Application of Spatial Modulation to Underwater Acoustic Communication

Daniel B. Kilfoyle, Ph.D.
Science Applications International Corporation
406 Sippewissett Road
Falmouth, MA 02540
phone: (508) 274-1197 fax: (508) 457-0865 email: daniel.b.kilfoyle@saic.com

James C. Preisig, Ph.D.
Woods Hole Oceanographic Institution
Department of Applied Ocean Physics and Engineering
Woods Hole, MA. 02543
phone: 508-289-2736 fax: 508-457-2914 email: jpreisig@whoi.edu

Contract Number: N0001401C0422

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 define 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 may be summarized as an exploration of the possibilities offered by spatial modulation. Later phases would then focus on transitioning these techniques to practical U.S. Navy systems. Several technical issues are being addressed.

Practical limits on the number of resolvable sub-channels will be sought. More specifically, the maximum attainable number of simultaneous, independent communication channels will be experimentally determined for several channels using relevant array apertures. Experiments will be conducted in channels representative of those encountered by U.S. Navy systems such as shallow, littoral locations.

Report Documentation Page	*Form Approved* *OMB No. 0704-0188*

1. REPORT DATE **30 SEP 2002**	2. REPORT TYPE	3. DATES COVERED **00-00-2002 to 00-00-2002**

4. TITLE AND SUBTITLE **Application of Spatial Modulation to Underwater Acoustic Communication**	5a. CONTRACT NUMBER
	5b. GRANT NUMBER
	5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)	5d. PROJECT NUMBER
	5e. TASK NUMBER
	5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **Science Applications International Corporation,,406 Sippewissett Road,,Falmouth,,MA, 02540**	8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)	10. SPONSOR/MONITOR’S ACRONYM(S)
	11. SPONSOR/MONITOR’S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT

Approved for public release; distribution unlimited

13. SUPPLEMENTARY NOTES

14. ABSTRACT

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 define the potential for spatial modulation in U.S. Navy underwater communication systems and develop practical prototypes suitable to meet U.S. Navy needs.

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**	**Same as Report (SAR)**	**8**	

The tolerance of the communications system to imperfect knowledge of the time-variant impulse response will be determined. This will lead to an understanding of the trade-off between the accuracy of knowledge of the communications channel and system performance. In some channels, historical databases may provide sufficiently accurate information while others may require characterizations based on real-time, in-situ measurements. Channel characterization schemes will be developed to efficiently represent the stable, exploitable features of the acoustic channel. Experimental data already obtained suggests that channel reverberation that is uncompensated for by the receiver is a major performance limiting feature.

Different performance criteria will be investigated each dictating potentially different spatial modulation and system adaptation strategies. Implementations that maximize power transfer of a single user, maximize rejection of discrete noise sources, identify and exploit the most stable sub-channels, or minimize the residual channel delay spread will be sought and demonstrated.

Recently, the program objectives have been focused on the application of spatial modulation to array apertures that can be supported by autonomous underwater vehicles such as those envisioned by the AO Future Naval Capability.

The FY03 program is intended as a risk-reduction effort prior to the possible inclusion of spatial modulation into the acoustic communication sub-systems of AUVs. Spatial modulation requires the availability of transmitter arrays, a design feature that is largely absent from current AUV designs. As such, the costs and benefits that spatial modulation offers must be understood prior to investing in a physical upgrade of U.S. Navy equipment. The current program is addressing the question of whether spatial modulation is even possible with the limited aperture of an AUV, the primary risk. Experimental results thus far indicate that substantive capacity gains are, in fact, possible. The FY03 program seeks to address two additional risk areas, namely those of the impact on network operations and the eventual processor demands on a receiver. The objective of the FY03 program is to position spatial modulation for adoption into mainstream AOFNC architectures within two to three years.

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.

In the experiments conducted this year, a single bit stream was coded via concatenated coding. A high rate outer block code was first used followed by an interleaver to provide protection against burst errors. The resultant, encoded bit stream was then convolutionally encoded with a trellis-coded modulation algorithm [13]. Successive coded symbols were then mapped to successive transducers as in figure 1. This particular approach has several advantages that make it well suited to underwater acoustic communication applications. First, the overall coding efficiency is high (89%) which maintains the advantage of high spectral efficiency that spatial modulation offers. Second, the inner convolutional code structure supports joint equalization and Viterbi decoding thereby giving the adaptive filter update process the benefit of coding gain. Finally, by introducing dependency between the transmitted data streams, tolerance to fading of the signal from any one transducer is created.

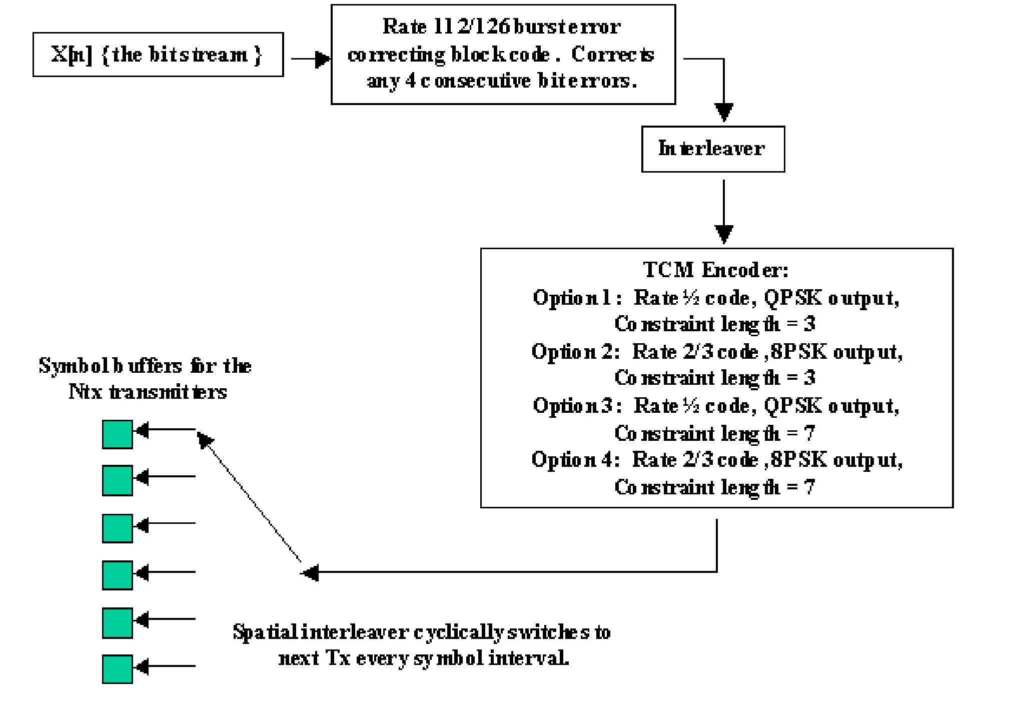

Figure 1. The process for mapping a given stream of bits to the modulation symbols transmitted from the array elements is shown here. A concatenated coding scheme is used whereby the data is initially block encoded and interleaved. Subsequently, the bits are transformed to quadrature symbols using a trellis-code modulation algorithm and, finally, assigned to individual array elements for broadcast.

For the purpose of receiver design, communication via spatial modulation is a form of multi-user communication. Rather than relying on frequency division multiple access (FDMA) or code division multiple access (CDMA) techniques, the spatial modulation receiver relies on the differing spatial signatures of the data streams to separate them. The algorithm used in these experiments was based on the multi-user receiver structure described by Stojanovic and Zvonar [14] with extensions to exploit the error control coding and synchronized nature of the parallel data streams. Referring to figure 2, the first step is a coarse timing and carrier synchronization typically done via correlating with a training sequence prepended to each packet of symbols. The equalization and channel separation task is accomplished with the joint application of tapped delay lines on each received signal, decision feedback filters for all data streams, and a digital phase locked loop. Decisions are based on a minimum distance metric that compares the symbol estimate vector to a map of valid messages. For the coded signal design, the decisions are made with a Viterbi algorithm that operates in concert with the equalizer on a symbol to symbol basis. Soft decisions with low latency (typically less than 10 symbols) are released to support the filter update while hard decisions are released with a higher latency. More specifically, ν_j is the received data for the jth receiver element. T_s is the symbol interval.

N_1 and N_2 are the durations before and after the timing reference that have delay tap support. $\mathbf{a}_{ki}$ is the linear transversal filter for the k^{th} data stream and the i^{th} symbol interval for the first receive element. $\mathbf{b}_{ki}$ is the linear transversal filter for the k^{th} data stream and the i^{th} symbol interval for the second receive element. The architecture is readily generalized to include more receiver elements. $\mathbf{c}_{ki}$ is the linear transversal feedback filter for the k^{th} data stream and the i^{th} symbol interval for the second receive element. Each data stream has a unique feedback filter continue previous decisions for all other data streams. Similar processing blocks for the other data streams then feed their estimates to a specialized Viterbi algorithm that traverses one stage in its trellis before releasing a soft decision and a hard decision for one symbol of each of the data streams.

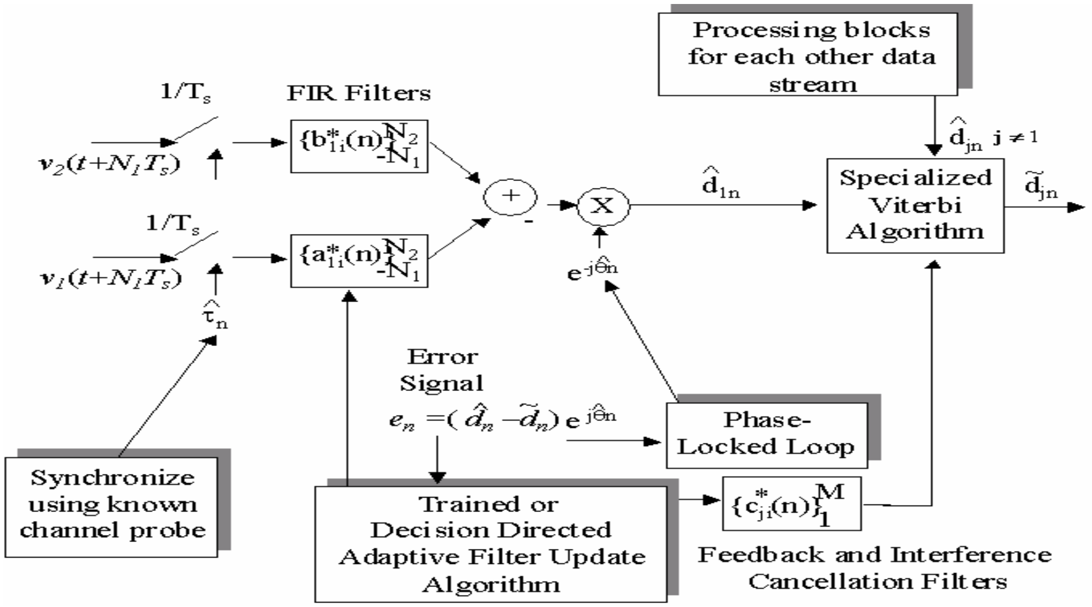

Figure 2. This schematic representation of the receiver algorithm shows the flow of data from synchronization to equalization with carrier phase tracking and demodulation.

The approach employed in this research is to explore variants of the signal modulation and the receiver algorithm in sea trials. To define the limits of this technology, various array configurations and source-receiver geometries have been and continue to be tested.

WORK COMPLETED

A receiver algorithm has been developed and tested that jointly performs carrier phase tracking, equalization, parallel channel demodulation, and error correction. The module has been successfully exercised on experimental data obtained during two sea trials of spatial modulation this year. The first, conducted in Buzzards Bay, MA, explored various array configurations and levels of spatial modulation using signals in the 8 - 12 kHz regime. The second sea trial, conducted in Vineyard Sound, MA, again explored several array configurations but used signals in the 22 – 28 kHz regime. In support of that test, a new HF transmit array system was built.

RESULTS

In recognition of the recent U.S. Navy interest in AUV networks within littoral environments (as espoused by the AO FNC), the two sea trials this year were limited to vertical and horizontal apertures consistent with deployment on or from an AUV. While the data involving horizontal apertures is still being analyzed, the vertical aperture data shows value in using spatial modulation with AUV systems. Specifically, by assuming Gaussian statistics, the post-equalization SNR of each spatially modulated data stream can be used to compute the overall capacity (in an information theoretic sense) of the channel. Similarly, the post-equalization SNR of the non-spatially modulated signal can also be used to compute a capacity.

For the first experiment (10 kHz center frequency), capacity improvements were demonstrated to vary from 15% to 60% for a source-receiver separation of 500 m. Receive apertures of 0.4 and 3 meters, in particular, yielded 35% and 60 % capacity increases respectively for a 1 meter transmit aperture. For source-receiver separations of 1.5 and 2.5 km, no capacity improvements were found.

In the second experiment (25 kHz carrier), the capacity improvements were more modest but achievable at longer ranges. Specifically, using a 1.0 meter transmit aperture (2 elements) and a 0.12 meter receive aperture (4 elements), capacity improvements of 35%, 40%, and 12% were demonstrated at 0.5, 1.5, and 2.5 km respectively.

Both of these tests were conducted in nearly isothermal water with both a rough sea surface and soft sea bottom. Improved performance would be expected in ducted conditions where higher angle propagation paths do not suffer as much attenuation. In addition, future tests will explore the value of relaxing the aperture requirement for one end of the link as may be practical, for instance, where a larger tending platform is monitoring the data from numerous small AUVs. Finally, the possibility of using the substantially larger available horizontal aperture has been tested and is currently being analyzed.

IMPACT/APPLICATIONS

Spatial modulation, if successfully transitioned to fleet underwater acoustic communication systems, would increase the available data rates under conditions yet to be fully determined. The technique also allows for greater power efficiency (energy per bit) for a given information reliability. It also offers a mechanism for incorporating coding techniques without a commensurate loss in data rate. All of these attributes would enhance the performance of fleet systems.

TRANSITIONS

No transitions have taken place yet for this technology. The research and experimental plan is focused on developing a spatial modulation based system suitable for AUV networks with the goal of transitioning the technology to the U.S. Navy users of any AO FNC products. 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 Woods Hole Oceanographic Institution (WHOI) REMUS AUV. This on-going program will include the transition of the WHOI Micro-Modem into the first round of SAHRV vehicles purchased by the Navy. As these technologies mature, future P3I opportunities may become available. Another possible transition is through follow-on programs to the AOFNC, which may also lead to pre-procurement programs in anticipation of adding the vehicles to Navy field units.

RELATED PROJECTS

A demonstration effort for using spatial modulation at radio frequencies was conducted for the Defense Advanced Research Projects Agency. SAIC used both signal generation techniques and receiver algorithms that formed the basis for the research done here for ONR.

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. Ungerboeck, G., *Channel coding with multilevel/phase signals.* IEEE Transactions on Information Theory, 1982. **28**(1).

14. Stojanovic, M., and Zoran Zvonar, *Multichannel processing of broad-band multiuser communication signals in shallow water acoustic channels.* IEEE Journal of Oceanic Engineering, 1996. **21**(2): p. 156-166.

PUBLICATIONS

Kilfoyle, D. et al., “Spatial Modulation over Partially Coherent Multiple-Input / Multiple-Output Channels,” IEEE Transactions on Signal Processing, in press.