Acoustic Communication with Small UUVs Using a Hull-Mounted Conformal Array

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Abstract—**A new conformal array designed to enhance acoustic communication on small unmanned underwater vehicles (UUVs) is presented. The array is intended to improve the reliability and rate of acoustic communication to UUVs under conditions of multipath, multiuser interference, broadband or narrowband jamming and low signal-to-noise ratio. The array elements are constructed from a piezocomposite material that can be injection molded to nearly any shape, including into curves that match the hull radius of the vehicle. The array is encapsulated into a low-profile assembly 0.02 m thick and bonded directly to the hull of a REMUS vehicle. The frequency response and beampatterns were measured to determine the characteristics of the completed arrays. The array was deployed for initial trials in both horizontal and vertical orientations in shallow water. The performance of the array for both single and multiuser phase-coherent communication is presented.**

I. INTRODUCTION

Reliable command and control of small underwater vehicles is an essential part of single and multi-vehicle operations in civilian and military applications. The downlink to the vehicle is just as important as the uplink to a surface ship, subsurface node or buoy, but can be the most difficult to implement reliably. Vehicle self-noise and limited space for transducers are the most common problems encountered when integrating acoustic communication systems into underwater vehicles [1]. Careful design of the propulsion system can reduce the impact its noise may have on acoustic communications, but it is always a challenge to incorporate a multichannel acoustic array into the design of a typical small vehicle.

However, there is considerable benefit to use of an array as a communications receiver. Noise and interference from biological or man-made sources limit the SNR available from a single transducer, and in multi-user situations there may be many signals present simultaneously which create directional interference. While a multi-channel array is known to increase the reliability of an acoustic communication link [2], the limited space aboard small vehicles for arrays in the 10-30 kHz range has prevented their use from becoming commonplace. However, previous work on 21-inch vehicles has shown that phase-coherent communication using multichannel arrays can be accomplished on UUVs [3].

Small vehicles provide considerable incentive to consider novel approaches to array integration. Not only is space aboard small UUVs at a premium, but minimizing both weight and drag is very important if the primary mission of a vehicle is not to be compromised. The approach to array design described in this paper is to bond the individual elements directly to the pressure vessel. Recent advances in transducer technology have made it feasible to consider this approach on vehicles such as REMUS that have an outer diameter of only 20 cm. The conformal array is fabricated from a piezocomposite material that can be bonded to the hull and then encapsulated with a durable potting compound. The vehicle's hull is both the structural backbone of the array as well as an air-filled volume that increases the front-to-back ratio of the array at no additional cost in material weight.

The performance of a prototype conformal array is examined during a test where it is held fixed and a mobile source changes range and bearing to the array. While the array was designed to be used horizontally, it is instructive to compare the performance of both horizontal and vertical orientations. This reveals some of the trade-offs associated with array design for small UUVs and provides some insight into the performance of small arrays for acoustic communications in general.

The paper is organized as follows. In Section II the conformal array, including the materials technology, array design and tank testing are presented. Section III has results from in-water testing in both single and multiuser modes, as well as different orientations. Section IV includes conclusions and areas of future work.

II. PIEZOCOMPOSITE CERAMIC ARRAYS

The array elements incorporate a 1-3 piezocomposite material which is built into an acoustic stack that is attached directly to the hull of a REMUS vehicle. The design takes the physical properties of the air-backed, thin-wall aluminum hull into account, and uses it to enhance sensitivity and increase the front-to-back ratio. The 1-3 piezocomposite material consists of an array of small piezoelectric ceramic rods that are molded using an injection process that is similar to that used in the plastics industry. The process includes mixing the ceramic powder with a binder, heating the mixture and injecting it into a cold mold, a low temperature firing to remove the binder, and then densification (sintering) and polarization. The rods are embedded in a polymer matrix and machined to the desired final thickness. Both hard and soft matrix materials can be used depending upon the application. The soft matrix provides the best receive sensitivity, typically 10 dB over the equivalent ceramic, but operates only to moderate depths. Hard matrix materials are usable to pressures above 1000 psi and have 5 dB better sensitivity than solid ceramic. Hard matrix materials have the added advantage that they can

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be conformed to shapes such as cylinders or spheres. Additional advantages of the injection molding process include better element to element uniformity and lower cost in high volume.

A. Array Design

The arrays designed for the REMUS vehicle were intended to support multiple frequency bands as required for different applications. These applications include compatibility with acoustic communication systems that use the 7-11 kHz band (UQC), the 10-20 kHz band, and for certain systems, 20-30 kHz. While near-term applications will just use one band at a time, in the future, a vehicle may need to monitor multiple bands in an acoustic network. Future systems may also use very broad bandwidth (10 kHz or greater) for multiuser communication or to minimize the probability of detection. Thus the bandwidth goal for the receiver was 10-40 kHz.

The size of the elements was selected to provide $\pm 33^\circ$ vertical beamwidth at 20 kHz. However, this selection is clearly a compromise because the operating frequency spans such a wide range. At 20-30 kHz this offers good performance for shallow or very shallow water where the depth is typically 3-20 m and the range is 500-2000 m. Almost all of the energy is received at shallow angles and the directivity of the array improves its response and thus the SNR. In the 10 kHz band the vertical beamwidth is doubled, but because this frequency is likely to be used for longer-range communication in deep water, the broader angle is actually an advantage.

The design goal for the horizontal beampattern was to get as close to $\pm 90^\circ$ as possible. Achieving this is difficult because the tube is longer than the array. This produces shading that narrows the beampattern as discussed in the calibration section below.

The array elements used in the transducer arrays were shaped to match the radius of curvature of the REMUS hull to make them low-profile and hydrodynamic. Flat elements with the same beampattern would be much thicker and increase the drag of the vehicle. The elements are bonded directly to the aluminum tube and the signal from each element is brought inside on a twisted, shielded pair using a feedthrough in the hull. Thus no additional wet connectors are required.

The conformal array prior to final encapsulation is shown in the top panel of Fig. 1. The pre-amplifier electronics are above the array, and an optional side-scan transducer is at the bottom. The lower panel of Fig. 1 shows the completed unit. The encapsulation is approximately 2 cm thick and the forward and rear edges are shaped to minimized drag. The physical specifications for the array are summarized in Table I.

Parameter	**Specification**
Element width	31 mm
Element height	62 mm
Element thickness	13 mm
Encapsulation thickness	22 mm
Weight (air)	2.5 Kg (per pair)
Weight (water)	1.2 Kg (per pair)
Overall length	500 mm
Overall height	150 mm

TABLE I
CONFORMAL ARRAY PHYSICAL SPECIFICATIONS.

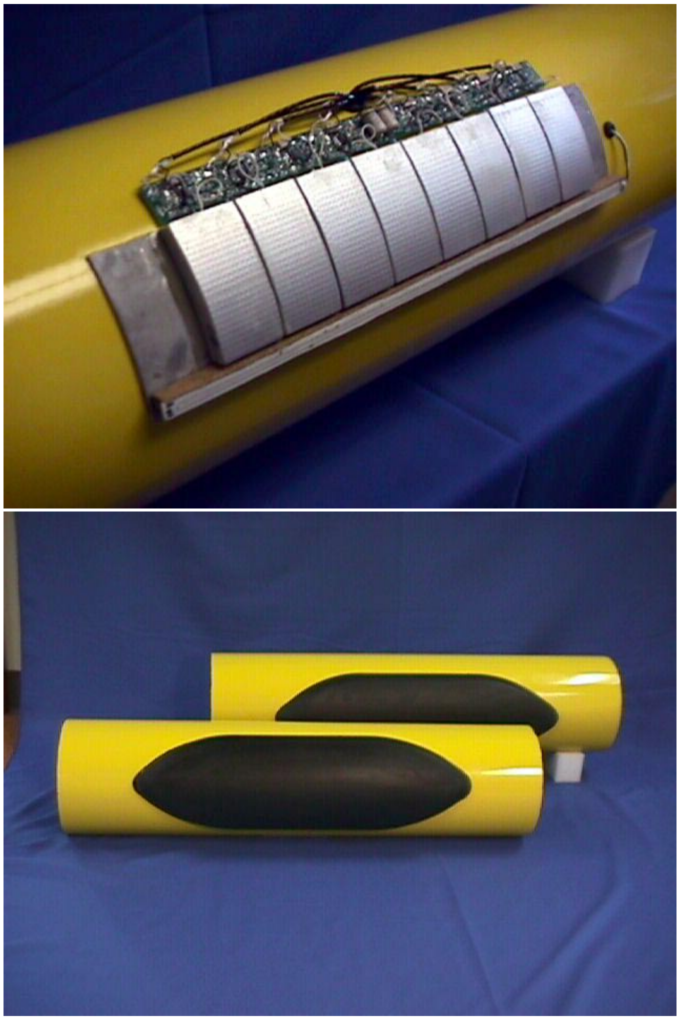

Fig. 1. Conformal arrays fabricated for the NUWC REMUS vehicle by Materials Systems Incorporated. Top: 8 element communications array, side-scan transducer and pre-amplifiers prior to encapsulation. Bottom: the completed assembly.

B. Calibration Results

The arrays were calibrated in a test facility operated by Code 8211 at the Naval Undersea Warfare Center in Newport, RI. The objectives of the tests were to confirm the design goals and characterize both the beampattern and receive response.

The receive response from 10 kHz to 40 kHz for one of the arrays is shown in Fig. 2. The response for channels 2-7 is very repeatable and throughout most of the band the channel-to-channel matching is 3 dB or better. Channels 1 and 8 are different from the other group by 1-3 dB in the 15-30 kHz region but are otherwise very similar. This difference may be due in part to edge effects at the two ends of the array. The roll-off at 40 kHz includes the low-pass response of the pre-

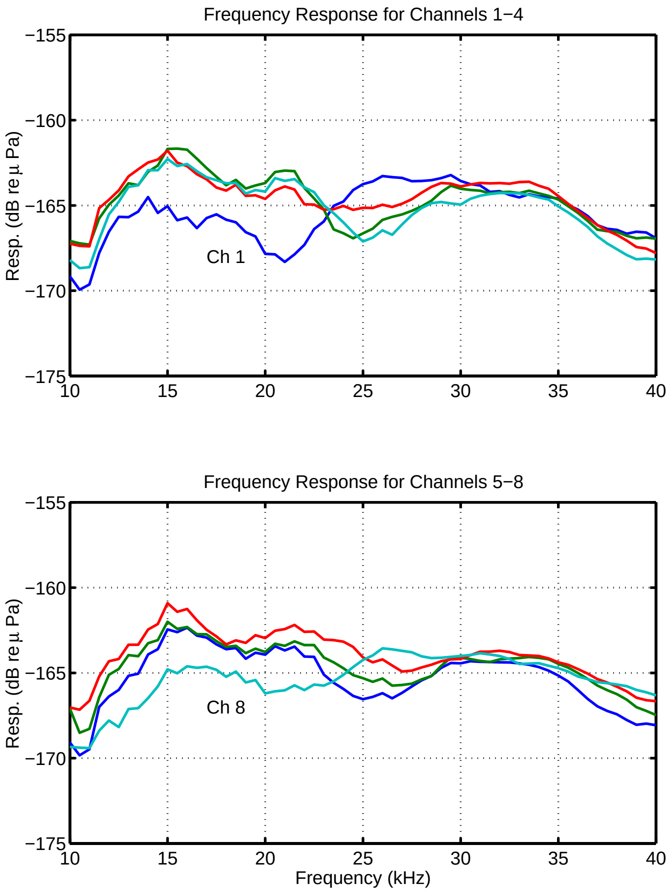

Fig. 2. Measured frequency response for one of the finished arrays. Channels 1 and 8 exhibit small differences from the other elements.

amplifier. The response of the piezocomposite itself is flat well above 40 kHz.

The horizontal and vertical beampatterns of the arrays were also measured in the calibration facility. Three frequencies were used, 10, 20 and 30 kHz. The vertical response is shown in Fig. 3. At 10 kHz the vertical response is ±75°, and at 20 kHz it decreases to approximately ±25°. At 30 kHz the -3 dB points are similar to those at 20 kHz, but the overall width of the main lobe is narrower and the response is 20 dB down at ±50°. The wide beamwidth at 10 kHz allows the array to be used in the UQC band in deep water where the source may be at a steep vertical angle with respect to the vehicle array. While the front-to-back ratio is only 8 dB at 10 kHz, at 20 and 30 kHz it is greater than 25 dB.

The horizontal beampatterns at 10, 20 and 30 kHz are shown in Fig. 4. The horizontal response varies with frequency as expected, but is nominally ±45°. While the low response to aft of the vehicle helps to reject noise from the propeller or control surfaces, the same reduced response looking forward leaves a gap in the overall directional capability of the acoustic communications receiver. While this beampattern is significantly different than the design goal, it is not completely unexpected from a line array fabricated on a long air-backed tube. Methods for broadening the horizontal response are under consideration but may require a compromise in physical construction.

III. Results

The arrays were tested by placing them on a fixed underwater platform at the NUWC Gould Island test range. They were interfaced to a multi-channel data acquisition system that performed realtime detection, demodulation and archiving for off-line analysis. The tests were performed with the array oriented both horizontally and vertically.

The primary acoustic communications signals of interest are broadband (greater than 5 kHz) PSK. While the encoding and constellation density may vary in the final application, it is instructive to examine the performance of a 5000 symbol per second, rate 1/7 block-encoded QPSK signal as described in a related paper [5]. This signal may be interpreted as a 10 kb/s uncoded data stream, or as a coded 1400 bps signal suitable for low SNR or multiuser operation. Signals corresponding to six different users were transmitted. As described in [5], the difference between the signals is the training sequence and the data. The same block code is used for all users.

The signals were transmitted from a small boat with a high-frequency transducer with toroidal beampattern and nearly flat frequency response. The center frequency was 23 kHz. One wavelength at this frequency is 0.065 m, so that the array element spacing is almost exactly $\lambda/2$. Additional details about the experimental setup are provided in [5].

The receiver is the multi-channel decision feedback equalizer (DFE) modified to directly include Doppler compensation and error-correction decoding. Reliable symbols are fed back to update the equalizer filters after soft-decision decoding so that the coding gain may be effectively used. Thus the equalizer operates reliably at symbol signal-to-noise ratios that are several dB lower than would otherwise be possible.

A. Single-User Communication

The signals corresponding to the six different users were first processed individually to check the difference in performance between the two array orientations. Four elements (every other one from the array) are used in this analysis. The results are in Fig. 5, where the histogram of MSE for all the data packets taken during each test are shown. The spread of MSE is broad because the source is moving at different speeds and changing range, but in general the same path is traced by the source vessel. The average MSE for the vertical array geometry is about 3 dB lower than that of the horizontal array tests. This translates to a significant difference in the possible rate or reliability level of the acoustic link using the two orientations. However, the single-user performance with the array horizontal is more than adequate for many applications, even if it is not as good as the vertical.

The difference between the two may be explained at least in part by the spatial coherence or diversity functions in shallow water. The adaptive equalizer takes advantage of the differences in the received signal across the array, and in this propagation environment the output SNR of the adaptive equalizer is limited primarily by inter-symbol interference (ISI),

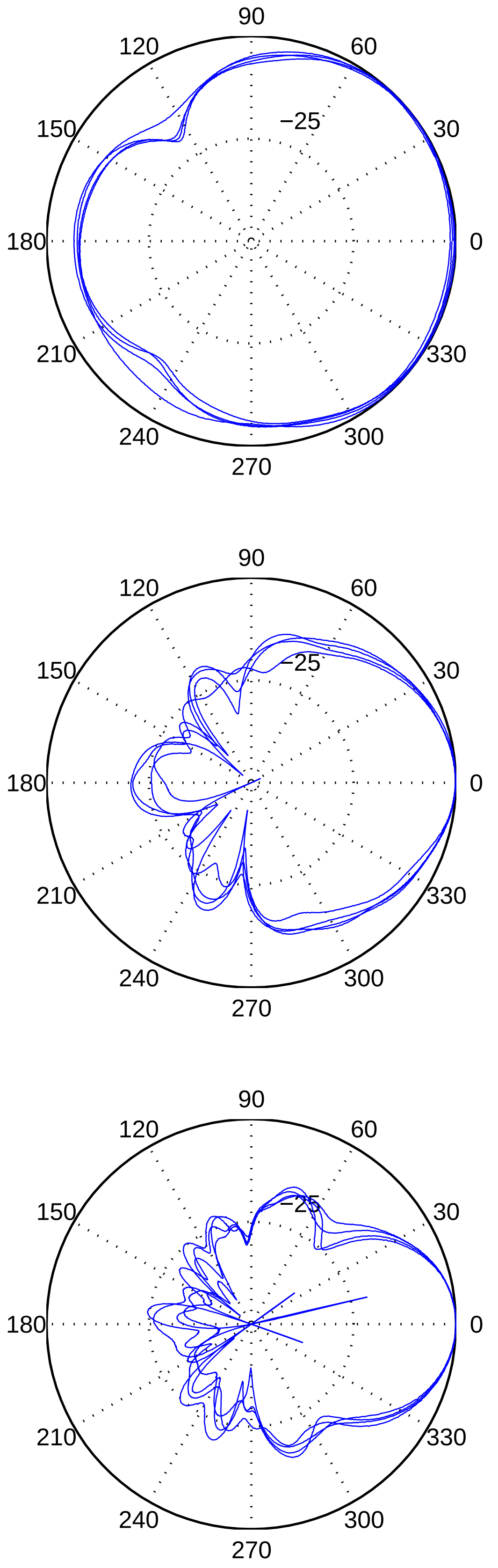

Fig. 3. Vertical beampatterns for channels 1-4. Top: 10 kHz. Middle: 20 kHz. Bottom: 30 kHz. The overall scale is 50 dB. Zero degrees is horizontal and 330 represents -30 degrees.

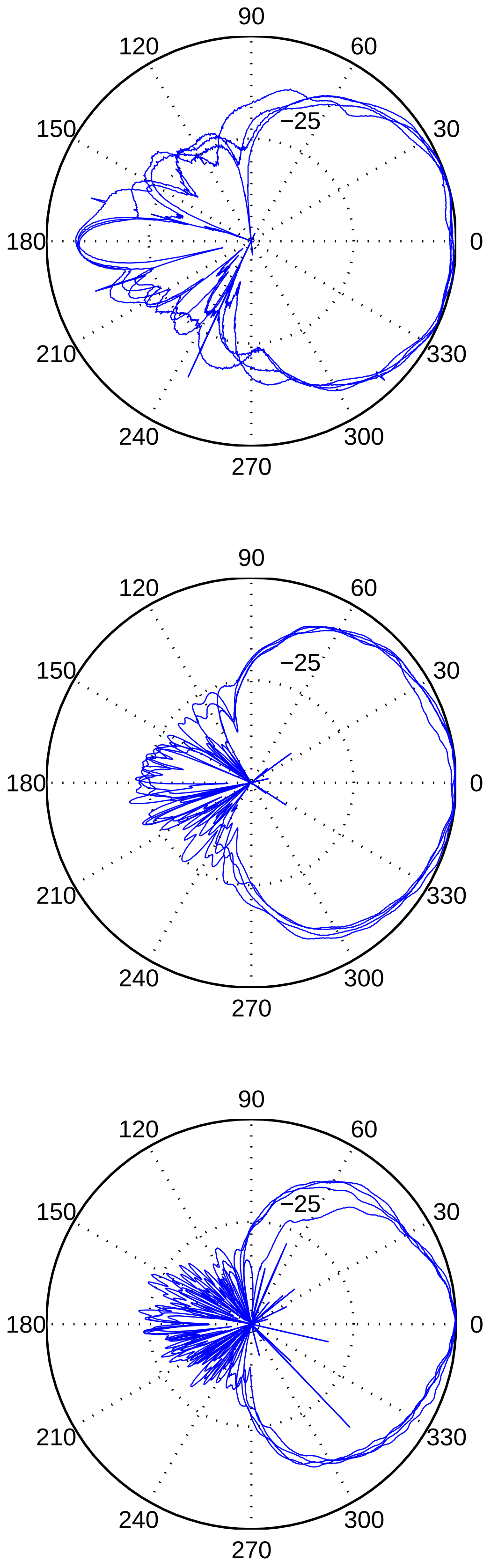

Fig. 4. Horizontal beampatterns for channels 1-4. Top: 10 kHz. Middle: 20 kHz. Bottom: 30 kHz.

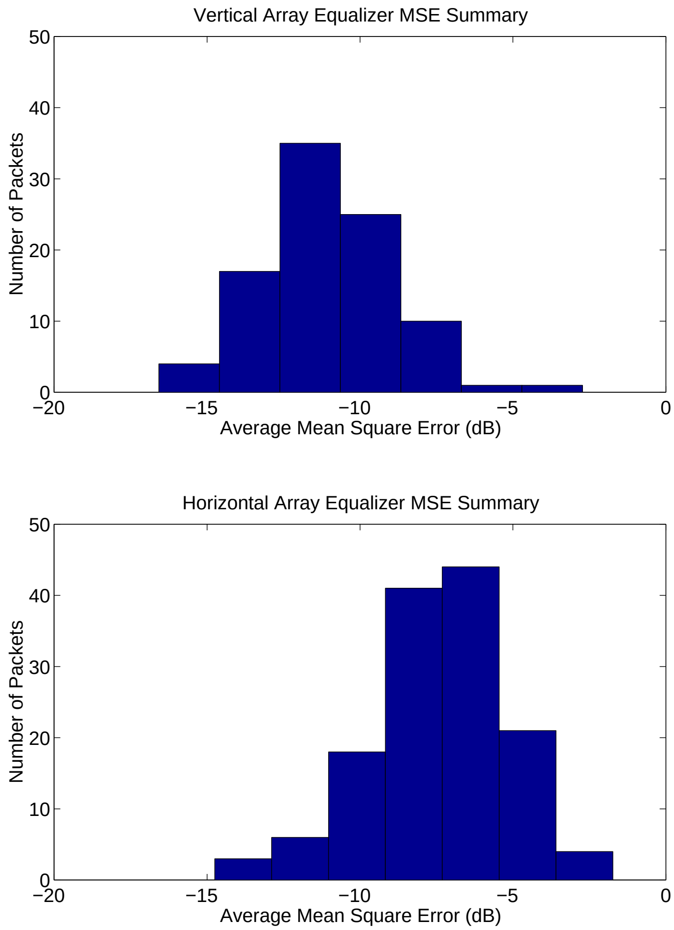

Fig. 5. Equalizer mean square error (MSE) histogram for a series of single-user tests in shallow water. The average MSE for the vertical array (top) is lower than that of the horizontal (bottom) array orientation.

not noise. The multipath structure varies more in the vertical than the horizontal, and thus the adaptive equalizer works better when the array is oriented vertically.

In Fig. 6 a comparison of typical results using different numbers of elements in both orientations is presented. The objective of processing the data in this way is to determine the optimal number of channels from the array. The array may be drawn from in numerical order, or may be used with maximal channel separation. Two channel linear selection corresponds to channels 1 and 2, while sparse selection is channels 1 and 8. In the top panel of Fig. 6 it is apparent that 2 channels selected with maximum separation provides the lowest MSE when the array is horizontal. When the array is oriented vertically use of every other element gives the best MSE.

It should be noted that these data packets were not collected at the same time, so that the MSE cannot be compared directly, rather it is the trend that is important. The horizontal coherence is high and thus the gain from using two channels is highest when they are located as far apart as possible. More array elements contribute to the best solution when the array is vertical. The shape of these curves will change as conditions change.

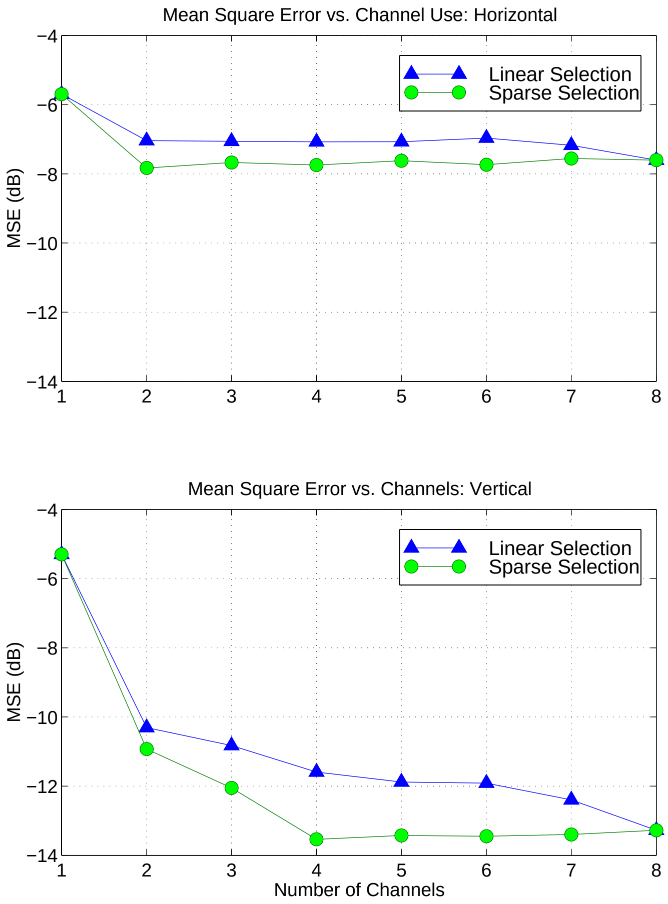

Fig. 6. Equalizer mean square error for the horizontal (top) and vertical (bottom) array orientation in the single-user case. Linear selection is [1], [1,2], [1,2,3], etc. Sparse selection is [1], [1,8],[1,4,8], etc.

B. *Multiuser Communication*

Comparative analysis of different arrays or approaches to multiuser communication is complicated because of the number of variables. For example, despite the fact that the transmitter vessel is following the same track while sending the signals for all users, the channel does vary. Selectively combining the different users' signals can result in either overly-optimistic performance estimates, or pessimistic worst-case performance (i.e. decoding failure). Rather than attempting to reach globally-applicable conclusions, we instead present some individual cases that help to illustrate the range of performance that might be expected. In this case two users are examined. Thus the total data rate is 2800 bps using the 5000 Hz bandwidth. Results with four users are presented in [5].

Two-user performance for two example cases of horizontal and vertical array placement are shown in Fig. 7. Two data packets from different users that have similar single-user MSE were selected and then combined without weighting. In both of the test cases the power differences between the two users was approximately 6 dB. The number of channels used for equalization was varied from one to eight, with channel selection done sparsely, i.e. maximal separation across the array.

In the top panel of Fig. 7 the performance of the equalizer for a horizontal array orientation is shown. The two-user sig-

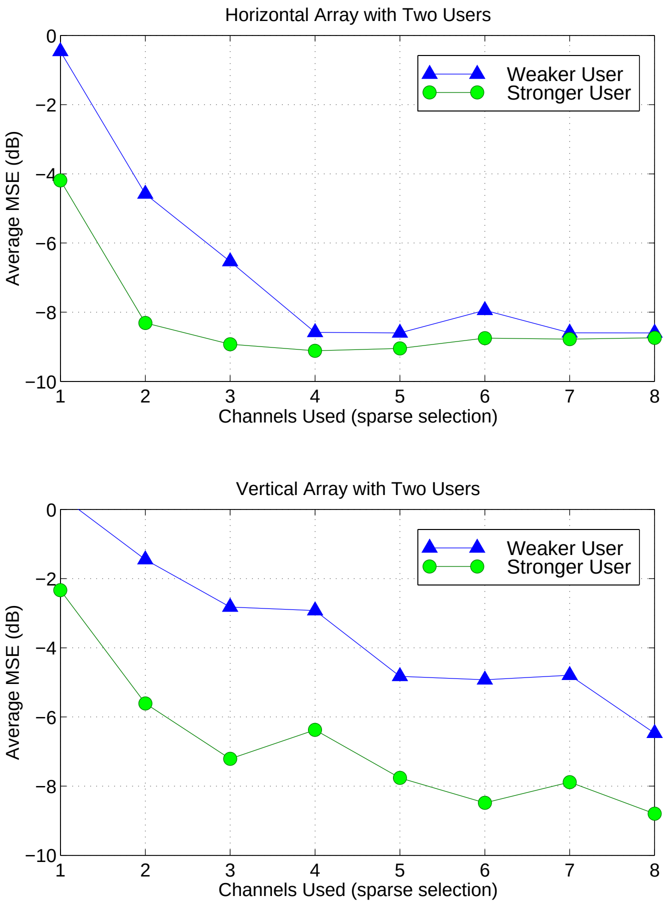

Fig. 7. Equalizer mean square error for the horizontal (top) and vertical (bottom) array orientation for two-user cases. Channel selection is sparse in all cases.

nal is processed for both users so that the performance of the weaker user can be examined with respect to the array usage. A 4 dB difference is apparent between the two for one and two channels, but when four channels are used the performance is within 1 dB.

In the vertical case (bottom of Fig. 7) the separation in performance between weaker and stronger users also starts out at approximately 4 dB and narrows as additional channels are used. However, the difference is typically higher than the horizontal case, and only with eight channels does it narrow to 2 dB.

While these tests are not by any means exhaustive, the preliminary conclusion is that the horizontal array, while not providing as good performance as the vertical array for single-user reception, actually does as well (and perhaps better in some cases) as the vertical array for two-user reception from sources separated in bearing.

IV. Conclusions and Future Work

A conformal array suitable for a small (20 cm diameter) UUV may use the vehicle's pressure case as a structural member and exploit the air-filled tube to increase the array front-to-back ratio without adding heavy or bulky backing material. Piezocomposite ceramic arrays offers excellent sensitivity compared to traditional ceramic solutions and in this case allowed shaping of the elements to match the vehicle's radius of curvature. Evaluation of adaptive equalizer performance results demonstrates that the array provides reliable communication when a subset of the array is used in either vertical or horizontal configurations.

For the single-user case with the array oriented horizontally, as few as two elements (either end) provide best results. When the array is vertical, every other element typically provides best performance. These results are for signals with carrier frequency selected such that the elements are at one-half wavelength. The data confirm heuristic arguments that communications arrays on small vehicles should attempt to use all possible vertical aperture, and then all horizontal aperture.

In the two-user case the performance difference between the two orientations appears to narrow, with the horizontal array showing good two-user data recovery. The separation in bearing between the users may be best exploited by the horizontal array, indicating that for multi-user reception this array design may offer the best performance. By extension, the horizontal array will also offer good interference suppression from noise sources at angles separated from the desired user.

Future transducer work includes development of an array with a broader horizontal beam and the design of two dimensional arrays that work well for both single and multiuser communication. Future algorithm development and evaluation includes reduced-complexity processing that may provide more effective use of all elements of the array as described in [6].

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