The High Frequency Underwater Acoustic Channel

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***Abstract*-Underwater acoustic communication systems usually operate at frequencies below 40 kHz, which have low absorption rates that in turn enable long link distances. These links suffer from channel effects including multi-path, fading and doppler. Cellular and multi-hop strategies have been proposed that would use shorter path lengths, so would tolerate much higher absorption rates, and hence could work at higher frequencies. The short-range, high-frequency channel is not well documented. This paper reports on initial measurements of the short-range, high-frequency underwater acoustic channel. Re-examining the basic theory indicates that the short-range high-frequency channel should not suffer from the same multi-path or fading issues as the longer-range lower-frequency channel in common use. Initial collected and processed field data supports this conclusion. The implication is that relatively simple modems should provide adequate performance on the high-frequency channel. Coupled with large available bandwidth, these high frequency modems should offer data communication rates well in excess of those generally available.**

I. Introduction

Most contemporary underwater acoustic communication systems operate below 40 kHz. Such low frequency acoustic links are viable over relatively long distances, normally many kilometres. However these signals exhibit undesirable characteristics such as doppler shifts that are both large, and vary substantially over the signal bandwidth, and time-varying multi-path that complicates equaliser design. In addition, although the relative bandwidth of these low frequency signals is large, the absolute channel bandwidth is small because of the low carrier frequency. The small bandwidth means such links provide only data rates.

Operating at higher frequencies allows channels to have larger absolute bandwidth. Large absolute bandwidth offers scope for higher data rates. High frequency acoustic signals are not generally used because they are strongly absorbed in water, limiting the useful link distance of such signals. However cellular and multi-hop schemes have been proposed that provide communication over long distances, without necessarily requiring individual links to be long [1][2]. Some work has been performed in this field, though usually in a cluttered environment, and often with the terminal very close to the surface [3]. Beaujean, et al [3] have shown that operating at high-frequencies is possible, and that high frequencies enable a wide raw channel bandwidth that yields increased in data rates.

The high frequency underwater acoustic communication channel is not well characterised. This lack of channel information adds unnecessary risk to the development of effective high data-rate underwater modems.

In section 2 we examine the underlying causes of channel artifacts and describe their expected effects on a high-frequency short-range channel. Section 3 describes the experimental setup, section 4 reports on initial trials and interprets the results, leading to a conclusion in section 5.

II. Previous Measurements and Expected Results

Signals propagating in the underwater acoustic channel suffer from attenuation, reflection and refraction.

A. Attenuation

Attenuation is well understood [4] so was not directly measured in these experiments. At high frequencies, long paths are impractical due to strong absorption. Therefore we are investigating the short range path, and will use a maximum path length of 100 m. Multi-hop relay or a non-acoustic backhaul channel can be used to provide communication over ranges in excess of this limit if required.

B. Reflection

Reflection from the water surface is generally strong, while reflection from the bottom varies widely depending on the bottom composition. When the water surface is smooth the reflection is specular, so the signal received at the destination is seen to arrive as a series of sharp wavefronts as shown in figure 1(a). Conversely, when the surface is rough the reflection is diffuse and the signal arrivals are spread over a large number of small, non-coherent signal arrivals as seen in figure 1(b). For low to medium frequency channels wind can cause sufficient surface disturbance to change the surface reflection from a specular reflection that is constant with time, to a reflection that is diffuse, at least when viewed over the channel measurement period.

The nature of the reflection from a surface is a function of the surface roughness relative to the wavelength and the angle of incidence. The frequency used in this investigation is 20 times shorter than those typically used in underwater acoustic communication, making surface irregularities larger relative to the wavelength. Even in calm conditions the water surface appears rough compared to wavelengths of approximately 1.8mm, meaning that results are more likely to resemble figure 1(b) rather than the more commonly seen 1(a).

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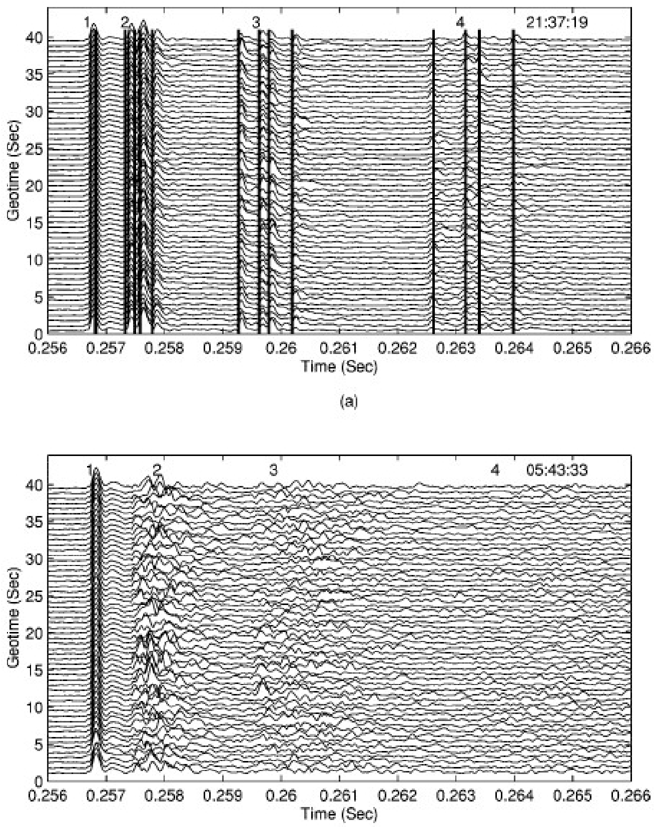

Figure 1. Channel impulse response due to wind [5]

At the scale of millimetres the bottom tends to be rough, so bottom reflections are unlikely to be specular.

C. Refraction

Sound travels faster in denser media, such as at depth in the ocean. The 'fast-deep' path is well known, but is it likely to be seen in the channel under investigation?

Using a velocity of propagation difference of 0.016 m^2/s due to hydrostatic pressure [6] change with depth, the path difference between the direct and the fast deep path for a 100 m nominal path length is 4.6×10^{-6} m, or 3 ns. For an 820 kHz signal this equates to a phase difference of less than 1°, meaning that a discernable strong deep path due to hydrostatic pressure alone is extremely unlikely at ranges of 100 m or less.

Near the surface, temperature is normally the dominant driver of sound speed. Speed variations due to temperature of up to 0.3 m^2/s [6] have been observed in the surface layer. When these result in upwards refraction they could cause path differences approaching a wavelength - meaning that fading may exist in specific circumstances.

III. Experiment and Equipment

A pseudorandom noise signal was transmitted laterally using a reflector[7]. The signal was recorded at various distances with an omni-directional hydrophone. The recordings were cross-correlated (post-processed) against the transmitted signal to obtain time resolution down to 21 μs. The transmitter was floating on a small spar buoy with the reflector at 5 m depth. The hydrophone was suspended from a small boat at a 5 m depth. Both transmitter and receiver were subject to some movement due to surface perturbation. A schematic of the experimental setup is shown in Figure 2.

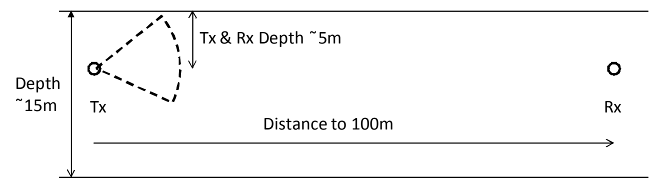

Figure 2. Test Arrangement

IV. Results

A plot of the typical cross-correlation results is shown in Figure 3. This shows a strong, although intermittent, main arrival with no apparent multi-path arrivals. The x-axis is labeled in distance with arbitrary zero point, increasing distance from the source is to the left. There were no signal arrivals (early or late) outside this view. While the time of arrival is clear, the detection is intermittent. This is due to doppler effects, which are investigated in the next section.

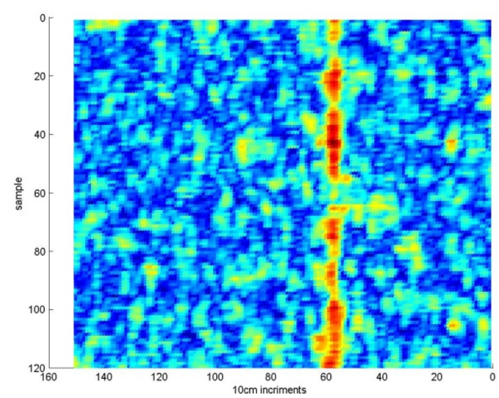

Figure 3. Typical 100 m path result

A. Doppler Detection

The matched filter used for detection is relatively long (50 ms). This gives high processing gain, and also good doppler resolution (20 Hz).

Figure 4 shows the conventional cross-correlation, processed as multiplication in the frequency domain for a nominal 5 m separation in Googong Dam, a freshwater reservoir near Canberra, Australia. This figure shown a time period of 1 second on the vertical axis. The 5 m path results are used for this doppler investigation because their SNR is better than the 100 m path data shown in Figure 3. Although a clear main arrival appears at a distance of around 5 m, periods of poor signal reception are evident. The dual arrival, with 0.1 m separation is an artifact of the reflector used and can be repeated in laboratory trials. In addition the 0.1m path difference is too small to be traditional multipath in this scenario, and the 0.1 m difference is independent of the scenario. It is not a channel characteristic.

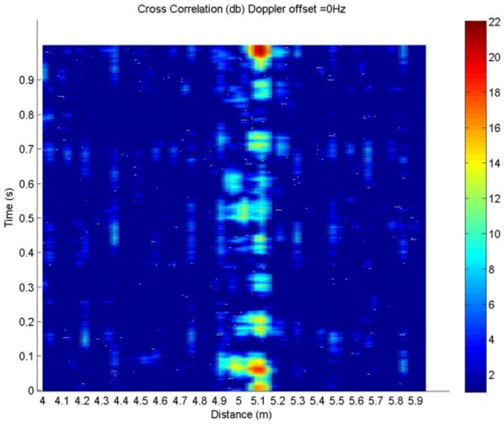

Figure 4. 5 m path recording

The intervals of poor reception above are due to the received signal not correlating with the matched filter. This is because the doppler shift on the signal is greater than the inverse of the matched filter length. In other words, the doppler shift equates to at least a whole wavelength over the filter length. In our case the filter length is 50ms, meaning that the doppler resolution (doppler bin width) is 20Hz.

Six matched filters of 20 Hz width were used to measure doppler. The recovered sections of the signal over the same 1 second period as the previous figure can be seen in Figure 5. The missing portions of the 0 Hz cross-correlation above are evident in other doppler bins. In this case the maximum doppler excursion is approximately +/-80 Hz, and the rate of change of doppler is in excess of 500 Hz/s. Although conditions were relatively calm, the transducer and hydrophone were impacted by surface movements. Terminals implemented as submerged moorings would be subject to less disturbance.

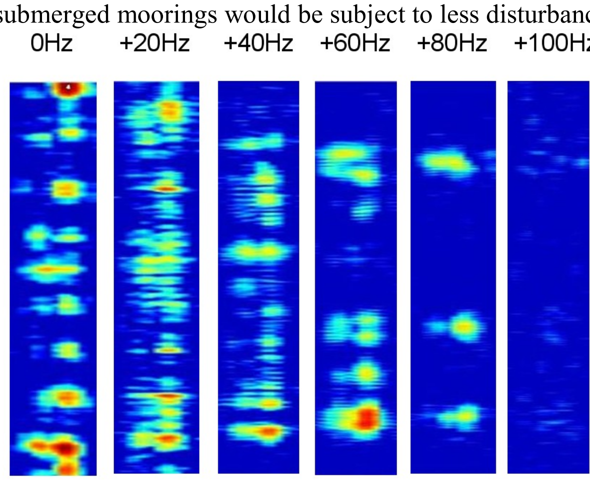

Figure 5. Doppler response for 5 m recording. (shifts are +/-)

V. Conclusion

The high frequency channel (820 kHz) does not appear to exhibit the multi-path effects that complicate underwater acoustic communication at low frequencies, so simple modulation schemes may work at high-frequencies. The maximum observed doppler shift was around 100 Hz, and the maximum observed dopper rate was less than 1000 Hz/s. These rates appear quite high, but at a frequency 820 kHz, the symbol rate could easily be of the order of 100 ksymbols/s. So the maximum doppler shift would be around 0.1% of the symbol rate, and the maximum doppler rate is only 1% of the symbol rate. In conjunction with the large bandwidth available at high frequencies this may make high data rates possible using simple modems. We are currently confirming and extending on these measurements and their implications.

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