REPORT DOCUMENTATION PAGE	Form Approved OMB No. 0704-0188

1. REPORT DATE *(DD-MM-YYYY)*	2. REPORT TYPE	3. DATES COVERED *(From - To)*
17-12-2008	Performance/Technical Report (Annual)	Jan 2008 - Dec 2008

4. TITLE AND SUBTITLE
MIMO Underwater Acoustic Communications for Rate Enhancement and Range Extension
FY07 Year End Report

5a. CONTRACT NUMBER

5b. GRANT NUMBER
N00014-07-1-0193

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)
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5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
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8. PERFORMING ORGANIZATION REPORT NUMBER
#2

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
Office of Naval Research
875 North Randolph Street
Arlington, VA 22203-1995

10. SPONSOR/MONITOR'S ACRONYM(S)
ONR

11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for Public Release; distribution is Unlimited.

13. SUPPLEMENTARY NOTES

14. ABSTRACT
Our research focuses on the horizontal underwater acoustic communications. During this year, our research on multi-input multi-output underwater acoustic communications (MIMO-UAC) can be categorized into two thrusts: Robust MIMO-UAC with Low-Complexity Receivers and 2. Enhanced Channel Estimation and Symbol Detection for High Speed MIMO-UAC. In terms of MIMO-UAC with low-complexity receivers, we have established a simple windowed least squares (LS) channel estimator, developed a differential MIMO scheme obviating channel estimation, and analyzed the effects of different doubly-selective channel models in UAC scenarios. For high-speed MIMO-UAC, we have focused on the channel estimation and symbol detection problems in MIMO-UAC. We have presented a cyclic approach approach for designing training sequences with good auto- and cross-correlation properties. Iterative adaptive approach (IAA) coupled with Bayesian information criterion and RELAX has been presented as an approach for estimating the channel impulse response. We also proposed a new detection method called RELAX-BLAST. Our proposed schemes are tested via both simulations and field data from the acoustic communications experiment (RACE'08) conducted by the Woods Hole Oceanographic Institution (WHOI).

15. SUBJECT TERMS
Underwater acoustic communications, multi-input multi-output (MIMO), transmit beamforming, differential modulation, diversity

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
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FY08 Year End Report
"MIMO-UAC for Rate Enhancement and Range Extension"

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LONG-TERM GOALS

Our proposed research will focus on the horizontal underwater acoustic communications (UAC). Building on co-located and/or distributed multiple transducers and hydrophones, we plan to develop multiple-input multiple-output (MIMO-)UAC systems to provide range/rate enhancement.

OBJECTIVES

Nearly all underwater communication scenarios encounter the asymmetry issue, since the communicating nodes include small size sensors, autonomous underwater vehicles (AUV), large size underwater sinks and large vessels such as ships and submarines. Our research aspires to design MIMO systems addressing needs of both sides of this asymmetry. Specifically, for the error-sensitive command-disseminating communication links, we design *robust MIMO* strategies that emphasize on the transmitter (command center) processing while providing superb error performance even in turbulent sea and allowing for very simple receivers (sensor or AUV). For the data-centric information collecting communication links, we design *high speed MIMO* schemes that place most of the complexity and processing on the receiver (information sink) side, while allowing the sensors to transmit data at highest possible rate without much processing. In the latter scenario, we also investigate the cooperative communications among distributed sensors.

APPROACH

1. Robust MIMO-UAC with Low-Complexity Receivers

Under this research thrust, we study a simple channel estimation approach and a differential (de)modulation scheme. Both designs are tailored for low-complexity receivers. To ensure the robustness of these approaches against various UAC channel conditions, we also analyze effects of different doubly-selective channel models.

Windowed Least Squares Channel Estimator Based on Basis Expansion Model (BEM): Consider an $\boldsymbol{N}$-symbol transmitted block with $\boldsymbol{P}$ pilot subblocks each with length $\boldsymbol{N_p}$. To eliminate the interference between the pilots and the data, $\boldsymbol{L}$ zeros are inserted after each data and pilot subblock. The system diagram is shown as Fig. 1 with detailed steps as follows:

- Step 0: Add a Window at the Receiver.
  With a diagonal window matrix $\boldsymbol{W}$ being multiplied to the received vector $\boldsymbol{y}$, we have:
  $$\boldsymbol{Wy} = \boldsymbol{WHx} + \boldsymbol{Wz} = \widetilde{\boldsymbol{H}}\boldsymbol{x} + \boldsymbol{Wz} \quad (1)$$
  where $\widetilde{\boldsymbol{H}}$ is the windowed channel matrix, $\boldsymbol{x}$ is the transmitted vector and $\boldsymbol{z}$ is noise.

- Step 1: Estimate the BEM Coefficients of the Windowed Channel.
  Stacking the windowed received symbols from the pilots, we obtain
  $$\boldsymbol{W}_P\boldsymbol{y}_P = \sum_{i=1}^{N}\begin{bmatrix}\boldsymbol{D}_{i,1}\boldsymbol{U}_1\\ \vdots \\ \boldsymbol{D}_{i,P}\boldsymbol{U}_P\end{bmatrix}\breve{\boldsymbol{g}}(i) = \boldsymbol{\Phi}\breve{\boldsymbol{g}} + \boldsymbol{W}_P\boldsymbol{z}_P = \boldsymbol{\Phi}_K\breve{\boldsymbol{g}}_K + \boldsymbol{\Phi}_{N-K}\breve{\boldsymbol{g}}_{N-K} + \boldsymbol{W}_P\boldsymbol{z}_P \quad (2)$$
  where $\boldsymbol{D}_{i,p}$ has the i-th column of the inverse DFT matrix on the diagonal, $\boldsymbol{U}_p$ is the pilot matrix, subscript P means pilots, and subscripts K and $N-K$ mark the low frequency submatrix (BEM) and the high frequency one (model fitting bias), respectively. We obtain the BEM coefficients as
  $$\widehat{\boldsymbol{g}} = \boldsymbol{\Phi}_K^{-1}\boldsymbol{W}_P\boldsymbol{y}_P \quad (3)$$

- Step 2: De-Window and Recover the Channel Coefficients.

We also design the optimum pilot pattern by evaluating the mean square error (MSE) of the channel estimate. In addition, we devise a sliding window approach and only retain the estimates at the center of each window location. The resultant optimum pilot pattern is shown in Fig. 2.

<u>Differential MIMO-UAC and Effects of Doubly-Selective Channel Models:</u> In [2], we proposed a differential MIMO scheme using the time-invariant equivalent channel based on DFT BEM. Following similar steps, we obtain the time-invariant equivalent I/O within a block based on arbitrary BEMs as:
$$\bar{\boldsymbol{y}}(p) = \boldsymbol{Gu}(p) + \boldsymbol{\Omega}^{-1}(p)\big(\boldsymbol{\Xi}(p)\boldsymbol{u}(p) + \tilde{\boldsymbol{z}}(p)\big) \quad (4)$$
where p is the subblock index, $\mathbf{u}(\mathrm{p})$ is the $\mathrm{M}\times 1$ transmitted subbolck, $\boldsymbol{\Xi}(\mathrm{p})$ is the model fitting bias matrix, $\tilde{\mathbf{z}}(\mathrm{p})$ is the noise, $\mathbf{G}$ is the equivalent time-invariant channel equivalent we want and $\boldsymbol{\Omega}(\mathrm{p})$ is:
$$\boldsymbol{\Omega}(p) = \begin{bmatrix}\boldsymbol{B}_{p(M+L)+L} & \boldsymbol{0}_{K\times K} & \cdots & \boldsymbol{0}_{K\times K}\\ \boldsymbol{0}_{K\times K} & \boldsymbol{B}_{p(M+L)+L+1} & & \\ \vdots & & \ddots & \vdots \\ \boldsymbol{0}_{K\times K} & \cdots & \boldsymbol{0}_{K\times K} & \boldsymbol{B}_{p(M+L)+L+M-1}\end{bmatrix}. \quad (5)$$
The $K\times K$ equally-spaced decimated basis matrix $\boldsymbol{B}_n$ links the K channel coefficients to K BEM coefficients: $\boldsymbol{g}(l) = \boldsymbol{B}_n^{-1}\boldsymbol{h}_n(l) - \boldsymbol{B}_n^{-1}\boldsymbol{\eta}_n(l)$, where $\boldsymbol{h}_n(l)$ is the $K\times 1$ equally-spaced decimated channel vector and $\boldsymbol{\eta}_n(l)$ is the corresponding model fitting bias vector. For DFT BEM, $\boldsymbol{B}_n = N/K\boldsymbol{B}_n^H$ is a scaled unitray matrix, while for DPSS BEM it is not. Accordingly, with DPSS BEM, the noise term in (4) will be colored and the model fitting bias changed. This is not the case for DFT BEM though its original model fitting bias $\boldsymbol{\Xi}(\mathrm{p})$ is greater than that for DPSS BEM in the MSE sense.

Such a transform between channel coefficients and BEM coefficients is involved in all BEM-based systems. For our differential system, BEM is used to construct the time-invariant equivalent channel per block; whereas for coherent schemes, BEM coefficients are estimated to recover the channel coefficients. In our simple WLS channel estimator [4], the channel estimation MSE is:
$$\mathrm{MSE} = E\{\|\boldsymbol{h}-\boldsymbol{h}\|^2\} = E\{\|\boldsymbol{W}^{-1}[\widetilde{\boldsymbol{\eta}} - \boldsymbol{B}\boldsymbol{B}_K^{-1}(\widetilde{\boldsymbol{\eta}}_K + \boldsymbol{W}_K\boldsymbol{z}_K)]\|^2\} \quad (6)$$
where $\widetilde{\boldsymbol{\eta}}$ is the model fitting bias after windowing. Since DPSS BEM approximates the true channel more precisely than DFT BEM, the norm of the model fitting bias $\widetilde{\boldsymbol{\eta}}$ and $\widetilde{\boldsymbol{\eta}}_K$ of DPSS BEM in (6) is smaller than that of DFT BEM [1]. However, for DPSS BEM, the noise will be colored since $\boldsymbol{B}_K$ is not

unitary. This is clearly not the case for DFT BEM. Therefore, there is again a tradeoff between the modeling accuracy and the noise coloring effect, as in the differential case.

2. Enhanced Channel Estimation and Symbol Detection for High Speed MIMO-UAC

We address two key issues regarding the design of a high speed MIMO-UAC system, namely channel estimation and symbol detection. To enhance channel estimation performance, we propose a cyclic approach (CA) for designing training sequences and an iterative adaptive approach (IAA) for estimating the channel taps. Regarding symbol detection, we present a minimum MSE (MMSE) based detection scheme, called RELAX-BLAST, which combines vertical Bell Labs Layered Space-Time (V-BLAST) algorithm and the cyclic principle of RELAX.

Training Sequence Design: Consider phase coherent communications over $N \times M$ MIMO-UAC multipath channels. For multipath channels, training sequences with good auto- and cross-correlation properties are required. Training symbols have a generic form of $x_n(t)=e^{j\phi_n(t)}$, where $\phi_n(t) \in [0,2\pi)$ is the phase of the training symbol $x_n(t)$ sent by the n^{th} transmitter, $n = 1,2,\ldots,N$ and $t = 1,2,\ldots,P$ with P being the total training length. Let $\mathbf{X} \in C^{(P+R-1)\times NR}$ contain N training sequences and their delayed versions, where R is the number of the channel taps. Our goal is to make $\varepsilon = \left\|\mathbf{X}^*\mathbf{X} - P\mathbf{I}\right\|_F^2$ small, where $\left\|\cdot\right\|_F$ denotes the Frobenius matrix norm, and $\mathbf{I}$ is an identity matrix. Let $\mathbf{U}$ be an arbitrary semi-unitary matrix. Then minimizing ε can be formulated in the following related way

$$\{\phi_n(t)\} = \arg\min_{\{\phi_n(t)\},\mathbf{U}^*} \left\|\mathbf{X} - \sqrt{P}\mathbf{U}^*\right\|_F^2, \text{ subject to } \mathbf{U}\mathbf{U}^* = \mathbf{I}. \quad (7)$$

This optimization problem can be solved by a cyclic approach (CA) as follows:

- Step 0: $\mathbf{U}$ is initialized to be $\left[1/\sqrt{2}(\mathbf{I} + j\mathbf{I}) \quad \mathbf{0}\right]$.
- Step 1: With most recent $\mathbf{U}^*$, the solution to (7) is $\phi = \arg\left(\sum_{r=1}^{R} z_r\right)$, where $\{z_r\}_{r=1}^{R}$ are given numbers.
- Step 2: With most recent $\phi_n(t)$, the solution to (7) is given by $\mathbf{U}^* = \bar{\mathbf{U}}\tilde{\mathbf{U}}^*$, where $\sqrt{p}\mathbf{X} = \bar{\mathbf{U}}\mathbf{\Gamma}\tilde{\mathbf{U}}^*$ is the singular value decomposition (SVD) of $\sqrt{p}\mathbf{X}$. Iterate Steps 1 and 2 until the difference of the cost function in (7) between two successive iterations becomes lower than a predefined threshold.

The Channel Estimation Algorithm (IAA): The second phase of channel estimation involves the design of the algorithm that will estimate the channel impulse response (CIR), denoted as $\mathbf{h}$, using the training sequences (or the previously detected symbols) $\mathbf{S}$, and highly contaminated measurements $\mathbf{y}$. The channel estimation problem at each receiver has the generic form: $\mathbf{y}=\mathbf{Sh}+\mathbf{e}$, where $\mathbf{e}$ represents the additive noise. We consider IAA for estimating $\mathbf{h}$. IAA makes no assumptions on the statistical properties of $\mathbf{e}$. Let $\mathbf{P}$ be a diagonal matrix whose diagonal elements are $P_r=|h_r|^2$, where h_r represents the r^{th} element of $\mathbf{h}$. If the r^{th} column of $\mathbf{S}$ is written as $\mathbf{s}_r$, then the IAA can be implemented as:

- Step 0: Initialize $P_r = \left|\mathbf{s}_r^*\mathbf{y}\right|^2 / \left(\mathbf{s}_r^*\mathbf{s}\right)^2$.
- Step 1: With most recent $\mathbf{P}$, Calculate $\mathbf{R}=\mathbf{SPS}^*$.
- Step 2: With most recent $\mathbf{R}$, Update $\hat{h}_r = \dfrac{\mathbf{s}_r^*\mathbf{R}^{-1}\mathbf{y}}{\mathbf{s}_r^*\mathbf{R}^{-1}\mathbf{s}_r}$, $P_r = \left|\hat{h}_r\right|^2$. Iterate Steps 1 and 2 until convergence.

Sparse channel estimates can be obtained by combining IAA with the Bayesian informaiton criterion (BIC). Moreover, the RELAX algorithm can be used to improve the IAA with BIC estimates further.

Symbol Detection: Following the CIR estimation is the design of the detection scheme for estimating the payload symbols. We use a MMSE based filter for symbol detection, and propose the RELAX-BLAST algorithm. RELAX-BLAST first detects the symbol with the dominant channel taps and subtracts it from the measurements. Then, it estimates the next dominant symbol from the residue signal. Then the two already detected symbols are updated in an iterative manner until the difference of the RELAX-BLAST estimates between two successive iterations becomes less than a certain threshold. Once these two symbols are subtracted from the measurements and the third strongest symbol is estimated, the three symbols are again updated in an iterative manner until all three estimates do not improve anymore. This process is repeated until all N symbols are detected and updated.

3. Distributed MIMO Communications with Differential (De)Modulation

Relay networks allow a source to communicate with a destination via a number of relay nodes. By forming virtual antenna arrays in a cooperative manner, spatial diversity gain can be achieved without imposing antenna packing limitations. Most previous work on relay networks focused on the coherent modulation assuming availability of the CSI. To reduce hardware complexity and communication overhead, we consider differential modulation in this research. We quantify the average error performance in decode-and-forward (DF) and amplify-and-forward (AF) networks as follows:

$$\bar{P}_{ser}^{AF} \approx \frac{1}{2^{2L-1}} \sum_{l=1}^{L} \binom{n+L-1}{L-1} \sum_{k=0}^{L-1-n} \binom{2L-1}{k} \prod_{l=1}^{L} \left[\frac{1}{\bar{\gamma}_{r_l,s}} + \frac{1}{\bar{\gamma}_{d,r_l}} ln(\bar{\gamma}_{d,r_l}) \right]$$

$$\bar{P}_{ser}^{DF} \approx \frac{1}{2} \sum_{D} \left\{ \prod_{l \in D} \left[1 - \frac{1}{2\bar{\gamma}_{r_l,s}} \right] \prod_{k \notin D} \left[\frac{1}{2\bar{\gamma}_{r_k,s}} \right] \left[1 - \mu \sum_{j=0}^{|D|-1} \binom{2j}{j} \left(\frac{1-\mu^2}{4} \right)^j \right] \right\}, \quad \mu = \frac{\bar{\gamma}_{d,r}}{1+\bar{\gamma}_{d,r}}$$

Where $\bar{\gamma}_{i,j}$ is the average signal-to-noise ratio between nodes i and j. We not only give these formulas in closed-form, but also prove their convexity in both energy allocation and relay locations. Based on these, resource optimization can be performed to further enhance the system performance.

WORK COMPLETED

In terms of robust MIMO-UAC with low-complexity receivers, we have established a simple windowed LS channel estimator, developed a differential MIMO scheme obviating channel estimation, and analyzed the effects of different doubly-selective channel models in UAC scenarios. For high-speed MIMO-UAC, we have focused on the channel estimation and symbol detection problems in MIMO-UAC. We have presented the CA approach for designing training sequences with good auto- and cross-correlation properties. IAA coupled with BIC and RELAX has been presented as an approach for estimating the CIR. We also proposed a new detection method called RELAX-BLAST. Our proposed schemes are tested via both simulations and field data from the acoustic communications experiment (RACE'08) conducted by the Woods Hole Oceanographic Institution (WHOI).

RESULTS

1. Robust MIMO-UAC with Low-Complexity Receivers

WLS Channel Estimator: We first simulate a typical underwater acoustic environment with carrier frequency 12 kHz and transceiver moving velocity 2.4 knots. The simulation parameters are given in Table I. Figs. 3 and 4 show the MSE and BER comparisons of our WLS with other alternatives. The windowed approach (WLS-Blackman) outperforms the unwindowed one (WLS-Rectangular). Unlike our WLS estimator, the MMSE estimator in [3] assumes the *complete* channel statistics. However, our simple WLS significantly outperforms [3]. To test the **robustness** of our approach, we selected 3 data frames from the RACE'08 data, during the roughest periods when the channels vary intensively. Our WLS achieves a remarkable 0.24% uncoded BER when the regular LS estimator fails (~50% BER), both providing a data rate of 10.3kbps at 1000m Tx-Rx distance.

Differential MIMO-UAC: The simulated DFT BEM gives consistently lower BER than DPSS BEM as in Fig. 5. In RACE'08, we compared with a plain OFDM system. The uncoded BER for all data frames at 1000m transmitter-to-receiver distance is plotted in Fig. 6. In turbulent sea conditions, the plain OFDM gives an uncoded BER exceeding 10%, while our BEM-based differential schemes consistently provide around 0.1%. The BER averaged over all data frames is 0.12% and 0.13% for our schemes. It is worth noting that this remarkable performance is achieved with very simple differential decoding at the receiver, obviating any channel estimation requirement.

2. Enhanced Channel Estimation and Symbol Detection For High Speed MIMO-UAC

Consider a simulated 4×1 multi-input single-output (MISO) system with time-invariant channels. Fig. 7 shows the modulus of the simulated CIRs corresponding to the four transmitters with R=30 delay taps. Fig. 8 shows the MSE of the channel estimates obtained by MP (matching pursuit), OMP (orthogonal matching pursuit), LSMP (least squares matching pursuit) and IAA with QPSK training and CA training. We can see that with the QPSK training, IAA significantly outperforms MP, OMP and LSMP whereas with the CA training, the performance gap between IAA and other algorithms diminishes. Next, we evaluate the BER of CLEAN-BLAST and RELAX-BLAST for a 4×12 MIMO system. Herein we name V-BLAST as CLEAN-BLAST to emphasize its analogy to the CLEAN algorithm used in spectral estimation. Each transmitted package contains a CA training sequence with P=512, a payload sequence consisting of 6000 QPSK modulated symbols. IAA is used for channel estimation. The average BERs over 100 Monte-Carlo trials are shown in Fig. 9. We observe that RELAX-BLAST shows much better performance than CLEAN-BLAST in the absence of severe error propagation. Experimental results in RACE'08 employing a 4×24 MIMO system show that the proposed scheme enjoys an average uncoded BER of 0.38% at a payload bit rate of 31.25 kbps and an average coded BER of 0% at a payload bit rate of 15.63 kbps.

3. Distributed MIMO Communications with Differential (De)Modulation

In Fig. 10, we plot the error performance contour for a fixed total energy budget of 15dB and the energy consumption contour for target error rate of 0.1%, for the differentially modulated AF relay protocols. We observe that, counter-intuitively, relays off the direct line linking the source and destination can outperform those sitting on this direct line.

IMPACT/APPLICATIONS

The natural bandwidth limitations of coherent underwater acoustic channel suggest a technical breakthrough. MIMO signal processing is a promising bandwidth efficient method to high data rate and high quality services. Building on both coherent and differential approaches, and considering both co-located and distributed transceiver units, our promising results are expected to favorably impact high-rate long-range MIMO-UAC designs.

Table I: Simulation parameters for coherent detection

Max. Doppler 10 Hz	Sym. duration 1/6000s	Max. delay 10 ms	$L = 60$
$N = 1800$	$P = 9$	Pilot energy 61	Profile $s(l) = e^{-0.1.l}$
Modulation QPSK	Equalizer MMSE		

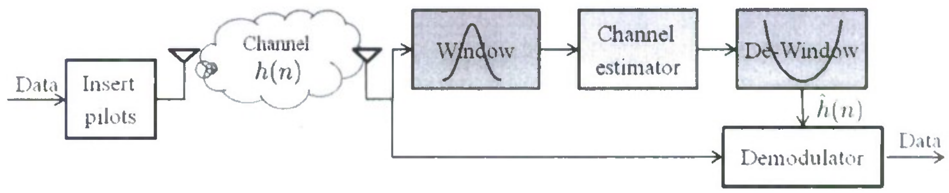

Figure 1: System diagram for the coherent detection with our windowed least squares channel estimator.
[graph: The windowing and de-windowing operations are implemented only at the receiver and only on pilots, affecting neither the transmitted data pattern nor the demodulator .]

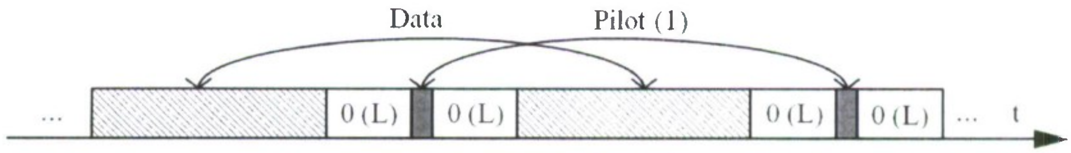

Figure 2: The optimum pilot pattern
[graph: Each pilot subblock consists of one pilot symbol padded by L zeros before and after.]

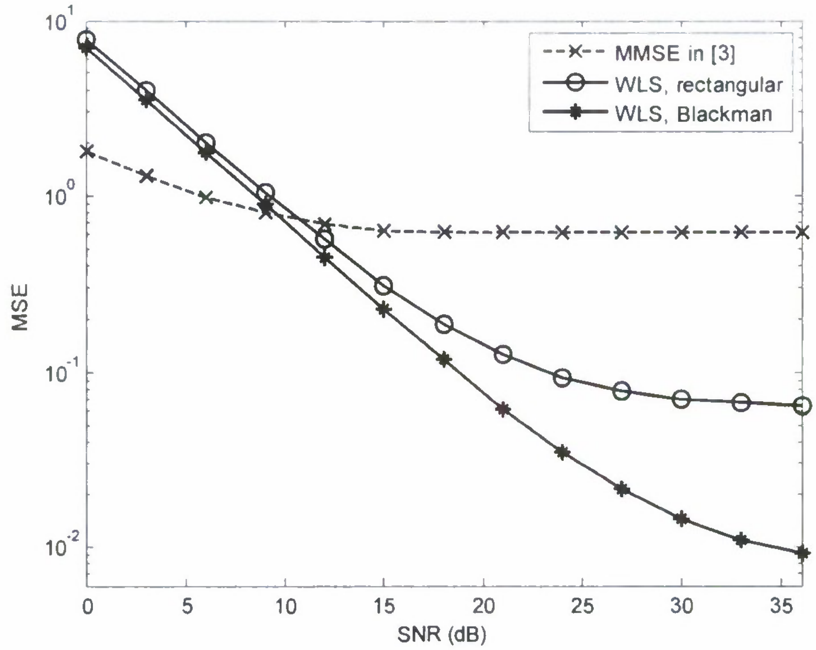

Figure 3: Chanel estimation MSE vs. SNR for different channel estimators. Single transducer and single hydrophone are used.
[graph: Our WLS estimator with a Blackman window has the best performance.]

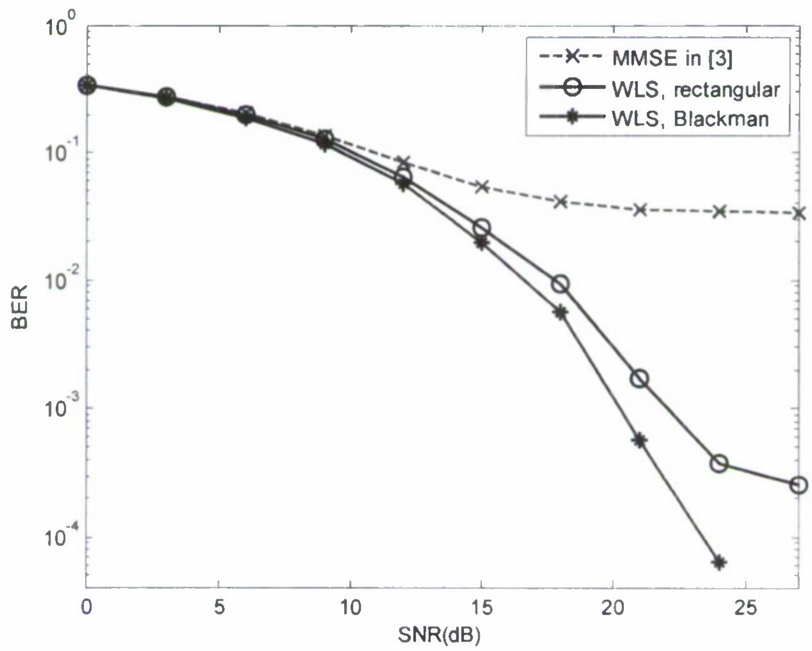

Figure 4: BER vs. SNR for coherent detection with different channel estimators. Single transducer and single hydrophone are used.
[graph: Our WLS estimator with a Blackman window has the best performance.]

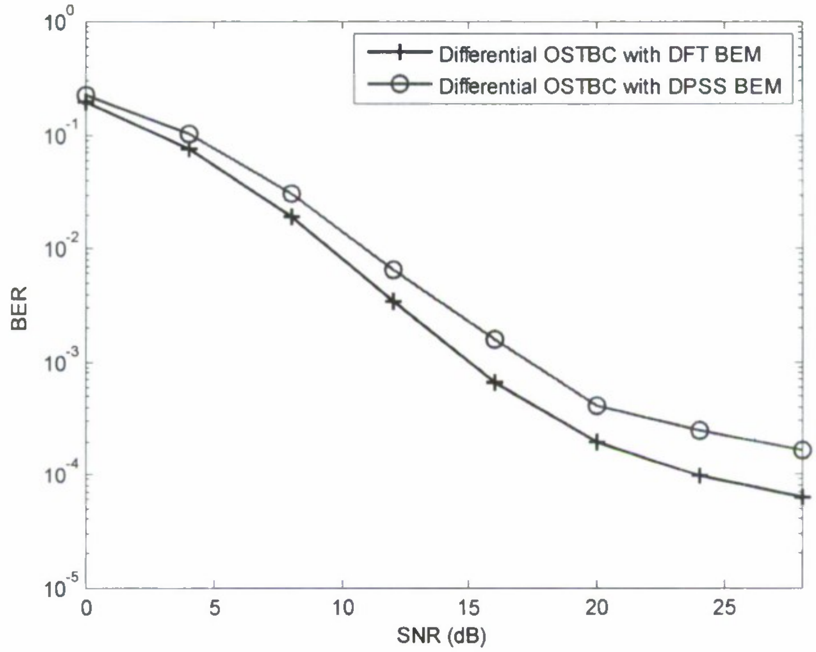

Figure 5: Average BER vs. SNR for differential OSTBC based on DFT BEM and DPSS BEM. Two transducers and one hydrophone are used.
[graph: DFT BEM outperforms DPSS BEM consistently.]

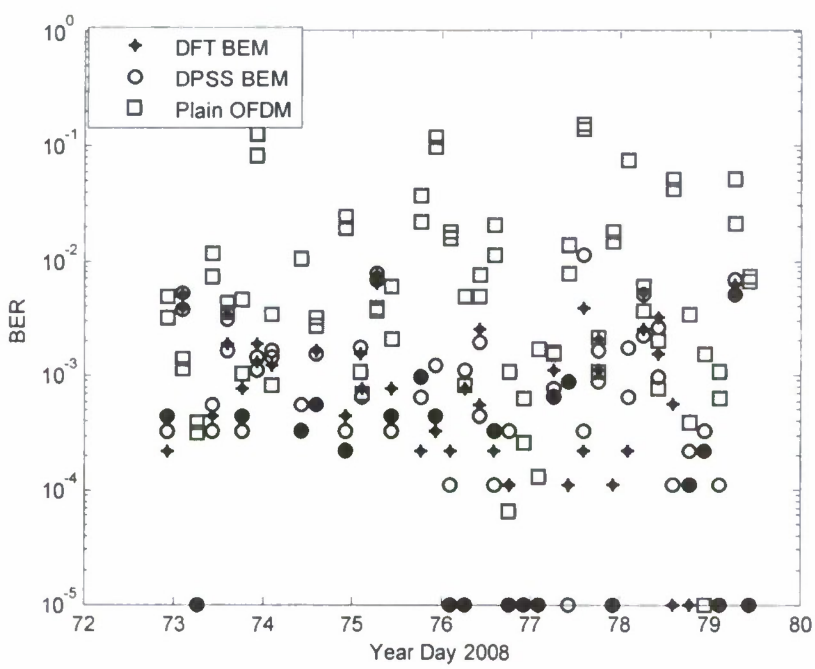

Figure 6: Uncoded BER for differential OSTBC using 2 transducers and 12 hydrophones in RACE'08 at 1000m distance. Zero-error is illustrated as 10^{-5}.
[graph: 1. The plain OFDM scheme has much worse performance than the BEM based ones. 2. DFT BEM is slightly better than DPSS BEM]

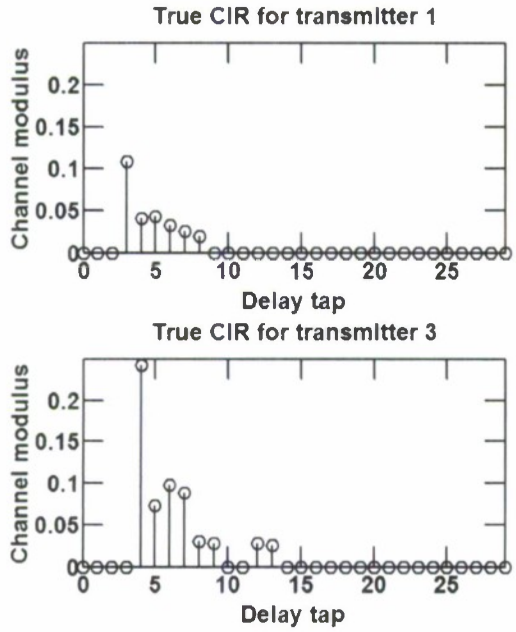

Figure 7: The modulus of the simulated CIRs between the four transmitters and the receiver in a 4×1 MISO system.

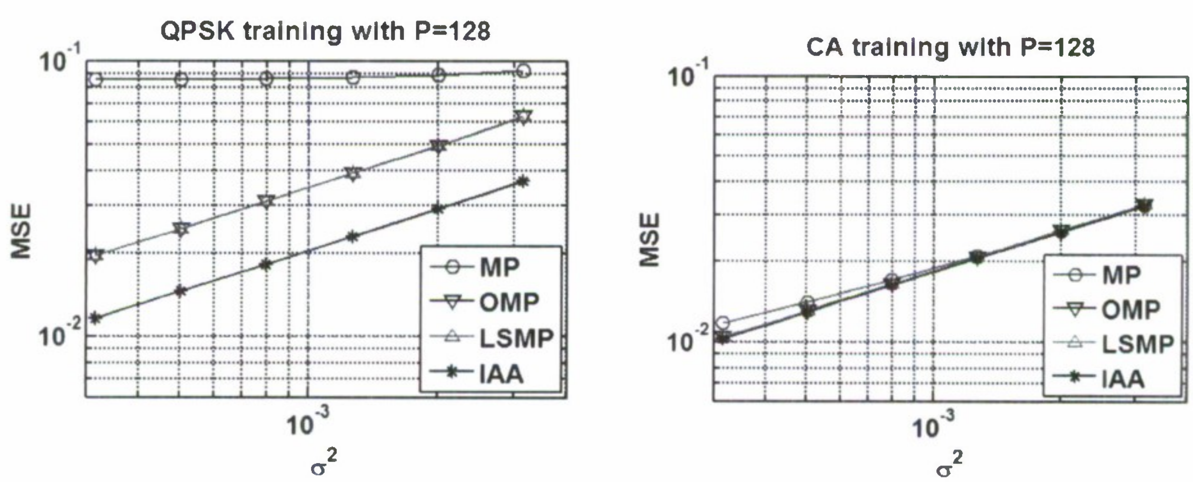

Figure 8: MSE of the CIR estimates for a 4×1 MISO system using the QPSK and CA training sequences with P=128 symbols. Each point is averaged over 100 Monte-Carlo trials.

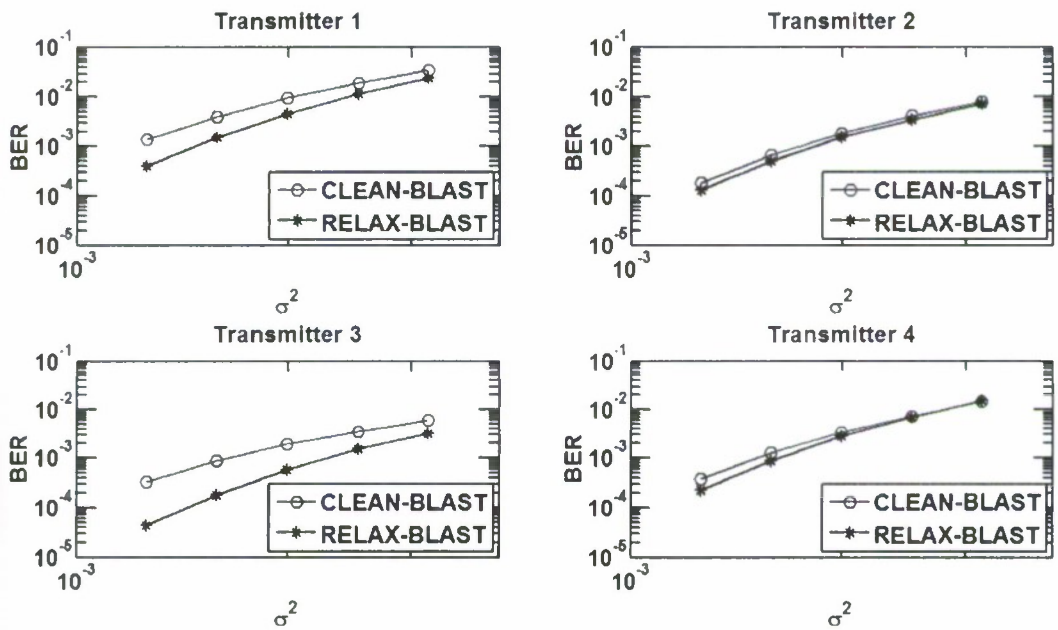

Figure 9: The BERs of each of the four transmitted payload sequences for a 4×12 MIMO system. The training sequences consist of P=512 symbols and are designed by the CA algorithm. The detection performance of CLEAN-BLAST and RELAX-BLAST are compared in terms of BER averaged over 100 independent Monte-Carlo trials for varying levels of the noise variance.

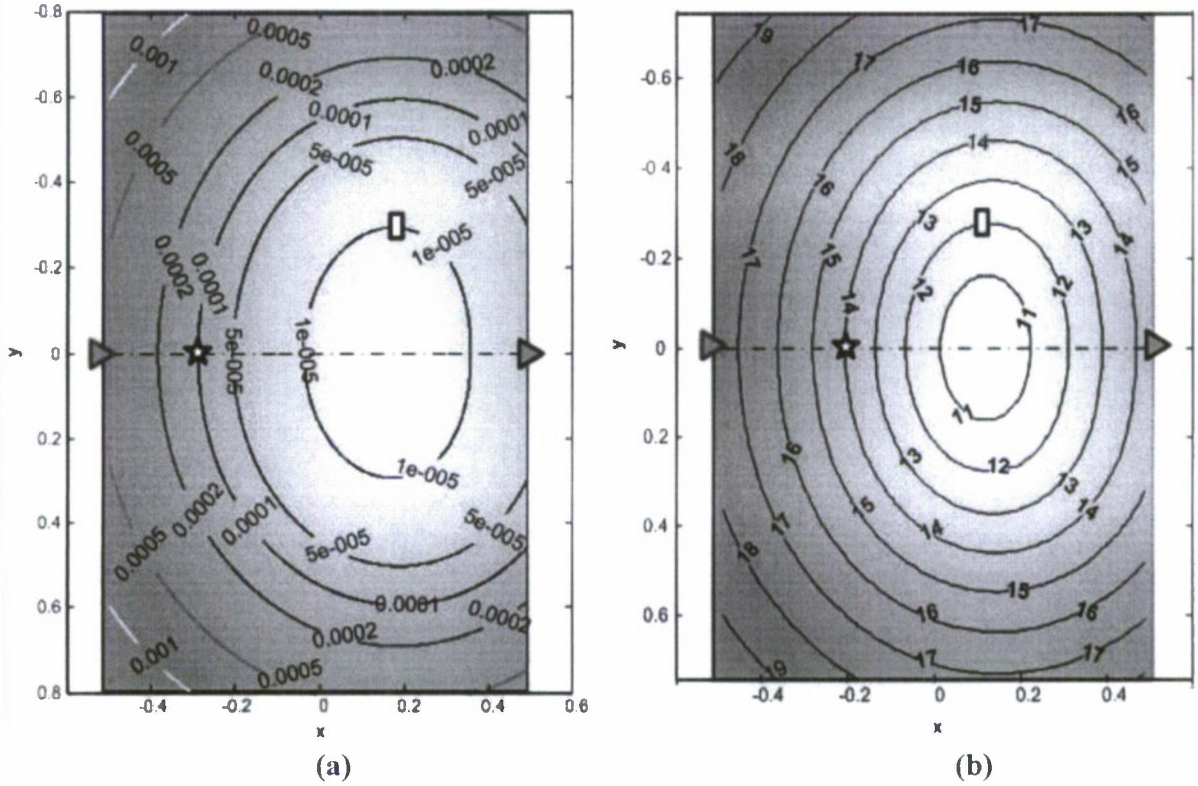

Figure 10: (a) Error Performance Contour and (b) Energy Consumption Contour of a 2-relay cooperative system. Differentially modulated AF protocol is used with total energy constraint of 15dB in (a) and target error rate of 0.1% in (b).
[graph: 1. Some relays off the direct source-destination line can perform better. 2. The relays from the inner loop should be chosen. 3. The relays closer to the destination receive more benefits.]

REFERENCES

[1] T. Zeman, and C. F. Mecklebräuker, "Time-variant channel estimation using discrete prolate spheroidal sequences," *IEEE Transactions on Signal Processing,* vol. 53, no. 9, pp. 3597-3607, September 2005.

[2] F. Qu, and L. Yang, "Orthogonal Space-Time Block-Differential Modulation over Underwater Acoustic Channels," in *Proceedings of Oceans 2007*, Vancouver, Canada, October 1-4, 2007.

[3] X. Ma, G. B. Giannakis, and S. Ohno, "Optimal training for block transmissions over doubly selective wireless fading channels," *IEEE Transactions on Signal Processing,* vol. 51, no. 5, pp. 1351-1366, May 2003.

[4] F. Qu, and L. Yang, "On the estimation of doubly-selective fading channels," in *Proceedings of Conference on Info. Science and Systems,* the Princeton Univ., Princeton, March 19-21, 2008, pp. 17-24.

PUBLICATIONS

1. Jun Ling, Tarik Yardibi, Xiang Su, Hao He, and Jian Li, "Enhanced channel estimation and symbol detection for high speed MIMO underwater acoustic communications," *13th IEEE DSP Workshop*, Marco Island, FL, January 4-7, 2009.

2. Tarik Yardibi, Jian Li, and Petre Stoica, "Nonparametric and sparse signal representations in array processing via iterative adaptive approaches," *42nd IEEE Asilomar Conference on Signals, Systems and Computers*, Pacific Grove, CA, USA, October 26-29, 2008.

3. Jun Ling, Tarik Yardibi, Xiang Su, Hao He, and Jian Li, "Enhanced channel estimation and symbol detection for high speed multi-input multi-output underwater acoustic communications." submitted to *Journal of the Acoustical Society of America*, August 2008 (under review).

4. Xiayu Zheng, Petre Stoica, Jian Li, and Renbiao Wu, "Adaptive arrays for broadband communications in the presence of co-channel interference," *IEEE Transactions on Signal Processing*, Vol. 56, No. 4, pp. 1589-1600, April 2008.

5. Tarik Yardibi, Jian Li, Petre Stoica, Ming Xue, and Arthur B. Baggeroer, "Source localization and sensing: A nonparametric iterative adaptive approach based on weighted least squares," submitted to *IEEE Transactions on Aerospace and Electronic Systems*, December 2007 (under review).

6. Xiayu Zheng, Yao Xie, Jian Li, and Petre Stoica, "MIMO transmit beamforming under uniform elemental power constraint," *IEEE Transactions on Signal Processing*, Vol. 55, No. 11, pp. 5395-5406, November 2007.

7. Rui Cao, and Liuqing Yang, "What affects resource optimization of cooperative networks?" in *Proceedings of IEEE Wireless Communications & Networking Conference*, Budapest, Hungary, April 5-8, 2009 (submitted).

8. Fengzhong Qu, and Liuqing Yang, "Rate and reliability oriented underwater acoustic communication schemes,"*13th IEEE DSP Workshop*, Marco Island, FL, January 4-7, 2009 (invited).

9. Woong Cho, Rui Cao, and Liuqing Yang, "Optimum resource allocation for amplify-and-forward relay networks with differential modulation," *IEEE Transactions on Signal Processing*, 2008 (to appear).

10. Fengzhong Qu, and Liuqing Yang, "Basis expansion model for underwater acoustic channels?" in *Proceedings of Oceans 2008*, Quebec, Canada, September 15-18, 2008.

11. Rui Cao, and Liuqing Yang, "Resource optimization for cooperative networks: effects of optimization metric, modulation format and relaying protocol," *IEEE Transactions on Signal Processing*, September 2008 (submitted).

12. Fengzhong Qu, and Liuqing Yang, "On the estimation of doubly-selective fading channels," *IEEE Transaction on Communications,* August 2008 (revised).

13. Woong Cho, and Liuqing Yang, "Optimum resource allocation for relay networks with differential modulation," *IEEE Transactions on Communications*, vol. 56, no. 4, pp. 531-534, April 2008.

14. Rui Cao, and Liuqing Yang, "Resource optimization of distributed MIMO systems," in *Proc. of International Symposium on Advances in Computer and Sensor Networks and Systems*, Zhengzhou, China, April 7-10, 2008 (invited).

15. Woong Cho, and Liuqing Yang, "Performance analysis of cooperative networks with differential unitary space time coding," in *Proc. of Intl. Conf. on Acoustics, Speech and Signal Processing*, Las Vegas, NV, March 30-April 4, 2008.

16. Fengzhong Qu, and Liuqing Yang, "On the estimation of doubly-selective fading channels," in *Proceedings of Conference on Info. Science and Systems,* the Princeton Univ., Princeton, March 19-21 2008, pp. 17-24.

17. Fengzhong Qu, and Liuqing Yang, "Orthogonal space-time block-differential modulation over underwater acoustic channels," in *Proceedings of Oceans 2007*, Vancouver, Canada, October 1-4, 2007.

PATENTS

1. "MIMO transmit beamforming under uniform elemental peak power constraint", US patent, filed in June, 2007, serial NO. 60944679.