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Adaptive Technique for Underwater Acoustic Communication

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1. Introduction

Compared with the electromagnetic wave channel, the UWA (Underwater Acoustic) channel is characterized by large transmission delay, transmission loss increased with distance and frequency, serious multi-path effect, and remarkable Doppler Effect. These characteristics greatly influence the performance of UWA communication, and restrict channel capacity. Performance of UWA communication is far away from telecommunication, even if employ the similar techniques. Especially, available bandwidth is limited by spread distance because transmission loss increases with longer range distance. For example, the bandwidth for 5 km is 10 kHz whereas the bandwidth for 80 km is only 500Hz. For constant data rate, the bandwidth is confined by maximum working range and worst channel environment, so the utilization ratio of channel is very low. Besides the reasonable modulation model and advanced signal processing method which improves the detection performance of the receiver, the most fundamental way for reliable communication is adaptive modulation which greatly improves utilization ratio of bandwidth.

Modulation and detection techniques used for UWA communication include phase coherent (PSK and QAM) and noncoherent (FSK) techniques. The choice of modulation mode is based on the UWA channel parameters, such as multipath and the Doppler spread, as well as the SNR. The spread factor of the UWA channel determines whether phase coherent communications are possible. If so, an equalizer is employed to combat any intersymbol interference. If the channel varies too rapidly, noncoherent signaling is chosen. The choice of modulation is determined by the operator.

The objective of this chapter is based on the analysis of characteristics of UWA channel, developing algorithms that can self-adapting select the best technique for time varying UWA channel. Then the dynamic modulation and bandwidth optimization for high-rate UWA communication are deduced. At last the simulation results are shown.

2. Fading characteristics of UWA channel

2.1 Characteristic of UWA channel

Due to the absorption of medium itself, the wavefront expansion in sound propagation, the bending of acoustic ray, the scattering caused by various kinds of nonuniformity in ocean and so on, the acoustic intensity will weaken in its propagation direction. The fading will change with distance, frequency and sensors location, which can be divided into large-scale fading and small-scale fading.

Large-scale fading: It is caused by sound propagation and sound ray convergence. The fading caused by sound propagation is composed by transmission loss and absorption loss, which is a function of range and frequency. It can be expressed as

$$TL = n \cdot 10 \log r + \alpha r \tag{1}$$

where n=1,2,or 1.5, r is the range of communication, α is absorption coefficeent, which is a function of signal frequency f, and its value can be given by Thorp experience formula:

$$\alpha(f) = \frac{0.11 f^2}{1+f^2} + \frac{44 f^2}{4100+f^2} + 3.0\times10^{-4} f^2 + 3.3\times10^{-3} \text{ dB/km} \tag{2}$$

In the process of signal propagation, sound energy is strong in one area while weak in another area which is known as convergence fading.

Small-scale fading: small scale fading is composed by multipath and Doppler spread. The impulse response function is

$$h(\tau,t) = \sum_{i=1}^{p} a_i(t)\exp\left[j\phi_i(t)\right]\delta\left[\tau-\tau_i(t)\right] \tag{3}$$

where P is the number of multiple paths, α_i and ϕ_i are the amplitude and phase of i-th path respectively. τ_i is the time delay of the i-th path, and is uniformly distributed between $\tau_{\min}$ and $\tau_{\max}$, where $\tau_{\max}$ is maximum delay spread . This kind of spread in time domain is corresponding to frequency selective decline in frequency domain, and the relation between coherence bandwidth B_{coh} and maximum relative delay is $B_{cok} = 1/\tau_{\max}$. Multipath fading which caused by interference of multipath signals is related to the frequency of the signal, physical characteristics of the ocean, spatial location of the transmitter and the receiver.

Doppler Effect is caused by the relative motion between the transmitter and the receiver or the medium flow in UWA channel. Because multiple paths spread through different tracks, the received Doppler frequencies are also different from each other. Therefore the received signal is frequency spreading and the spread is measured by parameter $f_d = f\upsilon_{\max}/c$, where $\upsilon_{\max}$ is the maximum relative radial velocity of multiple paths, c is the propagation velocity of sound waves, and f is the frequency of the signal transmission. Doppler spread in frequency domain is corresponding to time selective decline in time domain. Time selective decline is measured by relative time $T_{cok} = 1/f_d$ .The larger the relative time is, the slower channel varies. Conversely, the smaller the relative time is, the quicker channel varies.

By the above analysis, when the sea area, positions of the transmitter and of the receiver are established, large-scale fading is only the function of distance and frequency, and small scale fading is a random function of distance and time. In the adaptive UWA communication, big scale fading is slow fading, and small scale fading is fast fading. The relations between range and fading are shown in Fig.1. With defined distance, the relations between time and fading are shown in Fig.2.

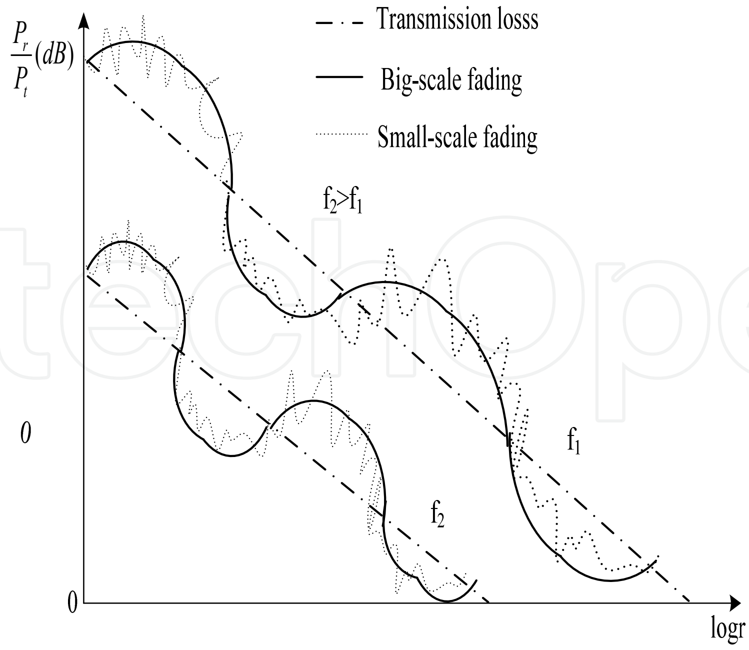

Fig. 1. The relations between range and fading

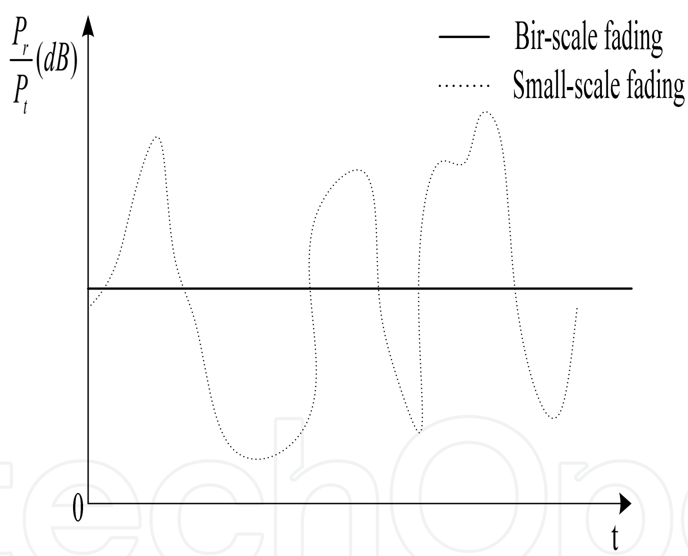

Fig. 2. The relations between time and fading

2.2 The relationship between bandwidth and frequency/ range in UWA channel

If only considering the large-scale fading, according to sonar function, the SNR(signal-to-noise ratio) of receiver will be

$$\mathrm{SNR} = SL - TL - NL - 10\log \mathrm{B} \tag{4}$$

where *SL* is sound source level (dB), *NL* is noise spectrum level, B is the bandwidth. Assuming *NL*=45dB, the relationship between SNR of receiver and frequency (1~30kHz), SNR of receiver and range(1~100km) are shown in Fig.3. From the figure we can see, if the transmitting power and the SNR of receiver are defined, the system bandwidth is the function of distance and frequency.

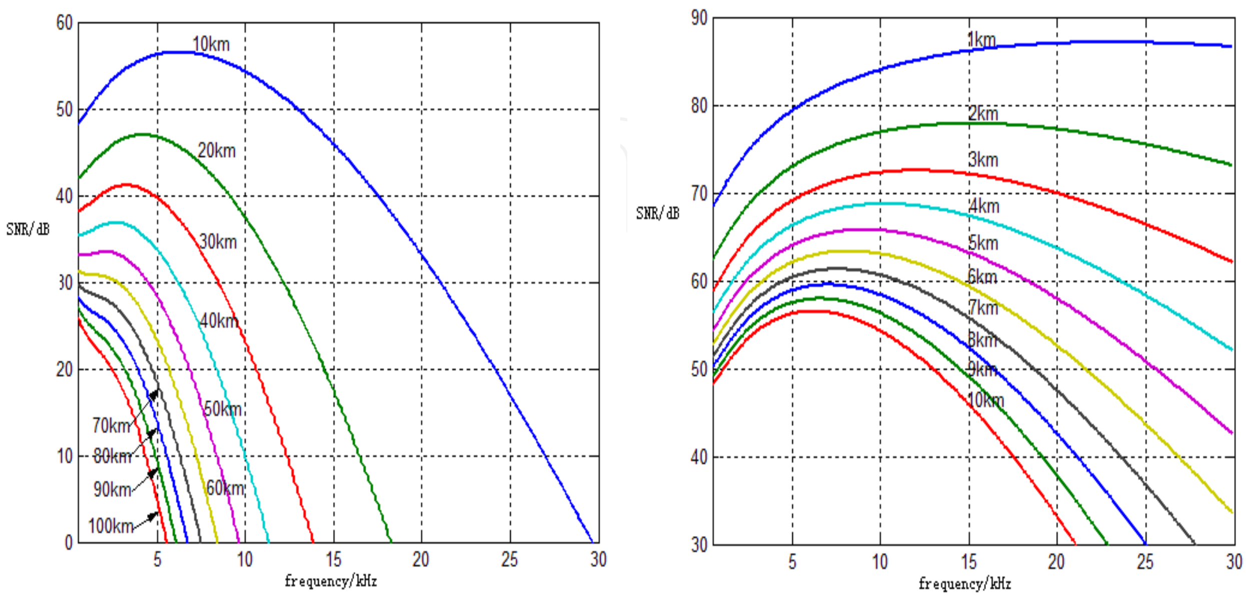

Fig. 3. The relationship between SNR and frequency, SNR and range

3. Channel capacity of UWA channel

3.1 Channel capacity of AWGN (Additive White Gaussian Noise) time invariant channel

Assuming *n(t)* is AWGN, $N_0/2$ is PSD (Power Spectral Density) of AWGN, $\overline{P}$ is the average transmitted power, B is the receiving bandwidth, *C* is the channel capacity per second(bit/s). When the channel gain is constant 1, the SNR of the receiver is constant $\gamma(t) = \overline{P}/(N_0 B)$, and then the channel capacity limited by average power can be expressed as

$$C = B\log_2(1+\gamma) \tag{5}$$

This formula shows the channel capacity is proportional to the bandwidth, and increases with the improvement of received SNR.

3.2 Channel capacity of time variant flat fading channel

Supposing the gain of stationary and ergodic channel is $\sqrt{g(t)}$, *g(t)* obeys distribution p(g), and is unrelated with channel input. So the instantaneous received SNR is $\gamma(t) = g(t)\overline{P}/(N_0 B)$, the distribution of $\gamma(t)$ is determined by $g(t)$, and the channel capacity is

$$C = \int_0^\infty B\log_2(1+\gamma)p(\gamma)d\gamma \tag{6}$$

If the sending power varies with γ , the interrupt threshold γ_0 can be calculated by the formula $\int_{\gamma_0}^{\infty}(1/\gamma_0 - 1/\gamma)p(\gamma)d\gamma = 1$, it can be proved when the optimal power allocation is $\frac{P(\gamma)}{\bar{P}} = \begin{cases} 1/\gamma_0 - 1/\gamma & \gamma \geq \gamma_0 \\ 0 & \gamma < \gamma_0 \end{cases}$, channel capacity achieves maximum as

$$C = \int_{\gamma_0}^{\infty} B\log_2(\gamma/\gamma_0)p(\gamma)d\gamma \tag{7}$$

This capacity can be obtained by the time-varying transmission rates. Instantaneous SNR γ corresponds to the rate $B\log_2(\gamma/\gamma_0)$. This formula shows: If channel condition gets deteriorated, then the transmitter will reduce sending power and transmission rate. If the SNR falls below the interrupt threshold γ_0, the transmitter won't transmit signal. This method is called time domain Power Water-filling Allocation method.

3.3 Channel capacity of time invariant frequency selective fading channel

Supposing the channel gain *H(f)* is block fading, the whole bandwidth can be divided into many sub-channels whose bandwidth are B, and in each sub-channel $H(f) = H_i$ is constant. The SNR of i-th channel is $|H_i|^2 P_j/(N_0 B)$, where P_j is the allocated power when $\sum_j P_j < P$. *P* is the upper limit of the total power. The channel capacity is the sum of the whole sub-channels

$$C = \sum_{P_j:\sum_j P_j \leq P} B\log_2\left(1 + \frac{|H_j|^2 P_j}{N_0 B}\gamma\right) \tag{8}$$

It can be proved when the optimal power allocation is $\frac{P(\gamma)}{\bar{P}} = \begin{cases} 1/\gamma_0 - 1/\gamma & \gamma \geq \gamma_0 \\ 0 & \gamma < \gamma_0 \end{cases}$, channel capacity achieves maximum as

$$C = \int_{\gamma_0}^{\infty} B\log_2(\gamma/\gamma_0)p(\gamma)d\gamma \tag{9}$$

Interrupt threshold can be calculated by $\sum_i (1/\gamma_0 - 1/\gamma_j) = 1$. The capacity *C* is achieved by allocating different power and data rate for multiple sub-channels. When SNR of channel is admirable, distribute more power and use high transmission rate. If channel gets deteriorated, the transmitter will reduce sending power and transmission rate. If the SNR falls below the interrupt threshold γ_0, the transmitter won't transmit signal. This method is called frequency domain Power Water-filling Allocation method.

3.4 Capacity of UWA channel

In order to simplify the analysis, this chapter assumes that the response function of the UWA channel is *H (f, t)*, and the bandwidth *B* can be divided into several sub-bandwidths by coherent bandwidth B_{coh}. Each sub-channel is independent time variant flat fading channel, then for the j-th sub-channel, the response function is $H(f,t)=H_j(t)$. According to the allocated average power of each sub-channel, the capacity of every flat fading sub-channel can be deduced. For sub-channels are independent from each other, the total power in time and frequency domain is the sum of capacity of each narrowband flat fading sub-channel.

$$C=\max_{\{\bar{P}_j\}:\sum_j \bar{P}_j \le \bar{P}} \sum_j C_j\left(\bar{P}_j\right) \tag{10}$$

where $C_j\left(\bar{P}_j\right)$ is the capacity of the sub-channel whose mean power is P and bandwidth is B_{coh}. Bandwidth can be given by Eq. 6 From the two dimensions Water-filling Allocation method of time domain and frequency domain, when $\frac{P_j}{P}=\begin{cases}1/\gamma_0-1/\gamma_j & \gamma_j\ge\gamma_0\\ 0 & \gamma_j<\gamma_0\end{cases}$, the channel capacity achieves maximum as

$$C=\sum_j\int_{\gamma_0}^{\infty} B_c \log_2\left(\gamma_j/\gamma_0\right) p\left(\gamma_j\right) d\gamma_j \tag{11}$$

Interrupt threshold γ_0 can be calculated by $\sum_j\int_{\gamma_0}^{\infty}\left(1/\gamma_0-1/\gamma_j\right)p\left(\gamma_j\right)d\gamma_j=1$, which is the same for each sub-channel.

To achieve the capacity in UWA communication, multi-carrier transmission should be used, and the power of each sub-channel is allocated by SNR. In one sub-channel, the transmission power and rate vary with the channel condition by Water-filling Allocation method.

4. Relationship between BER and SNR in digital communication

PSK(Phase Shift Keying), QAM(Quadrature Amplitude Modulation) and FSK (Frequency Shift Keying) are the common modulation models used in UWA communication. Supposing the transmission signal $s_T(t)$, then the received signal with AWGN is

$$s_r(t)=s_T(t)+n(t) \qquad (0\le t\le T) \tag{12}$$

where *n(t)* is AWGN sample with power spectrum density $\Phi_{nn}(f)=N_0/2$. *N0* is the average power spectrum density of AWGN. With the optimized receiver, symbol error rate, bit error rate and bandwidth ratio of several modulation models are shown in Table1. ε_b is signal power per bit.

According to Table1, when the BER is $P_b=10^{-6}$ or $P_b=10^{-4}$, the SNR that M-ary modulation needs to transmit 1bit information is shown in Table2. The interrupt threshold in UWA communication is defined by the SNR.

	SER	BER	bandwidth ratio
PSK	$P_B \approx 2Q\left(\sqrt{\frac{2k\varepsilon_b}{N_0}}\sin\frac{\pi}{M}\right)$	$P_b \approx \frac{1}{k}P_B$	$\frac{R_b}{W} = \frac{1}{2}\log_2 M$
QAM	$P_B \approx 4Q\left[\sqrt{\frac{3k\varepsilon_b}{(M-1)N_0}}\right]$	$P_b \approx \frac{1}{k}P_B$	$\frac{R_b}{W} = \begin{cases}\frac{1}{2}\log_2 M & M \le 4 \\ \log_2 M & M > 4\end{cases}$
FSK (non-coherent detection)	$P_B = \sum_{n=1}^{M-1}(-1)^{n+1}\binom{M-1}{n}\frac{1}{n+1}e^{\frac{-nk\varepsilon_b}{N_0(n+1)}}$	$P_b = \frac{2^{k-1}}{2^k-1}P_B$	$\frac{R_b}{W} = \frac{\log_2 M}{M}$

Table 1. SER, BER and bandwidth ratio of M-ary modulation models

	Modulation mode	M=2	M=4	M=8	M=16	M=32
$P_b = 10^{-6}$	PSK	10.51	10.51	13.95	18.42	23.34
	QAM		10.51	13.25	14.39	16.59
	FSK	13.51	10.75	9.23	8.21	7.44
$P_b = 10^{-4}$	PSK	8.39	8.39	11.71	16.14	21.01
	QAM		8.39	11.28	12.19	14.41
	FSK	11.39	8.77	7.35	6.43	5.76

Table 2. SNR to transmit 1bit information of M-ary modulation (dB)

5. Adaptive UWA communication

The UWA communication is power limited communication because of cavitation phenomenon and field effect. The large-scale fading is slow fading, and the small-scale fading is fast fading.

From analysis of section 3.4, adaptive modulation should be used to optimize the bandwidth ratio. By the use of multi-carrier transmission, the power of each sub-channel is allocated by SNR of receiver to achieve dynamic bandwidth. When SNR of channel is high, the transmitter distributes more power, or otherwise distributes less power. If the SNR falls below the interrupt threshold γ_0 , the transmiter will not transmit signal. In one sub-channel the transmission power and rate vary with the channel condition by Water-filling Allocation method. When SNR of channel is admirable, the transmitter distributes more power and uses higher transmission rate, or otherwise reduces sending power and transmission rate. If the SNR falls below the interrupt threshold γ_0 , do not transmit signal. It is dynamic modulation in one sub-carrier.

5.1 Adaptive transmission system

In adaptive modulation system, at first, the transmitter sends a test signal to link the receiver, and then the receiver estimates the instantaneous channel characteristics and feeds back the updates to the transmitter, at last the transmitter selects a suitable modulation scheme and bandwidth to transmit information. The receiver estimates channel and feeds back the updates to transmitter at the end of a frame. The adaptive system process block diagram is shown in Fig.4. The estimated received SNR of j-th channel at i-th time is $\hat{\gamma}_j[i] = \bar{P}_j \hat{g}_j[i] / (N_0 B_j)$. $\hat{g}_j[i]$ is the estimation of power gain of j-th channel. The relevant parameters are regulated based on estimated value at the time of integral times of code period *Ts*.

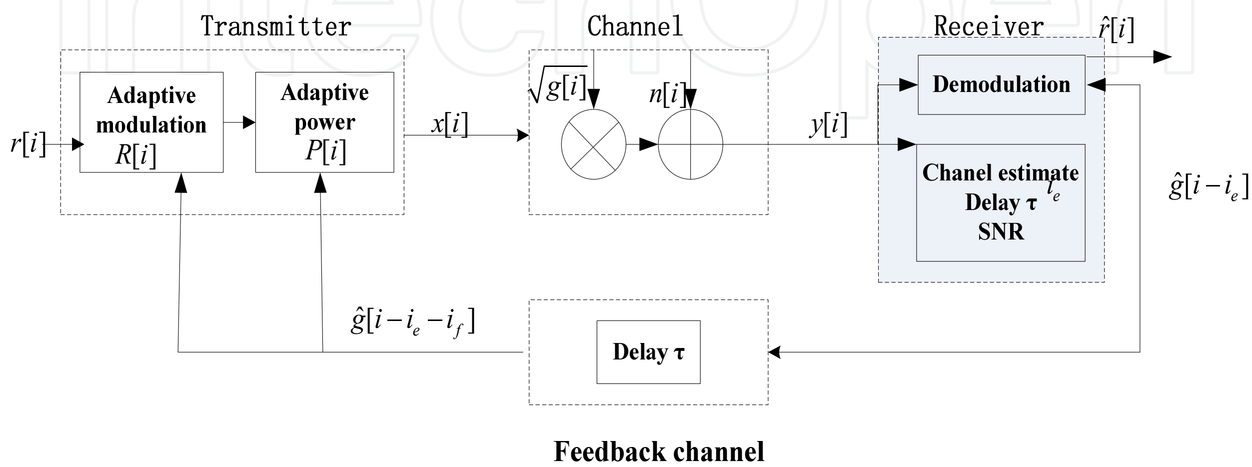

Fig. 4. Block diagram of adaptive system

5.2 The adaptability criterion of large-scale fading and small-scale fading

Supposing the transmitter sends information to the receiver at time i, after time delay i_e, the receiver receivs the estimated SNR $\hat{\gamma}_j[i]$ of j-th sub-channel at time i. Finally, with the additional feed back time delay i_f, the receiver gets the information after time delay $i_d = i_e + i_f$. Assuming the channel estimation and feed back information are both errorless, then the instantaneous BER is $P_b(\gamma) = P_b$, and supposing $\hat{g}[i - i_d]$ is the actual value, the total BER of QAM is

$$P_b(\gamma[i], \gamma[i - i_d]) \le 0.2[5P_b]^{\varepsilon[i, i_d]} \tag{13}$$

It can be improved when Doppler frequency shift *fd* meets $i_d = i_e + i_f < 0.001 f_d$, the average BER approaches desired value P_b. That is to say, the rate of channel variation effects the updates rate and estimated error of $\gamma[i]$.

As mentioned above, there are two aspects affecting channel gain, large-scale fading and small-scale fading. When Doppler frequency shift is small, the large-scale fading is constant and the small-scale fading varies slowly. In another word, in short range, estimated error and feed back delay can not weaken the system. When Doppler frequency shift is large, small-scale fading varies severely, that is system can not estimate channel and feed back information effectively in long range. Different adaptive control methods should be adopted according to different range, and there is a definite relation between control methods and communication range. Supposing the distance is *r*, UWA velocity is 1500m/s, time delay $i_d \geq 2r/c$, when $d < 0.001cf_d/2$, system chooses the model to adapt small-scale fading, otherwise to adapt large-scale fading.

5.3 Dynamic modulation and bandwidth optimization

Adaptive dynamic modulation and bandwidth optimization are powerful techniques to improve the energy efficiency and bandwidth ratio over UWA fading channel. Adaptive frequency and bandwidth are natural choices over UWA fading channel. Adaptive modulation and power management over UWA fading channel is investigated in this section.

5.3.1 Define carrier frequency and bandwidth according to the range

For any UWA communication system, the most important parameters are carrier frequency and bandwidth, which are mainly dependent on range and ambient noise. Receiver expects a high SNR, so the principle to choose a proper carrier frequency and bandwidth is to maximize SNR. Based on sonar equation, the optimal frequency can be determined by

$$f_0 = \left(\frac{70.7}{r} \cdot \frac{d(FM)}{df} \right)^{1/2} \tag{14}$$

in which, *FM* is defined as *FM=SL-(NL-DI+DT)*, *SL* is the Source Level of transmitter， *NL* is water ambient Noise Level. The 3dB bandwidth of the optimistic frequency is the system bandwidth.

5.3.2 Define the modulation model and adaptive fading model

For double spread UWA channel, the spread factor is the product of time spread and frequency spread. If the spread factor accesses or overs 1, the channel will be overspread. Non-coherent modulation FSK has been considered as the only alternative for overspread channel.

According the estimated distance *d* and Doppler frequency *fd*, if $d < 0.001cf_d/2$, then the system will adapt to small-scale fading that is fast fading, otherwise will adapt to large-scale fading.

5.3.3 SNR estimation

SNR is an important parameter to optimize modulation and bandwidth in two dimensions channel. There are two estimation methods, one is estimating by sending the test training sequence, and the other is estimating by direct signals received. The former one is inefficient for lower bandwidth availability, and the later one is the main method of SNR estimation.

Supposing the transmission signal is $s_T(t)$, then the received signal through UWA channel with AWGN is

$$y(t)=\sum_{l=1}^{p}\alpha_l \exp[j(\phi_l(t)]s_T(t-\tau_l f_o)+n(t) \tag{15}$$

The self-correlation function of the received signal is

$$\begin{aligned}\phi_{yy}(\tau)&=E[y(t)y(t+\tau)]\\&=E[y_I(t)y_I(t+\tau)]\cos 2\pi f_c\tau\\&-E[y_Q(t)y_I(t+\tau)]\sin 2\pi f_c\tau+\sigma_n^2\delta(\tau)\\&=\phi_{yIyI}(\tau)\cos 2\pi f_c\tau-\phi_{yIyQ}(\tau)\sin 2\pi f_c\tau\ +\sigma_n^2\delta(\tau)\\&=\sigma^2 J_0(2\pi f_m\tau)\cos(2\pi f_c\tau)+\sigma_n^2\delta(\tau)\end{aligned} \tag{16}$$

In the formula, σ^2 is signal power, σ_n^2 is noise power, $J_0(x)$ is the zero-order Bessel function of first kind, $f_m=\Delta f\ /\ f_0$ is normalization Doppler frequency. From the properties of channel impulse response, the above formula is discretized and normalized as

$$\varphi_{yy}(kT_S)=\frac{\sigma^2 J_0(2\pi f_m kT_s)\cos(2\pi f_c kT_s)}{\sigma^2+\sigma_n^2}\qquad (k=1,2,3...) \tag{17}$$

According to the definition of SNR

$$SNR=\frac{\varphi_{yy}(kT_s)}{J_o(2\pi f_m kT_S)\cos(2\pi f_c kT_s)-\varphi_{yy}(kT_s)}\qquad (k=1,2,3...) \tag{18}$$

If f_m is unknown, the equation set can be deduced from Eq.18

$$\begin{Bmatrix}\gamma=\dfrac{\varphi_{yy}(T_s)}{J_0(2\pi f_m T_s)\cos(2\pi f_c T_s)-\varphi_{yy}(T_s)}\\ \gamma=\dfrac{\varphi_{yy}(2T_s)}{J_0(4\pi f_m T_s)\cos(4\pi f_c T_s)-\varphi_{yy}(2T_s)}\end{Bmatrix} \tag{19}$$

γ can be calculated by the equation set. If the system adapts to slow fading channel, the estimated γ can be averaged.

5.3.4 Allocate the instantaneous power of each sub-channel based on the estimated SNR

First, the power of each sub-channel is allocated by $\dfrac{P_j}{P}=\begin{cases}1/\gamma_0-1/\gamma_j & \gamma_j\ge\gamma_0\\0 & \gamma_j<\gamma_0\end{cases}$. Then, instantaneous power of each sub-channel is allocated by $\dfrac{P(\gamma)}{\overline{P}}=\begin{cases}1/\gamma_0-1/\gamma & \gamma\ge\gamma_0\\0 & \gamma<\gamma_0\end{cases}$

5.4 The adaptive multi-carrier modulation in UWA communication

OFDM transports a signal-input data stream on several carriers within the usable frequency band of the channel. This is accomplished by partitioning the entire channel into *N* parallels, ideally orthogonal, and spectrally flat subchannels, each of equal bandwidth, and with center frequency *fn*, *n=1…N*. Thus an OFDM symbol is consisted of several subcarriers which are modulated as PSK or QAM. Each subcarrier can be independently modulated in adaptive modulation schemes or all subcarriers may be modulated in same manner. The bandpass OFDM symbol can be expressed as follows:

$$x(t) = \sum_{n=0}^{N-1} d(n) \mathrm{e}^{\mathrm{j}2\pi f_o t}, \quad t \in [t_0, t_0 + T_s] \tag{20}$$

where *Ts* is the symbol period, f_0 is the carrier frequency, *N* is the number of subcarriers, *d(n)* is the PSK or QAM symbol, and t_0 is the symbol of starting time. The bandpass signal in Eq. 20 can also be expressed in the form of

$$x(t) = [\sum_{n=0}^{N-1} d(n) \exp(\mathrm{j}\frac{2\pi}{T_s} nt)] \exp(\mathrm{j}2\pi f_0 t) = X(t) \times \exp(\mathrm{j}2\pi f_0 t) \tag{21}$$

The baseband signal *x(t)* is sampled at a rate of *fs*, then $t_k = k/fs$. The baseband signal *X(t)* can be expressed in the form of

$$X(k) = \sum_{n=0}^{N-1} d(n) \exp(\mathrm{j}\frac{2\pi}{N} nk) \,, 0 \le k \le (N-1) \tag{22}$$

where $x(k)=x(t_k)$. Eq. 22 shows that *x(t)* is the Inverse Fast Fourier Transform (IFFT) of *d(n)*.

At receiver the FFT is applied to the discrete time OFDM signal *x(t)* to recovery the *d(n)* symbols written in

$$d(n) = \sum_{k=0}^{N-1} X(k) \exp(-\mathrm{j}\frac{2\pi}{N} nk) \,, 0 \le n \le (N-1) \tag{23}$$

Noncoherent detection MFSK transports a signal-input data stream on selected carriers among *N* parallel channels based on coding. A MFSK symbol can be considered as a special case of OFDM symbols. The condition of *d(n)* to be satisfied is that

$$d(n) = \begin{cases} 1, & if \ sending \ subcarrier \\ 0, & others \end{cases} \tag{24}$$

It is clear from Eq. 22, 23 and 24 that dynamic adaptive modulation or demodulation combines MFSK and OFDM effectively and employs the FFT/IFFT algorithm to synthesize the modulation or demodulation without any other algorithms. It selects a suitable modulation or demodulation between OFDM and MFSK according to the estimated parameters of UWA communication channel.

6. Simulation and experiment

6.1 SNR estimation

In order to evaluate the performance of the dynamic adaptive system, an UWA communication experiment was conducted in a lake. The impulse response of the lake is shown in Fig.5.

According to the SNR estimated method, the 2FSK, 2PSK and 4QAM signals in different SNRs are respectively simulated in 100 times. Considering the SNR varying on the receiver and practical application, with the range of SNR [-10 dB, 10 dB], the estimated standard-deviations are shown in Fig.6

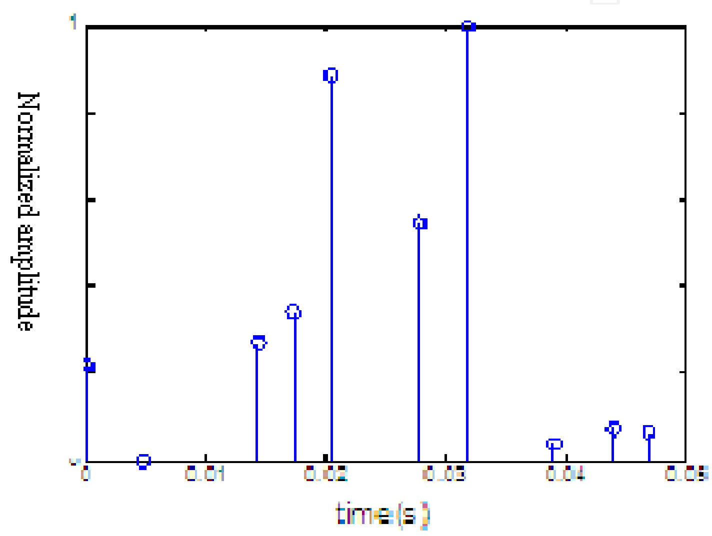

Fig. 5. Impulse response of the lake

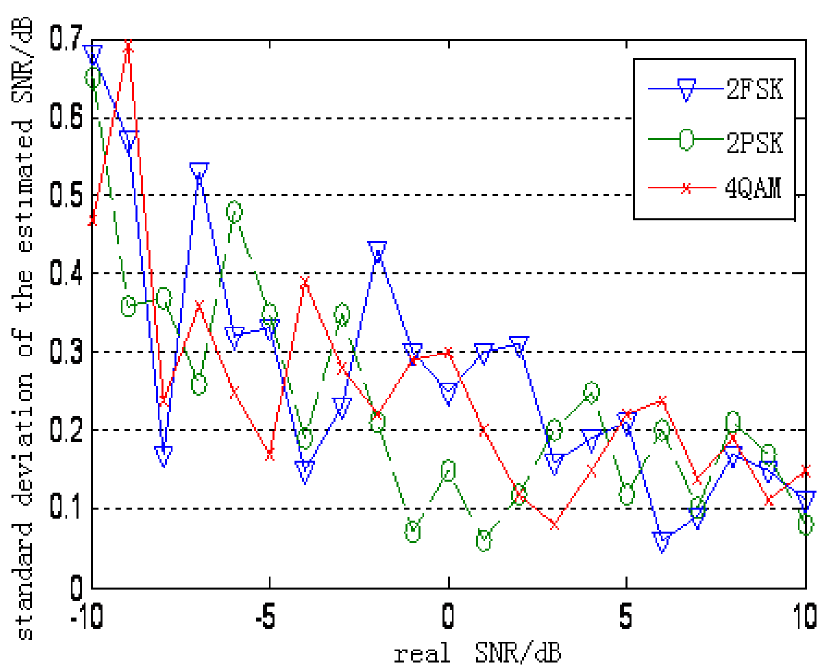

Fig. 6. Average SNR

From the figure, we can see the SNR estimated algorithm performance well. The standard deviation of estimated SNR is less than 0.7dB. So the estimation is available in adaptive UWA communication.

6.2 Simulations

The parameters of adaptive UWA communication system used for performance simulation are showed in Table 3. A linear frequency modulation signal is used for synchronization. The UWA channel is based on the Fig.5, and the relative velocity is 1.5m/s.

Modulation	Bandpass	Bandwidth	Guard interval	FFT /IFFT	Number of sub carrier
MFSK	2~2.2kHz	200Hz	0s	0.2s	1
	2~2.4kHz	400Hz			2
	2~2.8kHz	800Hz			4
	2~3.6kHz	1600Hz			8
OFDM	2~5 kHz	3 kHz	0.05s		300
	2~6 kHz	4 kHz			400
	2~7 kHz	5 kHz			500
	2~8 kHz	6kHz			600

Table 3. Adaptive UWA parameters

To overcome the ISI, system uses a grouped FSK modulation technique. The band is divided into 2 groups, only one of which is transmitted at one time. System uses multiple FSK modulation technique in a group. The band is divided into 2, 4 or 8 subbands based on bandwidth, in each of which an 8FSK signal is transmitted.

Fig. 7 and Fig.8 show that the bandwidth raises at the price of increasing SNR at the same error bit. Compared with Fig.3, 200Hz bandwidth 8FSK can be used for UWA communication at 100km range, and 1200Hz can be used for 40 km. OFDM with 3 kHz bandwidth can be used for UWA communication at 15 km range, and 6 kHz can be used for the short range.

6.3 Lake experiments

An UWA communication experiment which using adaptive system with 1/2 rate turbo error control coding was taken in lake. The results demonstrate the performance of adaptive communication system at the range from 5km to 25km. The modulation schemes, the number of subcarriers, data rate and the bit error rate are given in Table 4.

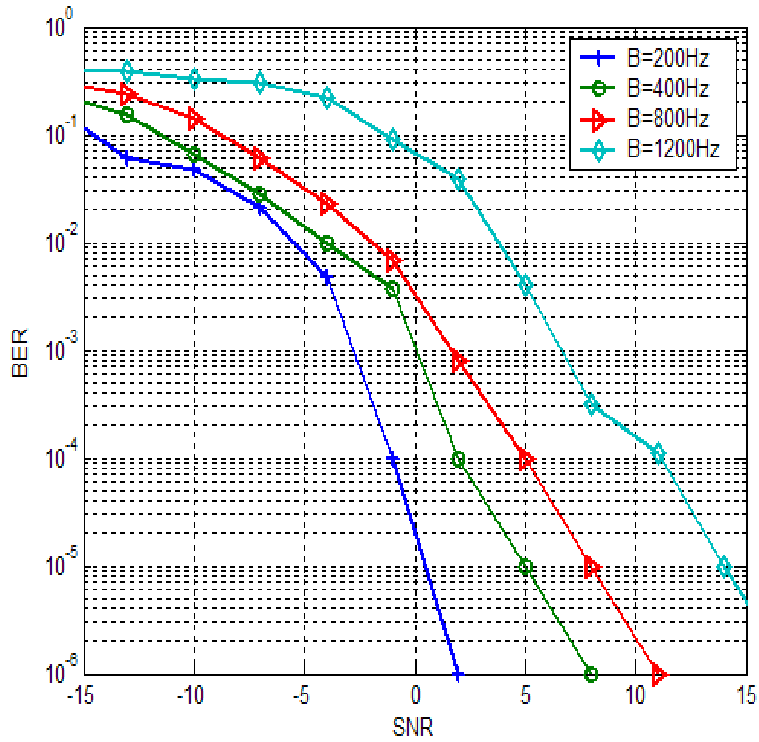

Fig. 7. BER Performance of four kinds of bandwidth of MFSK

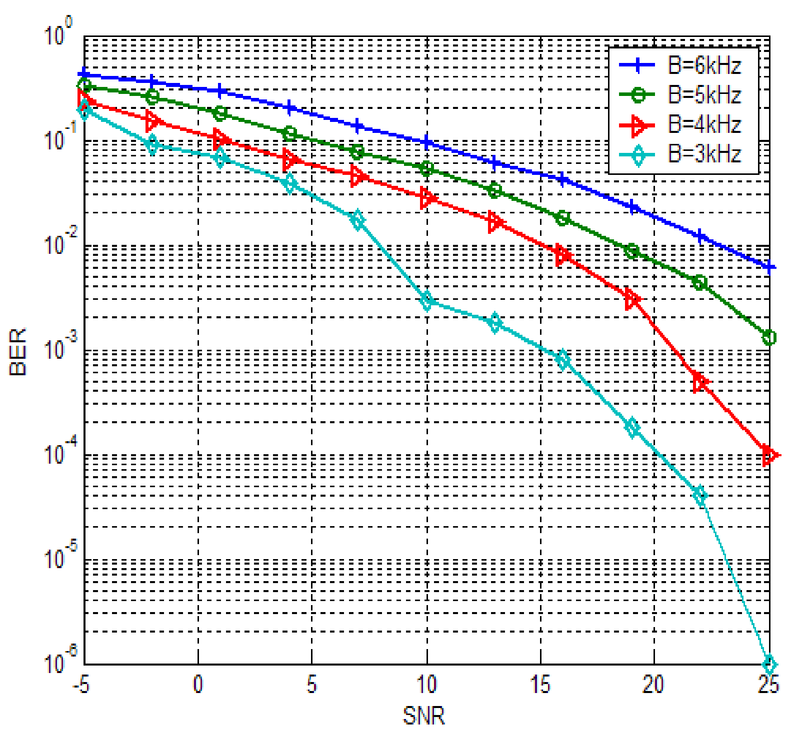

Fig. 8. BER Performance of four kinds of bandwidth of OFMD

Range /km	modulation	number of subcarriers	data rate bs-1	BER /%	BER after decoding
5	OFDM	1000	9090	5.33	$<10^{-4}$
10	OFDM	500	3400	8.40	$<10^{-4}$
15	OFDM	200	1360	8.32	$<10^{-4}$
25	8FSK	16	640	2.55	$<10^{-4}$

Table 4. Results of lake experiment

7. Conclusion

MFSK was seen as intrinsically robust for the time and frequency spreading of long range UWA channel. OFDM has been used in UWA communication at short or medium range. Adaptive UWA communication system combines MFSK and OFDM effectively, which dynamic selects modulation schema and optimizes bandwidth based on UWA communication estimation. This method has obvious advantages: being realized by DFT based filter banks as OFDM, good performance and the high frequency band efficiency in time varying fading UWA channel. Based on the results of simulation and experiments in a lake, it is shown that the adaptive UWA communication system is more efficient for high rate UWA communication not only at short range, but also at medium and long range.

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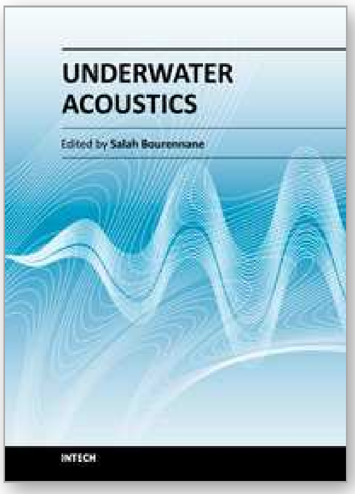

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