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4pUW6. Effects of multipath distortion on sparse signal parameter estimation
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Shallow underwater acoustic channel is typically characterized as sparse channel and the sparsity has been actively exploited to estimate the channel accurately. However, distortion of the multipath signal components degrades the performance of sparse approximation and the amount of distortion is dependent on specific time-varying channel condition which each multipath encountered during transmission. In this research we measure the signal distortion of multipath components and analyze its impacts on the sparse channel estimation. Especially, we are interested in the effects of the spatial difference of the distortion on sparse approximation of the multichannel receiver data. To this end, we use variety of experimental data sets which have different characteristics of multipath signal distortion and analyze the relation between the amount of distortion and the signal residual obtained from sparse approximation.

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I. INTRODUCTION

Many underwater acoustic channels show sparse signal transmission structure especially when signal bandwidth is sufficiently wide and the water depth is shallow. In such environment, only a few echoes dominate the received signal, and the channel can be characterized by describing only the non-negligible echoes instead of full-dimensional description (Li and Preisig, 2007). Such sparse property enables sparse channel estimation which is particularly useful for rapidly time-varying channel where the existing least-square method often fails to give stable solution.

Recently, it was attempted to estimate time-varying signal parameters using the multi-element receiver array (Byun et al., 2012a; Byun et al., 2012b). In particular, it estimates signal parameters such as time delay, Doppler shift, incidence angle, and complex amplitude of assumed number of multipaths. However, the proposed incidence angle estimation assumes full coherence of each multipath signal at different receiver elements. That is, the multipath signal which underwent similar path to the array must have similar distortion at different array elements if the ratio of array size to wavelength is not too large. However, random characteristics of the underwater acoustic channel make a significant gap between the ideal assumption and real measurement signal so that the signals at different sensors usually have partial coherence only. The level of spatial coherence is affected by specific channel conditions and the degree of their interaction with transmitted signal.

In this paper, we study the multipath distortion and its spatial variation under moving surface wave condition. For the purpose of analyzing distortion of individual paths, we try to decompose each path component from superimposed received signal using a modified version of channel replay method. Then the decomposed signals are analyzed to evaluate the spatial coherence of signals arriving at different array elements.

II. SIGNAL MODEL

The underwater acoustic channel is time-varying multipath channel which can be characterized by the input delay-spread function (Bello, 1963). The input delay-spread function is also called as the time-varying impulse response and describes time-varying channel output to input signal as follows:

\[ y(t) = \int_{-\infty}^{\infty} h(t, \tau) x(t - \tau) d\tau + n(t) \]  

(1)

where \( h(t, \tau) \) is the input delay-spread function, and \( n(t) \) is additive noise. Here, \( t \) and \( \tau \) refers to time and time delay, respectively.

When the channel output is composite of a limited number of distorted signals, the channel can be represented by the ultra-wide band (UWB) signal model (Molisch, 2005; van Walree and Otnes, 2012) and for the multichannel array case, it is expressed by

\[ h_m(t, \tau) = \sum_{p=1}^{P} \alpha_{p,m}(t) \chi_{p,m}(t, \tau) \otimes \delta(t - \tau_{p,m}) \]  

(2)

where \( \alpha_{p,m}, \tau_{p,m} \) and \( \chi_{p,m}(t, \tau) \) are the complex amplitude, the time delay, and the signal distortion of the \( p \)-th path at the \( m \)-th sensor, respectively and \( \otimes \) denotes convolution. If we assume that the variation of the complex amplitude is both temporally and spatially negligible and also that the signal distortion is determined by single time delay and Doppler shift which are common for all the array elements, then the distortion in (2) can be expressed by

\[ \chi_{p,m}(t, \tau) = e^{j2\pi(m-1)\phi_p} e^{j2\pi f_s \tau} \delta(\tau) \]  

(3)

and Eq. (2) becomes

\[ h_m(t, \tau) = \sum_{p=1}^{P} \alpha_p e^{j2\pi(m-1)\phi_p} e^{j2\pi f_s \tau} \delta(t - \tau_{p,m}) \]  

(4)
where $\phi_p$ and $\nu_p$ denote the incidence angle and the Doppler shift of the $p$-th path component.

Eq. (4) is similar to the multi-scale-multi-lag (MSML) signal model (van Walree and Otnes, 2012) but the signal scaling by time-varying delay was neglected in (4). Coherent processing for incidence angle estimation (Byun et al., 2012a) is based on (4) and thus requires that the path distortion is parameterized as given in (3).

### III. MULTIPATH SIGNAL DECOMPOSITION

We investigate the plausibility of the signal model given in (4) via experimental data analysis. In order to evaluate the spatial and temporal coherence of individual multipath component, we decompose each multipath component from the received signal in which all multipath signals are superimposed.

For the purpose of it, we use the time-varying channel replay technique (van Walree and Otnes, 2012) but modify the original version to exploit multichannel array to separate the multipath signals having different time delay and incidence angle. In particular, the input delay-spread function is first filtered in the angle domain and also in the time delay domain. The filtered input delay-spread function is interpolated to give channel output with the sample frequency of input signal. Finally, the signal responsible for the selected range of delay and angle is synthesized using (1) but the original input delay-spread function is replaced by the filtered and interpolated version of it. Of course, the multipaths to be separated should have enough time delay and angle difference otherwise unwanted leakage from close paths occurs inevitably.

Using the decomposed path signal, we compare the spatial difference among the different sensor pairs. Because we use wideband probe signal, we define the signal coherence of each decomposed signal as follows:

$$C(m,n,p) = \max_{\tau} \frac{\left| \langle \hat{y}_{p,m}^*(t) \hat{y}_{p,n}(t+\tau) \rangle \right|}{\sqrt{\langle \hat{y}_{p,m}^*(t) \hat{y}_{p,m}(t) \rangle \langle \hat{y}_{p,n}^*(t) \hat{y}_{p,n}(t) \rangle}},$$

where $C(m,n,p)$ denotes the signal coherence of the $p$-th path signal arriving at the $m$-th and $n$-th sensors, and $\hat{y}_{p,i}$ refers to the $p$-th path signal at the $i$-th sensor. Therefore even if two signals are distorted by the channel, the coherence of them becomes the maximum if the distortions on two signals are the same and one of them is shifted-only version of the other. Allowing time delay shift prevents the propagation delay within the array from degrading signal coherence.

### IV. EXPERIMENTAL ANALYSIS

We apply the proposed signal decomposition method to the experimental data obtained from a large-scale water tank. The water tank is capable of generating surface wave with designated wave height and period including a regular wave condition which is difficult to be obtained by in situ measurement at sea. An omnidirectional hydrophone (B&K 8103) was used as the transmitter and an eight-element hydrophone array (B&K 8103) was used as the receiver. The channel probe signal was a pseudo-random noise (PN) sequence of 511 symbol length, and the raised-cosine pulse shaping filter was used with roll-off factor 1. The details of the experiment set-up are summarized in Table. 1, and the wave parameters of generated surface wave are shown in Table. 2.

Figure 1 shows the channel impulse responses (CIR’s) both for the original received signal and the decomposed multipath signals obtained by the proposed method. The six earliest paths which lastly reflected off the surface wave are chosen for reconstruction. The CIR of the reconstructed signal look very similar for the early arriving paths and become dissimilar as the reflection multiples.

Figure 2 compares the CIR of the decomposed signals with that of the received signal. For comparison, the decomposed multipath signals were superimposed again and then cross-correlated with the probe signal. The peaks of the reconstructed CIR are in good agreement with the original CIR, and this shows that the multipaths were decomposed reasonably well.

We also calculated the Doppler shift of each decomposed signal and showed them in Figure 3. The Doppler shift is caused by moving surface wave and is higher for multiply reflected signals because of their rapid time-delay variation. As shown in the figure, the decomposed signals have similar Doppler shift even for different sensors, and the period of Doppler shift variation coincides with the surface wave period. As the number of reflection increases, the variance of Doppler shift estimate also increases, and this is natural consequence...
considering more rapid time-variability by larger grazing angle and lower signal-to-noise ratio of multiply reflected signals.

Figure 4 shows the spatial coherence of the decomposed multipath signals calculated by (5). The upper three contours show the coherence when there is no surface wave while the lower ones show the result when the surface wave exists. The spatial coherence decreases as the signal undergoes more reflections and is higher for the case when no wave exists. Figure 5 shows the relation between the Doppler shift estimate and average spatial coherence for the path 3 and 4. They are shown to have strong correlation. The spatial coherence is low when the Doppler shift estimate is unstable or conversely, it is high when the Doppler shift is stably changing near at zero crossing.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Carrier frequency ($f_c$)</td>
<td>20 kHz</td>
</tr>
<tr>
<td>Symbol rate ($f_{sym} = 1/T_{sym}$)</td>
<td>10 kHz</td>
</tr>
<tr>
<td>Pulse shaping filter</td>
<td>Raised-cosine filter (order = 20, rolloff factor = 1.00)</td>
</tr>
<tr>
<td>Number of array elements ($M$)</td>
<td>8</td>
</tr>
<tr>
<td>Array element spacing ($d$)</td>
<td>3 cm ($\approx 0.4 \times \lambda$)</td>
</tr>
<tr>
<td>Transmit signal</td>
<td>511 symbol PN sequence</td>
</tr>
<tr>
<td>Transmitter-receiver range (m)</td>
<td>5.10 m</td>
</tr>
<tr>
<td>Transmitter depth</td>
<td>1.50 m</td>
</tr>
<tr>
<td>Receiver depth</td>
<td>1.10 m</td>
</tr>
<tr>
<td>Water depth</td>
<td>3.15 m</td>
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</tbody>
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TABLE 2. Surface wave parameters

<table>
<thead>
<tr>
<th>Wave condition</th>
<th>Period</th>
<th>Amplitude</th>
<th>Wavelength</th>
</tr>
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<tbody>
<tr>
<td>WAVE 2</td>
<td>1.5 sec</td>
<td>4 cm</td>
<td>3.51 m</td>
</tr>
</tbody>
</table>

FIGURE 1. Multichannel impulse response obtained by (a) the received signal and (b) the reconstructed signal where six paths were superimposed. The y-axis denotes the sensor number and the z-axis is shown in log scale (dB).
FIGURE 2. Comparison of the channel impulse response between the received (blue) and the reconstructed signal (red-dotted) at the eighth sensor when the surface wave exists.

FIGURE 3. The Doppler shift estimates of the decomposed signals. (a) Path 1, (b) Path 2, (c) Path 3 (d) Path 4. Totally sixty probe signal blocks were analyzed (i.e. t=0 to 3.066 sec).
FIGURE 4. Averaged signal coherence between the reconstructed multichannel data. (a) Wave 0 - Path 2, (b) Wave 0 - Path 4 (c) Wave 0 – Path 6 (d) Wave 2 - Path 2 (e) Wave 2 - Path 4 (f) Wave 2 - Path 6. The axes denote the sensor number.

FIGURE 5. Doppler shift and spatial coherence variation. (a) Wave 2 - Path 3 and (b) Wave 2 – Path 4.

V. CONCLUSION

We propose a method for decomposing multipath signals from the superimposed received signal and apply it to examine the spatial coherence of individual multipath component arriving at multielement receiver array. Analysis of multichannel experiment data gathered under regular surface wave condition shows that the proposed method decomposes received signal reasonably well into the multipath components with their Doppler shift preserved. It is also shown that the spatial coherence of individual multipath signal has strong relation with the measured Doppler shift variation.

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REFERENCES