Leveraging Advanced Sonar Processing Techniques for Underwater Acoustic Multi-Input Multi-Output Communications

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1 Abstract

This paper investigates the issue of high-rate, underwater acoustic (UWA) communication and the potential of multi-input multi-output (MIMO) techniques to achieve that end; further, this paper suggests that implementation of such a system would benefit from sonar array processing techniques such as multichannel combining. In order to justify this assertion, a comprehensive literature review was undertaken to assess the state of the art of research within the area of UWA telemetry. As a result of the literature review, several key papers demonstrate significant progress in the area of MIMO communications using sophisticated array processing techniques. This paper discusses their results and proposes future areas of research for UWA communication.

2 Introduction

With potential applications ranging from military to commercial to scientific, underwater acoustic (UWA) communications continues to be a growing area of interest to many in both the communications as well as sonar fields; however, due to the unique propagating physics of sound waves in water, the development of high-speed reliable digital communications systems has lagged behind the advancements made in terrestrial wireless communications. In short, the problem of the underwater channel is twofold: a fundamental bandwidth limit as well as a propagation speed orders of magnitude below that of terrestrial wireless radiation [1] [2]. In order to address these issues, recent focus has been given to spatial diversity techniques that seek to create orthogonal communication channels to improve spectral utilization. This paper focuses primarily on multi-input multi-output (MIMO) spatial diversity, in which a source transmits its message simultaneously over multiple transmit antennas to a receiver that utilizes multiple receive antennas, each with an independent look at the signal.

Spatial modulation seeks to use multiple, resolvable propagation paths between two arrays to create, in effect, parallel independent spatial channels within the single, physical ocean channel. The benefits are completely analogous to those of increased bandwidth [3]. At high signal-to-noise ratios (SNR), the capacity of the channel theoretically increases linearly with the minimum number of antennas present in the environment ($\min\{N_{\text{transmit}}, N_{\text{receive}}\}$ b/s/Hz per 3dB increase in SNR) under the assumption that the receiver knows the response of the channel and the system uses coherent signaling [4]. In order to take advantage of the MIMO gain, the data stream must be space-time encoded by emphasizing either increased system capacity for higher data rates or increased diversity for lower error rates. [3]. Assuming uncorrelated propagation paths and an accurate channel estimate, recovery of the N_{transmit} sequences is possible [3].

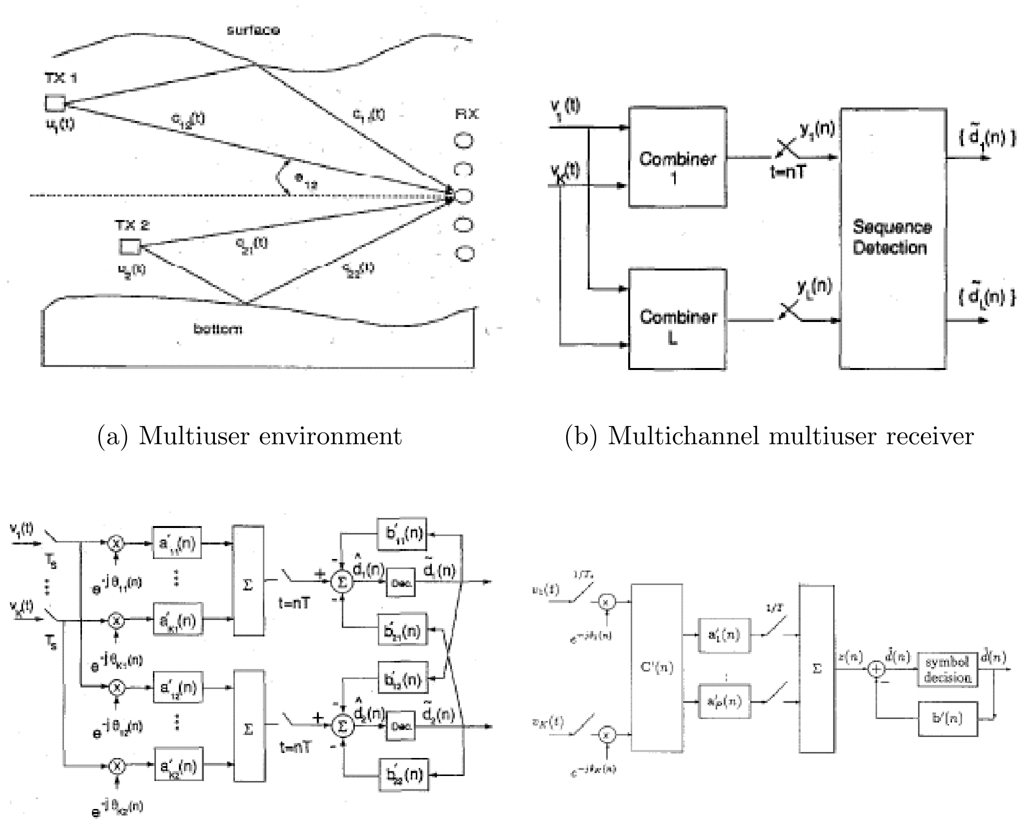
3 Problem Statement

Numerous variations of the MIMO receiver have been examined in the literature; however, with the availability of arrays of transducers in underwater sonar systems, this paper adopts a different receiver structure through the introduction of widely used sonar processing techniques. Filtering signals within the spatial domain, sonar array processing appears to provide an intuitive solution towards the end of independent spatial communication channels; therefore, in specific applications, array processing may prove at the least a desirable companion to and potentially an attractive alternative to analogous approaches in the temporal and frequency domains. Examples of such applications include steering nulls towards entities with which we do not wish to communicate, either for security reasons or to limit co-channel interference, as well as utilizing the available spatial diversity to maximize the signal-to-interference plus noise ratio (SINR), eliminating the need for equalization filters with hopelessly many taps in channels that exhibit significant multipath spread.

4 Related Work

Focusing on the issue of high-bandwidth communication in the presence of multiple users, the authors of [5] propose a multichannel receiver that exploits the spatial diversity inherent in ocean multipath. As can be seen in Figure 1, the system consists of multiple transmitting sources and a multiple element receiving array; furthermore, each source broadcasts a signal that experiences multipath fading. As a result, the received waveform is corrupted by a combination of intersymbol interference (ISI), co-channel interference (CCI), otherwise known as multiple access interference, and additive noise.

Taking advantage of the spatial diversity present in the above communication scenario, Stojanovic and Zvonar first derive the optimal multichannel multiuser receiver, which consists of a bank of optimal combiners and a maximum-likelihood sequence estimator (MLSE). The optimal combiners themselves consist of a bank of N_R channel matched filters whose outputs



(a) Multiuser environment

(b) Multichannel multiuser receiver

(c) Full complexity combiner

(d) Reduced complexity combiner

Figure 1: Multichannel multiuser system developed by Stojanovic et al. [5]. (a) Depiction of the multichannel, multiuser environment. (b) Multichannel, multiuser receiver. The structure of the combiner can be seen in figures (c) and (d). The full complexity combiner adapts and updates all of the branches of the input array, whereas the reduced complexity receiver attempts to reduce the number of branches to the number of multipath arrivals before adapting and applying the multichannel equalizer.

are summed and sampled at the symbol rate. Two obvious problems prohibit the use of the optimal multichannel multiuser receiver: computational complexity of the MLSE and lack of a priori knowledge of the underwater channel. Replacing the MLSE with with an equalizer and the optimal combiner with a bank of adaptive filters, the authors arrive at the receiver structure espoused in [5].

The multichannel combiner in [5] comes in two flavors: full and reduced complexity. The former consists of a bank of N_R adaptive filters that theoretically converge to the channel matched filters of the optimal combiner, whereas the latter introduces a spatial precombiner stage that essentially beamforms to the direction of each multipath arrival. Consequently, the number of adaptive filter reduces from the number of array elements to the number of spatial propagation paths. Though suboptimal, the authors of [5] suggest that use of the reduced complexity receiver stands as the preferred choice for use in multiuser, multichannel scenarios due to its reduced computational complexity and minimal performance degradation when compared to the optimal combiner.

Adopting the multichannel receiver structure of [5], Kilfoyle et al. apply the abstraction of multiple users to the specific case of multiple transmit antennas for the purposes of MIMO communications [3]. Their experiments examined the performance of the MIMO communication system for a shallow water channel, which presumably exhibits significant multipath, at a range of 0.5km. Comparing the performance of four different methods of spatial modulation, two of which rely on subarray techniques that directly map a single information stream into N_T information streams and two of which utilize beamforming using steering vectors derived a week in advance, the authors delineate the advantages and disadvantages of each approach. The results of the experiment are presented in Figure 2. Note the space-time coding gain achieved by the subarray techniques. Intuitively, it makes sense that subarraying outperforms beamforming in a spatial diversity scheme, owing to the fact that beamforming inherently confines the spatial propagation, and in turn, limits the available spatial diversity; therefore, the system that achieves the most spatial diversity (subarraying) offers higher space-time coding gains. On the other hand, the power efficiency ratio, the ratio of the signal power received at the hydrophone array to the transmit power, indicates that broadband beamforming surpasses both subarraying and narrowband beamforming in terms of power throughput. Although the transmit and receive hydrophones exhibit little to no mobility, recalling that the channel estimation occurred a week in advance of the experiment, the broadband beamforming approach endured the variability of the underwater channel over time; therefore, despite the fact that interference rather than power limited the communication performance in this particular experiment, many UWA communication applications could greatly benefit from the power efficiency of broadband beamforming.

	Sub-Array A			**Sub-Array B**			**SVD-narrowband**			**SVD-broadband**		
	SNR (dB)	*Coding*	*Efficiency*	*SNR (dB)*	*Coding*	*Efficiency*	*SNR (dB)*	*Coding*	*Efficiency*	*SNR (dB)*	*Coding*	*Efficiency*
Conventional	20	0 dB	-1.5 (dB)	19.9	0 dB	+ 1.5 dB	20.3	0 dB	- 0.7 dB	20.9	0 dB	+ 6.3 dB
2 Parallel	14.2/15.2	+1.1 dB		13.8/14.4	+0.8 dB		12.7/13.2	- 0.7 dB		13.9/12.1	-0.1 dB	
3 Parallel	12.4/12.0/10.8	+5.4 dB		11.2/10.6/10.8	+4.2 dB		10.5/11.1/11.8	+ 3.0 dB		9.9/9.2/8.8	+1.8 dB	

Figure 2: Results reproduced from the spatial diversity experiments conducted by Kilfoyle et al. [3]. Coding gain computed by computing the theoretical increase in SNR necessary for a single transmitter to signal at the same data and error rate as the multi-transmitter systems. Power efficiency measured from the ratio of transmit power to receive power. The efficiency ratio computed with respect to the power efficiency measured from a conventional single antenna system.

The multichannel receiver structure of [5] also emerges in [6] with particular focus on space-time coding techniques for high data rate underwater acoustic MIMO communications. Specifically, the authors propose and evaluate communication systems utilizing both space-time trellis codes (STTC) as well as layered space-time codes (LSTC) using multiband modulation. As a compromise between single carrier systems that require lengthy equalizers and orthogonal frequency-division multiplexing (OFDM) systems that require sophisticated Doppler estimation and tracking algorithms, multiband modulation seeks middle ground between receiver complexity and carrier tracking ability, though it requires sophisticated hardware to implement [6].

After developing the theoretical framework of the multiband MIMO receiver, the authors

Year	Data rate (kb/s)	Bandwidth (kHz)	Range (km)	Data type	Prob. of error
2005	6	23	2_S	1 tx, turbo coded BPSK	~ 0
2005	16	23	2_S	4 tx, turbo coded BPSK	~ 0
2005	32	23	2_S	4 tx, turbo coded QPSK	~ 0
2005	24	23	2_S	2 tx, STTC QPSK	$\sim 5 \times 10^{-3}$
2005	36	23	2_S	2 tx, STTC 8PSK	$\sim 3 \times 10^{-3}$
2005	48	23	2_S	4 tx, STTC QPSK	$\sim 10^{-2}$
2005	12	3	2_S	6 tx, STTC QPSK	$\sim 10^{-2}$

(a) Results from Roy et al. [6]

Year	Data rate (kb/s)	Bandwidth (kHz)	Range (km)	Prob. of error
1989	500	125	0.06_D	$< 10^{-7}$
1985	$20 - 30$	10	3.5_D	$< 10^{-4}$
$1993 - 94$	$0.6 - 3$	$0.3 - 1.0$	$89 - 203_{S,D}$	$< 10^{-2}$
1994	6	3	0.04_S	N/A
1994	6	3	4.0_D	N/A
1994	20	20	0.09_S	$\sim 10^{-3}$
1995	$1.1 - 2.2$	$0.6 - 2.2$	$0.5 - 8.0_{S,D}$	$< 10^{-3}$
1996	0.2	0.2	50_D	$< 10^{-4}$
1997	$0.9 - 1.8$	N/A	$4.0_S - 8.0_D$	$< 10^{-4}$
1998	$1.67 - 6.7$	$2 - 10$	$4.0_S, 2.0_S$	N/A

(b) Previously achieved results.

Figure 3: (a)Experimental results reported by Roy et al. [6] (b)Included are some historical benchmarks of previous underwater acoustic communication systems [6]

of [6] benchmark their proposed receiver with extensive experimentation. The results of the experiments are presented alongside a selection of previously achieved results in Figure 3. Comparing the performance of the space-time coding techniques, STTC achieves higher data rates at the expense of higher error rates, whereas the LSTC offers greater robustness to errors at the expense of capacity; however, the authors note that with an additional high-rate outer Turbo code applied prior to LSTC, the bit error rate becomes negligible with only a slight rate penalty [6]. In contrast, the reduced rates exhibited by LSTC result from the lack of coding between transmitter elements; therefore, without diversity encoding, the capacity suffers. Nevertheless, the experimental results presented in [6] demonstrate that both the STTC and LSTC MIMO communication systems attain markedly increased data rates as compared to conventional single antenna systems.

Reflecting the work of [6], the authors of [7] forgo the typical single carrier system in favor of a multicarrier design; however, unlike [6], the receiver design proposed by [7] multicarrier modulation in the form of OFDM. Citing [8], the authors acknowledge the importance of non-uniform Doppler estimation and compensation for mobile underwater acoustic OFDM systems; however, their experimental setup focused on stationary environments, which makes possible the expectation of little to no Doppler. In such a scenario, the narrowband assumption holds true, and hence, any residual Doppler can be abstracted as a uniform carrier frequency offset (CFO), which significantly reduces the complexity of the receiver [7]. Utilizing two inputs and four outputs, the results of their MIMO-OFDM experiments are listed in Figure 4. Compared to the results of [6], the MIMO-OFDM system performance appears modest at first glance; however, considering the 1/2 coding rate emplyed (Roy et. al utilized rate .9 Turbo codes) as well as the simplified system design of OFDM compared to multiband modulation, the results of [7] emerges as a competitive alternative. It remains an open issue whether the replacement of half-rate low-density parity check (LDPC) codes with higher-rate Turbo codes or the introduction of additional transmit elements would result in MIMO-OFDM receiver performance similar to that found in [6].

Year	Data rate (kb/s)	Bandwidth (kHz)	Range (km)	Data Type	Prob. of error
2007	12.18	12	0.5s	2 tx, convolutional encoded OFDM	~0
2007	12.18	12	0.5s	2 tx, LDPC encoded OFDM	~0
2007	12.18	12	1.5s	2 tx, convolutional encoded OFDM	~0
2007	12.18	12	1.5s	2 tx, LDPC encoded OFDM	~0

Figure 4: Experimental results of the MIMO-OFDM receiver developed by Li et al. [7]

5 Future Work

Utilizing the LabVIEW MIMO toolkit developed at the University of Texas at Austin [9], this project seeks to expand the framework of [3] through the introduction of space-time codes; however, unlike [6] and [7], the project will restrict its focus to single carrier systems. In this manner, Doppler estimation and compensation reduce in complexity; furthermore, channel overhead reduces significantly without the requirement of a large ($\sim$20ms) guard intervals to overcome the potentially large multipath spread of the underwater acoustic channel. Consequently, intersymbol interference (ISI) and co-channel interference (CCI) emerge as the primary system impairments. With regard to these impairments, I intend to investigate the effectiveness of array processing towards the end of interference mitigation without sacrificing diversity.

References

[1] D. B. Kilfoyle and A. B. Baggeroer, "The state of the art in underwater acoustic telemetry," *IEEE Journal of Oceanic Engineering*, vol. 25, pp. 4–27, Jan. 2000.

[2] M. Stojanovic, "Underwater wireless communications: Current achievements and research challenges," *IEEE Journal of Oceanic Engineering Society Newsletter*, pp. 10–13, Spring 2006.

[3] D. B. Kilfoyle, J. C. Preisig, and A. B. Baggeroer, "Spatial modulation experiments in the underwater acoustic channel," *IEEE Journal of Oceanic Engineering*, vol. 30, pp. 406–415, Apr. 2005.

[4] L. Zheng and D. N. Tse, "Communication on the grassmann manifold: A geometric approach to the noncoherent multiple-antenna channel," *IEEE Trans. on Info. Theory*, vol. 48, pp. 359–383, Feb. 2002.

[5] M. Stojanovic and Z. Zvonar, "Multichannel processing of broad-band multiuser communication signals in shallow water acoustic channels," *IEEE Journal of Oceanic Engineering*, vol. 21, pp. 156–166, Apr. 1996.

[6] S. Roy, T. M. Duman, V. McDonald, and J. G. Proakis, "High-rate communication for underwater acoustic channels using multiple transmitters and space-time coding: receiver structures and experimental results," *IEEE Journal of Oceanic Engineering*, vol. 32, pp. 663–688, July 2007.

[7] B. Li, S. Zhou, M. Stojanovic, L. Freitag, J. Huang, and P. Willett, "MIMO-OFDM over an underwater acoustic channel," in *Proc. IEEE Oceans Conference*, (Vancouver, BC), pp. 1–6, 2004.

[8] B. Li, S. Zhou, M. Stojanovic, L. Freitag, and P. Willett, "Non-uniform Doppler compensation for zero-padded OFDM over fast-varying underwater acoustic channels," in *Proc. IEEE Oceans Conference*, (Vancouver, BC), pp. 1–6, 2004.

[9] R. Heath, S. Patil, S. Kirti, and R. Sarnanta, "The LabVIEW MIMO toolkit." Freely distributable LabVIEW toolkit for the design and simulation of MIMO systems available at http://users.ece.utexas.edu/ rheath/research/mimo/labview/. Copyright © 2002-2006 The Wireless Networking and Communications Group (WNCG) at The University of Texas Austin.