HIGH-RESOLUTION DIRECTION FINDING USING A SWITCHED PARASITIC ANTENNA

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ABSTRACT

Direction finding by exploiting the directional radiation patterns of an Switched Parasitic Antenna (SPA) is considered. By employing passive elements (parasites), which can be shorted to ground using pin diodes, directional radiation patterns can be obtained. The direction finding performance of the SPA is examined by calculating a lower bound on the direction finding accuracy, the Cramér-Rao lower Bound (CRB). It is found that the SPA offers a compact implementation with high-resolution direction finding performance using only a single radio receiver. Thus, exploiting SPAs for direction finding is an interesting alternative to traditional antenna arrays offering compact and low-cost antenna implementations.

1. INTRODUCTION

Direction finding is of great importance in a variety of applications, such as radar, sonar, communications, and recently also personal locating services. In the last two decades, direction finding and sensor array processing has attracted considerable interest in the signal processing community. The focus of this work has been on high resolution, i.e. a resolution higher than the width of the main lobe, Direction Of Arrival (DOA) estimation algorithms [3]. These algorithms exploit the fact that an electromagnetic wave that is received by an array of antenna elements reaches each element at different time instants. Although the performance of these systems is excellent, an unfortunate aspect is the high costs of employing a radio receiver for each antenna element. Furthermore, it is expensive to calibrate and maintain antenna arrays with many antenna elements.

Recently, it was proposed to employ an SPA for direction finding [6, 9] that only uses a single active radio receiver, thereby significantly reducing the cost. The SPA offers characteristics similar to an array antenna with several beams by using passive antenna elements that serve as reflectors when shorted to ground. Different directional patterns can be achieved by switching the short-circuits of the passive elements using pin diodes. The possibilities of exploiting these patterns for high-resolution DOA estimation will be examined in this paper, since no attempt to employ high-resolution DOA methods was undertaken in [6, 9].

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2. SWITCHED PARASITIC ANTENNA

Switched Parasitic Antennas offering directional patterns goes back to the early work of Yagi and Uda in the 1930's [1]. The concept is to use a single active antenna element, connected to a radio transceiver, in a structure with one or several passive antenna elements, operating near resonance. These passive elements are called Parasitic Element (PE)s and act together with the active element to form an array, as in the well known Yagi-Uda array [1]. To alter the radiation pattern, the termination impedances of the PEs are switchable, to change the current flowing in those elements. The PEs become reflectors when shorted to the ground plane using pin diodes [7] and when not shorted, the PEs have little effect on the antenna characteristics. The receiver is always connected to the center antenna element so there are no switches in the RF direct signal path.

An interesting possibility to obtain directional information is to sample the received signal with several different radiation patterns, since the switching time of a pin diode is only of the order of a few nanoseconds. This technique of oversampling the received signal is common in many communication systems, but here the oversampling is performed in both time and space, i.e. spatio-temporal oversampling. If the increased sampling rate (or bandwidth) poses a problem, a bandpass sampling strategy could also be employed. In this paper, the potential in using the different ra-

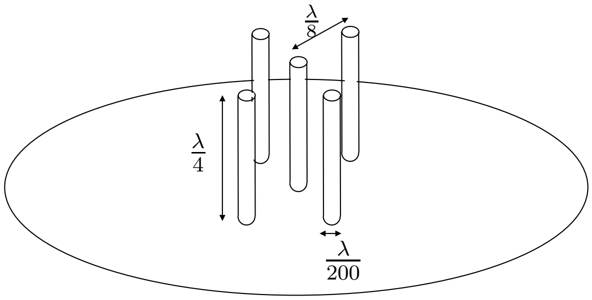

Figure 1: A five element monopole SPA. The center element is active and connected to the transceiver. The four passive antenna elements can be switched in or out of resonance using appropriately biased pin diodes.

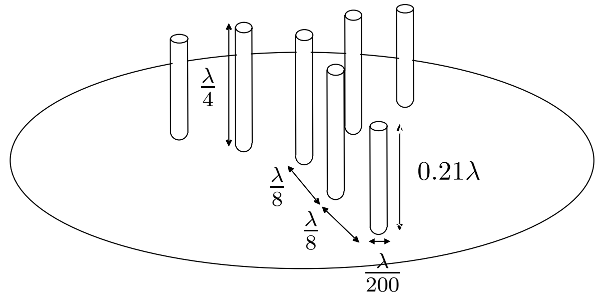

Figure 2: A seven element monopole SPA. The center element is active and connected to the transceiver. The three passive antenna elements closest to the active can be switched in or out of resonance using appropriately biased pin diodes. The three outermost monopoles are hardwired to ground.

diation patterns of an SPA for direction finding will be examined. However, further work is needed on the practical aspects of the antenna design as well as sampling strategies.

In the literature, it has been proposed to use monopoles on a ground plane [7] or patch antennas [5] as SPAs. In this paper, a monopole on a ground plane is used because of its omnidirectional properties. A four direction symmetry (4-DS) monopole parasitic antenna is shown in Figure 1 and a three direction symmetric (3-DS) antenna is shown in Figure 2. The antenna in Figure 2 has an additional circle of parasitic elements that always are shorted to ground. The effect of this arrangement is an increased directivity as their length are shorter than the corresponding resonant length ($\approx \lambda/4$) and will lead the induced Electro-Motive Force (EMF) [1]. The lengths and distances displayed in Figure 1 and 2 are not optimal in any way. Note that the resulting antennas are very compact ($\lambda/4$ & $\lambda/2$) compared to corresponding linear arrays with $\lambda/2$ separation distance (2λ & $3\lambda/2$).

The antennas in Figures 1 and 2 were simulated using HFSS (High Frequency Structure Simulator) from Agilent Technologies Inc. which is a 3D simulator using the Finite Element Method (FEM) to solve for the electromagnetic field. The software was used to calculate the far-field radiation pattern of the antenna for different settings of the switched parasitics. The monopole elements were cylindrical with an length to radius ratio $l/r = 100$ which have a first resonance at approximately 0.24λ [1].

The far-field power radiation pattern in the azimuth plane $F(\phi)$ for the 4-DS SPA is shown in Figure 3. The corresponding pattern for the 3-DS SPA is similar and not shown. The directivity of the two antennas are 9.9 dB and 10.0 dB respectively, thereby only a small gain in directivity was achieved by the extra ring of shorted parasites.

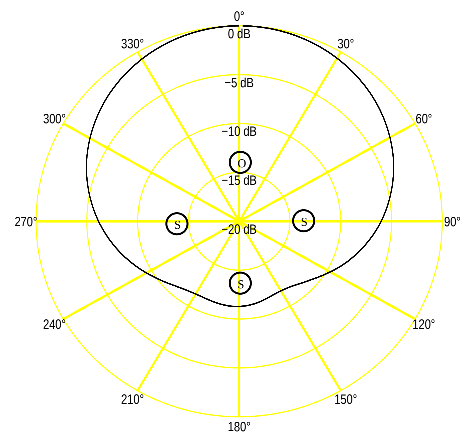

Figure 3: Power radiation pattern of the five element monopole antenna shown in Figure 1 with three parasitics shorted (S) to ground and one open (O).

Once the far-field radiation properties are found, it is straightforward to derive a model for the received voltages [2]. If p waves are incident upon an antenna with M symmetry directions, the received voltages can be written in matrix form as

$$\mathbf{x}(t) = \mathbf{A}(\boldsymbol{\phi})\mathbf{s}(t) + \mathbf{e}(t), \tag{1}$$

where the vector of measured voltages $\mathbf{x}(t)$ is $M \times 1$. The matrix $\mathbf{A}(\boldsymbol{\phi})$ ($M \times p$) corresponds to the response of the different symmetry directions and has elements $[\mathbf{A}(\boldsymbol{\phi})]_{qr} = F(\phi_r + 2q\pi/M)$. This matrix is typically called steering matrix in the sensor array processing literature. The signal vector $\mathbf{s}(t)$ is $p \times 1$ and contains the strength of the received fields. Finally, the noise vector $\mathbf{e}(t)$ is $M \times 1$.

In order for the analysis in the following sections to be valid, some additional assumptions are needed:

- the steering matrix has full rank, i.e., $\mathrm{rk}(\mathbf{A}) = p$
- $\mathbf{e}(t)$ is temporally white and circularly Gaussian

distributed: $\mathbf{e}(t) \in \mathcal{N}(0, \sigma^2\mathbf{I})$

- $\mathbf{s}(t)$ is also temporally white and circularly Gaussian distributed: $\mathbf{s}(t) \in \mathcal{N}(0, \mathbf{S})$

The noise is both spatially and temporally white, while the signal is only assumed to be temporally white. Furthermore, the signal is assumed to be uncorrelated with the noise.

3. DIRECTION FINDING PERFORMANCE

The data model (1) is identical to the usual data model used in sensor array processing [3], except for a new steering matrix. This will of course change the direction finding properties. Before the properties of a specific DOA estimation scheme is studied, a lower bound, the Cramér-Rao lower Bound (CRB), on the variance of the DOA estimates will be analyzed. Note that it is possible to asymptotically achieve this bound with many methods in the literature [3].

Expressions for the CRB was derived for an array of antenna elements in [4]; and can also be applied to the parasitic antenna by changing the steering matrix.

$$E\{(\hat{\boldsymbol{\phi}} - \boldsymbol{\phi}_0)(\hat{\boldsymbol{\phi}} - \boldsymbol{\phi}_0)^T\} \geq \mathbf{B} \tag{2}$$

$$\mathbf{B} = \frac{\sigma^2}{2N}\left[Re\{(\mathbf{D}^H\mathbf{P}_A^{\perp}\mathbf{D}) \odot (\mathbf{S}\mathbf{A}^H\mathbf{R}^{-1}\mathbf{A}\mathbf{S})^T\}\right]^{-1} \quad ,$$

where the elements of $\mathbf{D}_{qr} = \left.\frac{\partial F(\phi+2q\pi/M)}{\partial\phi}\right|_{\phi=\phi_r}$. Furthermore, $\odot$ denotes the Hadamard (or Schur) product, i.e., element-wise multiplication and $\mathbf{P}_A^{\perp} = \mathbf{I} - \mathbf{P}_A = \mathbf{I} - \mathbf{A}\mathbf{A}^{\dagger}$ [1] is the orthogonal projector onto the null space of $(\mathbf{A})^H$. The matrix $\mathbf{R} = \mathbf{A}\mathbf{S}\mathbf{A}^H + \sigma^2\mathbf{I}$ is the covariance matrix of the measured voltages $\mathbf{x}(t)$ and N denotes the number of time samples.

The square root of the CRB, i.e. the standard deviation, is shown in Figure 4 for the antenna configurations in Figure 1 and 2 as two waves are incident from $(30°, 30°+\Delta)$. Only the CRB for the first DOA, i.e. the wave arriving from 30°, is shown since the CRB for the second DOA will behave similarly. The standard deviation for a uniform linear array of three elements spaced $\lambda/2$ apart is compared to the 4-DS and 3-DS SPAs. As expected, the performance is better when using four rather than the three symmetry directions. Also, note that the three element array performance slightly better the 4-DS SPA. However, these results depend on the incidence angles, since the array will work best for broadside and worst for end-fire incidence.

In Figure 5, the standard deviation is shown for the same antenna configurations as in Figure 4 when two waves are incident from $(\phi_0, \phi_0 + 5°)$. The parasitic antenna, due to its symmetrical properties, offers similar direction finding performance properties for all incidence angles. The linear array performs worse than the parasitic antenna at end-fire incidence, while performing much better at broad-side incidence. However, for many direction finding applications, the direction finding performance of the parasitic antenna is sufficient and the cost reduction of using only a single radio receiver outweighs the loss in performance for broad-side angles. It should also be stressed that the antenna designs in Figure 1 and 2 are by no means optimal and better DOA properties may be obtained by a proper optimization.

[1] $\mathbf{M}^{\dagger}$ is the Moore-Penrose pseudo inverse of $\mathbf{M}$.

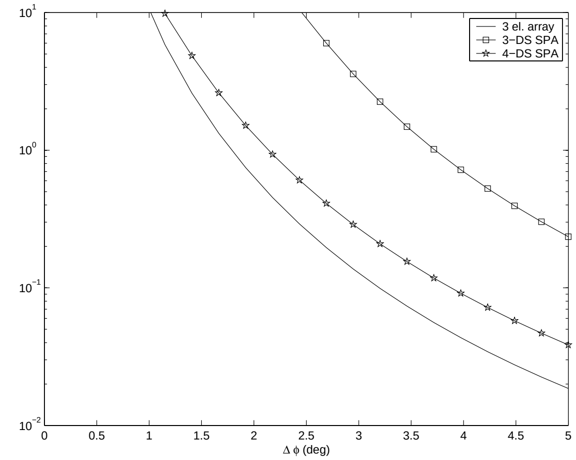

Figure 4: The square root of the CRB for the configurations in Figure 1 and 2 when two waves are incident from $(30°, 30°+\Delta)$ with SNR=10dB and 1000 samples.

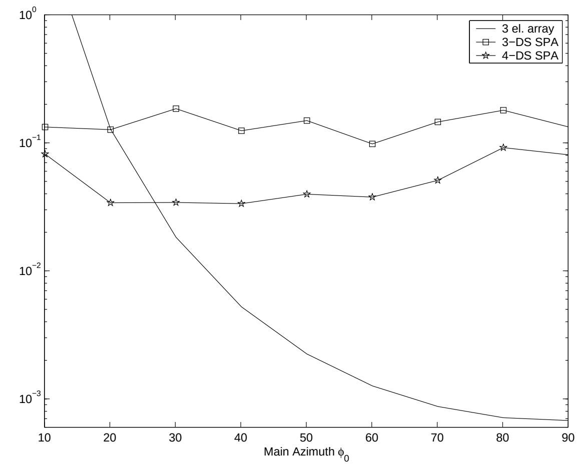

Figure 5: The square root of the CRB for the configurations in Figure 1 and 2 when two waves are incident from $(\phi_0, \phi_0 + 5°)$ with SNR=10dB and 1000 samples.

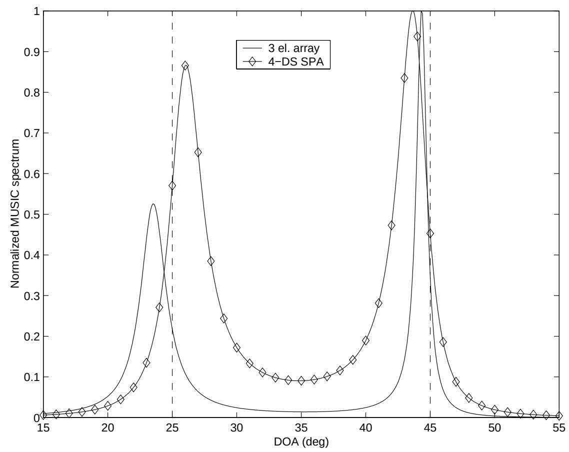

Figure 6: The normalized MUSIC spectrum when two waves are incident from 25° and 45° upon a 4-DS parasitic antenna and a three element array with SNR=10dB and 1000 samples.

4. ESTIMATION METHODS

The analysis in the previous section was based on the CRB on the estimation error. In this section, algorithms that approximately achieve this lower bound will be discussed. In principle, all DOA estimation schemes derived for a general antenna array can also be applied to a parasitic antenna by inserting a new steering matrix. For an overview of DOA estimation methods, see [3].

In [8], a popular high resolution DOA estimation method, MUltiple SIgnal Classification (MUSIC), was introduced where the DOA estimates are taken as those ϕ that maximizes the MUSIC criterion function

$$\hat{\boldsymbol{\phi}} = \arg\max_{\boldsymbol{\phi}} \frac{\mathbf{a}^H(\phi)\mathbf{a}(\phi)}{\mathbf{a}^H(\phi)\hat{\mathbf{E}}_n\hat{\mathbf{E}}_n^H\mathbf{a}(\phi)}, \tag{3}$$

where the steering vector $\mathbf{a}_q(\phi) = F(\phi + 2q\pi/M)$. Usually this is formulated as finding the p largest peaks in the "MUSIC spectrum". Here, $\hat{\mathbf{E}}_n$ denotes the $M-p$ eigenvectors corresponding to the $M-p$ smallest eigenvalues of the estimated covariance matrix $\hat{\mathbf{R}}$. A typical example of a MUSIC spectrum is shown in Figure 6, where two waves are incident from 25° and 45° upon a 4-DS SPA and a three element array with SNR=10dB and 1000 samples. This figure indicates that the SPA, in this case, offers a high-resolution direction finding performance similar to that of an antenna array without the cost of many radio receivers. Most other DOA estimation schemes [3] can also be applied to SPAs with similar results. For instance, the Stochastic Maximum Likelihood (SML) algorithm [4] for this type of antenna was implemented. The RMSE of the ML estimator achieved the CRB bound from Section 3, as expected.

5. CONCLUSIONS

The potential use of an Switched Parasitic Antenna for high-resolution direction finding was investigated. By employing passive elements, which can be shorted to ground using pin diodes, directional radiation patterns are obtained that can be used successfully to estimate DOAs. The main advantage with this concept is that only one radio receiver is needed, thereby reducing the costs significantly compared to traditional antenna arrays where one radio receiver per element typically is employed. Another advantage of the SPA is that a very compact implementation of the antenna is possible.

A data model for the SPA was presented and the direction finding performance was examined by calculating the CRB and the MUSIC estimator. It was found that the SPA offers a compact implementation with high-resolution direction finding performance using only a single radio receiver. Thus, exploiting SPAs for direction finding is an interesting alternative that offers several advantages over traditional arrays.

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