Coherent and Differential Acoustic Communication in Shallow Water Using Transmitter and Receiver Arrays

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***Abstract*-Underwater acoustic communication link performance is investigated under strong time-frequency variation. A state of the art split-step parabolic equation program was used to generate channel responses under a moving rough sea surface. A shallow water environment with 47.5m depth at 1km range was considered, with the sea surface characterized as a mature sea under a 10m/s (at 10m height) wind. OFDM signal structure with a reasonable trade-off between symbol duration and subcarrier bin width is found to address only partially the severely overspread channel. It is found that beamforming at the transmitter and at the receiver significantly improves both coherence time and frequency, allowing doubling of the effective throughput. Further improvement of the rate is achieved through differential modulation which avoids training overhead. A link with 4 transmitters and 10 receivers was found to support 1.8 bps/Hz effective rate at 1km using differential modulation on each OFDM subcarrier, more than 4 times the corresponding rate of a 1x1 link using pilot-based estimation and non-differential modulation on each OFDM subcarrier.**

I. INTRODUCTION

It has been very difficult to achieve spectral efficiencies in underwater acoustic communication comparable to the state of the art in terrestrial radio frequency (RF) communication. This discrepancy is due to the challenging and dynamic nature of the ocean environment used as a communication medium – poor link quality, spatial and temporal variation, and large delay spread. Underwater acoustic communication rates are often limited in doubly-spread channels where strong frequency selectivity and large Doppler spreads impose conflicting requirements on transmit signal design and reduce the quality of channel estimation necessary for high rate coherent communication[1]. A multi-element channel offers the promise of increased diversity and higher signal to noise ratio (SNR) through coherent combining of signals received at many elements, and possibly emitted by many transmitters. Accurate channel estimates are key prerequisites for such enhancements. Channel estimates are generally obtained by sending known "pilot" signals placed densely enough so as to allow adequate sampling of the channel both over frequency and over time. In a generally varying propagation environment, the time-varying impulse response must then be estimated separately from each transmitter to each receiver. Limitations imposed by the lack of coherence are most significant at the stage of learning the channel, where no benefit is derived from multiple elements.

As the underwater propagation environment is often well approximated as a layered structure, there is a strong correspondence between spatial modes of the communication channel and delays and temporal coherence of the channel. In particular, steeply propagating rays bring diversity against fading but also introduce significant delay spread. As such rays also strike the generally moving sea surface, they are also characterized by increased Doppler spread. It is therefore natural to seek to reduce both Doppler and delay spread through beamforming, if possible, at the transmitter and the receiver.

Another difficulty is designing the transmitted signal for overspread channel. Orthogonal Frequency Division Multiplexing (OFDM) is a well-established technique for simple and effective communication in a channel with significant frequency selectivity. Channel frequency and time variations impose conflicting requirements on OFDM signal design. Strong frequency variation are addressed through narrow subcarrier bin width, with corresponding long symbol duration. Coping with rapid channel time variation suggests short symbols, with corresponding wide subcarrier bins. Known "pilot" symbols are normally placed in the time-frequency plane densely enough to allow channel interpolation and yet sparsely enough to reduce such training overhead. An alternative to pilot placement is the use of differential modulation, which removes the need for overhead at the cost of degradation in SNR.

In [2] performance of OFDM in underwater communication has been examined under conditions of slow, near-constant Doppler drift. In [3] and [4] the

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sparse channel structure has been exploited to assist in channel estimation in slowly time-varying conditions. High spectral efficiency has been reported in [5] through the use of time-reversal array processing under apparently minimal temporal variation. Our previous work on underwater channel modeling [6][7] showed that in shallow water environment under a rough moving surface, an acoustic channel with high carrier frequency experiences severe spreading in both time and frequency which is much worse than the channels used in other reference designs. Examining the performance of acoustic communication links and evaluating the effective communication design in severe doubly-spread channels is therefore of great interest.

In this paper, an assessment of the performance of acoustic communications is carried out in shallow water using vertical beamforming at the receiver and/or the transmitter. A model based, data-driven methodology is developed to characterize acoustic propagation in shallow water under a rough moving sea surface. Channel responses corresponding to different transmitter and receiver pairs are generated and used in the communication design and evaluation through simulation. Pilot-based and differential modulations are compared under channel conditions that vary from underspread to severely overspread.

II. ENVIRONMENT AND CHANNEL MODELING

The changing sea surface is an important factor in determining channel characteristics at a given site, especially in shallow water, but it is far from the only factor. Short term variations in the sound speed profile, internal waves, bubble clouds and wave breaking also affect the channel characteristics. Aside from using a seasonally appropriate sound speed profile, this paper concentrates on moving rough surface effects as the mechanism for temporal variation in the acoustic channel.

At most temperate and higher latitude sites the extent to which underwater sound is shielded from the surface has a very strong seasonal dependence with the surface being least shielded when it is roughest. The moving rough sea surface causes an angular redistribution and Doppler shift of sound that interacts with it.

Although this is a complicated acoustic propagation problem, there are existing models that can cope with it provided a realistic description of the surface is available. The surface wave spectrum from ~0.03 Hz to ~0.5 Hz is routinely measured by wave buoys. The 15 cm and shorter acoustic waves of interest in underwater acoustic communications are also sensitive to frequencies in the surface wave spectrum well above 0.5 Hz. At those frequencies, measuring wave spectra is very difficult. There is still significant uncertainty over such basic matters as the shape of the spectrum and the time interval over which an individual spectrum should be a good approximation.

There have been attempts to fit the copious data at low frequencies and the sparse data at higher frequencies to produce analytical spectra depending on a few parameters that describe the spectrum from a few hundredths of a Hz up to 5 Hz and above. In the work reported here, the spectral model of [8] was used to generate a spectrum.

With a spectrum in hand, our approach to modeling propagation is as follows: An initial sea surface realization of the spectrum is generated using Fourier transform techniques. Later surface realizations are produced from the initial realization using the surface wave dispersion relation. The frequency band of interest is divided into a set of discrete frequencies. A rough surface parabolic equation code is executed for each possible source depth, surface realization, and frequency triplet. Each such run produces a complex pressure field at a selected set of range and depth points. These pressure fields are the inputs as channel responses to the communication design and evaluation discussed in the rest of the paper.

In order to carry out propagation modeling and computation, we use an extension to higher frequencies of an existing rough surface parabolic equation model developed in our previous work [9]. There the underlying parabolic equation code was the Range-dependant Acoustic Model (RAM) program [10].

We have tried to model conditions that one might encounter in the vicinity of National Data Buoy Center (NDBC) wave buoy 44014 (36.611N 74.836W, water depth 47.5m) in March. A geoacoustic bottom model for the site was constructed from information in the dBSeabed [11] database of marine seabed substrate measurements. We assume a constant bathymetry with the same depth as the buoy 44014 mooring point. The sound speed profile comes from the GDEM-V Version 3.0 climatological sound speed field [12]. We have not yet attempted to make the sound speed field range and time dependent. The spectral model we employ requires the wind speed at 10m, the friction velocity, and the inverse wave age as inputs. We use 10 m/s, 0.38 m/s, and 0.84 as the input parameters respectively. The transmission bandwidth is modeled from 9.5 KHz to 10.5 KHz with a step interval of 0.5 Hz. We use 101 surfaces spaced 0.01 sec apart, for a total duration of 1 second.

III. CHANNEL IMPULSE RESPONSES

Extensive computational facilities have been used to speed the channel simulations. Simulation bandwidth is 1000 Hz, centered around 10 kHz. The environment is shallow water with 47.5 m depth, and relatively constant sound speed as a function of depth. Channel responses are generated for 4 transmitters and 10 receivers, placed near the bottom and separated by half wavelength of the center frequency. Channel response for each source-receiver pair at a particular time and frequency is obtained by scaling the computed complex pressure (as described in section II) so as to assure desired SNR.

Both instantaneous and autocorrelation properties of the channel are illustrated in Figures 1-6. Figure 1 shows the power of the instantaneous channel impulse response. Significant arrivals are found to come in within 0.1 sec of the first arrival. The corresponding frequency spectrum is shown in Figure 2. The characteristic frequency scale of variation is seen to be under 10 Hz. Temporal variation in windy conditions is illustrated in Figure 3 where channel response at 10 kHz is shown as a function of time, with a characteristic time scale of under 100 ms. Joint time-frequency variation of the channel response is shown in Figure 4. Coherence may be quantified more precisely through appropriate autocorrelation functions. The Two Frequency Autocorrelation Function, is defined in terms of the frequency-dependent channel transfer function $H(t_0,f)$ as

$$C(f_2-f_1)=\left\langle H(t_0,f_2)H^*(t_0,f_1)\right\rangle_{t_0} \Big/ \left\langle \left|H(t_0,f)\right|^2\right\rangle_{t_0} \quad (1)$$

where (f_2-f_1) is the frequency difference between two frequency instances. The result is plotted in Figure 5. The averaging is carried out over time. For a single transmit/receive pair, at $C(f_2-f_1)$ =0.7, the channel coherence bandwidth B_c is about 4 Hz. Similarly, the temporal autocorrelation, is defined in terms of the time-dependent channel transfer function $H(t,f_0)$ at a constant frequency f_0 as

$$C(t_2-t_1)=\left\langle H(t_2,f_0)H^*(t_1,f_0)\right\rangle_{f_0} \Big/ \left\langle \left|H(t,f_0)\right|^2\right\rangle_{f_0} \quad (2)$$

where (t_2-t_1) is the time difference between two time instances. The result is plotted in Figure 6. The averaging is carried out over frequency. For a single transmit/receive pair, at $C(t_2-t_1)$ =0.7, the channel coherence time T_c is about 25 ms or 0.025 s.

A quick insight into communication difficulties may be obtained by attempting signal design. A coherence bandwidth of 4 Hz suggests that channel needs to be measured at least as frequently as every 4 Hz (e.g. 256-length FFT for 1 kHz signal in OFDM). The corresponding time "resolution" is 0.25 s (e.g. OFDM symbol period of 0.25 s duration). This far exceeds the 0.025 s coherence time of the channel. This is formalized through the consideration of the time-bandwidth product. For links with single omnidirectional transmitters and receivers it may be observed that T_cB_c =0.025×4=0.1. The coherence time-bandwidth product is less than one, which will be seen to degrade channel estimation accuracy significantly.

Both coherence time and frequency increase substantially if transmitters are used to form a coherent horizontal beam, as marked in Figures 5 and 6. The corresponding effective channel response, observed at one receiver, computed for four transmitters as

$$H_{1B}(t,f)=\sum_{m=1}^{4}H_{1m}(t,f) \quad (3)$$

For a vertical array explored here, above in-phase addition corresponds to forming a horizontal beam.

Even greater increases in coherence are observed when beamforming is applied at both receiver and transmitter arrays, containing 10 and 4 elements, respectively:

$$H_B(t,f)=\sum_{n=1}^{10}\sum_{m=1}^{4}H_{nm}(t,f) \quad (4)$$

Increases in frequency coherence may be explained by reasoning that in a stratified medium frequency variation is the result of delay spread encountered through multipath refraction and reflection from boundaries. Beamforming reduces the angular extent of the multipath, emphasizing horizontal paths and thus reducing the influence of the steep paths that accumulate longest delays. Shorter delay spreads that lead to greater frequency coherence. Temporal coherence is also improved in this channel where the cause of temporal variation is scattering from a moving sea surface. As beamforming reduces the strength of steeper paths striking the surface, the channel temporal variation is reduced. Relative emphasis of short travel time, steady horizontal paths is even stronger when beamforming is carried out at both transmitter and receiver.

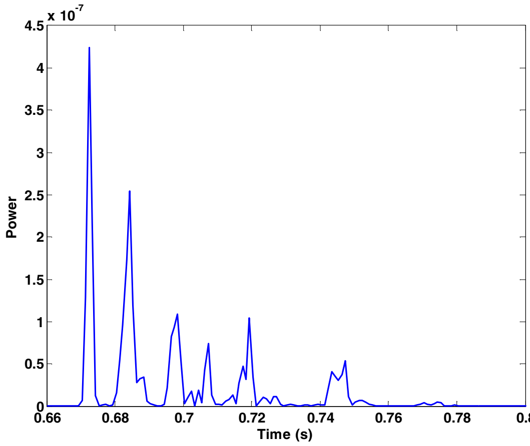

Figure 1. Instantaneous power of the acoustic channel impulse response at 1 km range in shallow water, 1000 Hz Bandwidth, receiver/transmitter depth of 46 m.

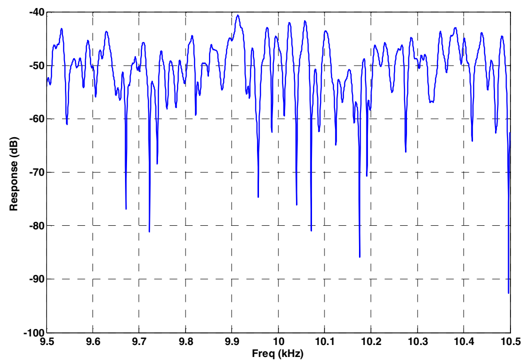

Figure 2. Instantaneous Power spectrum of acoustic channel impulse response at 1 km range in shallow water.

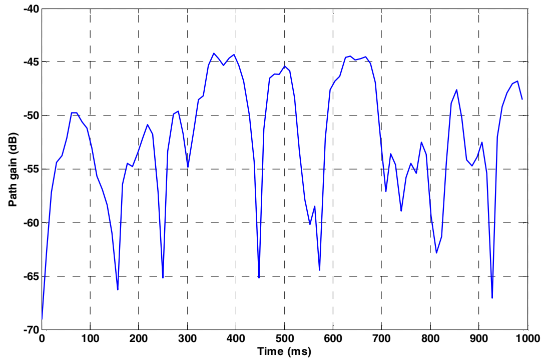

Figure 3. Instantaneous Power time variation at 10 kHz at 1km range under 10m/s (at 10m height) wind.

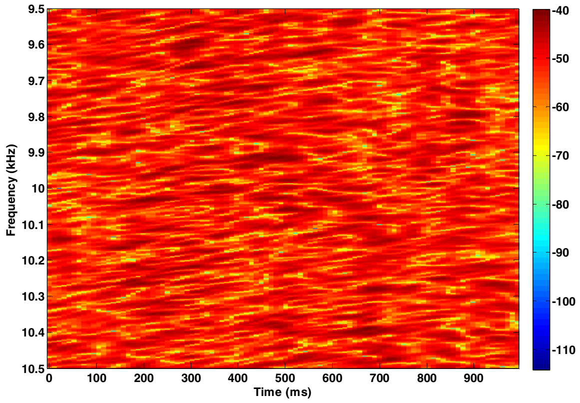

Figure 4. Instantaneous time-frequency power distribution at 1km under 10m/s (at 10 m height) wind.

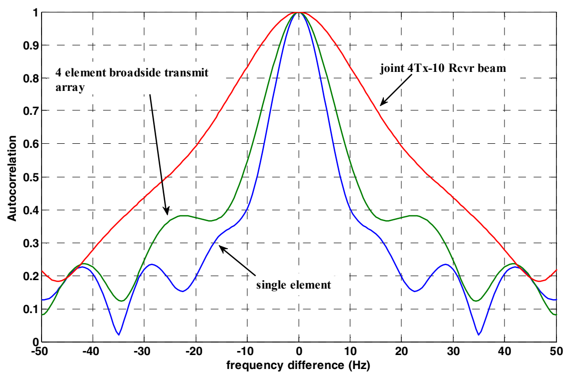

Figure 5. Amplitude of the frequency autocorrelation in shallow water at 1km range.

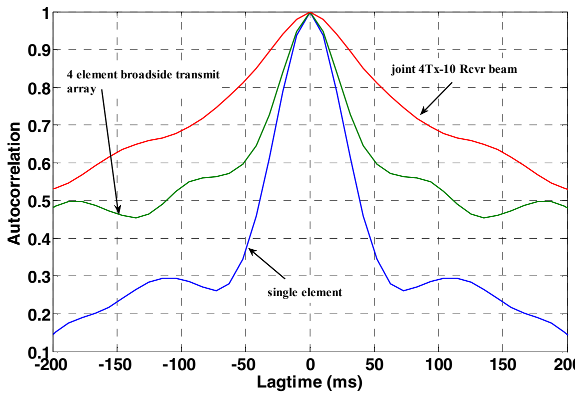

Figure 6. Amplitude of the time autocorrelation in shallow water at 1km range.

IV. LINK SIMULATION MODEL AND PROCEDURE

We developed a full scale link simulation model, which includes the generation of OFDM symbols with cyclic pre/postfixes, transmission through a time varying, frequency selective channel, OFDM detection and reception, symbol time estimation, channel estimation and Minimum Mean Square Error (MMSE) reception.

The OFDM signal format is chosen with 128 Fast Fourier Transform (FFT) length and symbol period of 0.12 second, higher than the coherence time of 25 ms. The corresponding subcarrier bin width of 8 Hz is somewhat higher than the coherence bandwidth. Cyclic pre-fix of 0.04 s is included as part of each symbol, accounting for most though not all of delay spread, in Figure 1. Other signal formats have also been considered but found inferior. The extreme time-frequency variability of this channel, as represented by the coherence time-bandwidth product discussed above necessitates a dense placement of pilot symbols, which are placed in a checkerboard pattern in the time- frequency plane. This imposes a 50% overhead penalty. Sparser pilot placement has been found to increase the error further. Channels with slower scale variability may be handled with sparser pilot placement. Channel estimation is implemented through 2-D interpolation of estimates obtained at pilot locations.

V. PERFORMANCE RESULTS

Performance is quantified in terms of the effective Signal to Interference plus Noise Ratio (SINR) and effective rate. SINR is defined in terms of expected signal s and estimated signal $\hat{s}: \rho_{eff} = \left\langle \left| s/(s-\hat{s}) \right|^2 \right\rangle$. This implicitly includes impairments due to channel estimation, uncompensated channel distortion and additive noise. This is a conservative assumption as it presumes such impairments to be irreparable. The effective rate is here defined as the Shannon rate with a 3dB (i.e. factor of ½) coding implementation penalty:

$$C_{eff} = \frac{B_{data}}{B_{data} + B_{pilot}} \log_2\left(1 + \rho_{eff}/2\right), \text{ (bps/Hz)} \quad (5)$$

The $\langle \ \rangle$ operator corresponds to averaging over time and frequency. The effective rate formula contains the “bandwidth utilization factor” accounting for “training overhead” due to pilot signal transmission. B_{data} and B_{pilot} refer to fractions of the time-frequency resources devoted to data and pilots, respectively. In case of coherent (i.e. non-differential) transmission the pilot overhead is 50% in this work, as discussed above. In differential signaling, the bandwidth utilization factor is 1, as there are no pilots there. The effective rate computed corresponds to the ergodic rate, implying that coding is expected to be carried over both frequency and time, with the channel undergoing extensive variation within the coding horizon.

It is found that beamforming at both transmitter and receiver doubles both coherence time and coherence bandwidth. Table 1 contains the performance results in stationary channels (i.e., zero wind speed), where the mean effective SINR is 3.8 dB and the effective Shannon rate is 0.5 bps/Hz. In this stationary channel, frequency selectivity is the main impairment, and the performance is improved by adapting the OFDM structure to consist of 256-bin OFDM, with a 0.19s symbol period.

Performance in time-varying channels, defined by a mature sea driven by a 10m/s wind is detailed for various array configurations in Table 2. The OFDM structure is adapted to the time-varying conditions, with 128-bin OFDM and 0.12s symbol duration. In a 1x1 Single Input Single Output (SISO) case, the effective SINR decreases to 0.8dB and effective rate is 0.4 bps/Hz under 10m/s wind speed. Beamforming 4 elements at the transmitter and 10 at the receiver improves the rate to 0.8 bps/Hz.

The rate is further markedly improved using the differential modulation in combination with OFDM and a-priory horizontal beamforming. As differential modulation does not require pilots, it naturally offers the highest effective throughput. In this case the empirical "goodput" using DQPSK was also found to be 1.8 bps/Hz, where "goodput" is defined as the number of delivered error-free bits/second/Hz.

TABLE 1
Simulated performance of a 1x1 (SISO) link at 20 dB SNR in shallow water at 1 km range under stationary sea surface, 256-bin OFDM and 0.19s symbol.

Configuration	Mean SINR (dB)	Ergodic Shannon-3dB rate (bps/Hz)
1x1 SISO with channel estimation	3.8 dB	0.5

TABLE 2
Simulated performance of various configurations in fully varying channel at 20 dB SNR in shallow water at 1 km range under rough moving sea surface, 128-bin OFDM, and 0.12s symbol.

Configuration	Mean SINR (dB)	Shannon-3dB rate (bps/Hz)
1x1 SISO with channel estimation	0.8	0.4
1x10 SIMO with channel estimation	3.9	0.5
4x10 single stream with a-priory (broadside) Tx/Rv beamforming	7.2	0.8
Differential (DQPSK) 4x10 single stream with a-priori (broadside) Tx/Rv beamforming	9.6	1.8

VI. CONCLUSION

In the shallow water environment under a 10m/s wind, time and frequency variability are found to be the dominant impairments to underwater communication links. Rapid time-frequency channel variation necessitates dense pilot placement, reducing the effective bandwidth available to data. Beam forming at the transmitter and at the receiver allow doubling of effective rates through improvement in both coherence time and coherence bandwidth of effective (beam) channel. It is found that differential modulation offers the best performance in these conditions, as it allows full bandwidth utilization (no pilots needed). Use of transmit/receive beamforming with differential modulation over OFDM signal structure offers over a factor of 4 improvement in rate compared to that achieved by a 1x1 link employing non-differential signaling.

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