Distributed 6D Vector Antennas Design for Direction of Arrival Applications

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Abstract— **We present a six-dimensional distributed vector sensor for Direction of Arrival estimation applications. A vector sensor should measure all 6 components of the electromagnetic field at the same location. Such sensor is motivated by recent analytical results, showing an improved estimation of the direction of arrival of the signal from a single source. Since the design of a collocated six-dimensional vector sensor is presently a major challenge, we consider a distributed approach for its design. Numerical simulations show that the performance of a distributed vector sensors in a multipath environment is greater than that of classical approaches with scalar arrays.**

I. Introduction

In the latest decades, the problem of finding the Direction of Arrival (DoA) of an electromagnetic signal in a multipath environment has been thoroughly investigated. With the aim to develop adaptive waveforms radar systems able to reduce the cell resolution and improve the sensitivity, the issue of finding the DoA of a signal has become especially important for radar applications. The first significant step was to develop new signal processing techniques such as ESPRIT [1] or MUSIC [2] in order to find DoA in the presence of a multipath environment. At the present time, the only practical way to estimate the DoA of an incoming electromagnetic signal is through array antennas: by measuring the phase shift among the elements it is possible to estimate the DoA of an incoming EM signal. Unfortunately, array resolution and accuracy are limited by the effective size of the array aperture. In general, a larger array aperture yields more accurate DOA estimates [3]. The array aperture may be enlarged by adding more antenna elements in the case of uniform half-wavelength spacing, by spacing the elements nonuniformly over a larger aperture, or by increasing the separation between elements in the case of uniform spacing [4]. However, adding more antennas has the obvious drawback of increasing hardware costs. Furthermore, nonuniform interelement spacing cannot be practically used because it would generally violate ESPRIT's requirement of two identical but translated subarrays [4]. Moreover, the spatial version of the Nyquist Sampling Theorem also poses an upper limit on the distance between elements in the case of uniform spacing without causing aliasing. Two identical sensors spaced over a half-wavelength apart will lead to ambiguity in DoA estimations [4]. With no a priori information, this ambiguity cannot be resolved using unpolarized scalar sensors. For those reasons, scalar arrays may not be an optimum choice for DoA application. Moreover, in the presence of multipath, they become further unreliable and inefficient. The main reason why scalar arrays are not suitable in multipath scenarios is due to the fact that the presence of a scattering environment violates the classical intuitive notion of there being only two polarization degrees of freedom for electromagnetic radiation [5]. This situation arises because in free space, radiated electric and magnetic fields are constrained to being perpendicular to one another and to the direction of propagation. Thus, once the direction of propagation is fixed, only two degrees of freedom remain. If there would not be any scatterer, a simple scalar array matched with the polarization of the incoming wave may be considered a good receiver and hence it could be used for DoA Estimation. However, in the presence of reflecting surfaces, multiple paths are possible between the two points. Although the wave propagating along the direct path cannot have an $\overrightarrow{E}$ component parallel to that path, the wave propagating along the reflected path can contribute such a component to the field at the receiver. More generally, the electromagnetic polarization is no longer constrained to being perpendicular to the line-of-sight. This concept can be simply extended to the case of the presence of a large number of scatterers. In this situation, it is evident that we may expect a decrease in the correlation between corresponding $\overrightarrow{E}$ and $\overrightarrow{H}$ field components.

II. Vector antennas

A way to overcome the aforementioned drawbacks is to employ co-located six-component (usually referred as "six-dimension") electromagnetic Vector Antennas [6]. A theoretical co-located six-component vector antenna consists of three identical and co-located, but orthogonally oriented, electrically short dipoles (called a "dipole triad" or "tripole") plus three identical co-located, but orthogonally oriented, magnetically small loops (called a "loop triad"). All six-component antennas are spatially collocated in a point-like geometry. Their advantages include:

- Vector antennas increase the number of degrees of freedom in wireless electromagnetic communications (up to 6 different channels). This feature, albeit not required for DoA application, may be very useful for communication purposes, e.g. in substitution or integration for MIMO (Multiple Input Multiple Output) technologies.
- Vector antennas show better performances in fading situations. As the environment fluctuates, or as the receiver

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moves through space, the measured electric and magnetic fields also fluctuate. For an antenna sensitive to just a single field component, the amplitude can occasionally come close to zero (fading). However, it is quite unlikely that all six vector components will vanish simultaneously.

- The six different components present high levels of correlation (due to the intrinsic co-location of the elements). This property can be exploited for signal recovery, yielding better estimations, upon suitable choices of signal processing algorithms.
- Ambiguity cannot be resolved using unpolarized scalar sensors. Conversely, as shown in Fig. 1, Vector Antennas do not show ambiguity for direction of arrival estimation [7].

Among these evident advantages, it is important to mention the fact that the Signal Processing community has welcomed the fact that the use of Vector Antennas for DoA estimation leads to an increase of the accuracy and the performance. In particular, Nehorai and Paldi [6] have thoroughly discussed DoA estimation using theoretical Vector Antennas. What unfortunately is still not available is an actual, working and tested realization of a 6D Vector Antenna. Contrary to what one may think, the actual realization of a full 6D Vector Antenna has not been completely accomplished. The main reasons are:

- Practical impossibility to collocate 6 different inputs at a single point in the space.
- Strong mutual coupling among the 6 elements of the Vector Antenna.

However, some attempts have been made in the last decade. They include:

- An initial attempt was made by Mitra et al. [5], in which they used 3 orthogonal sleeve dipoles half-wavelength with resonant frequency 880 MHz.
- An antenna system comprising of a loop and a dipole has been reported by Stancil et al. [8].
- Antenna systems consisting of co-located and co-polarized magnetic and electric dipoles (one loop and two orthogonal dipoles) arranged in a planar, stacked configuration is presented by Lazzi et al. [?].
- A first 4D Vector Antenna prototype has been developed by Lazzi et al. [9]; and,
- Full 6D Vector Antennas which measure all six components of electric and magnetic fields [10]–[13] have been manufactured. However they are large in size, the carrier frequency is generally below the typical frequency ranges of radar systems, they are relatively narrowband ($\leq$30 MHz), and are of a non-planar configuration.

We performed some preliminary measurements on a synthesized 6D co-located vector antenna [7]. The synthesized antenna is achieved by locating separately a dipole and a loop, first along the x axis, then along the y axis and in the end along the z axis. The loop and dipole antennas were designed and manufactured based upon the description provided by [?], [?] and operate at 2.65 GHz. Figure 1 shows the results of the MUSIC algorithm applied to the measured data. This figure

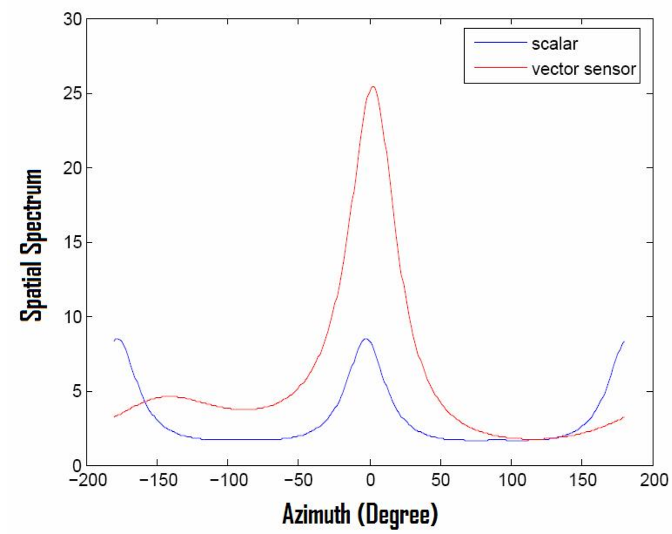

Fig. 1. MUSIC spatial spectrum: vector sensor (red line) and array antenna (blue line) results

shows the spatial spectrum for the synthesized vector antenna (red line) and for an array of two identical elements (blue line). This diagram shows a better performance of the vector sensor because the curve obtained with the vector antenna only has one maximum, while the curve obtained with the array antenna shows an ambiguous behavior.

III. Distributed element vector antenna

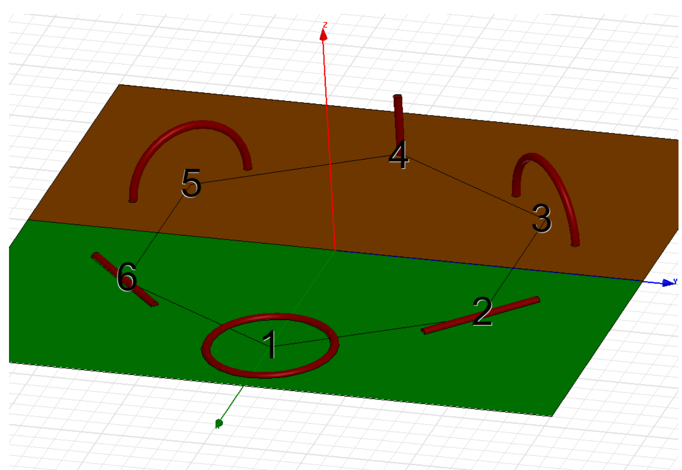

Fig. 2. Distributed 6D Antenna

We have developed a 6D vector antenna for radar application in the S band around 3 GHz. At this frequency, one of the major challenges is the coupling among the antenna elements. Coupling becomes a particularly difficult issue with co-located antennas. Furthermore, it is not trivial to physically collocate six connectors at the same geometrical point. Hence, we are currently considering a different design based on a distributed element approach. The performance of a distributed 6D vector antenna is even better than a co-located version, since the phase delays among sensors can be exploited to improve the efficiency of signal processing algorithms [14]. A simple representation of this novel antenna system is shown in Fig. 2.

A PCB is employed to align the six different components. The antenna system is designed to work at the carrier frequency of 3 GHz. The measurement of the magnetic field components is accomplished via loops and half loops orthogonally oriented to each other. The measurement of the electric field components is performed by using dipoles and monopoles orthogonally oriented to each other. Elements no. 1, 2, and 6 do not have a ground plane, in order to attain the radiation pattern of ideal loops and dipoles. Conversely, elements 3, 4, and 5 need a ground plane, due to the use of the image theorem. The choice of half wavelength dipoles and electrically large loops arises because it is not trivial to develop an antenna that simultaneously is electrically small and has a acceptable amount of received power at the frequency of 3 GHz. Fig. 3 shows our prototype of distributed vector antenna.

Fig. 3. Experimental Setup

IV. EXPERIMENTAL SETUP

We will perform measurement using the setup indicated in Fig. 4 inside the anechoic chamber in the Andrew Electromagnetics Laboratory at the University of Illinois at Chicago. The transmitter is an Agilent Technology Inc. arbitrary waveform generator E8267C-520, which can directly modulate an RF signal with a bandwidth up to 80 MHz. The receiver is an Agilent technology spectrum analyzer E4440A, equipped with an 80 MHz digitizer module. Our experiment consists in placing the distributed 6D Vector Antenna on a steering platform and in measuring the entire six components. Then, we will process the readings using an LMS-based DoA estimation technique. Knowing a priori the actual Direction of Arrival, we will measured the deviation between the estimated value and the actual one, giving an insight of the potential accuracy of a distributed vector antenna.

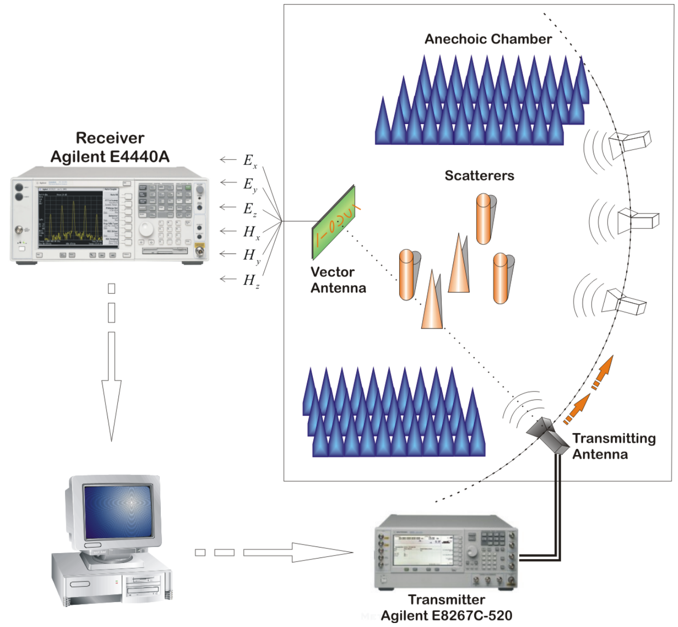

Fig. 4. Experimental Setup

Due to the finite size of the ground, the imperfection of the soldering process and several other factors, it is expected that the ideal radiation patter will not match the actual one. Therefore, a calibration process will be performed, in which the real radiation pattern of each element will be measured.

In the meanwhile, we performed simulations using the proposed distributed vector sensor where a complementary minimum mean square error function between estimated and actual DoA was computed. In this way, the location of its maximum indicates the expected direction of arrival. An algorithm based on this function selects the peak value as the best estimator for the DoA. Due to difficulties in accurately align vector antenna and transmitter, only azimuthal angles are considered. Results for three different simulations are shown

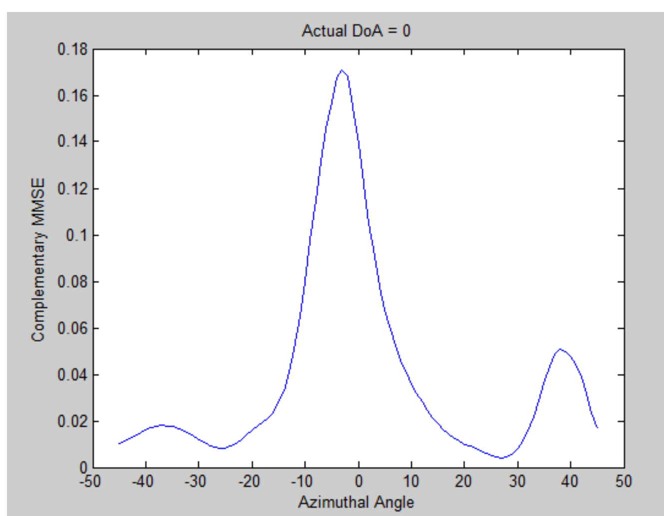

Fig. 5. Actual DoA : 0 degrees, Estimated Value : -2 degrees

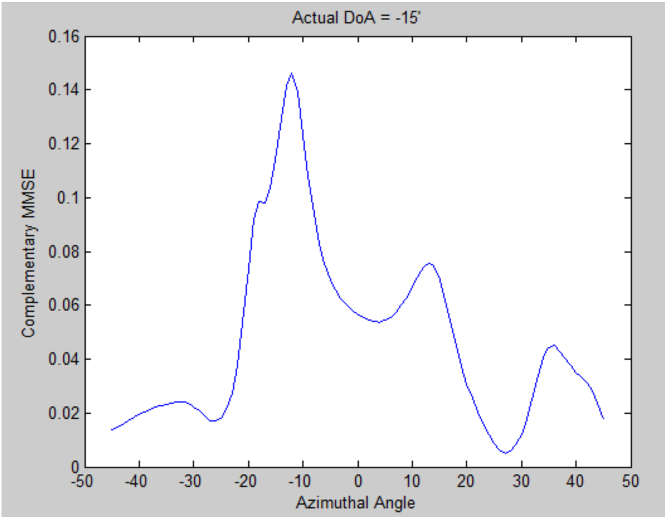

Fig. 6. Actual DoA : -15 degrees, Estimated Value : -12

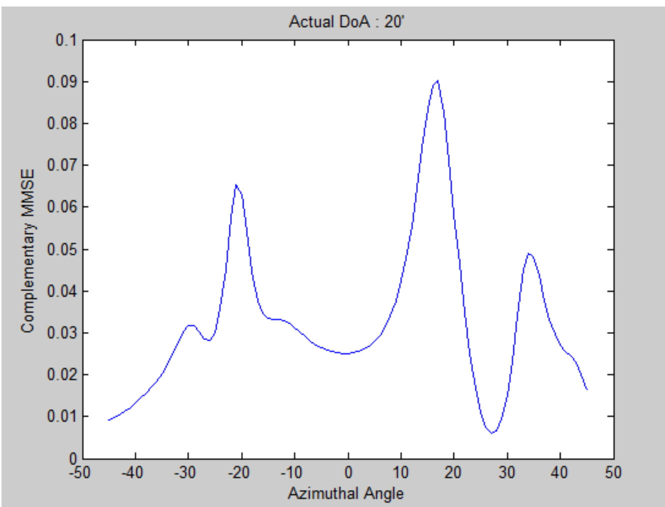

Fig. 7. Actual DoA : +20 degrees, Estimated Value : -18

in figures 5, 6, and 7. They are promising because they show a maximum error of only 3 degrees. In the future, we hope to improve this estimates.

V. Conclusion

We design, manufactured and tested a 6D distributed vector antenna. Preliminary numerical simulations using our Distributed Vector Antenna show promising results, with an error that is below 3 degrees.

References

[1] R. Roy and T. Kailath, "Esprit-estimation of signal parameters via rotational invariance techniques," *IEEE Trans. Acoust., Speech, Signal Processing*, vol. 37, pp. 984–995, Jul. 1989.
[2] R. O. Schmidt, "Multiple emitter location and signal parameter estimation," *RADC Spectral Estimation Workshop*, 1979.
[3] D. . W. Swingler and R. S. Walker, "Line-array beamforming using linear prediction for aperture interpolation and extrapolation," *IEEE Trans. ASSP*, p. 1630, Jan. 1989.
[4] K. T. Wong and M. D. Zoltowski, "High accuracy 2d angle estimation with extended aperture vector sensor arrays," *IEEE Acoustics, Speech and Signal Processing ICASSP-96 Conference Proceedings*, vol. 5, pp. 2789–2792, May 1996.
[5] M. R. Andrews, P. Mitra, and R. deCarvalho, "Tripling the capacity of wireless communications using electromagnetic polarization," *Nature*, vol. 409, pp. 316–318, 2001.
[6] A. Nehorai and E. Paldi, "Vector-sensor array processing for electromagnetic source localization," *IEEE Trans. Signal Process.*, vol. 42, no. 2, pp. 376–398, Feb. 1994.
[7] B. Elnour and D. Erricolo, "Experiments to measure the direction of arrival using a vector antenna," in *IEEE AP-S International Symposium on Antennas and Propagation and USNC/URSI National Radio Science Meeting and AMEREM*, Albuquerque, NM, July 9-15 2006.
[8] D. D. Stancil, A. Berson, J. P. V. Hof, R. Negi, S. Sheth, and P. Patel, "Doubling wireless capacity using co-polarized, colocated electric and magnetic dipoles," *Electron. Lett.*, vol. 38, no. 14, pp. 746–747, Jul. 2002.
[9] A. Konanur, K. Gosalia, S. Krishnamurthy, B. Hughes, and G.Lazzi, "Increasing Wireless Channel Capacity Through MIMO Systems Employing Co-Located Antennas," *IEEE Trans. Microw. Theory Tech.*, vol. 53, no. 6, pp. 1837–1844, June 2005.
[10] D. J. Farina, "Superresolution compact array radiolocation technology (supercart) project," *Flam and Russell Tech. Rep.*, vol. 185, Nov. 1990.
[11] E. P. A. Nehorai, "Superresolution compact array radiolocation technology (supercart) project," *Asilomar Conf.*, pp. 566–572, 1991.
[12] G. F. Hatke, "Performance analysis of the supercart antenna array," *MIT Lincoln Lab.*, no. AST-22, Mar. 1992.
[13] M. Kanda, "An electromagnetic near-field sensor for simultaneous electric and magnetic field measurements," *IEEE Trans. Electromagnetic Compatibility*, vol. 26, pp. 102–110, Aug. 1984.
[14] M. Hurtado and A. Nehorai, "Performance analysis of passive low-grazing-angle source localization using diversely polarized arrays."