Estimation of Direction of Arrival for Coherent Signals in Wireless Communication Systems

K. V. Nikolakopoulos, D. Anagnostou[1], C. G. Christodoulou[1] and M. T. Chryssomallis*,

Dept. of Electrical and Computer Engineering, Democritus University of Thrace, Microwaves Laboratory, Gr-67100 Xanthi, GREECE;
[1] Dept. of Electrical & Computer Engineering, The University of New Mexico Albuquerque, NM 87131-1356, USA.

Abstract: A spatial smoothing preprocessing scheme for solving problems encountered in direction-of-arrival estimation of fully correlated signals is analyzed. Simulation results are presented, that illustrate this scheme in comparison with the classical MUSIC technique. Finally, an improved spatial smoothing algorithm, which has the ability to detect more coherent signals, is introduced and its behaviour in comparison to the previous techniques is examined by simulating specific cases.

I. INTRODUCTION

There are various methods available for estimation of Angle-of-Arrival of a radio signal using an antenna array. The MUSIC algorithm, works on the premise that the signals impinging on the array are not fully correlated. Only under uncorrelated conditions the source covariance matrix S satisfies the full rank condition, which is the basis of the MUSIC eigen-decomposition. The performance of MUSIC degrades severely in a highly correlated signal environment as encountered in multipath propagation. Some techniques have been proposed to make MUSIC work in the presence of coherent signals, which usually involve modification of the covariance matrix through a preprocessing scheme called spatial smoothing [1]. One method of spatial smoothing is based on averaging the covariance matrix of identical overlapping arrays and requires an array of identical elements built with some form of periodic structure, such as the uniform linear array. In this work a complete analysis of the spatial smoothing preprocessing scheme is presented and an improved spatial smoothing scheme, called the forward/backward smoothing scheme is introduced.

II. PROBLEM STATEMENT AND SPATIAL SMOOTHING TECHNIQUES

For q plane waves, impinging with directions $\{\theta_1,...,\theta_q\}$ on a uniform linear array composed of p identical sensors ($q < p$), the received signal can be expressed in matrix form as [2]:

$$\boldsymbol{r}(t) = \boldsymbol{A}\mathrm{s}(t) + \boldsymbol{n}(t) \tag{1}$$

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$s(t)$ and $n(t)$ are the signal and the noise matrices, and A is the $p \times q$ matrix

$$A = [\alpha(\theta_1), ..., \alpha(\theta_q)] \qquad (2)$$

and $\alpha(\theta_i)$ is the "steering vector" of the array in the direction θ_i:

It follows that

$$E[r(t)r(t)^H] = R = ASA^H + \sigma^2 I, \qquad S = E[s(t)s(t)^H] \qquad (3)$$

where ^{H} denotes the conjugate transpose. **S** is diagonal when the signals are uncorrelated, but nondiagonal and singular when some signals are fully correlated. In general, if k out of the q wavefronts are correlated, the application of the conventional MUSIC algorithm will detect $q-k+1$ signals, but only $q-k$ directions-of-arrival, corresponding to the incoherent wavefronts, will be resolved. The singularity of covariance matrix does not allow the successful application of the eigenstructure technique. This can be overcome by using the preprocessing scheme introduced by Evans *et al.* [3]: the uniform linear array with p identical sensors is divided into overlapping subarrays of size m, with sensors $\{1, ..., m\}$ forming the first subarray, sensors $\{2, ..., m+1\}$ forming the second subarray, etc. A covariance matrix of every forward subarray can be defined and the forward averaged spatially smoothed covariance matrix $\overline{\mathbf{R}}^f$ is taken as the sample mean of the subarray covariance matrices. The price paid for detection of coherent signals using forward averaging spatial smoothing is the reduction in the array aperture. A p element array can detect only $p/2$ coherent signals using MUSIC with forward averaging spatial smoothing as opposed to p-1 noncoherent signals that can be detected by conventional MUSIC.

It is possible to detect up to $2p/3$ coherent signals by making use of a set of forward and conjugate backward subarrays simultaneously. In this scheme, in addition to splitting the array into overlapping forward subarrays, the array is also split into overlapping backward arrays. The backward averaged spatially smoothed covariance matrix $\overline{\mathbf{R}}^b$ is defined as the sample mean of the subarray covariance matrices. Finally the forward/conjugate backward smoothed covariance matrix $\hat{R}$ is defined as the mean of $\overline{\mathbf{R}}^f$ and $\overline{\mathbf{R}}^b$.

III. SIMULATION RESULTS

As a first case three planar waves, two coherent and one independent of the others, are considered. Applying the conventional MUSIC and the Spatial Smoothing technique [4], we obtained the results shown in Fig 1. It is clear that conventional MUSIC cannot identify the coherent signal at 30°, while with Spatial Smoothing the three peaks corresponding to the directions-of-arrival of all the three signals are clearly seen.

In Fig. 2 the case of four coherent signals is shown. Applying the conventional MUSIC algorithm only one peak is resolved. However, applying the spatial smoothing preprocessing scheme with four subarrays of five sensors each, and then applying the eigenstructure method of Schmidt [4] to the spatially smoothed covariance matrix, the four peaks corresponding to the directions-of-arrival of all the three signals are clearly seen.

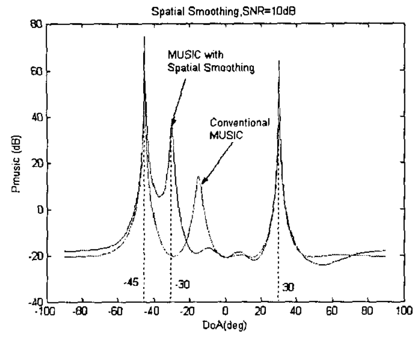

Fig. 1 Comparison of Conventional MUSIC with Spatial Smoothing technique for the case of two coherent waves and one incoherent wave received by an 8-element uniform linear array at angles 30, -30, and -45 degrees, respectively.

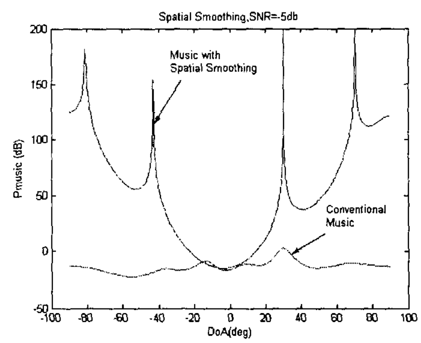

Fig. 3 Comparison of Conventional MUSIC with Spatial Smoothing technique in coherent multipath environment. Four coherent signals arrive at an 8-element linear uniform array at angles 30, -43, 70 and -81 degrees, respectively.

Last example considers five coherent planar waves (Fig. 4.). The application of the forward method does not resolve all coherent signals. However, using the using the Forward/Backward method with five forward and five backward subarrays of five sensors each, and then applying the eigenstucture technique to the spatially smoothed covariance matrix yielded the results shown in second curve of the same figure. All five directions of arrival can be clearly identified and the improvement on performance is also visible in this case.

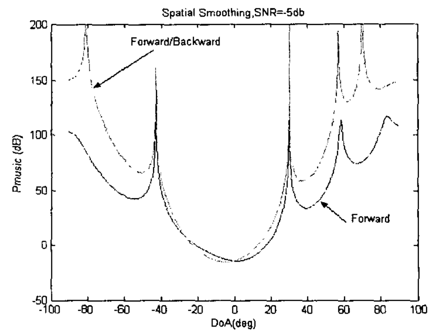

Fig. 4 Comparison of Forward Spatial Smoothing technique with Forward/Backward method. Five coherent signals arrive at a 9-element uniformly spaced array at angles -81, -43, 30, 57°and 70 degrees, respectively.

Studying more cases it is proven that the Forward/Backward spatial smoothing technique works better also for the cases that the signals impinge on the array with very small separation angle. For the uniform linear array of eight elements, which has a 3 dB mainlobe beamwidth equal to 12.6 degrees, signals with separation angle up to two degrees can be clearly detected.

IV. CONCLUSIONS

This work re-examines the problem of locating the directions of arrival of coherent signals. Initially, conventional MUSIC with forward averaging spatial smoothing technique is examined, which presents reduced resolution. An improved spatial smoothing scheme, called forward/backward smoothing technique, which uses simultaneously a set of forward and complex conjugated backward subarrays is introduced. With this technique up to $2p/3$ coherent signals can be detected, using a uniform linear array of p elements.

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