A new improvement of RAKE algorithm based on prediction of multipath structure of underwater acoustic channel

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Abstract

An underwater acoustic spread-spectrum communication system is established in this paper. Compare the performances of a direct sequence spread spectrum system and a Rake receive system through simulation based on the decision of multipath structure under the assumption of dual beam channel in shallow water with thermocline, the approximate expression of the bit error rate is given. Simulation results show that multipath structure with certain features could truly play the role to eliminate inter-symbol interference (ISI) and improve performance of the receive system. A demodulation algorithm is proposed based on the characteristics of multipath structure prediction and the feasibility of it is verified through processing the trail data.

Keywords: multipath structure; inter-symbol interference; Rake
A New improvement of RAKE Algorithm Based on Prediction of Multipath Structure of Underwater Acoustic Channel

1 Introduction

Since the diversification of time–space–frequency characteristics, underwater acoustic communication system is more complex than electromagnetic wave communications system. From analogy to digital communication, from the non-coherent to coherent communication, underwater acoustic communication still faces many challenges. First, because of the absorption and attenuation of underwater acoustic propagation channel, the energy of the acoustic signal decreases rapidly with propagation distance increases, also there is strong noise, such as ambient noise and ship noise, propagation loss and noise reduced signal to noise ratio (SNR), resulting in increased bit error rate [1,2]. Secondly, affected by multipath effect or Doppler Effect, signals travel in the underwater communication channel, especially in shallow water channel; generate inter-symbol interference (ISI) when they reach the receiver [3,4].

Multipath effect is the main reason which brings in ISI. Different group velocities of some order normal mode pulses that compose sound field or different paths that sound waves travel in underwater channel is the origin of Multipath effect from normal mode theory or ray theory.

Spread spectrum communication system obtains the processing gain (spreading gain) which could be used to suppress noise and interference encountered in the signal propagation process and to improve performance of the communication system by taking advantage of the correlation of the pseudorandom sequence. After decades of development, whether in the military or civilian areas, spread spectrum communications have been widely used [6-9]. Underwater acoustic communication Modem produced by LinkQuest Co., Ltd achieves high-speed underwater acoustic communication use spread spectrum as basic communication system [10]. Spread spectrum communication combined with Rake receiver technology could improve system performance by searching and separating signals travel in multipath employing the auto-correlation properties of the spreading codes, finally combining them according to certain criterion (selective, equal gain or maximum-ratio).

In electromagnetic wave communication, the maximum delay spread of the multipath fading channel is \( T_m \), Rake receiver uses a broadband, pseudo-random signal having a certain bandwidth \( B \) and \( B >> 1/T_m \). The width of the self-correlation function is in the order of one symbol period (1/B), so it is feasible to distinguish various multipath components for coherent combination [11, 12].

Affected by reflections of surface and seabed, multipath structure of shallow water underwater acoustic channel is too complex to utilize. Complexity of multipath structure is the origin of ISI each other and results in damage of autocorrelation. That is: in shallow water underwater acoustic communication, Rake receiver does not improve system performance for sure.
This paper establishes a direct sequence spread spectrum communication system under the assumption of dual beam channel in shallow water with thermocline according to ray theory. Rake receiver is implemented using pilot comb equalization algorithm to estimate the phase offsets and compensate them. Comparison of the performances of direct sequence spread spectrum system and the Rake receiver in dual-beam channel is presented. The approximate expression of bit error rate (BER) of the two systems is derive. This paper puts forward a multipath structure prediction method for selecting the system demodulation algorithm, and verifies it with the trail data.

2 Dual-beam channel multipath structure in shallow water with thermocline

In summer and autumn season, many shallow water areas with thermocline appear in offshore of China. In this case, water is generally composed of three layers: the surface layer, the intermediate layer, the bottom layer, the depth of them is h, d, H, respectively. The speed of sound of surface layer and bottom layer are $c_0$ and $c_1$, Sound speed of the intermediate layer decreases rapidly with depth, called negative thermocline. Sound speed gradient in the upper and lower thermocline is very small, that is surface and bottom layer are close to the uniform layer. Sound ray propagation paths are different, and there are certain rules simulated in the use of Bellhop model.

The nature of multipath effect is the differences of time that sound waves arrival receiver through different propagation paths. Reference [13] presented the causes of multipath structure in shallow water with negative thermocline using ray theory. The research showed that within a certain range, there is a stable structure of multipath and different frequency pulses have similar macro-structure and micro-structure. This paper assumes that there are only two path, direct ($s_1(t)$) and secondary ($s_2(t)$), reach the receiver, the other paths are invalid path, as Figure 1 shows.

Under the assumption of dual-beam channel, when transmitter and receiver are above the thermocline, delay between direct and second wave can be expressed as equation (1)
\[ \Delta T = \frac{2H \sqrt{c_0^2 - c_1^2}}{c_0 c_1} \left( 1 + \frac{2d}{3H} \right) \]  

(1)

Features of multipath structure include parameters such as amplitude and delay between each path. It is hard to calculate the amplitudes of each path through the normal mode theory or ray theory because of the complexity of the marine environment and underwater acoustic channel. Parameters of multipath structure in a certain season and area are obtained by means of trails. Assume amplitudes of direct wave and second wave are \( \alpha, \beta \), respectively, system function of the dual-beam propagation channel can be expressed as equation (2)

\[ h(t) = \alpha \delta(t) + \beta \delta(t - \Delta T) + n(t) \]  

(2)

In order to facilitate the calculation of SNR, assumed \( \beta < \alpha \), normalized \( \alpha = 1, 0 < \beta < 1 \), system function can be expressed as equation (3)

\[ h(t) = \delta(t) + \beta \delta(t - \Delta T) + n(t) \]  

(3)

3 Direct sequence spread spectrum communication system

3.1 Communication waveform design

Direct sequence spread spectrum (DSSS) communication signal structure shown in Figure 2.

<table>
<thead>
<tr>
<th>Frame synchronization</th>
<th>Synchronization sequence</th>
<th>Information sequence</th>
</tr>
</thead>
</table>

Source: (Author, 2013)

**Figure 2: DSSS signal structure**

Each Frame of communication signal is composed of frame synchronization signal and the information signal. Frame synchronization signal is a known sequence modulating spreading code. In burst packet communication mode, it is used to capture or synchronizes signal frame. Information signal includes synchronization sequence and information sequence. After capturing signal frame, receiver utilizes synchronization sequence to track spreading code for fine synchronization. Information sequence carries origin information.

Information signal \( s(t) \) is balance QPSK direct sequence spread spectrum modulation of information sequence \( d_0(t) \) and synchronization sequence \( d_1(t) \). \( s(t) \) can be expressed as equation (4)

\[ s(t) = A d_0(t) C_1(t) \cos(2\pi f_0 t) + A d_1(t) C_2(t) \sin(2\pi f_0 t) \]  

(4)

\( C_1, C_2 \) are two different Gold codes, noise suppression ability and communication rate are determined by their lengths. \( f_0 \) is carry wave frequency.
3.2 Transmitter

Transmitter shown in Figure 3. Baseband signal is obtained by original information modulating spreading code. Passband signal is obtained by baseband signal modulating carry wave. Finally, communication signal is emitted by the transmitter.

![Figure 3: DSSS Transmitter](source: (Author, 2013))

3.3 DSSS receiver

DSSS receiver shown in Figure 4. Correlation of frame synchronization signal provides feasibility to synchronize and track data frame. Once capturing signal frame, origin information is recovered after digital demodulation and dispreading.

![Figure 4: DSSS receiver](source: (Author, 2013))

3.4 Rake reviver

During dispreading process, Rake receiver technology makes use of correlation of spread code, searches and separates effective paths, finally combine them in accordance with certain rules. Synchronization sequence and information sequence employed herein are synchronized, this paper searches paths using synchronization sequence to avoid the accumulation of synchronization error. Rake receiver is a baseband signal processor and added some pilot information in sequence information, in order to overcome phase offset produced during demodulation, Information sequence shown in Figure 5.

\[
\text{pilot bit:1} \cdots \cdots \cdots \text{bit:n pilot bit:1}
\]

![Figure 5: Information sequence structure](source: (Author, 2013))

There are three combining criterions called selective, equal gain and maximum-ratio could be used in Rake receiver commonly. Although maximum-ratio criterion which demands maximum output SNR could achieve the best performance, it is almost impossible for underwater acoustic communication because of unknown distribution function of the channel as prior knowledge. In this paper, equal gain criterion is adopted for signal combining, and the system executes combined result to statistical decision to restore the original information. Rake receiver shown in Figure 6.
4 BER comparison between DSSS and Rake receiver under assumption of dual-beam channel

4.1 BER expression

Transmitter signal \( s(t) = Ad(t)C(t)\cos(2\pi f_0 t + \varphi_0) \), system function of dual-beam channel can be expressed as equation (3), receive signal can be expressed as \( r(t) = s(t) * h(t) + n(t) \), that is expressed as equation (5)

\[
r(t) = Ad(t-T_{id})c(t-T_{id})\cos(2\pi f_0 + \varphi) + \beta Ad(t-T_{zd})c(t-T_{zd})\cos(2\pi f_0 + \varphi_2) + n(t)
\] (5)

\( Ad(t-T_{id})c(t-T_{id})\cos(2\pi f_0 + \varphi) \) is direct arrive signal wave and \( \beta Ad(t-T_{zd})c(t-T_{zd})\cos(2\pi f_0 + \varphi_2) \) is the secondary one.

Assume direct wave is synchronized to receiver, \( \hat{T}_d = T_{id} \), \( \hat{f}_0 = f_0 \), \( \hat{\varphi} = \varphi_1 \), signal after demodulation and dispersing can be expressed as equation (6)

\[
y(t) = Ad(t-T_{id}) + \beta Ad(t-T_{zd})c(t-T_{zd})\cos(\varphi_2 - \varphi_1) + n'(t)
\] (6)

The first item is the demodulation result of direct wave, and the second item can be considered as ISI cause by secondary wave. Because of correlation of spread code, \( E[c(t-T_{zd})c(t-T_{id})] = -1/(2^m-1) \), the power of secondary wave can be expressed as equation (7)

\[
P_2 = \frac{\beta^2 A^2}{2} \left( -\frac{1}{2^m-1} \right)^2 \cos(2(\varphi_2 - \varphi_1)) + 1 \leq \frac{\beta^2 A^2}{4}
\] (7)

For PSK modulation system, BER can be expressed as \( Q \) function. Spreading length of DSSS is \( M \), noise power is \( N_0/2 \), and then SNR and BER can be expressed as equation (8) and (9)
\[ SNR = \log \left( \frac{A^2}{2} + 10 \log M \right) - \log \left( \frac{\beta^2 A^2}{4} + 10 \log \frac{N_0}{2} \right) = \log \left( \frac{\frac{A^2}{2} + G}{\frac{\beta^2 A^2}{4} + n_0} \right) \]  

(8)

\[ ber_{dss} = Q \left( \frac{A^2}{2} + G - \left( \frac{\beta^2 A^2}{4} + n_0 \right) \right) \]  

(9)

For Rake receiver, power of direct wave is \( A^2/2 \), power of secondary wave is \( \beta^2 A^2/2 \), ISI power of direct wave impacting secondary wave is \( A^2/4 \), ISI power of secondary wave impacting direct wave is \( \beta^2 A^2/4 \). BER of Rake receiver can be expressed as equation (10)

\[ ber_{\text{rake}} = Q \left( \frac{A^2}{2} + \frac{\beta^2 A^2}{2} + G - \left( \frac{\beta^2 A^2}{4} + \frac{A^2}{4} + n_0 \right) \right) \]  

(10)

From equation (9) and (10),

\[
\begin{align*}
ber_{dss} & > ber_{\text{rake}} & & 1 \sqrt{2} < \beta < 1 \\
ber_{dss} & = ber_{\text{rake}} & & \beta = \frac{1}{\sqrt{2}} \\
ber_{dss} & < ber_{\text{rake}} & & 0 < \beta < \frac{1}{\sqrt{2}}
\end{align*}
\]  

(11)

BER of DSSS and Rake receiver with variety of \( \beta \) shown in Figure 7.

Source: (Author, 2013)

**Figure 7:** BER of DSSS and Rake receiver with variety of \( \beta \)
4.2 Simulation result

Simulation results of two receive algorithms under different SNR with variety of $\beta$ shown in Figure 8.

![Graphs showing BER of two receive algorithms under different SNR with variety of $\beta$.](source)

Figure 8: BER of two receive algorithms under different SNR with variety of $\beta$

It is could be found that when power of secondary wave less than a certain value, BER of DSSS is lower than Rake receiver; when power of secondary wave exceeds that value, BER of DSSS is high than Rake receiver under some different SNR. It should be noted it can be considered as direct wave when the secondary wave's amplitude greater than 1.

These results suggest that the two sides of multipath effect of underwater acoustic channel. When the power of second wave is low, its SNR is low similarly, multipath effect is reflected as the main source of ISI resulting in the coherent combined SNR decreases. At this time, direct wave dispersing is affected. When the power of second wave is relatively high, multipath effect is reflected as diversity energy, synthesis SNR of direct wave and secondary wave becomes high. At this time, performance of communication becomes better.

That is, although each path can be separated taking advantage of autocorrelation property of the spreading code, signal structure is damaged by increase of communication distance, propagation loss and serious disturbance. At this second, even if all the power can be resolved, it does not reduce the error rate for sure.

4.3 A demodulation method based on characteristics of multipath structure prediction

Since different multipath structures result in different performances of two demodulation algorithms above, before the demodulation, we can use the multipath prediction analysis module to estimate basic characters of it, in order to determine which demodulation scheme employed to optimize system performance. Demodulation algorithm based on multipath prediction shown in Figure 11.

5 Method test using trail data

Trail data in Qiandao Lake in Zhejiang Province, China, April 2011 was used to test method above. Qiandao Lake is upstream of Xin'anjiang Reservoir, underwater situation is complicated.
because there were mountains or village before. The carrier frequency is 6 kHz, bandwidth is 2 kHz, PSK modulation, the spreading code number order is 6.

5.1 Multipath structure prediction
Multipath structural changes 0 ~ 70s is shown in Figure 9.

![Figure 9: Multipath structural changes 0 ~ 70s](image)

Source: (Author, 2013)

5.2 Demodulation result
Table 1 shows the demodulation results of DSSS and Rake receiver.

<table>
<thead>
<tr>
<th>time[s]</th>
<th>0</th>
<th>10</th>
<th>20</th>
<th>30</th>
<th>40</th>
<th>50</th>
<th>60</th>
<th>70</th>
</tr>
</thead>
<tbody>
<tr>
<td>DSSS</td>
<td>0</td>
<td>0.03125</td>
<td>0.03125</td>
<td>0.046875</td>
<td>0.015625</td>
<td>0.078125</td>
<td>0.078125</td>
<td>0.03125</td>
</tr>
<tr>
<td>Rake</td>
<td>0</td>
<td>0.015625</td>
<td>0</td>
<td>0.03125</td>
<td>0.015625</td>
<td>0.14</td>
<td>0.046875</td>
<td>0.09375</td>
</tr>
</tbody>
</table>

As shown in Figure 15, it is supposed that in the 0 ~ 40s, in addition to the direct wave, the secondary wave was significantly greater than the noise power before and after, BER of Rake receiver is lower than the DSSS; in 50~70s, conversely, BER of Rake receiver is higher, because there is only a significant direct wave, along with lower energy and other path-aliasing interfere with each path which is the source of ISI. In the situation, the combination could not improve the system performance, but makes the error rate increases.

6 Conclusions
According to ray theory, a shallow water underwater channel multipath structure with negative thermocline and direct sequence spread spectrum communication system were established in
this paper. Comparison of BER between DSSS and Rake receiver and approximate expressions of them were presented. Simulation results showed that two sides of multipath effect of underwater acoustic channel which are diversity combining energy and source of ISI. Rake technology could overcome multipath interference and improve system performance in certain conditions. In this paper, demodulation algorithm based on multipath structure prediction method was proposed; Lake Trail data analysis results verified the feasibility of the method.

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References