Analysis of Channels Impulse Response Due to Transducer Movements in Underwater Acoustic Communication

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Abstract. This study discussed the effect of transducer movement in underwater acoustic communication based on simulation analysis. A proposed underwater communication testing platform which is a 10 m x 2.5 m x 1.5 m mini towing tank is used as the communication channel. In the simulation analysis, channels boundary interaction is simulated using image method consists of 6 ray element and the transducer movements is assumed to have relative velocity between each other. Due to the relative velocity, Doppler frequency shift is occurred and gives amplitude variation in Channels Impulse Response (CIR). Several Doppler spread value was given to analyze the CIR. The simulation result indicates that, Relative velocity Doppler effects contributes big amplitude variation in the arrival structure of channels impulse response (CIR). When relative velocity or Doppler spread increases, the amplitude variation and the phase variation of arrival structure also increases.

1. Introduction

The simple ping signal which is used by sonar that operates in audible band was developed as the fundamental improvement for underwater communication [1]. Recently, numerous developments had been introduced in this field i.e. simulation or measurements approach in ocean, point to point acoustic link until the applications of autonomous network for ocean observations [2]. Besides the numerous applications, underwater acoustic communication (UAC) has many challenges and problems. Due to strong absorption of high frequency sounds by sea water the available bandwidth was very limited [3]. Small scale fading usually appears in digital communication, which is because of the signal time spreading and time variant nature from the channel [4]. It is a result of the motion within channel and specifically movement of source and receiver. Doppler spread and coherence time were the parameters which are usually used to describe the channel’s time-varying nature [5]. Several inter symbol interference (ISI) and fluctuations in the received signal occur due to fluctuation of random amplitudes and phases of multiple arrivals. Multipath and time-varying effect can be characterized by channel impulse response (CIR). It was considered varying over time if the channels itself are not in stationary condition [6]. Time-varying effect will reduce the communication quality and become very challenging point for researchers to solve this problem. In 2007, Chitre [7] investigated the variations of arrival time lag and amplitude which are determined by transducer movement and Doppler effects. Assigning the time-varying multipath effect as the main topic, the purpose of this study is to simulate underwater acoustic communication in testing platform. A 10 m x 2.5 m x 1.5 m mini towing tank is proposed as the suitable and very challenging testing platform to test the underwater communication process under time-varying condition. Utilizing the benefit of wave making towing tank, Kusuma [8]
presented simulation analysis of underwater acoustic communication using mini towing tank as channel of communication which the result indicates that this channel has a characteristic that multipath effect is the main challenging problem. However, in this simulation study discussed the effect of transducer movements in underwater acoustic communication testing platform. The transducer movement is assumed to have relative velocity between each other. Due to the relative velocity, Doppler frequency shift is occurred and gives amplitude variation in Channels Impulse Response (CIR). All of the simulation process is conditioned in accordance with the measurement in real condition. Channels impulse response is analyzed with considering several values of Doppler frequency shift and comparing it with the original impulse response. The aim of this analysis is to understand the characteristics and sensitive variables of time-varying multipath effect in the testing platform.

2. Methodology

2.1. Channel Modeling
In the simulation process, Binary phase–shift keying (BPSK) signals with 2 ms in length and centered at 10 kHz was transmitted from source to the receiver. Furthermore, the interactions between acoustic signals and boundaries of towing tank may give multipath effects. To analyze channel’s boundary interactions, the method of image was applied with considering 8 reflection paths as shown in Figure 1. The 6 ray elements which shown in Figure 1. i.e. Direct path (dp), Surface path (sp), Surface bottom path (sb), Bottom surface path (bs), Bottom path (bp), Left wall path (lw), Right wall path (rw) and back wall path (bw). The interaction between signal and boundaries generates multiple travel paths in the signal transmission. The channel impulse response (CIR) of multipath arrival can be written as

$$H(\omega) = \sum_{n=1}^{L} a_n e^{-j\omega \tau_n}$$  \hspace{1cm} (1)

Here, $a_n$ and $\tau_n$ are the amplitude and time delay of the $n$th ray respectively. Doppler spread is one of parameter which is used to describe channel’s time-varying nature. The time variance itself is a result from the movement of transducer or channel itself. For Doppler frequency shift due to moving transducer, multipath signals are emitted from source at different angles and arrive at receiver with different angles [17]. Maximum Doppler frequency shift ($f_D$) can be written like the following equation

$$f_D = f \frac{v}{c} \cos(\theta)$$  \hspace{1cm} (2)

Where, $f$ is carrier frequency, $v$ is moving speed of transducer, $c$ is sound speed and $\theta$ is the emission or arrival angle. If we consider the range of cosine is within -1 and +1, then $f_D$ becomes

$$\pm f_D = f \frac{v}{c}$$  \hspace{1cm} (3)

Furthermore, the maximum Doppler angular frequency shift of the $n$th ray is

$$\omega_n = 2\pi f_n \left| f_n \right| \leq f_D$$  \hspace{1cm} (4)

Thus, the impulse response affected by Doppler shift becomes:

$$H(\omega, t) = \sum_{n=1}^{N} a_n e^{-j\omega \tau_n + j\omega t}$$  \hspace{1cm} (5)
2.2 Time Reversal Mirror

Time Reversal Mirror (TR) or Passive Phase Conjugation (PPC) in frequency domain were proposed to focus energy at desired depth thus to mitigate the effects of multipath dispersion and inter-symbol interference (ISI) from time-varying condition. TR can be classified into active time reversal and passive time reversal process [9]. The active time reversal process must implement directly in real environment, on the other hand, passive TR procedure for transmitting signals was implemented via computer simulation. Suppose that \( s(t) \) is the source signal time domain, \( p(t) \) is the receive signal time domain, \( h(t) \) is the channel impulse response (CIR) between the source and the receiver. Furthermore, \( p(t) \) in time domain can be expressed as the following equation:

\[
p(t) = h(t) \otimes s(t)
\]

(6)

Where \( \otimes \) denotes the convolution integration. According the process of TR, if source location is interchanged with receiver location and source signal is changed to time reversal signal of receiver, then the received signal \( z(t) \) and its time reversal signal \( z(-t) \) at original source location can be expressed as the following equations respectively.

\[
z(t) = h(t) \otimes p(-t)
\]

(7)

\[
TRM(t) = z(-t) = h(-t) \otimes h(t) \otimes s(t)
\]

(8)

The output of \( TR(t) \) is similar with original source signal.

2.3 Image Method

In this technique, the Green’s function is decomposed into the free-space Green’s function plus a sum of contributions from image sources, which fall outside the region of interest [10]. From the benefit of this method, it can be explored into underwater communication especially in the shallow water to simulate the boundary condition. As we know that the main problem for shallow-water communication channel, especially in the underwater communication testing platform is the reflection from the boundary. The interaction between signals and boundaries will be extended multipath and refractive properties and induced severe inter-symbol interference in the received signal. The solution of the problem is where the upper interface is soft and the lower interface is hard. Here, the channel surface and bottom are considered as two mirrors. The rays which hit the surface and bottom are then starting exactly at the images of the actual sources of origin. With this logic the whole image or mirror method is developed and thereby it is easy to provide mathematics for multipath propagation [11]. A schematic representation of the contributions from the physical source at depth \( z_r \) and the first three image sources, leading to the first four terms in the expression for the total field can be described by the following equation:
\[ P(r, z, \omega) \approx A(\omega) \left\{ \frac{e^{-j\lambda_{01}}}{L_{01}} + \hat{R}_1(\varphi_{02}, \omega) \frac{e^{-j\lambda_{02}}}{L_{02}} + \hat{R}_2(\varphi_{03}, \omega) \frac{e^{-j\lambda_{03}}}{L_{03}} + \hat{R}_4(\varphi_{04}, \omega) \frac{e^{-j\lambda_{04}}}{L_{04}} \right\} \]

Where \( A(\omega) \) is amplitude of the signal and \( i = 1,2 \). Then the length's of all rays can be write as

\[ L_{m1} = \sqrt{r^2 + (2D_m - z_s + z)^2} \]  

\[ L_{m2} = \sqrt{r^2 + (2D_m + z_s + z)^2} \]  

\[ L_{m3} = \sqrt{r^2 + (2D(m+1) - z_s - z)^2} \]  

\[ L_{m4} = \sqrt{r^2 + (2D(m+1) + z_s - z)^2} \]  

3. Simulation Process

In the simulation, first analysis is simulated stationary channel condition, this condition means that the transducer position was fixed and without the movements of transducer occur during the transmission process. The stationary channel was simulated as the original condition of the channels impulse response (CIR). After that, the second analysis is considering the movement of transducer with the assumption of relative velocity between each transducer. Due to the relative velocity, Doppler frequency shift is occurred and gives amplitude variation in Channels Impulse Response (CIR). Several value of Doppler spread is analyzed to understand the effect of each Doppler spread value to CIR. With adding random analysis in CIR allowed us to provide time-varying condition for this case. Furthermore, the CIR for each case will be compared between original condition and time-varying condition. The simulation input data and diagram for the interaction of ray element with channel boundary in the testing platform can be shown in Table 1 and Figure 1 respectively. These cases will be discussed respectively as the following sections in order to understand clearly the influence of each case in underwater communication.

| Parameter          | Symbol | Value                        |
|--------------------|--------|------------------------------|
| Range              | \( m_x \) | 6 m                          |
| Water Depth        | \( D \)  | 1.5 m                        |
| Source Depth       | \( z_s \) | 0.5 m                        |
| Receiver Depth     | \( m_z \) | 0.2 m                        |
| Sound Speed        | \( C \)  | 1500 m/s                     |
| Carrier Frequency  | \( F_c \) | 10 kHz                       |
| Sampling Frequency | \( F_s \) | 200 kHz                      |
| Transmitted Time   | \( T_t \) | 0.02 s                       |
| Transmitted Symbol | \( B_s \) | 100 bits BPSK Signal         |
| Doppler Spread     | \( f_D \) | 5 Hz, 10 Hz, 15 Hz, 25 Hz, 40 Hz, 50 Hz, 80 Hz, 100 Hz |
| Ray Element Number | \( N \)  | 6                            |

4. Simulation Analysis

4.1 Analysis of Channel Impulse Response at Original Condition

In this paper, it only shows the simulation results for one-time signal transmission at 6 m distance of communication. The Binary phase-shift keying signaled with consists of 100 bits symbol was transmitted through the channel. The transmission time is 0.02 s with 200 kHz carrier frequency. The communication result is characterized in the arrival structure to analyze the arrival time of CIR as
shown in Figure 2 (a). Furthermore, the received signal shown to analyze the frequency shifting due to Doppler effects as shown in Figure 2 (b). The result indicates that 6 ray element of image method describes the interaction between the signal and boundary of the channel and contributes the multipath condition. Based on previous research, this condition will reduce the communication quality and bit error rate was high [8]. However, this condition will more complicates if the transducer have relative velocity between each other. In order to understand how big the movement of transducer affects this CIR, the original condition is given random analysis of Doppler frequency shift.

![Channel Impulse Response](image1)

**Figure 2.** (a) Channels impulse response and (b) Received signal of 6 m distance of communication without the movement of transducer (Original)

### 4.2 Analysis of Channel Impulse Response Affected by Doppler Frequency Shift

In this case, the transducer movement is assumed to have relative velocity between each other. Due to the relative velocity, Doppler frequency shift is occurred and gives amplitude variation in the arrival structure of CIR. Eight variations of the Doppler spread were evaluated i.e. \( f_{D} = 5 \) Hz, \( f_{D} = 10 \) Hz, \( f_{D} = 15 \) Hz, \( f_{D} = 25 \) Hz, \( f_{D} = 40 \) Hz, \( f_{D} = 50 \) Hz, \( f_{D} = 80 \) Hz and \( f_{D} = 100 \) Hz. Doppler Spread is determined by the relative velocity of the transducer based on equation (2-5) respectively.

| Condition of CIR                  | Frequency Shifting at Ray Element (Hz) |
|-----------------------------------|---------------------------------------|
| Original                          | 0.1996 0.1981 0.1854 -0.1817 0.1713 0.1427 |
| Doppler Shifts (\( f_{D} = 5 \) Hz) | 0.1992 0.1975 0.1853 -0.1809 0.1704 0.1417 |
| Doppler Shifts (\( f_{D} = 10 \) Hz) | 0.1982 0.1958 0.1848 -0.1792 0.1689 0.1419 |
| Doppler Shifts (\( f_{D} = 15 \) Hz) | 0.1975 0.1919 0.1853 -0.1806 0.1702 0.1365 |
| Doppler Shifts (\( f_{D} = 25 \) Hz) | 0.1882 0.1745 0.1800 -0.1609 0.1488 0.1085 |
| Doppler Shifts (\( f_{D} = 40 \) Hz) | 0.1869 0.1928 0.1395 -0.1712 0.0960 0.0655 |
| Doppler Shifts (\( f_{D} = 50 \) Hz) | 0.1855 0.1285 0.1845 -0.1784 0.1221 0.0558 |
| Doppler Shifts (\( f_{D} = 80 \) Hz) | 0.1502 0.1771 0.0244 -0.1409 -0.06355 -0.0826 |
| Doppler Shifts (\( f_{D} = 100 \) Hz) | 0.1876 -0.0179 -0.0232 0.0848 0.02695 -0.1034 |
Figure 3. (a,b,c) Channels impulse response of 6 m distance of communication with 15 Hz, 25 Hz, 40 Hz Doppler Spread and (b) Received signal of 6 m distance of communication with 15 Hz, 25 Hz, 40 Hz Doppler Spread
With the similar procedure and process from previous case, the Doppler spread effect and frequency shift can be analyzed in the arrival structure and received signal figure 3 (a, b, c) and (d, e, f) above. These figures indicate that, Relative velocity Doppler effects contributes amplitude variation in the arrival structure of channels impulse response (CIR). When relative velocity or Doppler spread increases, the amplitude variation and the phase variation of arrival structure also increases. Relative velocity Doppler effects leads to a significant error rate when Doppler spread ($f_d$) is larger than 15 Hz. The full comparison between stationary condition and Relative velocity Doppler effects can be shown in table 2 above. The comparison allows us to understand the characteristic of amplitude variation at each Doppler spread.

5. Conclusion

This simulation study discussed the effect of transducer movement in underwater acoustic communication. The transducer movement is assumed to have relative velocity between each other. Due to the relative velocity, Doppler frequency shift is occurred and gives amplitude variation in the arrival structure of CIR. The results can be concluded that amplitude variation increases when the Doppler spread increases and gives a significant frequency shifting when Doppler frequency spread above 15 Hz. However, the current study was limited by frequency domain cases. Further investigation, such as, combination effect between multipath effect and relative velocity Doppler effect is need to be consider for further parametric study as the real condition approach.

6. References

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