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Characterization of underwater acoustic communication channel

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The objective of this work is to study the multipath underwater channel characteristics by estimating the channel impulse response and its derived functions such as scattering functions, power delay profile and Doppler spread. This work performs the channel characterization from the data measured from south- west Bay of Bengal during July 2017 at a range of about 1 km and 3 km in a depth of approximately 20 m. To estimate the channel impulse response, Linear Frequency Modulated (LFM) pulse with the bandwidth of 4 kHz and the center frequency of 11 kHz is used as a probe signal. Experimental data analysis shows the variations between two channels of 1 km and 3 km ranges. Other characterization functions such as multipath intensity profile and Doppler power spectrum are estimated from the channel impulse response. The estimated channel parameters convey that the channels are quasi stationary and the Doppler frequency spreads are due to the movement of the transmitter and receiver positions.

[**Keywords**: Channel characterization, Channel impulse response, Doppler spread, Scattering function, Underwater acoustic communication]

Introduction

Knowledge of transmission parameters and the statistical channel characteristics such as multipath delay spread, Doppler spread, coherence time and coherence bandwidth are required for designing any reliable communication system. However, the possibilities of the measurement of transmission characteristics are limited, especially in case of overspread channels. The shallow water channel has numerous challenges for underwater acoustic communication. In practical, these channels are significantly dynamic due to many aspects such as background ambient noise, movement of transmitter and receiver positions, propagation loss, attenuation due to absorption time-varying sound speed profiles, boundary reflections and scattering. Hence, the acoustic waves transmitted in these channels suffer a long propagation delay, fading, multipath reflection, limitation in bandwidth, and high spatial and temporal variability[1,2]. Channel Impulse Response (CIR) is the basis for computation of transmission characteristics[3.] Amplitude, phase variations, and temporal correlation of individual paths are analysed from the measured CIRs, and knowledge of channel physics and statistics is required to construct a realistic acoustic channel model or simulator. Channel simulation based entirely on acoustic modelling is highly ambitious, and it requires *in situ* channel soundings, *i.e.*, measurements of the time varying impulse response to validate the models. Channel characterization by sounding will improve the understanding of system performance at sea. The shallow water acoustic communication channels are classified as a multipath fading channel. If the spread exceeds the symbol time of the communication system, due to multipath delay, which can lead to intersymbol interference (ISI)[4].

Any shallow water channel typically has significant Doppler spread in the frequency domain, or short coherence time if it is viewed in the time domain. These issues are more at higher frequencies (> 10 kHz) where the channels are desirable as more bandwidth is available[1,2]. The reverberant and time varying nature of the channel poses many obstacles to high rate communication[5,6]. Measuring and analysing a channel's parameters are necessary step for designing a successful communication system. In reality, one finds that every shallow water is different in some details and varying behaviour at different times, which makes modelling an ideal underwater acoustic communication channel challenging. The signal arriving at the receiver may have many delayed and attenuated reflections of the replicas of the transmitted waveform. When it is compared with the transmitted signal, it is considerably spread in time and hence may cause ISI in the received signal. Due to time variability in the multipath, each received signal induces some random amplitude, phase, and Doppler shift fluctuations.

The underwater communication channels are modelled as the time varying response but this approach is not complete due to the lack of information about the environment particularly at high frequencies[7,8]. An alternate approach is to understand about the channel by studying temporal and spatial variation of the channel impulse response from the experimental data[9-11]. Channel characterization studies depend on the experimental data collected in a particular environments, and suggest different or many analytical models that fit the experimental measurements, while some authors mentioned that the Rayleigh fading will provide a good match for their measurements[6,8]. There is a strong time dispersion observed in the impulse response of a channel with multipath propagation which causes ISI in the received signal that could be observed as frequency selective fading. In a typical multipath communication channel, the received signal composed of several reflected paths with different path distances and angles of arrival, and Doppler shift of each arriving path, induced by water surface, local movements, are generally different from each other. Due to these, Doppler spreading of the communication signal spectrum will be seen on the received signal[12,13].

All the information necessary for channel characterization can be derived from the CIR. To estimate CIR, two signals are needed: the known transmitted signal i.e.) probe signal and the received signal. The proper selection of probe signal is a prerequisite for reliable channel characterization. LFM (linear frequency modulated) chirp, a HFM (hyperbolic frequency modulated) chirp, white noise, and a DSSS BPSK (direct sequence spread spectrum binary phase shift keying) signal are some of the probe signals used for channel characterization[14]. Here LFM signal is used as the probe signal for channel characterization due to the autocorrelation of the LFM signal exhibits less side lobes than discrete frequency. Optimum bandwidth is based on the availability of hardware and the required speed of communication sequence. As the bandwidth goes high the speed can be improved. Since the unit impulse to have infinite bandwidth, is not practically possible, a bandwidth of 4 kHz chosen for estimating the channel response.

The impulse response $h(t)$ of any linear system is the response when the input to the system is equal to the unit impulse or delta function. The response of a linear system $y(t)$ shown in equation (1) to an arbitrary input signal $x(t)$ is found[14-16] by convolving $x(t)$ with $h(t)$,

$$y(t) = x(t) * h(t) = \int_{-\infty}^{\infty} x(\tau)h(t-\tau) \qquad \dots (1)$$

Where, τ is the time at which the impulse was applied. When the input and output signals are known, impulse response can be estimated by applying convolution or cross-correlation. The scattering function provides the average power output of the channel as a function of time delay (τ) and Doppler frequency (λ).

The underwater channel response is further considered to be a Wide-Sense Stationary. The channel autocorrelation function R_h in the time domain can be represented as:

$$R_h(\tau_1,\tau_2;\Delta t) = E[h^*(\tau_1,t)h((\tau_2,t+\Delta t)] \qquad \dots (2)$$

The scattering function is defined as the Fourier transform of autocorrelation function with respect to the Δt parameter[17]

$$S_c(t,\lambda) = \int R_h(\tau;\Delta t)e^{-j2\pi\lambda\Delta t}d\Delta t \qquad \dots (3)$$

The multipath intensity profile (MIP) or power delay profile $P(\tau)$, shown in equation (4) gives the average power output as a function of time delay τ. It is computed by summing the power levels over the λ values of the scattering function, as in

$$P(\tau) = \int S_c(t,\lambda) \qquad \dots (4)$$

The MIP denotes the delay spread of the channel. In general, an underwater multipath channel causes a transmitted pulse to arrive at the receiver as distinct components spread out over time. The spreading function[7,8] is a most useful representation of the arrival delay spreading and the Doppler spreading of any underwater acoustic channel response. By estimating discrete Fourier transform of a Hilbert transformed response $h(t,\tau)$, with respect to the real time, spreading function is obtained.

$$S_c(f,\tau) = \int_{-\infty}^{\infty} h(t,\tau)e^{-i2\pi ft}dt \qquad \dots (5)$$

This spreading function S_c gives the deterministic distribution of signal power as a function of frequency shift and delay time. In this case the output is represented as a weighted sum of delayed and Doppler shifted replicas of the transmitted signal. Doppler power spectrum $P(\lambda)$ provides the signal intensity as in terms of the Doppler frequency λ and it is derived by summing the power of spectral components over the time delay τ of the scattering function

$$P(\lambda) = \int S_c(\tau, \lambda)\, d\tau \qquad \ldots (6)$$

The power delay profile gives the power distribution over time delay[17]. The Doppler spectrum is a power spectral density that characterizes the distribution of received signal power as a function of frequency shift. Doppler shift and Doppler spread of the multipath arrivals provide the average and rms delay spread in Hz.

$$Doppler_{spread} = \sqrt{\frac{\int (\lambda - Doppler_{Shif})^2 |P(\lambda)| d\lambda}{\int |P(\lambda)| d\lambda}} \qquad \ldots (7)$$

Where λ is the Doppler frequency in Hz and $P(\lambda)$ is the power spectral components at frequency λ.

Experimental setup

This experiment was conducted for checking the performance of hardware as well as channel characterization in shallow water southwest Bay of Bengal during June 2017. The experiment was conducted for two different ranges i.e. a range of 1km and 3km. LFM signal provides good autocorrelation and therefore are widely used as the probe signal in underwater communication. LFM signal with the bandwidth 4 kHz centre frequency of 11 kHz and pulse width of 100ms was chosen as a transmitting or probe signal to study the channel response. The probe signal obtained at the receiver location is used for channel characterization. Two mechanized boats were used for transmitter and receiver in this experiment as shown in Figure 1. Both the transmitter and receiver boats were anchored and their engines were switched off during the experiment conducted. The spherical transducer along with tilt sensor was suspended with appropriate dead weight from the transmitter boat to maintain stationary position. In another boat, the receiver with tilt sensor was suspended with weight arrangement. The transmitter section consists of power amplifier with the matching circuit for transducer and battery unit. Signal generation was done using the laptop audio port for the desired frequency range. The source consecutively broadcasted the signals in every 5 sec with the source level of approximately 180 dB re 1 μPa.m at centre frequency of 11 kHz.

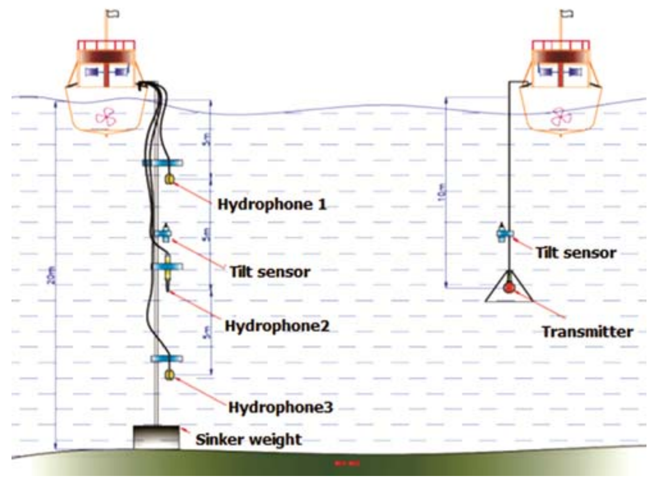

Fig. 1 — Experimental setup

The received signals from all three hydrophones are collected by the data acquisition system with the sampling frequency of 100 kHz. All three hydrophones output are used for channel characterization. Here the receiver boat was at one particular location, and only the transmitter boat was moved away from the receiver for 1km and 3km ranges. This experiment location was characterized as a coarse sandy sediment bottom which had the sound speed of about 1650 m/sec derived based on the empirical relationship. The ratio between the sound speed of bottom sediment C_b and water C_w is represented as $C_b/C_w > 1$ which corresponds to the fast sound speed bottom. Hence, most of the energy incident on the bottom is reflected and the communication channel in this location is reverberant. During this experiment, sound speed and temperature profiles were measured at transmitter and receiver locations. An almost constant sound speed profile was observed at the transmitter and receiver locations with the variation of 1532 to 1534 m/s (Figure 2). The temperature variation observed was 26 ± 0.8 °C. The experiment was conducted with the parameters as given in Table 1.

Results and Discussion

The channel impulse response, spreading function and Doppler spectrum from three hydrophone outputs at the receiver side at a depth of 5, 10 and 15 m, respectively are considered for analysis. The analysis

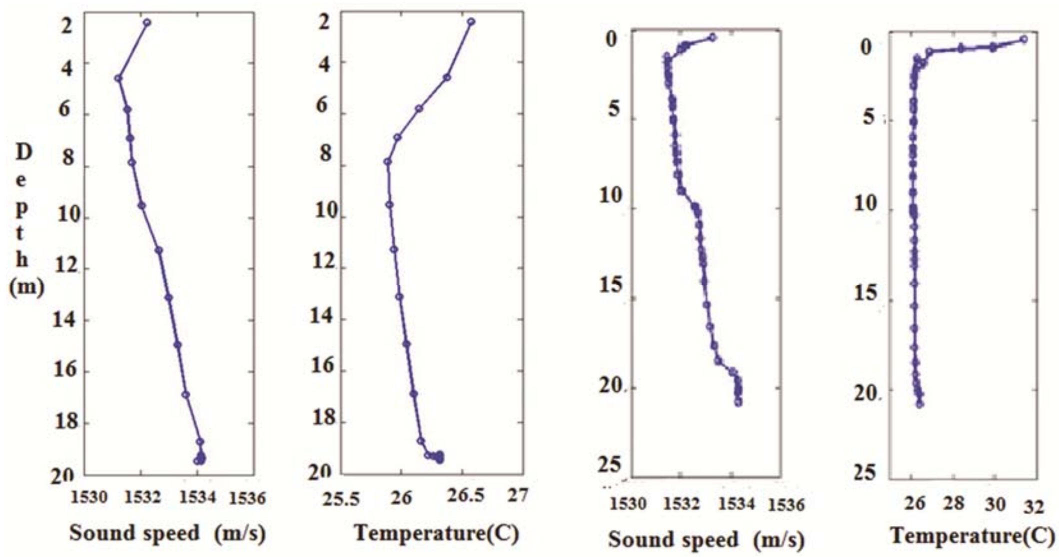

Fig. 2 — Sound speed and temperature variation at transmitter and receiver position (3 km) respectively

Table1 — Parameters for transmission and reception

Parameters	Values / Description
No of transmitter (TX)	1
No of receivers (RX)	3
Directionality (TX)	Omni
Directionality (RX)	Omni
Probe signal	LFM
Center frequency	11 kHz
Water column depth	~20 m
Range	1 km and 3 km
Bottom	Coarse sandy sediment
Sound speed variation (medium)	1531 to 1534 m/sec
Sound speed of bottom	1650 m /sec
Temperature variation	26.8 ± 0.5 °C

was carried out on the data collected for two different channels of 1km and 3 km ranges with a water depth of approximately 20 m. A channel with the range of 1 km is called channel 1 and the range of 3 km is denoted as channel 2. Figure 3(a) shows the received LFM signal of the all three hydrophones in channel 1 and Figure 3(b) represents the received LFM signals of channel 2, respectively. It is observed that the received signal contain the direct signal and overlapped reflected signals.

The desired portion of the probe signal and data packets are taken by correlating the transmitted probe signal and the noisy received signal. The channel impulse response estimation $h_i(t)$ is obtained by truncating the received probe with multipath arrivals from the received signal. This is estimated by match filtering the replica of the LFM chirp transmitted with

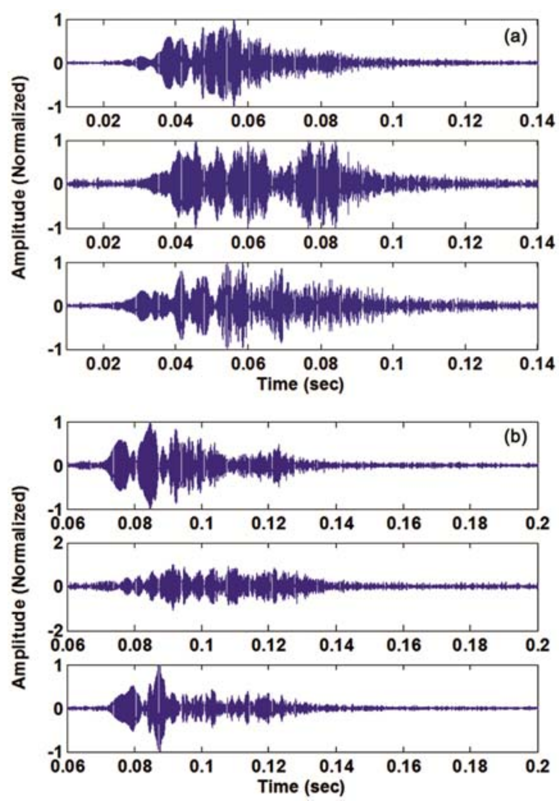

Fig. 3 — Received signals from hydrophone 1, 2 and 3 for (a) channel 1 and (b) channel 2

the measured signal at all three receiver positions for channel 1 and channel 2. Figure 4(a) shows the impulse response of the channel 1 and Figure 4(b) represents the impulse response of the channel 2.

It is observed that the received signal contains the direct signal and overlapped reflected signals. It is also

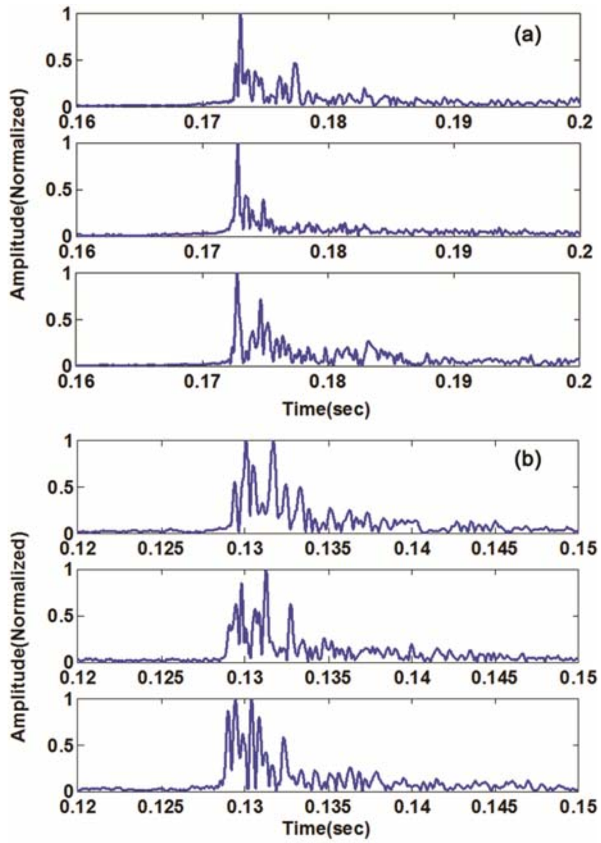

Fig. 4 — Channel response from hydrophone 1, 2 and 3 for channel 1 and 2

noted that the received signal at each hydrophone revealed that there are six multipath components for channel 1 and seven for channel 2. Each hydrophone output containing many unstable arrivals may cause the acoustic channel that is used for underwater acoustic communication will be a difficult environment for phase coherent underwater communication. The MIP of the channels 1 and channel 2 of middle hydrophones i.e. at 10 m depth are shown in Figure 5 and Figure 6, respectively evident that there are distinct multipath components occurring.

The Doppler spread of the channel is a measure of how rapidly the channel is changing with time. The results of the Doppler spread are less indicates that a slowly varying channel with time, while a large value gives rise to a rapidly time-varying channel. In general, the Doppler spread also expresses the spectral width spreading of the received signal. In shallow water, the reflections from the boundaries are the primary reason for the time variance of the channel. Though the receiver boat was in the same location, due to the movement of transmitter two channels of 1km and 3 km range are obtained. The

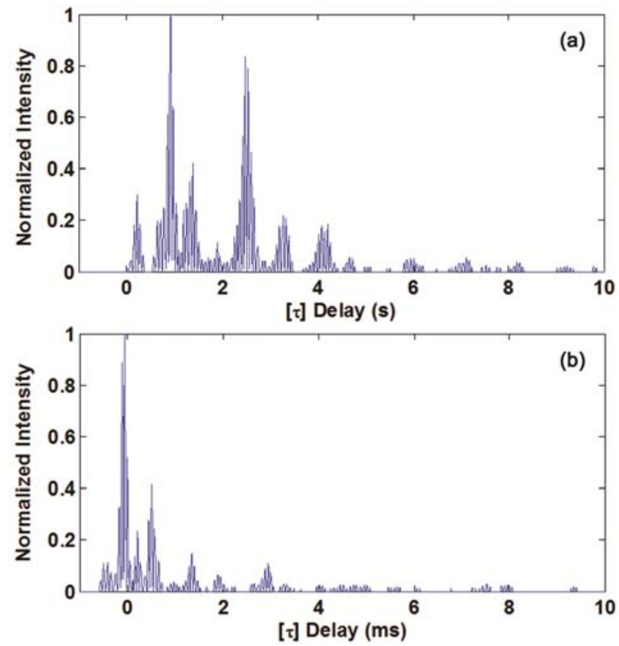

Fig. 5 — Multipath intensity profile for (a) channel 1 and (b) channel 2

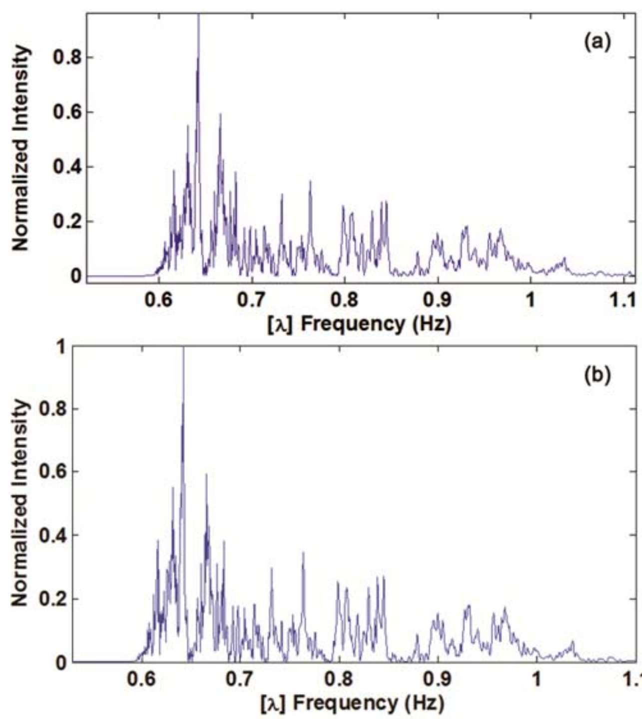

Fig. 6 — Doppler Power spectrum for (a) channel 1 and (b) channel 2

delay spread of the channel appeared with many strong multi-path components. This phenomenon is caused by the acoustic waves being reflected off the boundaries due to shallow water channel. In channel 1, as shown in Figure 4(a), there is a strongest reflection

Table 2 — Multipath intensity, Doppler shift and Doppler spectrum

Multi path Arrivals	Channel 1 (1 km range)				Channel 2 (3 km range)			
	Time (ms)	Intensity (Normalized)	Doppler shift (Hz)	Doppler spread (Hz)	Time (ms)	Intensity (Normalized)	Doppler shift (Hz)	Doppler spread (Hz)
1	0.0	1.00	0.31	1.80	0.00	0.32	0.62	2.63
2	0.03	0.21	0.45	1.82	1.00	1.00	0.68	2.76
3	1.01	0.42	0.38	1.91	1.50	0.41	0.75	2.82
4	1.52	0.18	0.42	1.93	2.0	0.13	0.8	3.23
5	2.03	0.14	0.49	1.95	2.51	0.82	0.85	3.01
6	2.53	0.12	0.65	2.01	3.51	0.23	0.95	2.93
7	-	-	-	-	4.12	0.21	0.96	2.98

at approximately 2.5 sec which is not present in Figure 4(b), which shows the channel is time variant. Doppler power spectrum was estimated and plotted in Figure 5(a) and Figure 5(b) for comparison. These plots of the Doppler power spectrum are different and imply that these 2 channels are quite alike. Each strong multipath arrival has the Doppler shift of approximately less than < 1 Hz. Table 2 shows the intensity of multipath arrivals, Doppler shift and Doppler spread for channels 1 and 2.

Conclusion

The shallow water acoustic communication channel has been characterized from the experimental data collected from south-west Bay of Bengal. The characterization was carried out based on the estimation of the channel temporal impulse response by transmitting probe signals of LFM signals a bandwidth of 4 kHz and the center frequency of 11 kHz. Probe signals are transmitted using a omni-directional transducer and recorded by three hydrophones, spaced vertically covering a water column depth of 20 m with the horizontal ranges of 1 km and 3 km. Channel functions such as channel impulse response, multipath intensity profile and Doppler spectrum are estimated and presented. The channel characterized in this work shows a fluctuation in amplitude and multiple reflections from the boundaries. Doppler shifts of approxima-tely 1 Hz and the Doppler spread of less than 3 Hz were also observed in both channels 1 and 2 and were mainly caused by the boundary reflections from surface and bottom including the movement of the transmitter and receiver boats. A few strong multipaths are observed in the short range channel 1 when compared to channel 2 and the delay spread is less than 5 sec. As the horizontal range increases the number of multi-paths decreases in the channel impulse responses.

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Conflict of Interest

The authors declare that they have no competing or conflict of interest to influence the work reported in this paper.

Author Contributions

First author has contributed for data collection, review of literature, data processing, writing manuscript; other authors have contributed for review of research methodology, data analysis, manuscript review and editing.

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