Linear frequency modulation signal for channel impulse response measurement in shallow water environment

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Abstract. Understanding the characteristics of channel propagation plays a very important role in the design of underwater acoustic communication. Underwater acoustic channel (UAC) model is usually carried out by measuring directly at a specific location and time. This paper presents the use of Linear Frequency Modulation (LFM) signal for channel impulse response estimation and power delay profile (PDP) measurement in a shallow water environment. Measurements were made in a laboratory-scale towing tank with three variations of distance and depth. Furthermore, the measurement results are compared with the existing underwater acoustic channel model. The measurement results show that the response impulses at the three distances have almost the same pattern and the resulting amplitude is similar to the existing underwater acoustic channel model simulation. The RMS delay spread generated from the three distances has a value of about 0.2 msec. Meanwhile, the maximum excess delay obtained at a distance of 120 m has the highest value, which is 29 msec.

1. Introduction

The role of underwater communication and network is crucial for commercial and military needs. In recent decades, the amount and quality of research in the field of underwater communication has risen rapidly. The need to communicate between sensor nodes in a sensor network requires the characterization of an underwater acoustic channel. Due to the complexity of the underwater environment for communication, many researchers have focused on different aspects of characterizing an underwater acoustic communication channel as in [1]. Each environment has different characteristics that affect the performance of a digital communication system [2]. Therefore, it is necessary to characterize the underwater communication channel based on the measurement of the channel parameters where the communication system is applied.

Sound propagation in the ocean is very complex and must be well understood. Moreover, sound propagation in a shallow water environment. Shallow water acoustic communication channel categorized as a multipath fading channel. Usually, in shallow water the signal experiences a long
multipath delay spread, resulting in intersymbol interference (ISI) if the delay spread exceeds the symbol period in the communication system. Significant Doppler distribution in the frequency domain or short coherent time in the time domain is a phenomenon that often occurs on this channel. Due to reflections on the ocean’s boundaries and refractions due to the sound speed that varies with depth, sound tends to propagate through multiple trajectories. Sea temporal variability combined with low sound speed can cause significant Doppler shifts. As a result, the channel will be affected by time and/or frequency dispersion.

Some studies regarding the characterization of shallow water acoustic channels include the following: Loubet and Jourdain [3] who examined the Northern Sea at a depth of 500 m, Cook and Zaknich[4] at a depth of 4 m of Fremantle Fishing Boat Harbor in Western Australia. In 2011, Borowski conducted his research on multipath underwater acoustic communication channel[5] and P. Van Walree [6] in 2009. Research on probe signal for estimating impulse response has also been carried out in [7] using pseudo-noise (PN)-sequence signal, exponentially sine swept (ESS), and amplitude-modulated ESS (AM-ESS). The measurement of response impulse is to get the characteristics of the underwater acoustic channel.

This paper presents an evaluation of the use of Linear Frequency Modulation (LFM) signal as a probe signal for impulse response measurement in shallow water acoustic channel. In this study, the shallow water environment is represented by the environment of a towing tank which has dimensions of 200 m x 12 m x 6 m. The measurement data is used to get the propagation parameter, namely the channel impulse response (CIR). Furthermore, the results obtained are compared with the underwater acoustic channel (UAC) model performed by Parastoo Qarabaqi [8].

This paper is organized as follows. Section 2 describes the measurement setup, linear frequency modulation signal as a probe signal, and channel impulse response (CIR) estimation. Section 3 presents a comparison of the CIR obtained from measurement with the UAC model performed by Parastoo Qarabaqi. Section 4 summarizes the results that were obtained in this study.

2. Measurement-Based Model of Shallow Water Environment

2.1. Measurement Setup

The impulse response measurement is carried out on a towing tank belonging to the Indonesian Hydrodynamics Laboratory (IHL)-BPPT which has 200 m in length, 12 m in width, and 6 m in depth. Before the impulse response measurement process, the same scenario was carried out to determine the environmental noise character as in the study [9]. The measurements were made along with the towing tank with 3 variations of distance and depth. The scenario can be shown in Figure 1. The towing tank has a wall and bottom made of concrete material. The media inside is freshwater and with 999.9720 kg / m³ ~ 1.0 kg/liter density at 4°C (39°F) and the liquid has a temperature between 27°C-29°C. There are no transient waves and noise in the towing tank [10].

At figure 1, an underwater speaker is placed at a depth of 3 m below the surface as a sound source. There is a distance of 20 m between the pool wall and the speaker. The underwater speaker is connected to a power amplifier and a personal computer (PC) as a signal generator. As a receiver, the hydrophone array is arranged vertically with a space of 0.045 m between the hydrophones. This distance is set based on the wavelength and the space of the transmitter to the receiver. Thus, it can be expressed as \( d < \frac{\lambda_{\text{min}}}{2} \) where \( d \) is the distance between the hydrophones and \( \lambda_{\text{min}} \) is the minimum wavelength of the received signal. The value obtained is a safe distance from aliasing. The hydrophone array is connected to a digital mixer, which is a device for recording sound transmitted from the underwater speaker and then received by the hydrophone array connected to the receiving PC for signal processing. The probe signal is generated using software on a PC equipped with a sound card and power amplifier.
The conversion process to an acoustic signal is done by an underwater speaker device. The speaker is Aquasonic AQ339 with the following specifications: 135 Watt power, an impedance of 4 Ω, and a frequency between 20 Hz-17 kHz. The pattern of the speaker has almost omnidirectional with a peak at 0° angle [7]. Meanwhile, the UW hydrophone used has the following specifications: frequency range between 1 Hz to 100 kHz, sensitivity −190 dBre: 1 V/μPa(+4 dB, 20 Hz–4 kHz), and has an internal capacitance of 25 nF. The hydrophone reception pattern is almost omnidirectional and has the strongest response to the signal coming at an angle of 0° with a normal line.

2.2. Linear Frequency Modulation Signal as Probe Signal

The impulse response estimation is obtained by sending a probe signal from the transmitter to the receiver. In this measurement, an LFM signal, also known as chirp, is used as the probe signal. The determination of the LFM signal is based on the autocorrelation properties of the LFM signal with the following equation:
the following equation:

\[ x(t) = \exp(j\theta(t)) \]  

(1)

\( \theta(t) \) denotes the instantaneous phase with the following equation:

\[ \theta(t) = 2\pi(f_0t \pm Kt^2), \text{with } -\frac{T}{2} \leq t \leq \frac{T}{2} \]  

(2)

\( f_0 \) denotes the center frequency at time \( t = 0 \), while \( K \) is the increase in frequency or chirp rate. Figure 2 shows the chirp signal in a time domain and its spectrum in the frequency domain.

Figure 2a shows an exponential chirp waveform, which is a sine wave that increases in frequency exponentially over a period of time. Figure 2b is a chirp signal spectrogram showing the linear level of frequency changes in the time function. The intensity of plotting is proportional to the energy content in the signal at the indicated frequency and time. LFM signal has been widely used as a channel probe signal in underwater acoustic communication because it has good autocorrelation properties [9]. In this measurement, the LFM signal used has a frequency range from 12 kHz to 15 kHz with a recording duration of 100 msec.

2.3. Impulse Response Estimation

The channel impulse response estimation is obtained by cross-correlating the LFM signal on the reference with the

![Diagram](image-url)

**Figure 3.** CIR estimation process

![Diagram](image-url)

**Figure 4.** Cross-correlation of reference signals and received signals
LFM signal received on the hydrophone array. The impulse response estimation obtained by cross-correlation is shown in the block diagram of Figure 3. A reference signal is needed in the impulse response estimation process because the reference signal is a sample that is considered accurate with a distance of 1 meter from the source. There are three variations in this measurement scenario. Three variations of the distance between the source (transmitter) and receiver are: 40 m; 70 m; and 120 m and each distance varies in depth: 1.5 m; 2.5 m; and 3.5 m.

The probe signal is generated using software, and then the generated signal is transmitted to the receiver using an underwater speaker. Before being processed, the LFM signal received on each hydrophone must be synchronized with the reference signal first. This measurement uses three hydrophones on the receiver. The synchronization process aims to match the signal position in each frame. The next process is cross-correlating between the signal received and the reference signal. This process result can be shown in Figure 4. Then, a filtering process is carried out to get the impulse response estimation.

3. Comparison of The Underwater Acoustic Channel Model with The Measurement Result

The channel impulse response amplitude is obtained from the average amplitude of the recorded signal on each hydrophone. The impulse response is modeled as:

\[ h(t) = \sum_{i=1}^{\infty} \sum_{j=1}^{k} A_{ji} \delta(t - \tau_{ij}) \]  

(3)

where \( A_{ji} \) is attenuation caused by transmission loss and accumulation of the reflection coefficient and \( \delta \) is the Dirac function. One method of measuring CIR can be done by autocorrelation, by utilizing a wideband test signal [7]. The value of -20 dB relative to the highest level of the impulse response signal is used as the lowest threshold level that will be processed in the analysis of the measurement results. The measurement results show that at all variations of distance, the signal experiences several reflections. CIR estimated is compared with the UAC model conducted by Parastoo-Qarabaqi [8]. The parameters used for the simulation are shown in Table 1.

| Parameter                  | Value                  |
|---------------------------|------------------------|
| Towing tank dimension     | 12 m x 200 m x 6 m     |
| Tx-Rx distance            | 40 m; 70 m; 120 m      |
| Depth variation           | 1.5 m; 2.5 m; 3.5 m    |
| Sound speed               | 1500 m/sec             |
| Minimum frequency         | 12 kHz                 |
| Sampling frequency        | 48 kHz                 |
| Bandwidth                 | 3 kHz                  |
| Water density             | 1000 gram/cm³          |
| Chirp duration            | 100 msec               |
| Doppler spread            | 4 Hz                   |
Figure 5. CIR at a distance of 40 m with a depth of (a) 1.5 m (b) 2.5 m (c) 3.5 m

| PDP parameter       | Depth |
|---------------------|-------|
|                     | 1.5 m | 2.5 m | 3.5 m |
| Mean excess delay   | 11.54 | 11.83 | 11.835 |
| RMS delay spread    | 0.19 msec | 0.22 msec | 0.215 msec |
| Maximum excess delay| 13.51 msec | 11.45 msec | 11.45 msec |

Figure 6. CIR of UAC Model at 40 m (a) 1.5 m (b) 2.5 m (c) 3.5 m

The channel impulse response (CIR) consists of a direct path and multipath signal. Figure 5 shows CIR at a distance of 40 m. The pattern has peak values at t = 11 msec and the sidelobes decrease
regularly at \( t < 11 \) msec and \( t > 11 \) msec, and at \( t > 20 \) msec the amplitude of the multipath is close to zero. The mean excess delay and the maximum excess delay value are relatively small. The amplitudes of the multipath produced are almost uniform at all depth variation.

Power Delay Profile (PDP) describes the average power as a function of time delay and different observation time and can be expressed in the following equation:

\[
P(\tau) \propto \frac{1}{T} \int_{-\tau/2}^{\tau/2} |y(t, \tau)|^2 dt
\]

\( T \) in the equation is the observation time interval, and \(|y(t, \tau)|^2\) denotes the square of the incoming signal at the receiver. Parameters related to PDP are the mean excess delay, RMS delay spread, and excess delay spread. The mean excess delay is the first moment of PDP with the following equation:

\[
\bar{\tau} = \frac{\sum_k \tau_k P(\tau_k)}{\sum_k P(\tau_k)}
\]

The RMS delay spread is at the root of the second PDP moment and is defined in the following equation:

\[
\sigma_r = \sqrt{\bar{\tau}^2 - (\bar{\tau})^2}
\]

with:

\[
\bar{\tau}^2 = \frac{\sum_k \tau_k^2 P(\tau_k)}{\sum_k P(\tau_k)}
\]

Maximum excess delay (\( X \) dB) is the delay time on multipath, in which the energy of the incoming signal at the receiver still exceeds the lowest limit (\( \geq -20 \)dB). The power delay profile parameter has the values as shown in Table 2.

The underwater acoustic channel (UAC) model is time-varying and the model is useful for statistical observation of the underwater channel in a multipath environment. Figure 6 shows the simulation result of CIR at a distance of 40 m. When compared with the measurement results in Figure 5, there are similarities in the resulting multipath patterns. The multipath that occurs appears denser at \( t \geq 0 \) msec, meanwhile, the lower amplitude of the trajectory is getting to the right. This can be observed in Figure 6 on the right which is an enlargement of the image to the left and the yellow line shows a higher amplitude value than the blue colour. The largest multipath amplitudes are generated at a depth of 2.5 m and 3.5 m from the surface, while the measurement results have a slightly larger amplitude achieved at a depth of 3.5 m.

Figure 7. CIR at a distance of 70 m with a depth of (a) 1.5 m (b) 2.5 m (c) 3.5 m
At 70 m, the resulting multipath pattern is slightly different when compared to the multipath pattern at 40 m. This can be shown in Figure 7. The peak amplitude values are obtained at $t = 16$ msec at a depth of 1.5 m, while at a depth of 2.5 m and 3.5 m the peak values are obtained at $t = 17$ msec and $t = 19$ msec, respectively. At this distance, there are several groups of multipath, between the value of $t = 16$ msec to about $t = 25$ msec. There is an increase in the amplitude at $t > 25$ msec and forming a multipath pattern like in the first group, but with a smaller amplitude. Mean excess delay and the maximum excess delay produced are longer when compared with a distance of 40 m. Detail of the power delay profile (PDP) parameter at a distance of 70 m can be seen in Table 3.

Table 3. Parameter of PDP at 70 m

| PDP parameter        | Depth  |        |        |        |
|----------------------|--------|--------|--------|--------|
|                      | 1.5 m  | 2.5 m  | 3.5 m  |
| Mean excess delay    | 16.37msec | 17.57msec | 19.24msec |
| RMS delay spread     | 0.2msec | 0.285msec | 0.24msec |
| Maximum excess delay | 24.54msec | 26.1msec | 27.97msec |

The amplitude of the multipath produced is almost the same as the amplitude at a distance of 40 m. When compared with the simulation results in Figure 8, the resulting multipath pattern shows the density at $t \geq 0$ msec. This is similar to the multipath pattern generated at a distance of 40 m.
**Figure 9.** CIR at a distance of 120 m with a depth of (a) 1.5 m (b) 2.5 m (c) 3.5 m

**Table 4.** Parameter of PDP at 120 m

| PDP parameter       | Depth   |          |          |          |
|---------------------|---------|----------|----------|----------|
|                     | 1.5 m   | 2.5 m    | 3.5 m    |          |
| Mean excess delay   | 18.17 m | 16.72 m  | 15.995 m |          |
| RMS delay spread    | 0.34 m  | 0.27 m   | 0.24 m   |          |
| Maximum excess delay| 28.89 m | 27.23 m  | 29 m     |          |

**Figure 10.** CIR of UAC Model at 120 m (a) 1.5 m (b) 2.5 m (c) 3.5 m
However, at a distance of 70 m, the amplitude of the multipath is smaller when compared to the amplitude at a distance of 40 m. This is because the path losses generated at longer distances will be greater[11].

The resulting impulse response at a distance of 120 m can be shown in Figure 9. This multipath pattern is similar to the resulting impulse response at a distance of 70 m where there are several groups of multipath. The first group has a pattern similar to the pattern at a distance of 40 m with peak amplitude values obtained at t = 16 msec at a depth of 1.5 m and t = 17 msec at a depth of 2.5 m and 3.5 m. The second group has almost the same pattern as the first group with a smaller amplitude. The resulting mean excess delay and maximum excess delay are shorter than the 70 m distance. From the three variations of the distance, the result of the impulse response obtained has a relatively constant amplitude with a slightly different path pattern between the multipath obtained at a distance of 70 m and 120 m. If compared with the simulation results in Figure 10, there is a similarity in the resulting track pattern, which is denser when t ≥ 0 msec. In the simulation results, the amplitude of the multipath tends to decrease with increasing distance. However, the real measurement results at a distance of 120 m tend to be constant and even higher when compared to the amplitude at a distance of 40 m. This is due to the reflection on the pool wall or the surface and surface of the pool which allows there to be a point where the reflections that occur will reinforce each other.

4. Conclusion

The measurement evaluation of CIR in the shallow water environment has been conducted using three variations of the distance between transmitter and receiver: 40 m, 70 m, and 120 m with three depths: 1.5 m, 2.5 m, dan 3.5 m. From the whole series of measurements, the results show that the channel impulse response at three distance variations has almost the same multipath pattern. LFM or chirp signal can be used to estimate channel impulse response well. The PDP parameter shows that the RMS delay spread generated at the three distances has an average value of 0.2 msec. While the highest maximum excess delay is 29 msec obtained at a distance of 120 m with a depth of 3.5 m.

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