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Design Considerations for Shallow Water Acoustic Communication Systems

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Relevant characteristics of the underwater channel used for acoustic communications are briefly described. There is a trade-off between achievable transmission range and data throughput. Transmission range of several kilometers with carrier frequency of 50kHz and several tens of kilometers with frequency less than 10 kHz might be possible using only 75 watts of acoustic power. Also, we investigated the required acoustic power for certain transmission ranges at given signal-to-noise ratio (SNR) values and the effect of wind speed. A shallow water channel model is proposed to study signal attenuation and arriving angles of the multipath. As the signal time delay increases, the arriving angle of the reflected signals becomes larger, allowing us to limit the number of multipath signals using a directional receiver. We will see that using directional receiver is better suited for a channel with a small range-to-depth ratio (RDR) and that equalization methods are better suited for a channel with a large RDR. Finally, hardware complexity for designing shallow water acoustic communication systems is studied using a currently available digital signal processing (DSP) technology.

1. Introduction

The characteristics of an underwater acoustic channel impose certain limitations on the design of underwater acoustic communication systems. Transmission loss and ambient noise limit the achievable transmission range and the usable carrier frequency and therefore achievable data rates. Intersymbol-interference due to multipath propagation and Doppler spreading caused by the relative motion of transmitter/receiver are other impairments to the achievement of high data rate transmission.

In this paper, design problems associated with shallow water acoustic communication systems are considered. In section 2, relevant characteristics of the underwater channel used for acoustic communications are briefly described. The required acoustic power to achieve a certain transmission range for a given signal-to-noise ratio (SNR) value is investigated. In section 3, investigating the relation between transmission range and arriving angles of multipath signals, we found that use of a directional receiver is better suited for a channel with a smaller RDR and that equalization methods are better suited for a channel with a large RDR. In section 4, hardware complexity for designing shallow water acoustic communication systems is studied using currently available DSP technology.

2. The Underwater Acoustic Channel and Achievable Transmission Range

In this section, relevant characteristics of the underwater channel used for the acoustic communications are briefly described. Based on these characteristics, we investigate the achievable transmission range at given channel conditions and system requirements. The factors that limit range and rate of acoustic signal transmission include transmission losses, ambient noise and cavitation threshold.

A. Transmission losses

As an acoustic wave propagates outward from its source, its intensity decreases. The rate of this intensity spreading depends on the channel geometry. Let us define a shallow underwater channel as a channel with a RDR approximately larger than 10. In a shallow water channel, transmission loss (TL) is governed by the cylindrical spreading law, that is [1, 2],

$$TL = 10 \log r \tag{1}$$

where r is transmission range.

In addition to the spreading loss, the attenuation of the signal is caused by the conversion of some portion of the radiated energy into heat and lost to the medium during propagation. This attenuation due to absorption is a function of frequency and limits the usable frequency for a particular transmission range. The absorption coefficient $\alpha(f)$ in dB/m as given by [3] is:

$$\alpha(f) = \left[\frac{2.34 S f_T f^2}{f_T^2 + f^2} + \frac{3.38 f^2}{f_T}\right] \times \left(1 - 6.54 \times 10^{-4} P\right) 8.686 \cdot 10^{-6} \tag{2}$$

where S is salinity in ppt, f is frequency in kHz, T is temperature in °C, P is pressure in kgf/cm^2 and

$$f_T = 21.9 \times 10^{[6 - 1520 \cdot (T + 273)]} . \tag{3}$$

The transmission loss is then the sum of the spreading loss and the attenuation, that is,

$$TL(f) = 10 \log r + r\alpha(f) . \tag{4}$$

B. Ambient noise

Ambient noise in an underwater channel is caused by several sources [4]. Its intensity in dB re 1 μPa per $\sqrt{Hz}$, termed as noise level (NL), are given below where frequency f is expressed in kHz.

- Turbulence noise:

$$NL_1 = 17 - 30 \log f . \tag{5}$$

- Shipping noise:

$$NL_2 = 40 + 20(D - 0.5) + 26 \log f - 60 \log(f + 0.03) , \tag{6}$$

where D is shipping density with value between 0 (light) and 1(heavy).

- Surface agitation noise:

$$NL_3 = 50 + 7.5\sqrt{w} + 20 \log f - 40 \log(f + 0.4) , \tag{7}$$

where w is wind speed in m/s.

- Thermal noise:

$$NL_4 = -15 + 20 \log f . \tag{8}$$

The total noise due to these contributions is:

$$NL = 10 \log \sum_{i=1}^{4} 10^{\frac{NL_i}{10}} \tag{9}$$

The total in-band noise NLB for a narrow band receiver is given by:

$$NLB = NL + 10 \log B \tag{10}$$

where B is bandwidth in Hz.

C. Achievable transmission range

In this section, the achievable transmission range for underwater communication is investigated considering the carrier frequency, acoustic power transmitted and wind speed. When the power radiated by a sonar projector exceeds the cavitation level, cavitation bubbles begin to form on the surface and just in front of the projector. This limits the acoustic power which can be transmitted. The cavitation threshold I_T in watts/cm^2 at depth z is [7, 8]:

$$I_T = 0.3\gamma\left(P_C(0) + \frac{z}{33}\right)^2 \tag{11}$$

where γ is a factor expressing the near-field effect on the cavitation limit with a value between 0.3 and 0.6, $P_C(0)$ is ambient pressure in atm. at the water surface, and z is depth in feet. When multiplied by the face area of the projector (in cm^2), the cavitation threshold represents the maximum transmitted power (in watts). At water surface with the atmospheric acoustic pressure of 1 atm., the cavitation threshold is $I_{TO} = 0.33$ watts/cm^2. Let us assume that a total radiated acoustic power W at the onset of cavitation is distributed uniformly over an effective projector area A. With a threshold I_{TO} at water surface ($z = 0$), the relationship between maximum power W_{max} and depth z in feet is given by:

$$W_{max} = A I_{TO} \cdot \left(1 + \frac{z}{33}\right)^2 . \tag{12}$$

For instance, a piston projector with a 10 cm diameter face is limited by cavitation to maximum power of about 26 watts when operated near the water surface. The cavitation threshold increases rapidly with depth, enabling greater power to be transmitted.

At a depth of 20 m, the projector can radiate 232 watts, approximately 8.9 times its maximum power at the surface. A typical acoustic transducer produces pressure of 190 dB re 1μPa at 1 meter away on the maximum pressure axis (source level, SL), requiring 71 watts of acoustic power.

The maximum detectable range for a required SNR can be obtained using Eq. (4), Eq. (10) and an expression for SNR,

$$SNR = SL - TL - NLB + DI \qquad (13)$$

where TL is transmission loss as previously defined and DI represents directivity index.

Fig. 1 shows maximum detectable range vs. frequency for SNR = 0 dB. Results indicate that maximum detectable range decreases with increasing frequency. This is due to the larger attenuation at higher frequencies. Unfortunately, although reducing frequency allows for an increase in transmission range, it also results in decreased information throughput. With an operating frequency of 50 kHz, communication range is limited to several kilometers. Fig. 1 also shows that the detectable range decreases with the increased noise associated with higher wind speed.

As an example of underwater communications, assume that $f = 10$ kHz, $w = 20$ knots and $D = 0$ (light shipping). Then, total noise is 53 dB re 1 μPa per $\sqrt{\text{Hz}}$ and the total in-band noise is 86 dB re 1μPa when a typical value of quality factor $Q = f/B = 5$ is employed [5, 6]. Assuming $DI = 0$ dB (non-directional transducer) and $SL = 190$ dB re 1μPa, the practically achievable maximum transmission range is about 70 km. This range decreases to 60 km for heavy shipping noise ($D = 1$).

When designing a remote transmitter, the power is an important consideration because low power consumption is essential for a prolonged time of operation. Fig. 2 shows the acoustic power required to achieve certain transmission ranges at given SNR values. Depending on applications, the desired communication performance requires different power associated with different values of SNR. Even with a few tens of watts of acoustic power, signal transmission up to several tens of kilometers is possible. Fig. 3 shows the relationship between achievable transmission range and wind speed. As wind speed increases, the achievable range decreases due to the increased ambient noise caused by surface agitation.

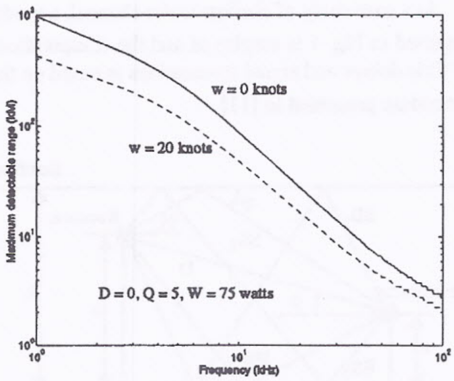


Fig. 1. Maximum detectable range vs. frequency

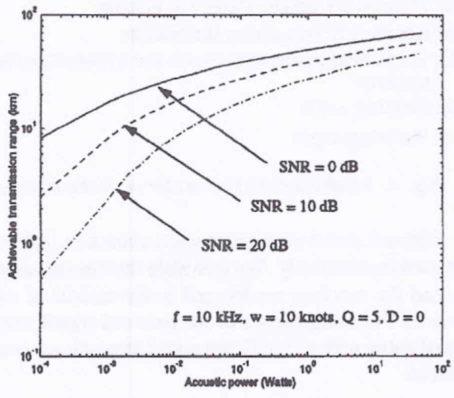


Fig. 2. Acoustic power vs. achievable transmission range

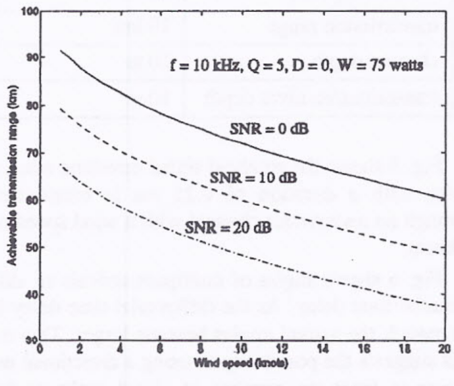
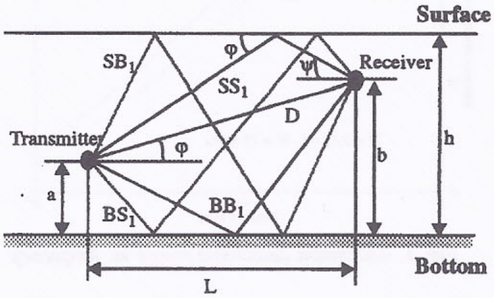


Fig. 3. Achievable transmission range vs. wind speed

3. A case study of a shallow water channel

As a case study of shallow water channel, a model depicted in Fig. 4 is employed and the computations of time delays and signal attenuations is based on the procedure presented in [11].



a: Transmitter height above the bottom
b: Receiver height above the bottom
L: Horizontal distance between the transmitter and receiver
φ: Grazing angle
ψ: Arriving angle

Fig. 4. Model for shallow water acoustic channel

Channel and system parameters shown in Table I are used for this study. We postulate that the transmitter and the receiver are located in the middle of the channel. For computation of the received signal, only signal paths with a significant signal strength are considered.

Table I: Channel and system parameters

signalling rate	5.0 ksymbols/s
carrier frequency	10 kHz
transmission range	10 km
channel depth	20 m
transmitter/receiver depth	10 m

Fig. 5 shows the received signal envelope when a pulse with a duration of 0.25 ms is transmitted through an underwater channel with a wind speed of 5 knots.

Fig. 6 shows angles of multipath arrivals vs. differential time delay. As the differential time delay is increased, the arrival angles become larger. This result suggests the possibility of using a directional receiver to limit the number of signal paths at the receiver.

Let us assume that a directional receiver with the simplified beam pattern depicted in Fig. 7 is employed. This beam pattern has a constant level within the main lobe and another constant level with a side lobe. That is, all multipath signals arriving outside the main lobe are subject to equal suppression. Therefore, signal strength of the multipath arriving from outside of the main lobe is attenuated by a directional receiver. Here, we assume that the side lobe level is 20 dB below the main lobe.

Fig. 8 depicts the maximum signal delay vs. wind speed with and without a directional receiver. At low wind speed, the maximum signal delay is quite large and the benefit of a directional receiver is noticeable. If the system is operating with an non-directional transducer, the maximum signal delay extends over 450 symbols (90 ms) for wind speed less than 4 knots. However, using a directional receiver with a beam-width of 5°, the maximum signal delay can be reduced to 77 symbols (15.4 ms). This will eventually enable us to use a smaller number of equalizer taps, resulting in reduced hardware complexity.

Fig. 9 shows the maximum signal delay as the distance between transmitter and receiver is varied. At a horizontal range less than 2 km, the multipath delay spread can exceed 100 ms, which corresponds to 500 symbols duration. Fig. 10 shows largest arriving angle vs. distance between transmitter and receiver. At shorter transmission ranges, the arrival angles of signal paths are larger which allows us to use a directional receiver effectively to remove reflected signal paths with a larger angular spread. At large horizontal ranges, the largest arrival angles decreases, requiring a high resolution directional receiver, but maximum signal delay is also reduced to an amount relatively easy to equalize. This indicates that the beamforming approach is better suited for channels with small RDR and equalization methods are better suited for channels with a large RDR.

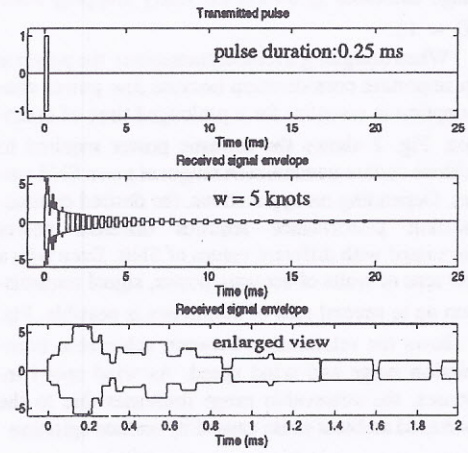


Fig. 5. Received signal envelop when a pulse is transmitted

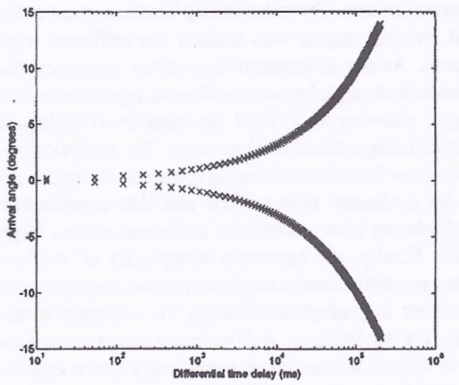


Fig. 6. Arrival angles vs. differential time delay

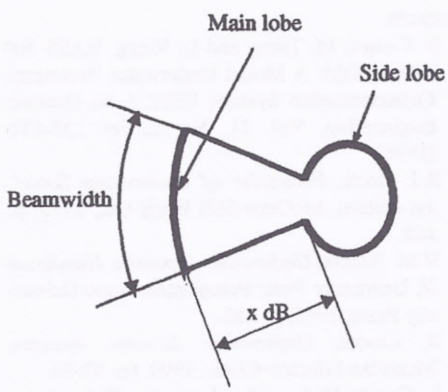


Fig. 7. Simplified beam pattern

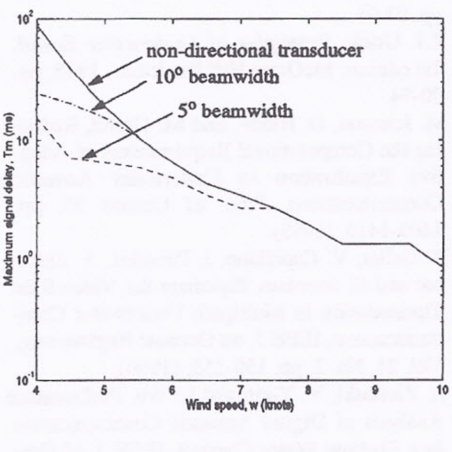


Fig. 8. Maximum signal delay vs. wind speed

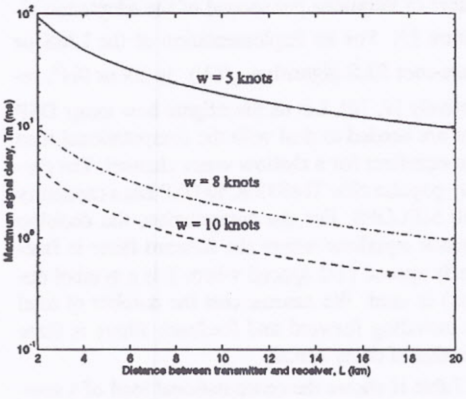


Fig. 9. Maximum signal delay vs. distance between transmitter and receiver.

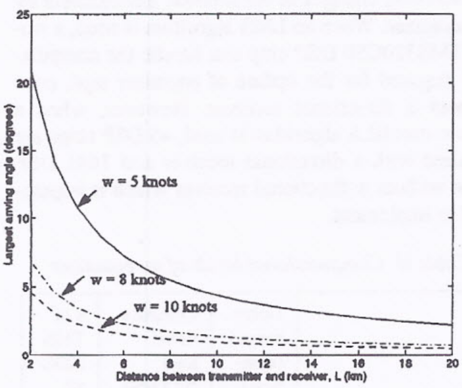


Fig. 10. Largest arriving angle vs. distance between transmitter and receiver

4. The consideration of hardware complexity

An equalizer can be used to cope with intersymbol interference introduced by multipath propagation. In this section, we will investigate the hardware complexity associated with an equalizer. In order to produce optimum equalizer output, the coefficients of an equalizer are iteratively updated. Frequently employed algorithms for the update of an equalizer's coefficients are least-mean-square (LMS) and square-root recursive-least-square (RLS) algorithms. The computational load of the equalizer, expressed by required floating point operations per second (FLOPS), is approximately given as:

$$FLOPS = f(N) \times updates/s \qquad (14)$$

where $f(N)$ is the computational load of the iteration of the adaptive algorithm and $updates/s$ is the number of iterations per second of the adaptation algorithm [9]. For an implementation of the LMS or square-root RLS algorithm, $f(N)$ is 2N or $9N^2$, respectively [9, 10]. Let us investigate how many DSP chips are needed to deal with the computational load of an equalizer for a shallow water channel. The currently popular chip TMS320C50 DSP has a capability of 50 MFLOPS. For the computation, the decision feedback equalizer where the forward filter is fractionally spaced (T/2 spaced where T is a symbol duration) is used. We assume that the number of total taps including forward and feedback filters is three times that of delay spread.

Table II shows the computational load of a sample system with channel conditions given in Table I at wind speed of $w = 4$ knots. Note that this computational load is only for rejecting multipath signals and tracking changes in the acoustic environment by an equalizer. When an LMS algorithm is used, a single TMS320C50 DSP chip can handle the computation required for the update of equalizer taps, even without a directional receiver. However, when a square-root RLS algorithm is used, 46 DSP chips are required with a directional receiver and 1641 DSP chips without a directional receiver which is impractical to implement.

Table II. Computational loads of an equalizer

		Delay spread (symbols)	Computational load (FLOPS)	# of TMS 320C 50
LMS	non-directional receiver	450	1.35×10^7	1
	directional receiver (BW = 5°)	75	2.25×10^6	1
square -root RLS	non-directional receiver	450	8.20×10^{10}	1641
	directional receiver (BW = 5°)	75	2.28×10^9	46

5. Summary

In this paper, the signal propagation in a shallow water channel was studied to investigate the required acoustic power needed to achieve a certain transmission range. Analyses indicated that communication over several tens of kilometers with frequency less than 10 kHz might be possible using only 75 watts of acoustic power. The relationship between time delay and arriving angles was studied for different wind speeds. As the differential time delay increases, the inter-arrival angle between reflected signals becomes larger, allowing us to limit the number of multipath signals using a directional receiver. The analytical results show that a beamforming approach is better suited for a channel with a RDR and that equalization methods are better suited for a channel with a large RDR. Finally, the hardware complexity of shallow water acoustic communication systems employing an equalizer is studied considering the currently available DSP technology. A directional receiver enables us to reduce the hardware complexity but a square-root RLS algorithm is still impractical to implement since it requires as many as 46 processors.

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