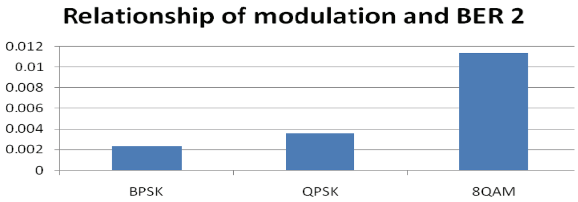


Fig. 7. Relationship of modulation and BER 2.

As the chart shows when changing system parameters, adjusting cycle prefix length to be 19.96 ms, and still choosing the symbol length as four times of the cycle prefix, the bit error rate relationship is demonstrated in Fig. 8. with comparison, it can be inferred that the increasing data rate and bandwidth will significantly increase the error rate.

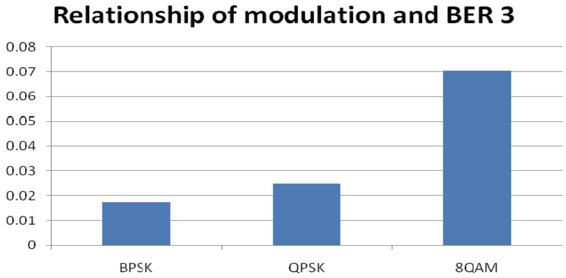
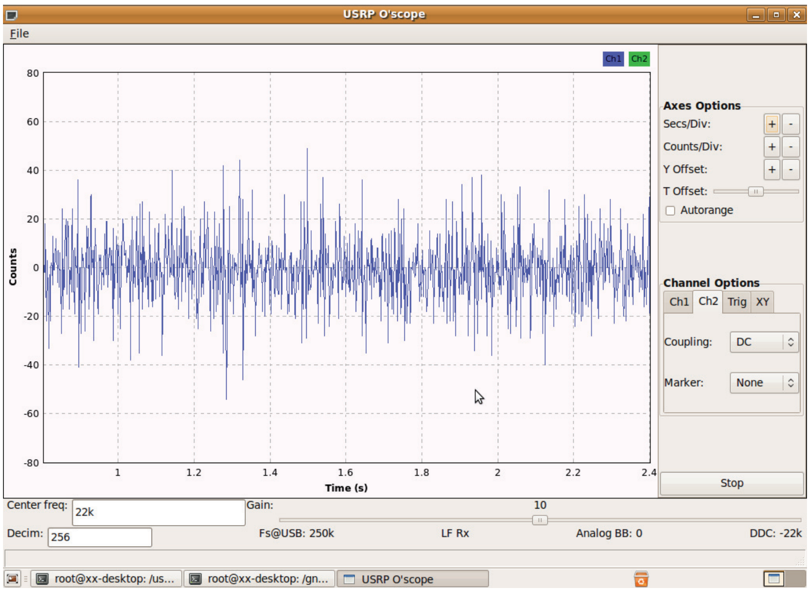


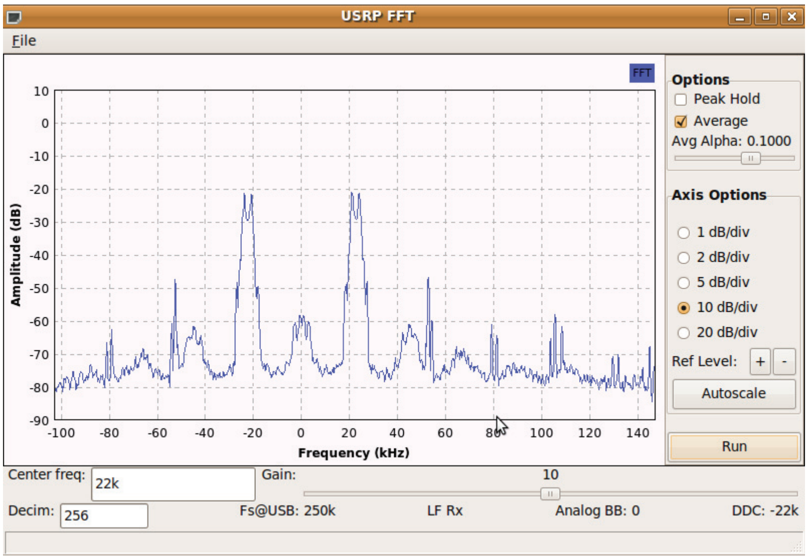
Fig. 8. Relationship of modulation and BER 3.

Fig. 9 and 10 are the waveform in time domain and frequency domain with the central frequency of 22 kHz, bandwidth of 6.2 kHz and BPSK modulation mode through the software radio platform.



Coupling: DC
Marker: None
Center freq: 22k
Gain: 10
Decim: 256
Fs@USB: 250k
LF Rx
Analog BB: 0
DDC: -22k

Fig. 9. OFDM time-domain waveform.



Options

☐ Peak Hold

☑ Average

Avg Alpha: 0.1000

Axis Options

● 10 dB/div

Center freq: 22k

Gain: 10

Decim: 256

Fs@USB: 250k

LF Rx

Analog BB: 0

DDC: -22k

Fig. 10. OFDM frequency domain waveform.

8. Conclusions

In underwater communication networks, the acoustic channel has strong frequency selectivity. Aiming at the characteristics of underwater acoustic channel, this paper proposes a method of Multi-Rates using OFDM basing channel estimation, a relation model between transmission rate and distance is derived. By building the model of Multi-Rates, the network throughput and transmission efficiency will be improved as a whole.

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