Application of Spatial Modulation to the Underwater Acoustic Communication Component of Autonomous Underwater Vehicle Networks

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LONG-TERM GOALS

There have been two fundamental advances in underwater acoustic communication in the last two decades. The first occurred in the early 1980's with the introduction of digital signaling techniques [1]. That facilitated both error correction and reverberation mitigation. The second advance has been the successful application of coherent signaling techniques [2]. That facilitated dramatic improvements in bandwidth efficiency and, hence, data rates. Since the introduction of coherent systems in the early 1990's, however, performance gains have been moderate and mostly attributed to important but largely technical algorithm improvements [3]. Spatial modulation offers the hope of yet another fundamental advance in performance by both enabling higher data rates and offering a strategy for improving performance in intersymbol interference (ISI) limited channels. The research conducted in this program seeks to define both the potential for spatial modulation in U.S. Navy underwater communication systems and develop practical prototypes suitable to meet U.S. Navy needs.

OBJECTIVES

This program seeks to apply spatial modulation to a variety of practical ocean acoustic channels such as those encountered by U.S. Navy acoustic communication systems. The current phase of the work is driven by a desire to successfully transition the technology to meet a near term Navy need. Specifically, requirements derived from the autonomous underwater vehicle (AUV) platforms currently being considered by the Autonomous Operations Future Naval Capability (AOFNC) have been adopted. FY03 efforts have adopted aperture and frequency range constraints consistent with current AOFNC development efforts and sought to define spatial modulation performance within these bounds. Specific objectives of this current effort are:

1. Continue to accrue experimental validation of spatial modulation under AOFNC AUV constraints.
2. Demonstrate spatial modulation in networked environments.
3. Reduce the computation load of receiver algorithm to facilitate a real-time implementation.

APPROACH

The issue of how to map an information stream onto a transmit array is a rich area of current research in the wireless radio frequency industry. Many older approaches to spatial modulation for multiple-input / multiple-output channels center on a singular value decomposition of a known channel transfer function matrix [4] [5] [6]. These techniques require knowledge of the channel by the transmitting system. Recent approaches suggest various mappings of coded and uncoded data streams to the available transmitters [7] [8] [9] [10] [11] [12]. These approaches are motivated by channels typically encountered in RF wireless systems, namely channel transfer function matrices whose elements are independent, Rayleigh fading variables and channels with negligible intersymbol interference (ISI). The underwater acoustic channel typically carries neither of these traits in that receiver elements are often partially correlated and ISI is far from negligible.

The current effort addresses two issues relating to communication links within an underwater network comprising multiple platforms including AUVs, submarines, and surface vessels. First, appropriate array geometries are being studied that both conform to the aperture constraints of AUVs and simultaneously provide adequate spatial degrees of freedom to support simultaneous spatial modulation links between multiple platforms. At a simplistic level, vertical aperture helps with spatial modulation while horizontal aperture helps with multi-user separation. The design space is rich with trade-offs. The extensive practical experience of Lee Freitag and other WHOI personnel plays a large role in the execution of this task. A general-purpose array whose aperture spans the anticipated design space for AUVs has been constructed to support the testing of multiple configurations during a single test. Based on predicted performance using propagation models, tests will be designed involving a central "mother ship" that is communicating with at least two subordinate AUVs. For this program, only the aperture of the AUV will be represented and no effort will be made to mimic the AUV structure itself. The testing will be conducted near the Gould Island Acoustic Test Range (GIATR) during Fall 2003 under the presumption that it represents an environment representative of a AOFNC mission.

Second, much of the effort to date has focused on the physical feasibility of spatial modulation. The receiver algorithm has thus favored performance over complexity. A reexamination of the algorithm is needed that quantifies the tradeoff between performance and complexity. Complexity reduction techniques that would enable implementation on a real-time system that is sustainable in AUV processor footprint are needed. For example, the horizontal and vertical apertures could be processed sequentially rather than jointly. Similarly, spatial and temporal degrees of freedom might be treated sequentially. While analysis has shown that recursive least square-based adaptive algorithms are necessary, the performance of fast transversal filter implementations is under study. In a more mundane vein, the core Viterbi algorithm that accomplishes decoding jointly with equalization has much room for speed improvement. The trade space between performance and complexity must be quantified via algorithm development and testing with field data. The goal is to recommend a receiver algorithm to ONR that may be viably implemented in a real-time system during a follow-on effort.

WORK COMPLETED

Most work was completed in GFY 2003 and reported in the GFY 2003 ONR Annual Report. The additional work completed in GFY 2004 related to an exercised option to conduct sea trials near Elba, Italy in October, 2003.

The NATO Undersea Research Centre, SAIC, SPAWAR, the University of Delaware, and the Woods Hole Oceanographic Institution conducted a collaborative sea trial in the waters off of Elba, Italy, between October 27 and October 30, 2003. This cruise sought to improve understanding of the propagation and scattering of high frequency acoustic waves (5-50 kHz) in the presence of oceanographic variability in shallow water regions [10].

The test assets included the R/V Alliance, which hosted a 14-element flexible hydrophone vertical line array (VLA) with 1 m spacing and a 12 element rigid hydrophone VLA with 15 cm spacing. Each hydrophone array was sufficiently wideband to record all signals transmitted. Two transducer arrays were hosted by the vessel Saralu including a 6 element, 2 m spaced, array tuned for operation between 9.5 and 14 kHz and a 3 element, 53 cm spaced, transducer array tuned for operation between 25 and 35 kHz. Packet-based waveforms were alternately transmitted in both frequency bands. An average power constraint was imposed. Testing parameters included the number of simultaneous, unique spatially multiplexed packets (1 to 6 at the mid-band and 1 to 3 at the high band) and symbol constellation size (4, 8, and 16-level quadrature amplitude modulation). Data was collected to support evaluation of a networked MIMO configuration with two separate arrays received on a cylindrical hydrophone array.

The two test sites were utilized specifically to provide contrasting environments that would aid understanding how propagation physics and communication performance are related. The site to the North of Elba had a nominal water column depth of 100 m with hard, reverberant bottom structure. The site to the South of Elba also had a nominal depth of 100 m but had substantial sediment deposits leading to severe bottom attenuation. Each site exhibited a warm surface layer atop a cooler bottom layer with an exceptionally steep gradient at the north site between the layers. These sites presented a novel environment to test spatial modulation

RESULTS

While a discussion of results has been published [15], a summary will be presented here. The MF system at the South site provided the highest spectral efficiencies measured thus far for underwater acoustic spatial modulation (Table 1). Using four transducers and a 6 m aperture, four parallel channels were created. As each achieved a post-equalization SINR between 13 dB and 14 dB, a capacity of 23 bits/Hz was estimated. That is a three-fold increase over the single channel case. The capacity estimate assumes the separate channels are truly parallel channels in the information theoretic sense and the residual noise is additive, white Gaussian noise. Using a modest coding scheme, at least 56 kbps would have been possible for this system using only 4.5 kHz of bandwidth. While the HF system was not able to achieve a post-equalization SINR as high as the MF system, spatial modulation afforded a 75% increase in estimated capacity at both sites. As with the MF test, the South site showed the highest marginal benefits for spatial modulation at HF. As the principal difference between the two sites was the bottom type, this result suggests an important hypothesis. Spatial modulation requires reverberation to generate a rich spatial structure but excessive reverberation stresses the equalization algorithm resulting in high levels of intersymbol interference. Note that the proportional advantage of spatial modulation (as compared to a single transducer) in terms of residual SINR is actually higher for the HF tests with only a 4 dB drop in SINR per channel when one uses three parallel channels rather than one channel. This compares to a 5 – 7 dB drop for the MF case. The difference is that the absolute SINR levels are much higher for the MF system. As is well known, the advantages of spatial modulation are more evident at high SINR.

Table 1. Post-equalization SNR for various levels of spatial modulation is shown here for the low frequency band at a range of 2.5 km at the South site. C has units of

	1 Chan	2 Chan	3 Chan	4 Chan	5 Chan	6 Chan
SNR_{out} (dB)	**23.5**	**19.1**	**16.3**	**13.0**	**9.1**	**6.0**
	-	**20.6**	**18.0**	**14.7**	**12.3**	**9.9**
	-	-	**17.2**	**13.8**	**11.3**	**5.0**
	-	-	-	**13.8**	**12.3**	**9.4**
	-	-	-	-	**8.4**	**3.9**
	-	-	-	-	-	**8.3**
C	**7.6**	**13.1**	**17.1**	**23.0**	**21.9**	**17.6**

The HF testing was also valuable in that it highlighted a receiver design issue unique to spatial modulation. For conventional acoustic communications, a decision feedback equalizer, through the placement of feedback filter taps, readily accommodates late multipath arrivals associated with particular propagation paths. For spatial modulation, however, these late arrivals may be crucial in creating parallel channels. As such, they must be represented with feedforward taps. Spanning the entire arrival range with feedforward taps degrades performance by encumbering the weight adaptation algorithm. Some preliminary analysis suggests a receiver operating in arrival angle space rather than element space is effective in this case. The issue will be examined in detail during the GFY 2005 effort when feedback from the receiver to the transmitter is available.

A networked spatial modulation experiment was also conducted by receiving signals on a cylindrical hydrophone volumetric array. The array had the approximate dimensions of an Odyssey vehicle with four staves of four hydrophones each. Superimposing transmissions from the Saralu at two different times simulated a network environment. The available data showed less than an average 0.1 dB reduction in post-equalization SINR for spatially modulated HF packets when another transmission was superimposed. In fact, even when the "interfering" packet had a 4 dB greater average received power, the array topology offered adequate degrees of freedom to cancel the interfering source and resolve the parallel channels with no significant loss in performance. The key conclusion here is that vertical degrees of freedom are necessary for spatial modulation leaving horizontal degrees of freedom to compensate for multiple access interference. Given the use of a planar or volumetric array, spatial modulation is compatible with network operations.

IMPACT/APPLICATIONS

Navy needs for acoustic communication have been established for current AUV development and demonstration programs. These include relatively high data rates (50 kbit/sec per kilometer is one stated goal) for certain missions where large amounts of sensor data are gathered and processed by an AUV. Timely reception of this data by other vehicles or human analysts may provide a significant tactical advantage in littoral engagements. Given the limited bandwidth available undersea, methods that offer a factor of two or more increased throughput are very attractive.

Examples of potential transitions include programs such as the pre-planned product improvement (P3I) for the Semi-Autonomous Hydrographic Reconnaissance Vehicle (SAHRV) that is based on the WHOI REMUS AUV. As these technologies mature, future P3I opportunities may become available. Another possible transition is through follow-on programs to the AO-FNC, which uses the 21 inch Bluefin Robotics AUV as a communications and navigation aid. The AO-FNC may also lead to pre-procurement programs in anticipation of adding the vehicles to Navy field units. An example of realistic source arrays that could be added with modest impact to an Odyssey class vehicle is shown in figure 1. On-going and proposed work will characterize the potential throughput increase possible with these practical apertures.

Figure 1. Odyssey-class (21 inch) AUV with both vertical and horizontal piezocomposite source arrays built of directional elements such as manufactured by Materials Systems Inc.

REFERENCES

1. Baggeroer, A., Donald E. Koelsch, Keith von der Heydt, and Josko Catipovic. *DATS - A Digital acoustic telemetry system for underwater communications.* in *Oceans '81.* 1981. Boston, MA: IEEE.
2. Stojanovic, M., Josko A. Catipovic, and John G. Proakis, *Phase-coherent digital communications for underwater acoustic channels.* IEEE Journal of Oceanic Engineering, 1994. **19**(1): p. 100-111.
3. Kilfoyle, D.a.A.B., *The State of the art in underwater acoustic telemetry.* IEEE Journal of Oceanic Engineering, 2000. **25**(1): p. 4-27.
4. Ebert, P.M., *Error Bounds for Parallel Communication Channels*, . 1966, Massachusetts Institute of Technology: Cambridge, MA.
5. Brandenburg, L.H.a.A.D.W., *Capacity of the Gaussian Channel with Memory: The Multivariate Case.* The Bell System Technical Journal, 1974. **53**(5): p. 745 - 778.
6. Foschini, G.J.a.M.J.G., *On Limits of Wireless Communications in a Fading environment when Using Multiple Antennas.* Wireless Personal Communications, 1998. **6**: p. 311-335.
7. Cioffi, G.G.R.a.J.M., *Spatio-Temporal Coding for Wireless Communication.* IEEE Transactions on Communication, 1998. **46**(3): p. 357-366.
8. Foschini, G.J., *Layered space-time architecture for wireless communication in a fading environment when using multiple antennas.* Bell Laboratory Technical Journal, 1996. **1**(2): p. 41-59.
9. Naguib, A.F.S., N.; Calderbank, A.R., *Increasing data rate over wireless channels.* IEEE Signal Processing Magazine, 2000. **17**(3): p. 76-92.
10. Foschini, G.J.G., G.D.; Valenzuela, R.A.; Wolniansky, P.W., *Simplified processing for high spectral efficiency wireless communication employing multi-element arrays.* IEEE Journal on Selected Areas in Communications, 1999. **17**(11): p. 1841-1852.
11. Tarokh, V.J., H.; Calderbank, A.R., *Space-time block codes from orthogonal designs.* IEEE Transactions on Information Theory, 1999. **45**(5): p. 1456- 1467.
12. Hochwald, B.M.S., W., *Differential unitary space-time modulation.* IEEE Transactions on Communications, 2000. **48**(12): p. 2041- 2052.
13. Jensen, F. B., et al., Results from the Elba HF-2003 Experiment, in High-Frequency Ocean Acoustics, Eds. M. Porter, M. Siderius, W. Kuperman, American Inst. Physics Press (2004). .

PUBLICATIONS

14. Kilfoyle, D. et al., "Spatial Modulation over Partially Coherent Multiple-Input / Multiple-Output Channels," IEEE Trans. on Sig. Proc., Mar 2003, **51**(3): p. 794-804.
15. Kilfoyle, D. and L. Freitag, "Spatial Modulation in the Underwater Acoustic Channel," Proceedings of the Adaptive Sensor Array Processing Workshop, Lincoln Laboratories, Lexington, MA, 2004.
16. Kilfoyle, D. et al., "Spatial Modulation Experiments in the Underwater Acoustic Channel," IEEE Journal of Oceanic Eng., accepted for publication.

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