

**New Techniques of DOA Estimation and Optimum
Beamforming for Wideband Sources Using Sensor Array
Data**

by
Monika

Submitted

In fulfilment of the requirements of the degree of
Doctor of Philosophy
to the

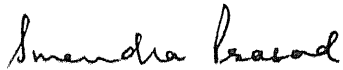


Department of Electrical Engineering
Indian Institute of Technology Delhi
June, 1999

Dedicated
to
my Late, Beloved Grand-Ma,
my inspiration

CERTIFICATE

This is to certify that the thesis entitled "**New Techniques of DOA Estimation and Optimum Beamforming for Wideband Sources Using Sensor Array Data,**" being submitted by Monika, to the Department of Electrical Engineering, Indian Institute of Technology, New Delhi, for the award of degree of Doctor of Philosophy, is a bonafide research work carried out by her under our supervision and guidance. The results contained in this thesis have not been submitted to any other University or Institute for the award of any other degree or diploma.



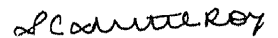
Surendra Prasad

Professor

Department of Electrical Engineering,

Indian Institute of Technology,

New Delhi 110016.



S.C.Dutta Roy

Professor

Department of Electrical Engineering,

Indian Institute of Technology,

New Delhi 110016.

Acknowledgements

Words are often a weak mode of revealing one's feelings. As the intensity of sentiments deepens, one fumbles for words and fails to express feelings truly and sincerely. In fact, I find myself running out of words...

To achieve anything one needs a Perfect Master, who can inspire, motivate and help. I was fortunate enough to have the privilege to work under the worthy tutelage of **Prof. Surendra Prasad** and **Prof. S.C.Dutta Roy**, my Hon'ble guides, who have always been a source of inspiration, encouragement and enlightenment to me in my work. Their incisive comments, insightful suggestions and valuable discussions showed me the correct path to complete my thesis in the best possible form. Despite their heavy administrative duties and various responsibilities they were always kind enough to spare sufficient time for me and for my work. In fact, it was a great experience for me to be associated with them.

I, also express my reverential regards to Prof. J.B.Srivastava, Dr. S.D.Joshi, Dr.B.S.Rajan, Dr. Arun Kumar, Dr. Jayadeva and Dr. S.Prakriya for the encouragement and help they have rendered in my work as and when it was needed.

I am deeply indebted to Mr. S.K.Gandhi, Mr. Ravinder Pathak, Mr. Sunil Khanna and Mr. G.S.Negi, who made it easy for me to work in the laboratory despite various constraints. In fact, they accommodated me so well that the laboratory became a second "Home" to me. I owe sincere thanks to Shri Fateh Singh, Mrs. Sushma Sachdeva and staff of Electrical Engineering Department for their assistance at various times.

One can not forget one's friends who always stood by in all the difficult times. I express my deep appreciation to my dear friends for their sincere help and pleasant company without which it would have been difficult for me to stay here and work.

My parents, brothers, sisters and other members of the family, inspite of missing me, have always supported me. I express my humble and sincere gratitude to them for their love and encouragement.

Monika
Monika

Abstract

We present, in this thesis, several novel ways of looking at the problems of wideband DOA estimation and beamforming via uniform linear arrays (ULA's). The choice of the ULA structure for our studies has been governed by its elegant mathematical characterization. The issues of interest in this thesis are those concerning maximum likelihood DOA estimation for wideband sources in spatially white Gaussian noise, optimum beamforming for wideband sources, DOA estimation in the presence of spatially correlated noise, design of robust beamformers and, finally, "spatial only" DOA estimation algorithms for wideband sources.

First, we obtain a 2-D linear predictor polynomial characterization of the spatial-temporal data at the output of a uniform linear array, assuming a harmonic model for broadband sources. This polynomial, it is shown, has the required DOA information embedded in its frequency dependent roots. It is further shown that methods like IQML and several of its later modifications can be suitably adapted for estimating the coefficients of this polynomial. Rooting of this polynomial at various harmonically related frequencies yields a set of frequency dependent DOA's, which can be combined in a least-squares framework to yield pseudo-ML estimates of the DOA's. It is shown that the performance of the proposed method is close to the Cramer-Rao bound in most situations of interest. Although based on a harmonic model for the source spectrum, the approach is seen to be robust; it does not break down when this assumption is violated, but degrades gracefully in performance with deviations from the harmonicity assumption.

We next examine the optimum beamforming problem for the broadband sources. It is shown that the polynomial model for the ULA space-time data also provides an appropriate framework for formulating three different types of optimum beamformers for the broadband sources, viz., the optimum combiner beamformer, the optimum notch or null steering beamformer, and the optimum interference-plus-noise rejector beamformer, all based on IQML (or modified IQML) estimation of the generating polynomial. These beamformers differ from the conventional broadband beamformers in that they are able to handle correlated sources and interferences (arising from multipath or smart jammers) with great ease, without the need for pre-processing techniques like spatial smoothing.

The next problem that we consider is that of estimation of the DOA's in the presence of spatially correlated noise of unknown covariance matrix. Unlike previous work, our aim here is to formulate a solution without any structural assumptions or parameterization of the

signal and noise covariances. Once again the tool employed is the polynomial characterization of the "spatial" or "spatial-temporal" data of a uniform linear array. It is now shown that this characterization provides a very convenient framework for obtaining a modified ML (MML) estimate of the unknown noise covariance matrix via a suitable projection of the observed covariance matrix onto a space which is the orthogonal complement of the so-called signal subspace. This, in turn, leads to the formulation of a cost function which is derived from the likelihood function, and which can be maximized by suitable search algorithms. A simple approximation of this function is also proposed which enables solution of the problem by using simple algorithms like IQML or its variants. The MML approach is shown, through simulation studies, to outperform the MAP approach proposed earlier in the literature, and is found to be robust against correlated signals and/or interferences.

In the rest of the work, we look at the broadband beamforming and DOA estimation problems once again, but from a different perspective. The motivation here is to investigate the effectiveness of using "spatial only" type processing to handle broadband sources and interferences.

Motivated by the recently proposed robust Hung-turner beamformer, we first propose an alternative "robust" beamformer using only a narrowband configuration, which can cause rejection of wideband and moving jammers more effectively. Basically, the ability of "flat" or "broad" nulls to provide robustness to wideband and moving jammers has been fully exploited here. This flatness is achieved by incorporating derivative constraints in the jammers and interference directions. However, since the jammer directions are not known a-priori, it is shown that a maximum likelihood characterization of the jammer subspace is an appropriate framework for formulating these derivative constraints. Furthermore, for the case of linear arrays, the elegant generating polynomial model for the array data enables estimations of the jammer subspace via the IQML class of algorithms. This, in turn, leads us to the formulation of a so-called "robust IQML beamformer" which greatly improves upon the performance of the "robust Hung-Turner" algorithm. In fact, simulation results show that the robust IQML beamformer yields nearly optimal performance for a wide range of wideband and moving jammer scenarios, with the help of just a few derivative constraints.

Finally, we consider the possibility of high resolution DOA estimation of broadband sources using "spatial only" processing. The motivation for looking for such algorithms is provided by some recent results in the literature which suggest, through the computation of

appropriate Cramer-Rao bounds, that in many applications of practical interest, there is little to gain by using detailed prior knowledge of the source power spectrum which, in any case, is rarely available. Use of space-time processing in such cases, to enable the processor to model the complete spatio-temporal source spectrum, is therefore not warranted. Consequently, we propose some algorithms for such "spatial only" processing, which neither use a tapped delay line at the sensor outputs, nor use separate processing at each frequency. Since DOA estimation is our primary concern here, we employ a "gross" model for the source temporal power spectrum, assuming it to have a "flat" shape over the bandwidth of interest. This, in turn, leads us to the formulation of two "search" or "cost" functions for the DOA's of the sources - one requiring a multidimensional search over the parameter space of unknown DOA's, and the other, a simple one dimensional MUSIC like search. While both the cost functions generally lead to good performance, the multi-dimensional cost function is seen to be specially useful for adverse conditions like closely spaced sources, or DOA estimation in the presence of correlated sources. Finally, it is demonstrated that the method proposed here is not unduly sensitive to the assumption of a flat power spectrum. Its performance is seen to be affected only marginally by the deviation of the actual power spectrum from a "flat" one.

Table of Contents

Acknowledgements	i
Abstract	iii
List of Figures	xi
List of Tables	xvii
List of Abbreviations	xix
List of Symbols	xxi
Chapter 1 Introduction	
1.1 Introduction	3
1.2 DOA Estimation Techniques	5
1.2.1 Narrowband DOA Estimation	5
1.2.2 Broadband DOA Estimation	11
1.3 Broadband Beamforming	20
1.4 Scope of the Present Work	27
1.5 Organization of the Thesis	27
Chapter 2 DOA Estimation of Wideband Sources using a Harmonic Source Model and a Uniform Linear Array.	
2.1 Introduction	33
2.2 Modelling and Problem Formulation	34
2.3 Maximum Likelihood Criterion	37
2.4 ML Criterion and the Model Parameters	39
2.5 A Wideband ML Estimation Algorithm	43
2.6 Simulation Results	47
2.7 Conclusion	57
Appendix 2A	58

Appendix	2B	60
Appendix	2C	61

Chapter 3 Optimum Broadband Beamforming for Coherent Broadband Signals and Interferences.

3.1	Introduction	65
3.2	The Broad Band Array Signal Model	66
3.3	Beamforming Problem in Correlated Interference	70
3.4	Subspace Characterization for Braodband Optimum Beamforming	74
3.5	Optimum Beamforming	77
3.6	Simulation Results	80
3.7	Conclusion	88
Appendix	3A	89
Appendix	3B	92
Appendix	3C	94

Chapter 4 A Modified Likelihood Function Approach to DOA Estimation in the Presence of Unknown Spatially Correlated Gaussian Noise using a Uniform Linear Array.

4.1	Introduction	99
4.2	Mathematical Model	101
4.3	Modified Likelihood Function for Estimation of DOA's in Spatially Correlated Noise	102
4.4	Approximation ML Estimator	106
4.5	Futher Simplification for the case of Uniform Linear Arrays	108
4.6	Broadband Array Processing in Spatially Correlated Noise	110
4.6	Simulation Results	111
4.8	Conclusion	116

Chapter 5	Robust Adaptive Beamforming for Wideband, Moving and Coherent Jammers via Uniform Linear Arrays.	
5.1	Introduction	121
5.2	Problem Formulation	123
5.3	Characterization of the Jammer Subspace and Solution to the Beamforming Problem	126
5.4	Implementation Issues and Remarks	128
5.5	Simulation Results	131
5.6	Conclusion	146
Chapter 6	Broadband DOA Estimation Using "Spatial-Only" Modelling of Array-Data.	
6.1	Introduction	151
6.2	Problem Formulation	152
6.3	Subspace Based Formulations for DOA Estimation	154
6.4	Analysis of the Multi-dimensional Search Function	159
6.5	Simulation Results	162
6.6	Conclusion	170
Chapter 7	Conclusion	
7.1	Introduction	175
7.2	Summary of Results	175
7.3	Remarks and Direction of Further Work	178
References		181
Publications Based on Results of the Thesis		189
Bio-Data		191