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13. ABSTRACT (Maximum 200 words)

Reliable communications in the crowded and hostile environment of the future battlefield is a difficult and challenging problem. Array processing technology must be a key element in any system designed to face these challenges. In this project we addressed some of the open issues which need to be resolved for a successful transition of advanced array processing techniques from theory into practice. The problems we considered can be divided roughly into five categories: (i) Array Processing in a Multipath Environment; (ii) Array Calibration; (iii) Diversely Polarized Arrays; (iv) Blind Array Processing; and (v) Array Processing for Broadband Signals. The report summarizes the key results obtained in this project, and provides a detailed bibliography listing over 100 publications prepared during this project.

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1 Introduction

This final report summarizes work performed under an Army Research Office contract DAAL03-91-C-0022 titled "Advanced Array Processing for Communications," during the period from 15 April, 1991 to 30 September, 1997. This work was a continuation and extension of work performed by the principal investigator under previous contracts with the Army Research Office (contracts DAAL03-86-C-0018 and DAAL03-89-C-0007).

The research results obtained in the course of this project have been documented in 110 publications in professional journals and conference proceedings, listed in section 4, and will not be repeated here. The purpose of this report is to describe the problems addressed in this project (section 2) and to present a brief summary of the main results (section 3).

2 Statement of Problem

Reliable communications in the crowded and hostile environment of the future battlefield is a difficult and challenging problem. Array processing technology must be a key element in any system designed to face these challenges. While some of the technologies needed for operating in this difficult environment, such as spread spectrum communications and advanced modulation and coding techniques, are fairly mature and well developed, array processing is a relatively new technology and its potential for providing significant gains in system performance has not been fully realized yet. Research and development efforts in the area of array processing are, therefore, expected to have relatively high payoff during the next decade.

While advanced array processing techniques have been discussed in the literature for quite some time, the practical implementation of these techniques was at an early stage of development when this contract started. Various experimental systems using techniques such as MUSIC have been in existence, but as far as we know, there were no fielded systems employing high-resolution array processing algorithms at the time.

In this project we addressed some of the open issues which need to be resolved for a successful transition of advanced array processing techniques from theory into practice. This plan was based on the experience and insight gained during the earlier phases of this project, and from our interactions with members of the U.S. Army Signal Warfare Center.

The problems we considered can be divided roughly into five categories, which are briefly described below.

1. Array Processing in a Multipath Environment.

The presence of multipath is a major obstacle to the proper operation of array processing systems. Understanding the ways in which multipath affects

the performance of the array, and developing processing techniques for optimizing performance in the presence of multipath, are central to the successful deployment of system utilizing antenna arrays.

2. Array Calibration.

Advanced array processing techniques require precise calibration of the array. We have studied in detail the sensitivity of direction finding and signal COPY to calibration errors. We have also investigated techniques for calibrating the array on-line and off-line.

3. Diversely Polarized Arrays.

Diversity is a key concept in communications, including for example frequency diversity and time diversity. Antenna arrays can provide a special form of diversity by using antennas with different polarization. We have investigated ways in which polarization diversity can be best used, and studied the performance advantages it offers.

4. Blind Array Processing.

Array processing techniques usually require detailed knowledge of the array response. In some situations, such as severe, rapidly changing multipath, it is impractical or impossible to measure or estimate the array response. So-called "blind" array processing techniques attempt to separate multiple co-channel signals without assuming any knowledge of the array response. We have studied and developed various blind signal separation techniques and evaluated their performance.

5. Array Processing for Broadband Signals.

Most array processing applications by far involve narrowband signals, i.e. signals whose bandwidth is small compared to its center frequency. In some applications, such as certain spread spectrum systems, underwater communications, etc., the narrowband assumption no longer holds. We have studied techniques for performing direction finding and signal COPY for broadband signals.

3 Summary of Main Results

3.1 Array Processing in a Multipath Environment

We have developed a number of direction finding algorithms capable of operating in the presence of high levels of signal correlation, which are often caused by multipath propagation. The interpolated array approach which we developed appears to be a very promising approach to the multipath problem [9, 13, 14, 15, 31, 59, 60, 64, 82, 100, 102]. Since its development, the interpolated array has been widely used by other researchers.

An important collection of results has been produced in this project on the performance analysis of direction finding and signal COPY algorithm. In a series of papers we carried out a detailed performance analysis for each of these algorithms [1, 3, 5, 10, 11, 17, 18, 19, 22, 24, 25, 37, 56, 61, 65, 67, 68, 72, 73, 74, 85, 88, 98, 102, 104, 105]. Closed form expressions for the covariance matrix of the DOA estimation errors were derived using a perturbation analysis. Evaluating these expressions for specific cases and comparing them to the Cramer Rao lower bound for the DOA estimates, provides insight into the statistical efficiency of these algorithms. The formulas for the error covariance are quite general, and can be specialized to provide results for other DOA estimation algorithms as well.

We have also developed the basic theory for arrays whose elements are located on several platforms, and may be moving relative to each other. Consider for example a DF system which combines a small fixed array and an small vehicle-mounted array. If the vehicle is stationary, we have a static (time-invariant) array whose properties are well understood. It is interesting to consider, however, what happens if the vehicle is in motion: does the resulting time-varying array have any performance advantages over the static array? Our study seems to indicate that time-varying arrays have potential advantages over time-invariant arrays of comparable dimensions. They are more robust to ambiguity errors, and to the presence of correlation between the sources. In a series of papers we quantified these advantages by developing bounds on the accuracy of direction estimation using time varying arrays. We have also developed computationally efficient estimation algorithms based on eigen-decomposition techniques for time-varying arrays [33, 35, 38, 42, 76, 79, 84, 91, 105].

3.2 Array Calibration

A focal point for our research has been the question: how to apply advanced high-resolution array processing techniques in the presence of various uncertainties in the array parameters. These uncertainties can take on many different forms: imprecisely known location of the array elements, unknown variations in the gain and phase of individual elements, and other deviations between the model on which these techniques are based, and reality.

The problem outlined above is of great practical importance. The accurate calibration of the array, required in order to apply "standard" high-resolution techniques, is very costly. Furthermore, in many situations it is practically impossible to maintain the array calibration. Consider for example a mobile communication antenna array which needs to be dismantled and reassembled in the field, its calibration changing each time it is moved. Or consider a conformal array mounted on the wing of an aircraft, where mechanical vibrations constantly change the shape of the array.

To address these problems, which are a major deterrent to the practical application of these promising high-resolution techniques, we have developed a number of techniques to self calibrate the array using "signals-of-opportunity". We were able to

show that it is possible to simultaneously estimate unknown source locations and the unknown array parameters, under some reasonable assumptions. It is important to note that this self-calibration procedure does not require that we know the directions of the calibrating sources.

More recently, we performed an extensive sensitivity analysis of direction finding techniques based on the covariance matrix of the received signals. Using the results of this analysis we can now quantify the effect of various types of calibration errors on the accuracy of the direction-of-arrival estimates, and on the ability of the array to resolve closely spaced sources.

Our work on the sensitivity issue and the self-calibration problem appears to be the first systematic attempt to analyze and improve the robustness of high-resolution direction finding techniques in the presence of various system errors. The publication of our key results [4, 12, 18, 23, 26, 27, 40, 45, 51, 54, 66, 75, 92, 99] seems to have stimulated an intensive research activity in this area as evidenced by papers published in recent years.

3.3 Diversely Polarized Arrays

An important part of our work focused on the exploitation of polarization diversity for direction finding problems. We were able to develop a number of computationally efficient algorithms for the simultaneous estimation of the direction of arrival and polarization parameters of multiple signals. By studying the performance of these techniques we were able to quantify the advantages of utilizing polarization diversity for both uncorrelated and correlated sources. It is quite clear from our studies that polarization diverse systems should be preferred in future direction systems. Such systems are not significantly more complex than systems which do not use polarization diversity, but are capable of improved performance if the signals of interest have different polarization characteristics. As expected, when the signals of interest have identical polarizations, the performance of a polarization diverse array is essentially the same as that of a corresponding uniformly polarized array. These results are summarized in [3, 10, 17, 19, 22, 24, 27, 28, 45, 61, 65, 67, 68, 72, 73].

3.4 Blind Array Processing

Our recent research has focused on the problems associated with using "smart" antenna arrays for mobile communications networks. Such antenna arrays are expected to play an increasingly important role in the future, since they make it possible to increase the capacity of the system, without requiring the allocation of more frequency channels. This increased capacity can be achieved by using directional antenna arrays which are able to separate multiple transmissions in the same frequency band, based on the fact that different transmitters are located in different directions relative to the receiver. In other words, each node in the network will need to be equipped

with a small mobile antenna array, and the associated receivers and signal processing hardware. Using this equipment it will be able to discriminate between different transmission based on their direction, as well as their frequency.

To make such a system work, it is necessary to develop algorithms which are able to take the mixture of signals received by the elements of the array, and separate them into their individual components. This must be done quickly and reliably, in the presence of rapidly changing propagation conditions. Conventional techniques for signal separation require detailed knowledge of the array response, i.e., of the voltages measured at the outputs of the different antennas, when it receives a transmission from a given direction. In many situations, especially in an urban environment, these transmissions undergo reflections from buildings, vehicles, or the terrain. (These reflections are referred to collectively as "multipath"). Thus, the array response to a given transmitter is unpredictable and unknown to the receiver. Consequently, conventional array processing techniques fail to properly separate signals in this environment.

Our work has focused on the development of signal separation techniques which do not require knowledge of the array response. Such techniques are commonly referred to as "blind" estimation technique. To accomplish the seemingly impossible task of separating the signals without any knowledge of the array behavior, these techniques rely on some fundamental properties of the signals themselves. For example, it is reasonable to assume that signals arriving from different transmitters would be statistically independent. Thus, if we are able to decompose the mixture of signals received by the array, into a sum of independent components, we would have accomplished the task of separating the signals.

Various techniques for decomposing signals into independent components have been proposed in the past. These techniques are computationally intensive and involve calculations of high order statistics of the array outputs. A recent breakthrough in this area has been the development of computationally simple adaptive algorithms, by a group of French researchers. The computational simplicity of these algorithms, makes it possible for the first time, to consider their use in practical real-time applications. We are in the process of developing improved versions of these "blind" adaptive algorithms and analyzing their performance. So far all of our work has been theoretical. However, in the near future we intend to test our algorithms on recorded real array data.

We believe that with this new class of algorithms, it will be possible to design small mobile arrays which will be able to work in the challenging environment of the future battlefield. These arrays will offer an interference rejection capability (by separating the desired signal from the interfering one), and the ability to carry out multiple communication links on a single channel. These "smart" antenna arrays will provide a significant enhancement of military and commercial communication networks. It is worth noting that significant research efforts in this direction are being undertaken by companies who design commercial mobile cellular communications networks.

Our work so far, which has been primarily theoretical, has been used by other researchers who work on the signal separation problem. The next phase of our work is aimed at providing a proof-of-concept by testing these algorithms on real-data. We believe that a successful completion of this phase will be followed by a rapid transition of this technology to the Army, and various DOD agencies. Our work on blind array processing is summarized in [2, 6, 44, 46, 53, 80, 98, 103, 106].

3.5 Array Processing for Broadband Signals

Most of the work on advanced array processing treats the case of narrowband signals. Various extensions of MUSIC to the broadband case have been proposed in the literature, based mainly on the idea of focusing the outputs of a sensor array so that broadband signals can be represented by low rank models, prior to applying the conventional MUSIC algorithm. In coherent signal subspace methods, focusing matrices are used to align narrowband components within the receiver bandwidth prior to forming covariance matrix estimates at each frequency. The estimated narrowband covariance matrices are then averaged to obtain focused covariance matrix wherein each source has a rank one representation. The resulting focused matrix can be estimated with an accuracy which reflects the full time-bandwidth product of the sources. Although coherent signal-subspace methods offer a significant improvement in detection and resolution thresholds over incoherent methods, in "multi-group" scenarios where the sources are clustered around several widely separated directions, formation of the necessary focusing matrices has thus far required preliminary estimates of the source directions. In the multi-group case, preliminary source location estimates have been used to spatially whiten the field, thereby reducing it to the single group situation, or more recently, to form rotational subspace focusing matrices.

In this project we developed an approach to the focusing problem similar to the spatial resampling technique, but more general in that it can be applied to arbitrary array geometries. Furthermore, this technique has some computational advantages since it allows the use of the root-MUSIC algorithm. The technique is based on the idea of array interpolation and is described in [15, 60, 64]. We have also performed a detailed performance analysis of this method [15]. See also [52, 97] for some related work.

4 List of Publications

The following is the list of publications written during this project.

Journal Publications

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- [2] B. Friedlander and B. Porat, "Blind Equalization of Digital Communications Channels Using High Order Moments," *IEEE Trans. Acoustics, Speech and Signal processing*, vol. 39, no. 2, pp. 522–526, February, 1991.
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5 List of Project Participants

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6 Report of Inventions

None.