NEXT GENERATION DIGITAL BEAMFORMING ARRAY OPTIMIZED BY NEURAL NETWORK BEAMFORMING TECHNIQUES

Arthur Sullivan, Christos Christodoulou, Charles W. Chandler

ABSTRACT

The next generation Digital Beamforming Array (DBFA) requires techniques beyond the existing adaptive processing and optimization approaches. By utilizing neural network processing and genetic algorithms that mimic complicated natural processes, such as the brain and natural selection, new and superior Antenna Arrays can be designed.

The use of Neural Networks and Genetic Algorithms combined with the existing techniques for DBFAs can yield the ultimate in "real-time," "smart" antenna performance. Cost is significantly reduced by; allowing large manufacturing tolerances, the use of inexpensive components, and correcting by neural network techniques.

This paper describes the technology and proposes a practical application of the technique to design a DBFA to track and transmit/receive telemetry from a shipboard vertically launched medium range missile.

KEY WORDS

Antenna, Array, Beam, Beamforming, Digital, Telemetry, Tracking, Neural Networks, Genetic Algorithms.

INTRODUCTION

The concept of performing signal processing digitally in an array, rather than in an analog manner as in the phased array and multiple-beam antenna, began in the late 1970s. The necessary monolithic components (necessary for small low cost receiving systems) and computer capabilities (mainly speed and memory) were not yet available but were anticipated. With the continuing swift advances in monolithic technology and computer capabilities, the Government, Universities and Industry expended considerable research efforts on investigating DBFA technology.

The major efforts on DBFAs were performed in the 80s. Toward the end of the 80s budgets were being slashed and most of the efforts were greatly reduced. At that time it appeared that the computer technology would not be advanced enough for practical DBFAs until about the beginning of the next century. The accelerated advances in computer speed and memory could not have been anticipated. By the mid 90s it was evident that the computer technology would be in place before the end of this century. DBFAs were still not practical for telemetry because of the extremely high cost of non-recurring engineering (NRE) on the monolithic components. In addition the monolithic components were only reasonable in cost in quantities in the tens of thousands.

In the telemetry area the next generation DBFAs are practical today because of the thriving wireless telecommunications market in the TCS band. Because of this, high- performance, low-cost RF chips are now available at frequencies very close to the telemetry S-band frequency range. Using this technology, complete S-band receiving systems can be designed with a production cost of less than $300.00.

Southhall (1-3), El Zooghby (4-5), and others have shown that low-cost phased arrays are practical by the use of neural networks and genetic algorithms. The results to date on phased arrays are astounding — especially when one considers that the only practical variable parameter is phase. The phase shifters are only three bits. Even with this restriction, near optimum phased arrays can be built for unprecedented low costs.

In the DBFA one can control amplitude and phase using 8 bits in each parameter. Astonishing capabilities are now achievable. Low cost DBFAs with optimum performance are now realizable.

It should be noted that these new “smart” adaptive array antennas can perform beamforming and angle of arrival tasks in “real time” once the neural network has first been trained “off-line.”

DIGITAL BEAMFORMING ARRAY CONCEPT

Digital Beam Forming is the method of forming an antenna beam digitally rather than in an analog fashion. A typical block diagram is shown in Figure 1. Signals received by each element are individually converted to "I" (in-phase) and "Q" (quadrature-phase) signals at an IF frequency. We currently propose this IF frequency to be 5.6 MHz since it is compatible with a 5.6 Mbit telemetry data rate. These analog signals are synchronously sampled and converted to 12-bit binary numbers. The converted digital signals contain all of the amplitude and phase information of the original signals, and can be amplitude and phase modified by the software in a digital computer to form the antenna beams desired. In digital beam forming, the high-cost and complicated analog components, such as attenuators and phase shifters, which are used to form an analog antenna beam network in phased arrays, are not required. This fact reduces the cost, increases the reliability and facilitates the implementation of the system.

NEURAL NETWORK-BASED DBFAs

Neural networks are a computing paradigm that involves several simple processing elements that can communicate with each other — originally developed to mimic the action of neurons in a human brain. Data are processed and passed on through communications channels called “connections.” These connections form a massively parallel network used to perform tasks that would otherwise be very difficult. Each connection is assigned a numerical weight that is modified through training to meet the particular task, such as adaptive-array beamforming. Given a set of sensor outputs, the neural networks can distinguish accurately the different angles of arrival (AOA) and, therefore, differentiate between the beams. Beam formation could also be done with this precise level of spatial separation, and so allow more signals to come from the same antenna.

The particular type of neural network recommended for angle of arrival estimation and beamforming is the Radial-Basis Function Network (RBFN), shown in Figure 2.

Information is passed through the input layer (DBFA) into a hidden layer of nodes, where it is processed. The preprocessing includes, among other things, the breaking up of the complex sensor values into real components, as well as the normalization of the input information through removing the initial phase of the sensor information and division by the norm of the input vector.

The number of hidden nodes depends on the complexity of the system involved and the amount of information to be processed, such as the number and type of elements that form the array, the polarizations involved, operational frequencies, number of targets to be tracked, data rates, etc. A weighted sum of the inputs is passed through a transfer function to the output nodes. The transfer functions in the hidden layer of a RBFN are Gaussian functions and, because these functions are determined by their center point and radius (the variance of the Gaussian), the units of the hidden layer are referred to as “radial units.”

After the appropriate network is created, the network is trained, off-line, using a series of sensor patterns created by known AOA and beamforming data that cover as many possible “real-life” scenarios as possible. Once the network is trained off-line, it can then “generalize” other cases in real time. That means, given a certain desired beam or null steering, the neural network can determine the appropriate excitation coefficients of the DBFA element that will yield the desired pattern. This ease of generalization is another of the RBFN features that make this type of network desirable for the application at hand. In Figure 1, a computer network will be a radial basis function neural network.

For illustration purposes the neural network-based method was applied to a 2-D array of isotropic elements. In Figure 3, an 8 x 8 array is used to track 10 different users, with $\Delta\theta = 10°$ (angular separation between consecutive desired signals) at $\phi = 30°$. The adapted pattern obtained from an RBFN with 150 nodes in the hidden layer is compared with the optimum Wiener solution (6). The network successfully tracked the desired signals and placed nulls in the direction of the interfering users. Finally, an array of 10 x 10 elements was simulated to track 19 signals consisting of nine desired users and 10 interferences. Figure 4 shows the adapted pattern as the network tracked all targets. The number of input/output pairs used in the training set for the two-dimensional arrays was 181.

The use of an RBFN and Generic Algorithms on a DBFA will be referred to as an Adaptive DBFA (ADBFA).

SHIPBOARD REQUIREMENT

To show an example of the Next Generation ADBFA we will choose an application of tracking and transmitting/receiving a medium range (100 miles) vertically launched shipboard missile with a wrap-around antenna. Typical parameters are as follows:

Frequency	2.2 to 2.4 GHz
Polarization	Any Polarization
EIRP	2 Watts
Elevation angle	0 to 8 degrees
Pre-detection noise bandwidth	5.6 MHz
Minimum C/N ratio	13 dB
Range	0 to 100 miles

Since a shipboard tracking system must be mounted on a mast, lightweight and minimum wind resistance are two of the most important factors that must be considered. For short-range missile tracking, a simple lightweight (and low-gain), single-axis-gimbaled array does an adequate job for the lowest cost. To track a longer-range missile one needs considerably more gain. With the increase in gain, elevation tracking (as well as azimuth tracking), is usually required. Since most requirements require 360-degrees of coverage, mast mounting is usually always desired. Therefore size, weight, and wind resistance are of paramount importance.

The ADBFA technology affords the lightest possible weight of any system achievable with today's technology. The elements described are printed-circuit dipoles in a circular waveguide (or cup). To achieve ultra lightweight, the cup can be made out of graphite composites; there is ample experience with this approach to attest to its viability. The weight of the entire element will be less than two ounces (not including a bandpass filter and preamplifier). With the bandpass filter and preamplifier, each element will still only weigh on the order of one-half pound. The entire array would have an absolute minimum wind resistance per aperture size.

To achieve an extremely low cost system it is proposed to use a lightweight azimuth-only rotator to rotate the ADBFA. Azimuth-only can be used because multipath nulls are eliminated in an ADBFA. Figure 5 shows the proposed ADBFA. Figure 1 is a block diagram of the ADBFA. The Azimuth tracking array utilizes 3 by 10 elements. The top and bottom elements are non active and loaded with a 50-ohm load. The non-active elements eliminate the requirement to compensate for mutual coupling and parasitic effects at the end elements. To computer compensate would narrow the frequency bandwidth of the array.

The three elements on the top of the array are aimed at zenith and are used for tracking during vertical launch. These elements have the same cup diameter as the other elements except that the cup is fiberglass, which allows for a broader beam width. Gain is not required for the vertical launch since the missile is so close. The center top element is used for the telemetry data to and from the missile. The two outer elements are used to determine the angular information to aim the array in azimuth until the vertically launched missile’s signal is low enough to be received by the three by ten array.

In order to keep the cost as low as possible no attempt is made to provide accurate positional data. Other means are usually available on the ship to provide accurate positional data when required.

Each group of three active elements is combined using 3-dB power dividers so that the center element receives twice the power of each of the outer elements. This gives a beam width of approximately 27 degrees and sidelobe levels of about 19 dB in azimuth. When the missile is low enough to be first received by the three by ten array it is still in close and only one row of three elements would be activated. This allows only the amount of gain necessary to yield a required C/N ratio with adequate margin. Azimuth tracking information is derived for the rotator by the use of a step-track algorithm. Since the azimuth beamwidth is very broad (approximately 27 degrees) the azimuth speed and acceleration of the rotator can be minimized.

As the missile increases its distance from the ship additional elements will be activated always keeping approximately the same C/N ratio. Only when the missile is at maximum range will all the elements be used. By keeping the C/N ratio relatively constant the system dynamic range problem is eliminated.

The system is extremely lightweight since each element of the array, including the band-pass filters and power dividers, is less than half a pound. The azimuth rotator has a very low maximum velocity since, when the missile is in close, the beamwidth is broad enough so that accurate pointing is not required. As the missile distance from the ship increases the dynamics of the missile with respect to the ship decrease. Since automatic tracking is not used the servo constants can be kept extremely low. Because of this a very light weight rotator can be used. If a graphite-composite rotator is used the weight of the entire tracking system could be held to about 40 lbs.

Another advantage of the DBFA is polarization matching. The block diagram of figure 1 shows only one polarization per element for clarity. Each element of the array consists of a pair of nested orthogonal printed circuit dipoles. Each receiver module is a dual receiver. Almost all polarizations are realized for different aspect angles of a wrap-around antenna. A conventional tracking system would employ a very expensive polarization diversity combiner with a polarization-matching loss of at least 0.2 dB. The Adaptive DBFA can match polarization to with in at least 0.001 dB at no cost (polarization is matched in the computer). This is a 0.2 dB increase in gain.

A conventional two-axis tracker must autotrack (step tracking could not be used because or the rapid change in elevation caused by multipath). This will introduce a tracking loss (crossover level plus tracking network, cables etc.) of about 0.3 dB which is not required for the ADBFA.

COMPARISON OF AN ADBFA & A CONVENTIONAL TRACKER

The ADBFA described eliminates a smooth-water null, which is on the order of 17 dB. To be conservative on our comparison we will assume a 15-dB null. The ADBFA adds the reflected and direct signal so that they are always in phase. For smooth water the reflected and direct signal are equal in amplitude. This is then a 6-dB increase in gain. This is a 21-dB advantage over a reflector system. Again to be conservative we will only use 18 dB for our null enhancement over a reflector antenna.

In the described system the ADBFA has a gain of about 20 dB. Allowing a 0.2-dB advantage for polarization matching, 0.3 dB for autotracking loss, and 18 dB for null enhancement; a reflector antenna would have to have a gain of 38.5 dB to have the same range as the ADBFA. This would require a reflector with a diameter of approximately 17-feet.

Murphy's law states that failures (preamplifier, filter, cable, etc.) will always happen right before an important mission. With conventional systems this often causes mission abortion. The Adaptive DBFA can be almost optimized, even when several elements are degraded, by the application of the RBFN on a real-time basis.

CONCLUSIONS

The ultimate in adaptability is achieved by combining Digital Beamforming Techniques and Neural Network Technology. The ADBFA will outperform any other sophisticated tracking system, and at a lower system cost. For the shipboard missile tracking application the ADBFA has the following advantages:

- LIGHTEST WEIGHT POSSIBLE / PERFORMANCE
- LOWEST COST / PERFORMANCE
- COST LOWERED SIGNIFIGENTLY BY ALLOWING LARGE MANUFACTURING TOLERANCES AND CORRECTING BY GENETIC TECHNIQUES
- OPTIMUM PERFORMANCE WITH DEGRADED ELEMENT
- BEAM ADAPTIVELY CONTROLLED FOR CONSTANT G/T
- 12-BIT IMPLEMENTATION
- PHASE CORRECTED TO A FEW SECONDS OF ARC
- AMPLITUDE CORRECTED TO A HUNDREDTH OF A dB
- 41 BY 11 INCH ARRAY OUTPERFORMS 17 FT REFLECTOR
- SIMULTANEOUS TRACKING OF MULTIPLE TARGETS
- NULL STEERING
- MULTIPATH CANCELLATION
- COMPLETELY OPTIMUM POLARIZATION DIVERSITY
- TECHNIQUE ALLOWS CHANGING DESIGN TO ACCOMMODATE ANY MISSION REQUIREMENT WITH MINIMUM NRE

LINK ANALYSIS

The multipath plot of Figure 6 shows the effect on transmission of reflections from a relatively smooth ocean. The plot is in the form of a coverage diagram in that it shows the decreases and increases in effective range due to multipath. The assumptions are a free space range of 100 miles, receive antenna height on the ship is 40 feet above the water, and the antenna has a beam width of 27 degrees, the peak of which is pointed at the source. The plot shows several significant nulls between 0 and 2 degrees elevation angle. The deepest null reduces the operating range to about 25 miles from about 178 miles without multipath (17 dB). In the ADBFA the data will be processed in the computer so that the maximum lobes are increased 6 dB over smooth water.

The Link Analysis for the 10-element ADBFA and for the assumed shipboard missile tracking application is shown in the Table of Appendix A and shows that; for a missile range of 100 statute miles, a missile effective-isotropic radiated power (EIRP) of two watts (+33 dBm), and a C/N ratio of 30 dB, the link margin is approximately 5.58 dB. This indicates that the Described ADBFA could track and transmit/receive data from the missile to 190 miles.

ACKNOWLEDGMENTS

The authors are grateful for the help and contributions of Ron Potter and Glen Walters in the planing, editing and preparation of this paper.

REFERENCES

1. R. L. Haupt and H. L. Southhall, "Antenna Array Beamforming Based on Biological Processes," *International Symposium on Antennas,* JINA '96, Nice, France, 12-14 November 1996

2. J. Southall, S. Santarelli, E. Martin, and T.O'Donnell, "Neural Network Beam Steering for Phased Array Antennas," *Proceedings of the 1995 Antenna Application Symposium,* University of Illinois, Robert Alterton Park. September 1995. USAF Rome Laboratory, Rome, NY.

3. Southall H. J. Simmers, and T. H. O'Donnell, "Phased Array Antennas with Neural Network Signal Processing," *Proceedings of the 1994 Antenna Applications Symposium,* University of Illinois, Robert Alerton Park. September 1994. USAF Rome Laboratory, Rome, NY

4. Ahmed El Zooghby, C. G. Christodoulou, and M. Georgiopoulos, *Performance of Radial Basis Function Networks for Direction of Arrival Estimation with Antenna Arrays*, IEEE Transactions on Antennas and Propagation, vol. 45, no. 11, pp. 1611-1617, Nov. 1997.

5. Ahmed El Zooghby, C. G. Christodoulou, and M. Georgiopoulos, *Neural Network-based Adaptive Beamforming for one and two dimensional antenna arrays*, IEEE Transactions on Antennas and Propagation, accepted for publication.

6. Mozingo, Miller, *Introduction to Adaptive Arrays*, John Wiley, 1980.

APPENDIX A – LINK CALCULATIONS

TELEMETRY LINK ANALYSIS FOR 3X8 CUPPED DIPOLE ARRAY	
Input Parameters	
Frequency	2.200 GHz
Source Transmitter Power	2.00 Watts
Loss: Transmitter to Antenna	0.00 dB
Source Antenna Gain	0.00 dBi
Range	100.00 Miles
Elevation Angle	8.00 Degrees
Polarization Mismatch Loss	0.00 dB
Tracking (Pointing Error) Loss	0.00 dB
Atmospheric Attenuation	-1.12 dB
Receive System G/T	-2.83 dB/Kelvin
Pre-Detection Noise Bandwidth	5.6 MHz
Carrier-to-Noise Ratio Calculation	
Source Transmitter Power	33.01 dBm
Loss from Transmitter to Antenna	0.00 dB
Source Antenna Gain	0.00 dBi
Source EIRP	33.01 dBm
Space Loss	-143.43 dB
Atmospheric Attenuation	-1.12 dB
Power Received by Isotropic Antenna	-111.54 dBm
Polarization Mismatch Loss	0.00 dB
Tracking (Pointing Error) Loss	0.00 dB
Receive System G/T	-2.83 dB/Kelvin
Boltzmann’s Constant	198.6 dBm/Hz-Kelvin
Pre-Detection Bandwidth	-63.98 dB/Hz
Carrier-to-Noise Ratio	20.25 dB
Required Carrier-to-Noise Ratio	-13.00 dB
Margin	**5.58 dB**
Free Space Range	190.00 Miles

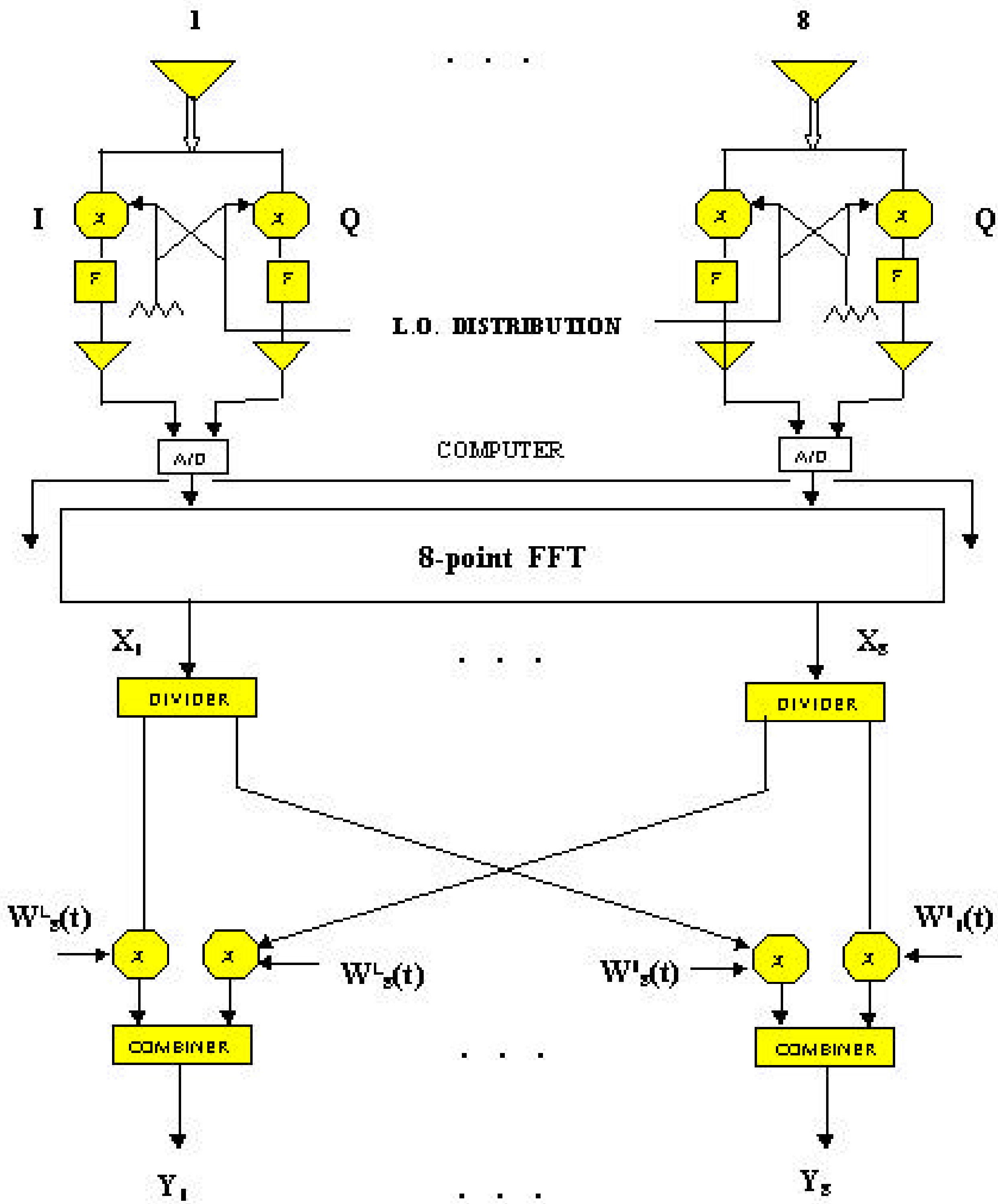

Fig. 1 Adaptive Digital Beamforming Array

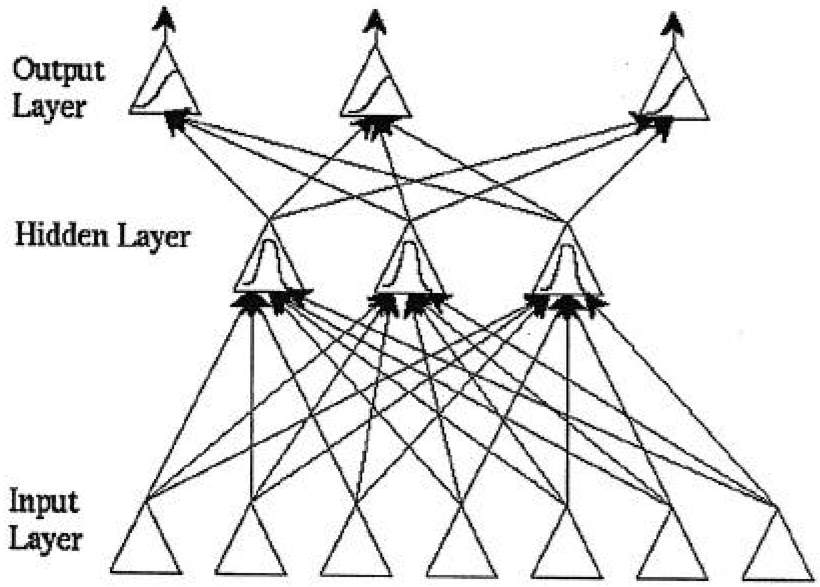

Fig. 2 Neural network architecture for adaptive beamforming

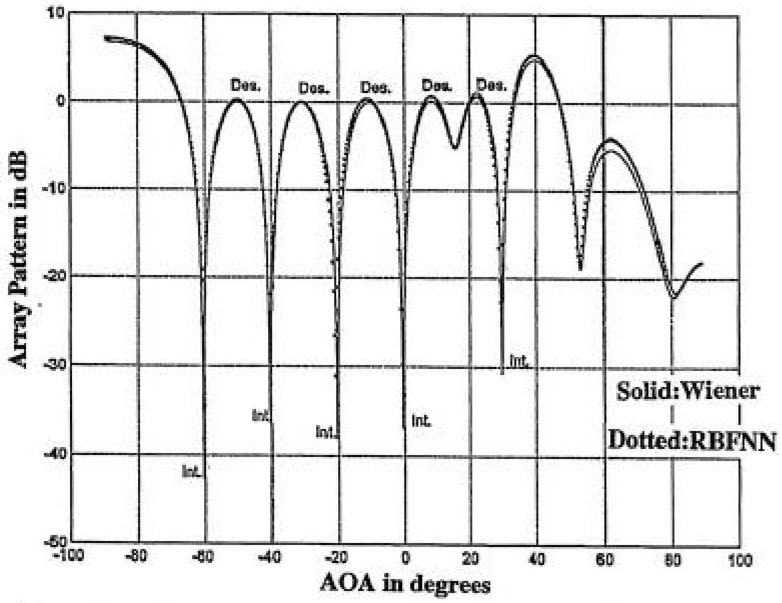

Figure 3 An 8x8 rectangular array, tracking 10 signals with $\Delta\theta = 10°$, $\phi = 30°$. Comparison between RBFNN & Wierner optimum weight solution at different Source locations.

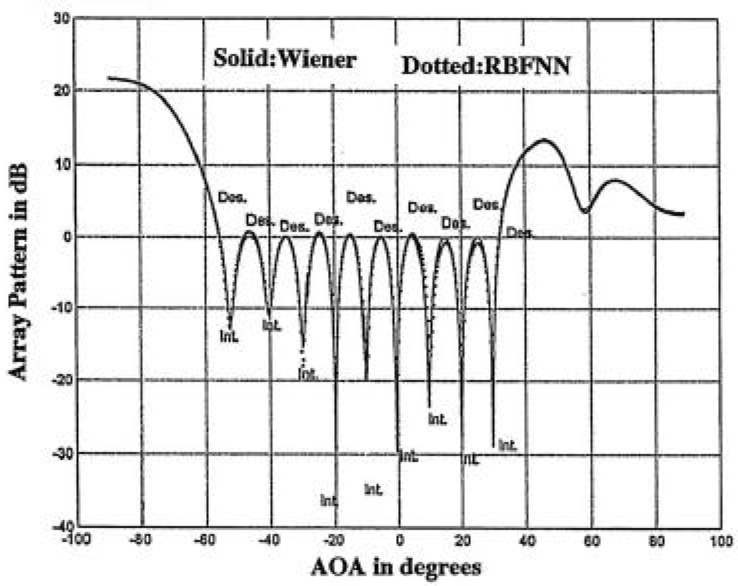

Figure 4 An 10x10 rectangular array, tracking 19 signals with $\Delta\theta = 5°$, $\phi = 45°$. Comparison between RBFNN & Wierner optimum weight solution.

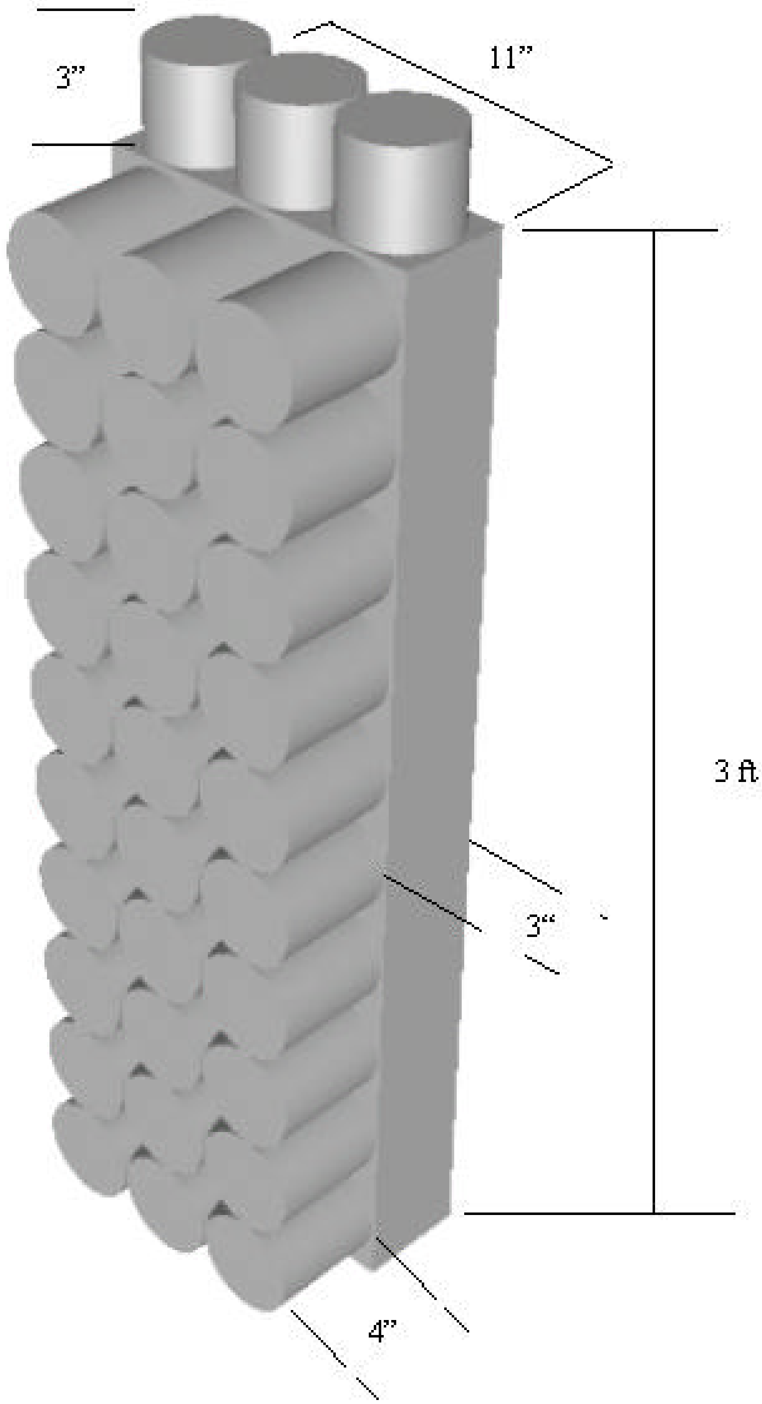

Fig.5 Physical layout of Adaptive Beamforming Array

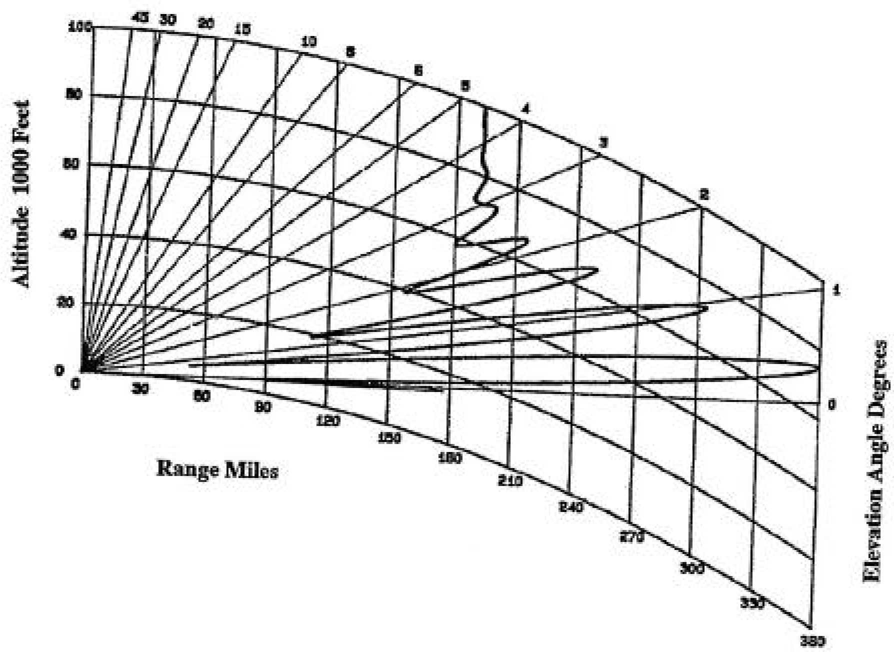

Figure 6 Multipath Plot