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3D Direction-of-Arrival Estimation using a Wideband Vector Antenna

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***Abstract*—In this communication, direction finding performances of a reconfigurable wideband vector antenna are predicted. The accurate estimation of the direction of arrivals across the 3D half-space of incoming electromagnetic fields is obtained over a 1.7:1 frequency range from only two colocated and orthogonal circular arrays of Vivaldi antennas.**

I. Introduction

The direction-of-arrival (DoA) estimation of incoming electromagnetic (EM) fields has gained a significant position in numerous civil and defense related applications [1]. Some applications may require a 3D coverage and wide operating frequency range. Keeping in mind that the estimation accuracy of the DoAs along with the spatial and frequency coverages mainly depends on the electrical performances of the antennas, it becomes important to focus on the development of specific direction finding (DF) antennas with 3D and wideband coverages capabilities. A way to estimate the DoA of an incoming EM field in the 3D space with a compact DF antenna consists of using a Vector Antenna (VA) [2]. Ideal VA is composed of six orthogonal and colocated antennas and combines three electric and three magnetic dipoles. These six dipoles allow the derivation of the DoA from the measurement of the six components of the incoming EM field. Several VA designs covering the 3D space have been reported. An active VA operating at frequencies below 30 MHz is studied in [3], while some of us proposed in [4] a passive VA for multi-band applications.

The DoA estimation performances of the passive, wideband and reconfigurable VA reported by the authors in [5] are assessed in this communication.

II. Reconfigurable Wideband Vector Antenna

The novel passive, wideband and reconfigurable VA, which was recently proposed by the authors [5], is shown in Fig. 1. It consists of two orthogonal and colocated dual-port semi-circular arrays of Vivaldi antennas. As specified in Table I, three components of the incoming EM field (H_x, H_y and E_z) can be measured over a 1.7:1 simulated impedance bandwidth (VSWR $\leqslant 2.3$) ranging from 2.08 GHz to 3.56 GHz thanks to the control of the amplitude and phase impressed at the four ports of the VA. The VA is included in a half-sphere of radius $0.52\lambda_0$, where λ_0 is the free space wavelength at the lowest operating frequency.

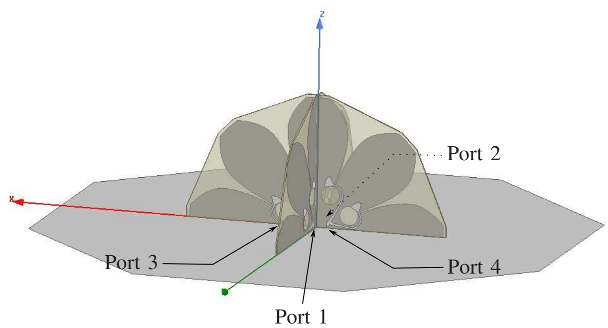

Fig. 1. Topology of the VA reported in [5] and ports numbering description

TABLE I
Excitation configurations for the measurement of the incoming EM-field components

Measured Component	Port 1	Port 2	Port 3	Port 4
H_x	1	$1\angle 180°$	0	0
H_y	0	0	1	$1\angle 180°$
E_z	1	1	1	1

III. Direction Finding Performances

Two simulated configurations are considered here to evaluate the DoA estimation performances of the reconfigurable wideband VA: (1) the antenna is mounted on an infinite ground plane, and (2) the antenna is mounted on a finite metallic and octagonal support with a circumcircle radius of $1.13\lambda_0$. DoAs are estimated in the 3D half-space using the well-known MUSIC algorithm (MUltiple SIgnal Classification) [6] and from full-wave EM simulations (HFSS software). Each DoA is defined by the azimuth angle $\phi \in [0; 360°]$ and elevation angle $\theta \in [0; 90°]$. The accuracy of the DoA estimation is derived from the computation of the Root-Mean-Square error of the angular distance, denoted by Δa_{RMS}, between the estimated DoA and the actual DoA (see, e.g., [4] for the detailed definition of Δa_{RMS}). Furthermore, the evaluation of the estimation performances is based on the following assumption: only one vertically polarized EM-wave is incident upon the VA. Other estimation parameters used for performing the simulations are summarized in Table II. Following [4], a calibration matrix derived from simulated radiation patterns of two magnetic and one electric dipoles is used to take into account eventual amplitude and phase distortions in the radiation patterns.

TABLE II
PARAMETERS USED FOR THE EVALUATION OF THE DIRECTION FINDING PERFORMANCES

DoA Algorithm	MUSIC
Number of incoming EM fields	1
Polarization of the incoming EM fields	Vertical
Angular coverage	$\phi \in [0^\circ\ ;\ 90^\circ]$ $\theta \in [0^\circ\ ;\ 90^\circ]$
Angular resolution	$\Delta\phi = 5^\circ$ $\Delta\theta = 2^\circ$
Incoming EM fields power density	-105 dBW.m^{-2}
Noise power level	-111 dBm
Incoming signal power density to noise ratio	36 dB.m^{-2}
Snapshots per DoA estimation	100
Number of estimations per DoA	20
Frequencies used the DoA finding	2.2 GHz 2.8 GHz 3.4 GHz

Fig. 2 reports the simulated Root-Mean-Square of angular distance Δa_{RMS} at three operating frequencies in the bandwidth of the VA. For both configurations, it can be observed that the Δa_{RMS} does not exceed 5 degrees in almost every directions in the 3D upper half-space within the antenna bandwidth. Furthermore, highest values of Δa_{RMS} are found in specific directions depending on the operating frequency and the configuration (infinite or finite ground plane). However, it can be observed that the use of the finite ground plane does not significantly degrade the estimation performances. From the simulation results reported in Table III, where the 95th and 99th percentiles of the Δa_{RMS} (which indicate the errors threshold for respectively 95% and 99% of all the obtained DoAs) are given, it can be predicted that the VA is suitable for 3D direction finding estimation with a very good estimation accuracy.

TABLE III
DF PERFORMANCES PREDICTED FROM FULL-WAVE ELECTROMAGNETIC SIMULATIONS

Infinite ground plane			
Frequency	max Δa_{RMS}	99th Δa_{RMS}	95th Δa_{RMS}
2.2 GHz	2.8°	2.3°	1.5°
2.8 GHz	4.0°	3.1°	2.3°
3.4 GHz	85.2°	12.0°	2.1°
Finite ground plane			
Frequency	max Δa_{RMS}	99th Δa_{RMS}	95th Δa_{RMS}
2.2 GHz	4.2°	2.4°	1.7°
2.8 GHz	3.8°	2.8°	2.0°
3.4 GHz	142.5°	51.8°	1.6°

CONCLUSION

The DF performances of a reconfigurable wideband VA which emulates two magnetic and one electric dipoles is presented, showing a design with a high level of DoA estimation accuracy over a 1.7:1 frequency range with a 3D field of view. Experimental validations of these predicted performances are on tracks.

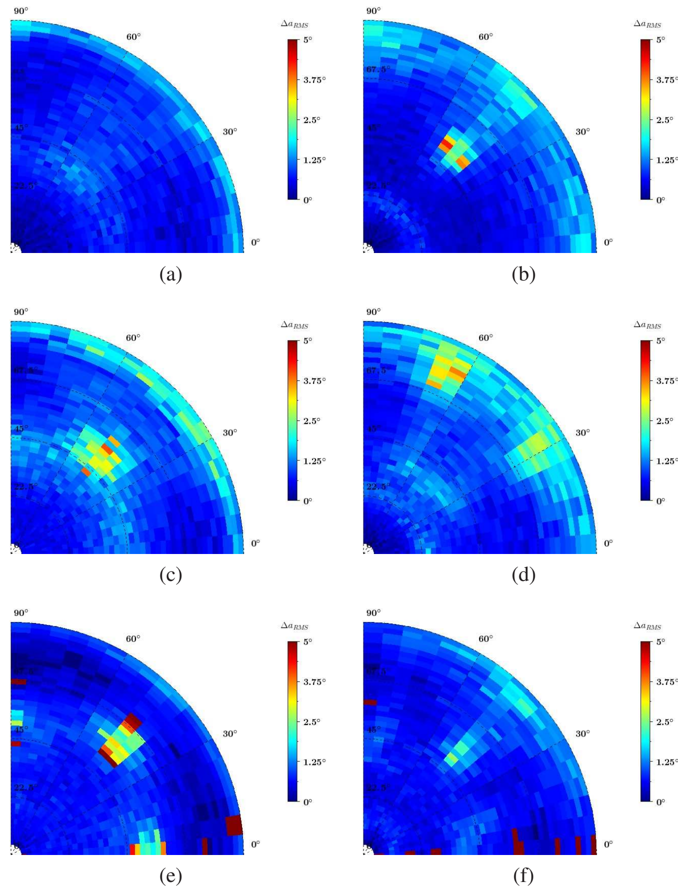

Fig. 2. Simulated $\Delta a_{\text{RMS}}(\phi, \theta)$ at: (a) & (b) 2.2 GHz, (c) & (d) 2.8 GHz, and (e) & (f) 3.4 GHz when the reconfigurable wideband VA is mounted on an infinite ground plane (left figures) or on a finite octagonal ground plane (right figures). Elevation angles θ are given on the radial axis and azimuth angles ϕ are given on the angular axis.

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