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Underwater Acoustic Channel Characterization of Shallow Water Environment

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Abstract: Understanding of channel propagation characteristics is a key to the optimal design of underwater acoustic communication. Generally, modelling of underwater acoustic channel is performed based on measurement result in certain site at certain times. Different sites might have different characteristics each of which can generally be described by a model obtained by averaging measurement results at multiple points in the same environment. This study describes a characterization of the underwater acoustic channel of tropical shallow water in a Mangrove estuary which has sediment up to 60 cm at the bottom. Such a channel model is beneficial for the design of communication system in an autonomous underwater vehicle for instance. The measurement result of delay spread parameter from three different points with the distance of 14~52 m has various values. The Root Mean Square (RMS) of delay spread ranges between 0.0621~0.264 msec and the maximum delay spread varies with the value of 0.187~1.0 msec. The PDF fitting shows that Rayleigh distribution describes the fading variation more accurately than Nakagami and Ricean.

Key words: Delay spread, fading, shallow water, scattering, characterization, distribution

INTRODUCTION

In the last three decades, many developments have been going on in underwater acoustic communication research activities. The application is directed to maritime, oceanography, oil offshore exploration and defense system. The research development in recent years have been to improve the performance of system reliability compared to the existing (Akyidiz *et al*., 2005).

In the implementation, Under Water Acoustic (UWA) communication is faced with more complicated channel problems, compared with the radio communication systems (Chitre *et al*., 2008; Domingo, 2008; Stojanovic and Preisig, 2009). There are three main factors in the underwater acoustic propagation, i.e., attenuation increase with carrier frequency, time-varying multipath propagation and relatively low sound speed (1500 m/sec). The appearance of multipath propagation channel is strongly influenced by the environment condition. This implies that different environments would result in different multipath parameters. Therefore, an understanding of UWA channel is a key success in the designing of UWA communication system properly. In addition, the extensive effects of global climate on ocean condition also have influence on the communication system performance (Sehgal *et al*., 2010; Liu *et al*., 2005).

Acoustic underwater communication in shallow water is challenging due to multiple paths emerging from reflections by the water surface and structures at the bottom. Hence, shallow water UWA channel must be modeled accurately based on actual measurement. The model will be beneficial for the design of communication systems in autonomous underwater vehicles for instance. Some measurement based models of the underwater acoustic channel have been proposed (Chitre, 2007; Qarabaqi and Stojanvic, 2009; Chitre *et al*., 2004; Aref and Arand, 2010; Borowski, 2009; Walree and Otnes, 2013; Santoso *et al*., 2012, 2016). There in a mathematical model has been used to represent the channel impulse in shallow water and time varying conditions. The channel is modelled as a superposition of multiple paths formed by channel geometries. Each path has a frequency dependent path loss and a random time-varying and expressed as a multiple distortions. But these researches are limited to a detail investigation of a short sequence of experimental data and have not studied a relation with the tropical shallow water region.

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From the above explanation, there is no consensus among researchers about the underwater acoustic channel model, especially for shallow water and tropical environment. To determine the fading, experimental measurement is a common way to develop a channel model for UWA communication systems in a certain locations.

MATERIALS AND METHODS

In this study, we describe a statistical characterization of UWA channel propagation of tropical shallow water environment based on measurement experiments. Propagation parameters which will be discussed here are delay spread and fading of the channel. While environmental and man-made acoustic noise are also an important factor in underwater channels (Widjiati *et al*., 2012, 2015).

Observation of the delay spread is started with channel impulse response measurement based on the Sousa method (Sousa *et al*., 1994) and combined with CFAR detection of continuous wave radar (Luo *et al*., 2010; Meng *et al*., 2008). This method is effective and quite simple based upon PN-sequence probe signal. The PN-sequence signal is generated by using a linear feedback shift register and some Exclusive-or (XOR) logic gates. To obtain the widest looping period, the generation process is done by using a Maximum Length Sequence (MLS) method (Borowski, 2009; Walree and Otnes, 2013; Caley and Duncan, 2013).

Shallow water acoustic propagation: The model development of a communication channel can be done with physical propagation model or by using a mathematical formulation of the channel impulse response. In a time-invariant channel, the output signal y(t) is a function of the input signal x(t) and is written as:

$$y(t) = \int_{-\infty}^{\infty} h(t,t)\, x(t\text{-}t)\, d\, t + n(t) \quad (1)$$

Where:

$h(t, \tau)$ = A time-varying impulse response

$n(t)$ = Additive noise. In the s equel, we set $h(t, \tau)$ as channel model terminology

A frequency flat propagation channel model that is used in the transmission loss calculation is aimed to calculate the Signal-to-Noise Ratio (SNR) when the transmission signal arrives at the receiver part. In a simple form it can be written as:

$$h(\tau) = a\delta(\tau\text{-}\tau') \quad (2)$$

where, τ is the propagation delay from transmitter to the receiver and a is a constant related to the transmission loss. The propagation delay can be associated with the network protocol but in the physical layer, it is not always a primary consideration. Although, the propagation model is implicitly or explicitly related with multipath propagation, this study is focused on the transmission loss calculation. The SNR based channel model, generally does not involve the signal distortion and assumed that communication system is noise limited. The multipath propagation is indicated with a time-variant frequency-selective model and is written as:

$$h(\tau) = \sum_{n=1}^{N} a_n d(\tau\text{-}\tau_n) \quad (3)$$

where a_n is a complex weighted parameter of the nth path which arrives at the receiver with the delay of τ_n. Equation 3 represents a static channel condition while most of UWA channel is a time varying channel.

The concept of multipath propagation of the underwater acoustic channel has a similarity with the wireless terrestrial. Therefore, we can adopt the multipath propagation concept from wireless channel (Proakis, 1997; Lurton, 2002). Signal propagation from transmitter to receiver has various paths. The receiver will capture the signals arriving at different times and with different magnitudes. The arriving signal at the receiver is composed of a Line of Sight (LOS) and signal reflected by the water surface or bottom. Multipath intensity profile or Power Delay Profile (PDP) presents the delay profile of average power of the channel:

$$P(\tau) \approx \frac{1}{T} \int_{t-\frac{T}{2}}^{t+\frac{T}{2}} |h(t,\tau)|^2\, dt \quad (4)$$

Where:

T = Time interval of observation

$|h(t, \tau)|^2$ = The squared magnitude of the channel impulse response

Parameters associated with the power delay profile are the mean excess delay, RMS delay spread and excess delay spread. Mean excess delay represent the average of all such excess delays and is written as:

$$\bar{\tau} = \frac{\sum_k P(\tau_k)\tau_k}{\sum_k P(\tau_k)} \quad (5)$$

The RMS delay spread indicates the variations of delay profile in time spreading. It gives a measure of time dispersion from the mean excess delay. It is the square root of the second moment of delay profile and is written as:

$$s_t = \sqrt{\overline{\tau^2} - (\overline{\tau})^2}\tau \quad (6)$$

Where:

$$\overline{\tau^2} = \frac{\sum_k P(\tau_k)\tau_k^2}{\sum_k P(\tau_k)}$$

Maximum excess delay is define as the time different between the first arriving impulse and the last arriving impulse. The last arriving is determined with respect to the particular threshold.

In shallow water areas, the acoustic propagation environment is characterized by water surface movement and rough sedimentation floor. This condition illustrated in Fig. 1 leads to multiple paths resulting from scattering by the two boundaries dominating over the direct path. Therefore, it is reasonable the hypothesize Rayleigh fading in this situation.

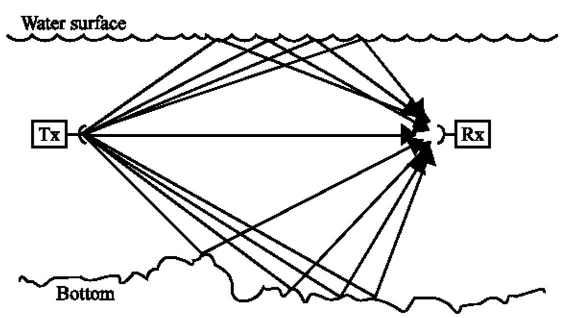

Fig. 1: Shallow water acoustic channel environment

Environment condition and measurement setup

Measurement in ekowisata mangrove: The measurement in Ekowisata Mangrove is located in the river of Kali Londo which is an estuary in the Madura Strait in Surabaya, Indonesia. The river has a depth of 3.5~8 m, width of 20 m and the bottom has sedimentation up to 60 cm. The flow in the river is in the slow category, quite fairly and there was no movement that generates surface wave (Lurton, 2002). The measurement was carried out in November when the environmental condition is relatively calm with a temperature of 33°C and humidity of 54%. The wind blows slowly at a speed <4 $msec^{-1}$. The measurement location in Ekowisata Mangrove is shown in Fig. 2.

Measurement setup: The measurement of delay spread and fading of the channel is carried out by using the equipment and setup as in Fig. 3 and 4. Overall, the system consists of a transmitter, a hydrophone reference with a position of 1 m apart from the transmitter and an array of hydrophones as a receiver.

The transmitter used a Personal Computer (PC-1) to generate a probe signal, namely PN-sequence for delay spread measurement and sinusoid signal for fading measurement. Generation process is carried out by using software in PC-1, supported by sound card and amplified by a power amplifier.

The conversion to audio signal is performed using an underwater speaker, Aquasonic AQ-339 which has the following specifications, 135 W of power, a 4Ω impedance and a frequency of 20 Hz~17 kHz. The underwater speaker has an angle of 0°. For angles ≥10°, the signal is decreasing.

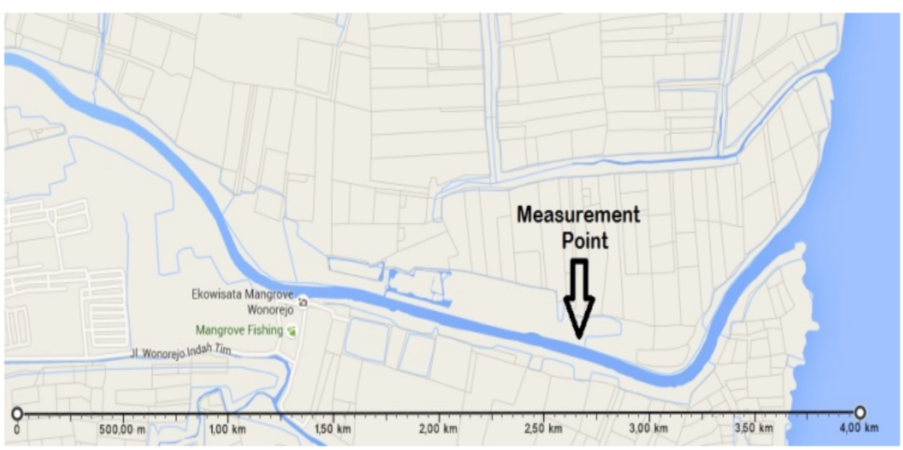

Fig. 2: Measurement location in Ekowisata Mangrove in Surabaya, Indonesia

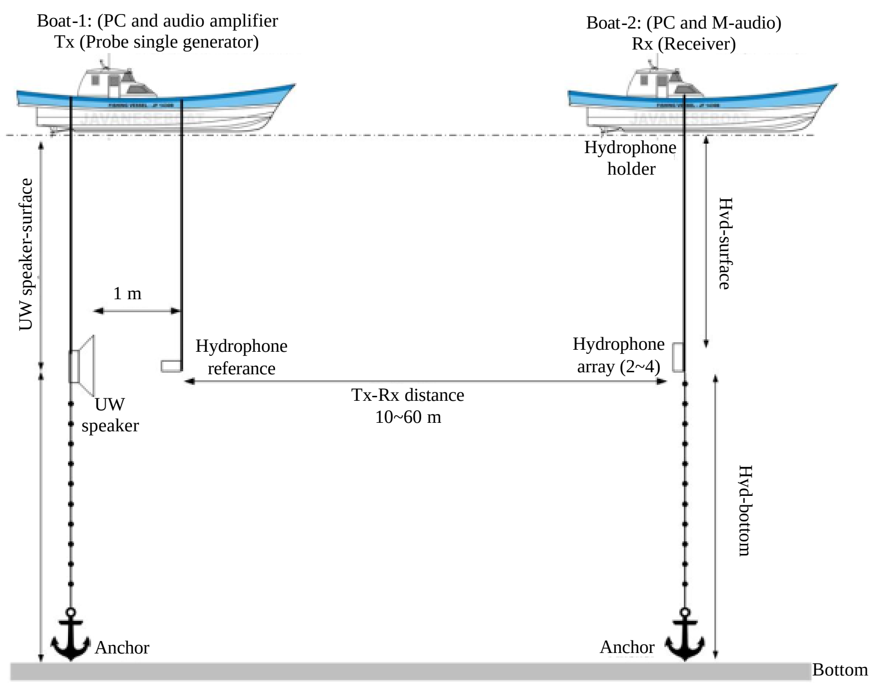

Fig. 3: Measurement setup in Ekowisata Mangrove

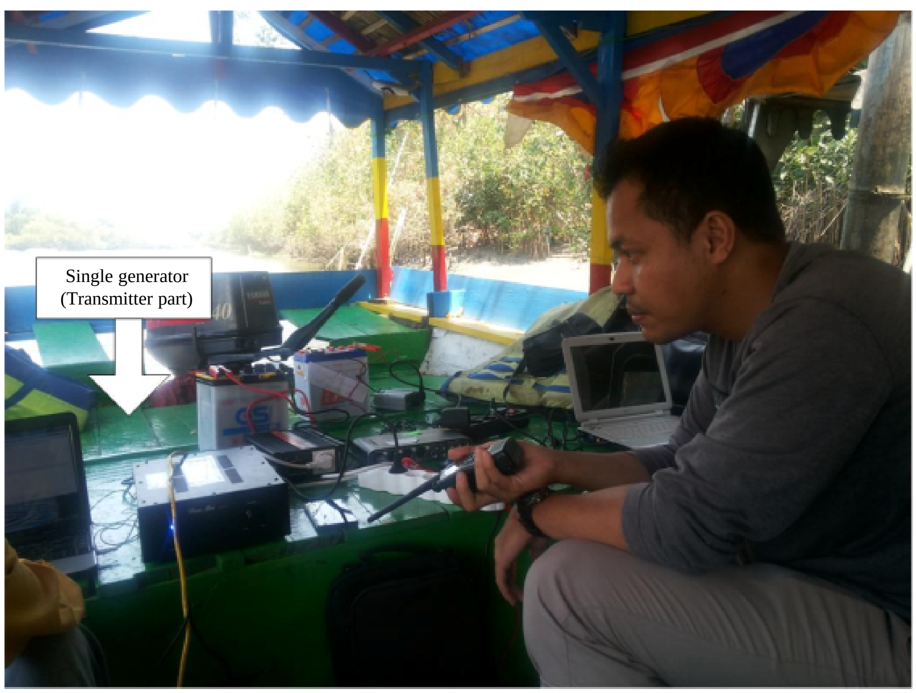

Fig. 4: Measurement activity in Ekowisata Mangrove

The received signal is captured by hydrophones that have the following specifications: frequency ranges of 1 Hz~100 kHz, a sensitivity of -190 dB re: 1 V/μPa (±4 dB 20 Hz~4 kHz). At a certain position (15, 30 and 50 m) from the transmitter, a receiver is placed, composed of vertical array of hydrophones with a space of 20 cm between hydrophones. The receiver is also supported with a digital mixer M-audio and a computer (PC-2) for recording process. Data were collected simultaneously through four hydrophones and stored for off line processing.

In this study, we have used the PN-sequence signal with n = 8~12 and the tap selection based on the Maximum Length Sequence (MLS). The chip rate is 5000 b/sec each bit with a duration of 0.2 msec. The PN-sequence signal modulates the carrier signal that has a frequency of 10 kHz. The modulation output is a Direct Sequence Spread Spectrum (DS-SS) signal (Luo *et al*., 2010). The measurement activity in Mangrove river is shown in Fig. 4.

RESULTS AND DISCUSSION

Delay spread analysis: The first measurement, position of transmitter (boat-1) is in the coordinate of (S: 07° 18.431’, E: 112° 49.405’). The receiver part (boat-2) in the other site of the river is in coordinates of (S: 07° 18.424’, E: 112° 49.413’). Hence, the distance between transmitter and receiver is 14.2 m. The environment is very shallow water of 4 m with relatively calm conditions. At the tide season, the depth of water is up to 7 m. The direction of sound propagation is almost perpendicular to the flow of the water that is relatively calm and without surface motion. The probe signal has duration of 0.4265 sec.

At the receiver, the processing is started with synchronization and frequency down conversion to obtain a baseband signal. Demodulation process is carried out to obtain an information sequence from transmitted signal and continued with cross correlation with the reference signal at the transmitter. As the received signals are periodic, the correlation is performed using circular correlation (Walree and Otnes, 2013; Santoso *et al*., 2012; Santoso *et al*., 2016; Sousa *et al*., 1994; Lou *et al*., 2010).

The result of Power Delay Profile (PDP) measurement is obtained as in Fig. 5. This PDP is resulted from averaging of 10 frames that have been obtained by correlation method continued with a noise-threshold technique proposed by Sousa *et al*. (1994). Basically, every frame has a certain PDP, according to environment condition when the measurement carried out. But, the variations of PDP between adjacent frames usually are quite small. Overall, there are four multipath components that appear with different magnitude as a function of their arrival time.

The measurement result showed that first component has a higher magnitude compared to the second and third.

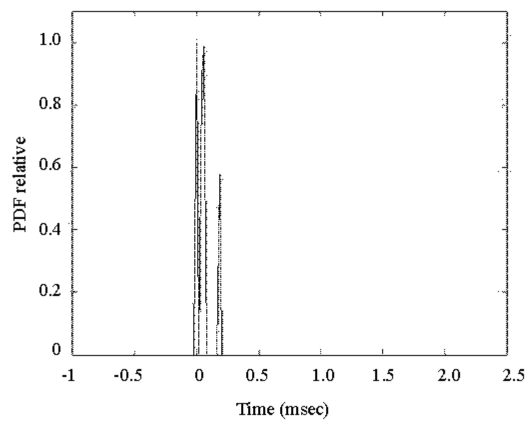

Fig. 5: Power delay profile at position 1

From the calculation of the delay spread parameter, we obtain mean excess delay of 0.06 msec, rms delay spread of 0.0621 msec and maximum excess delay of 0.1875 msec. It was conjured to be influenced by the propagation environment. When the measurement is carried out, there is almost not any interference from other sound source or activity on the surface. The other environmental effect comes from the bottom effect which has a basin in the middle of the river. Therefore, some of propagation paths are trapped.

The second measurement has been carried out with the transmitter at the same position. The receiver part (boat-2) is in the coordinate of (S: 07° 18.418’, E: 112° 49.433’). The distance between transmitter part and receiver part is around 28.5 m. The direction of sound propagation was across the water flow with the angle of 30°. The flow is relatively calm but there is a small movement at the surface.

The multipath pattern that appears in position 2 is different with the measurement result in position 1. Generally, there is some variation of the appearing multipath but a PDP can be obtained by averaging as in Fig. 6. There are 4 multipath components that are very close with difference of time of arrival being relatively short, about 0.02 msec between one path and the other. At the time of 0.2 msec there is one path component appearing and at the time of 1.0 msec, the last multipath component appears.

From the measurement some delay parameters are obtained, including the mean excess delay of 0.1211 msec, rms delay spread of 0.2643 msec and maximum excess delay of 1 msec. These values are bigger than the measurement result in position 1. The multipath is conjured to be due to the direction of sound that is against the water flow, so that, the sound propagation is delayed by the water flow.

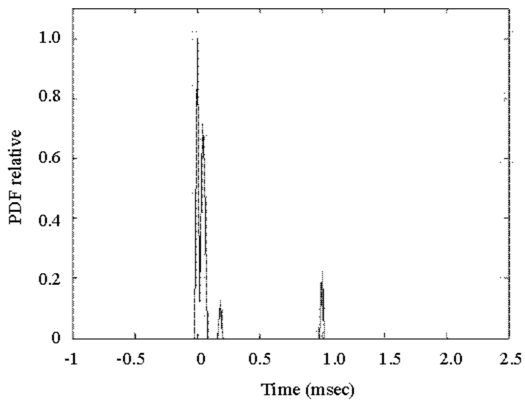

Fig. 6: Power delay profile at position 2

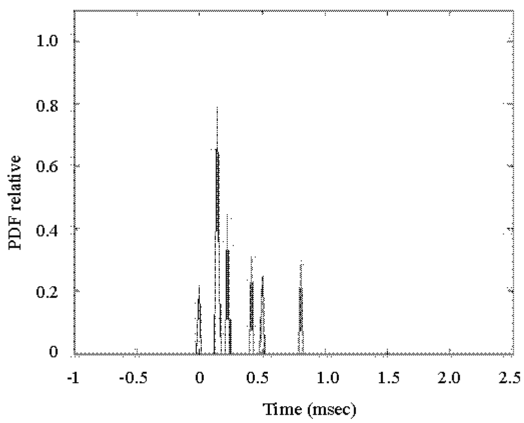

Fig. 7: Power delay profile at position 3

The third measurement has been carried out with the position of the receiver part in the coordinate of (S: 07° 18.414', E: 112° 49.351'). The position of the receiver (boat-2) is in line with the water flow and has a distance about 52.36 m to the transmitter. Sound propagation is almost in line with the water flow and making an angle of 15.6° with the direction of the water flow. The water flow is calm relatively and there is a small movement in the surface.

The multipath pattern in this measurement is as in Fig. 7. It is shown that the first path has a smaller value compared to the other multipath components. The biggest are the second and third multipath components with a small difference in arrival time. Overall, there are 7 multipath components and the last path arrives at the time of 0.8 msec, relative to the first multipath component.

From the measurement at the third position, the following delay spread parameters are obtained, mean excess delay of 0.2837 msec, rms delay spread of 0.2276 and the maximum excess delay of 0.8125 msec. The distance between transmitter and receiver is longer than the second measurement but the direction of sound is in line with the water flow. Therefore, some delay spread parameters become smaller.

Table 1: Comparison of delay spread parameters of three measurement locations

Tx-Rx (m)	Mean excess delay (msec)	RMS delay spread (msec)	Max excess delay (msec)
14.20	0.0600	0.0600	0.1875
28.50	0.1211	0.2643	1.000
52.36	0.2837	0.2276	0.8125

Overall, the comparison of delay spread parameters from three location measurement are listed in Table 1. The value of the rms delay spread and maximum excess delay of the second location is longer than the third location. It is probably due to the direction of propagation against the water flow, therefore, causing a resistance on the water propagation. Another problem caused by surface movement at the measurement is a shift of the refection point and the scattering of the signal propagation. The multipath component increases with different path length and arrival times, thus, increasing the maximum excess delay.

Fading analysis: Reflection by the surface and bottom of the river, causes wave propagation from transmitter to receiver to produce different paths. At the receiver, every single path will have a different time of arrival, phase and transmission loss. Interaction among multipath components causes amplification or attenuation in accordance with superposition concept. Weakening or degradation level of the input signals at receiver path is also known as multipath fading.

The measurement result of fading effect in Ekowisata Mangrove generally shows a similar pattern as in the three point measurements. The Probability Distribution Function (PDF) of fading is depicted in Fig. 8 with the dotted line. The pdf from measurement is compared with three theoretical distribution functions, i.e., Rayleigh (solid line), Rician (-+-) and Nakagami (-o-).

The similarity is evaluated by using the Mean Square Error (MSE) and Bhattacharya distance (Cha, 2008) as in Table 2. The fitting result showed that the pdf pattern from the measurement is relatively close to Rayleigh, compared to the Ricean or Nakagami distribution. The distance between pdf from the measurement with Rayleigh by using MSE is 1.4347×10^{-4} and by using Bhattacharya distance is 0.198.

Physically, there is a direct path between the transmitter and receiver. However because the condition is very shallow, the path formed by the reflection with the surface is large in number. Also, the river flow causes movement of the surface and in turn causes a shift in the

Table 2: The pdf distance

Distance measurement	MSE	Bhattacharya
Exp.-Ray	1.4347×10^{-4}	0.0198
Exp.-Rician	1.7001×10^{-4}	0.0250
Exp.-Nakagami	1.6675×10^{-4}	0.0232

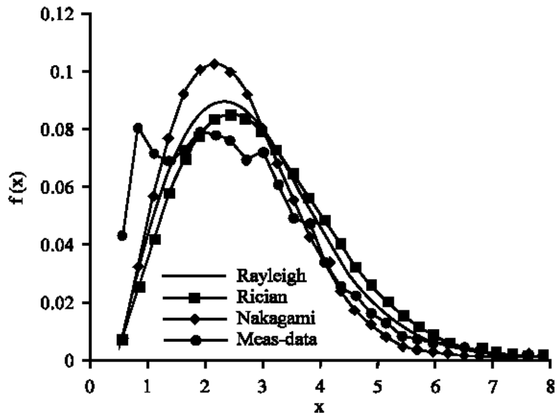

Fig. 8: Comparison of pdf fading between the measurement and theory

point of reflection. This leads to a scattering of the signal propagation. Accumulation of signal reflection in large quantities, produce a greater value than the direct path signal.

The law of large numbers state that average resulted from a large number of experiments will be close to the expected value and tend to become closer as more data are obtained. According to the Central Limit Theory (CLT), if the number of samples approaches infinity, the distribution pattern from the samples will tend to converge to the pattern of a Gaussian.

In line with the above reasoning, the multipath propagation with multiple reflections experienced by shift surface scattering will tend to have a shape of a Gaussian distribution. The envelope of a Gaussian fading signal is Rayleigh-distributed (Proakis, 1997). This is in agreement with the observation from the measurement.

CONCLUSION

Measurement and characterization of the underwater acoustic channel have been carried out in the shallow water environment in Ekowisata Mangrove, Surabaya. It represents tropical shallow water with sediment in the bottom. From the measurement channel parameters are obtained, i.e., delay spread and fading of the channel.

The measurement results of delay spread in three locations showed different values. From this phenomenon, it is found that changes in environmental condition cause a different pattern of propagation in the shallow water environment. The increase in value of the RMS delay spread and maximum excess delay will decrease the rate of transmission symbols in a communication system that will be applied in this environment.

The movement on the water surface and the rough surface of the bottom sedimentation of the river raises scattering on signal propagation. This causes the accumulation of indirect paths greater amplitude than the direct path and forms a fading pattern with Rayleigh distribution. Based on these statistical properties of the channel, communication system in underwater acoustic channels can be approximately designed.

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