On the Effects of Decoupling and Matching Networks in Phase Array Radiation Patterns for Radar Applications

Mariana Pralon, Reiner Thomä, Bruno Pompeo, Gabriel Beltrao, Leandro Pralon

Abstract— **Phased array systems employ a set of properly chosen radiating elements, geometrically configured and strategically excited in order to render a specific radiation pattern, best suited for a given application. When the total antenna size emerges as an application constraint, both size of the radiating elements as well as the distance between them need to be optimized. If the spacing between neighboring elements reduces to less than half of the free-space wavelength, electromagnetic coupling becomes stronger. The consequences are the following: the radiation patterns are distorted, the antenna ports become mismatched, and the effective degrees of freedom (DoF) are reduced. To overcome the degrading effects that strong electromagnetic coupling may bring to phased array radars, transmission lines are designed with the purpose of decoupling and matching the excitation ports. Within this context, this paper investigates the effects of an eigenmode based decoupling technique in phase array radiation patterns for Radar applications.**

Keywords— **phased array, radar, decoupling, matching, compact antenna arrays, decoupling networks.**

I. INTRODUCTION

Many modern systems employ phased array antennas in their configuration, e.g. radio stations, space probes, meteorological radars and modern military radar systems [1]. Since each application requires an adequate design, the appropriate choice of the radiating elements, the array geometry and the optimum current distribution of each active antenna element should be carefully studied in order to achieve maximum performance. Whilst many works related to the latter have been published in the literature [2], [3], [4], focused on achieving lower sidelobes levels, electronic steering the radiation pattern main lobe and generating nulls in specified directions, few have addressed the radiation element design or the array geometric characteristics, since these often have to meet more restrict constraints.

The size of the device used for mobile communication based applications is always one of the main concerns and, consequently research topics both in the academic community as well as in industry. Miniaturization techniques are constantly addressed to reduce such devices occupied volume, enhancing their feasibility and reducing their cost. As a consequence, it has become ever more desirable that the antennas used for mobile communication systems are the more compact the possible, giving rise to two possible outcomes. It is either possible to miniaturize the antenna radiating element itself, or it may be required that the radiating elements are placed together more closely in the array. On the one hand, the former introduces a high degree of complexity in the antenna element design, that already has to meet central frequency, bandwidth, gain and radiation pattern requirements. On the other, the latter introduces undesired coupling effects between elements.

Within this context, this paper investigates compact antenna arrays, with inter-element spacing smaller than half of the free-space wavelength. It is well known that when designing antenna arrays, the optimal distance between elements, which ensures negligible mutual coupling while avoiding ambiguity, is half of the wavelength in the free-space. If we reduce this spacing, adverse effects such as radiated far-fields pattern distortion, reduced bandwidth and polarization mismatch will arise. To mitigate the effects that emerge from mutual coupling, it is widely proposed, in publications such as [5], [6], techniques that are employed after the analog to digital conversion for the decoupling of array elements. However the digital signal will be already distorted by noise, and the degrading effects cannot be fully compensated. Alternatively, networks based on distributed or concentrated elements are designed, which are connected to the antenna array, for the decoupling and matching of array elements [7], [8]. This approach ensures the compensation of degrading effects brought by the strong mutual coupling in compact arrays.

This paper is organized as follows: In Section II, a brief overview on phased array antennas is performed. In Section III we describe the microstrip patch antenna arrays and detail the design of networks for the decoupling and matching of the radiating elements. Section IV presents the simulation results, and, finally, section V concludes and summarizes the work.

II. LINEAR PHASED ARRAY ANTENNA

A linear uniform phased array antenna consists of active elements placed in a line and equally spaced by a distance dx. Once dx and the kind of antenna for each element is defined, the resulting pattern generated by the array follows 1

$$f(\theta,\phi)=\sum_{i=1}^{n}U_i w_i e^{\frac{-2j\pi R_i\cos(\theta)\sin(\phi)}{\lambda}} \qquad (1)$$

where U_i is the radiation pattern for each element i, w_i is the complex excitation of each element i, R_i is the distance from a fixed point to each element i, ϕ is the elevation

Centro Tecnológico do Exército, Rio de Janeiro-RJ, Brasi, E-mails: pmariana, pompeo, bgabriel, pralon@ctex.eb.br
Ilmenau University of Technology, Electronic Measurement Research Laboratory, Ilmenau, Germany. E-mails: reiner.thomae@tu-ilmenau.de

of a fixed point from the horizontal plane that crosses the normal line to the antenna, θ is the azimuth of a fixed point from the normal angle in respect to the antenna and λ is the transmitted/received signal wavelength.

In the present work, the phase component related to ϕ can be suppressed since, for horizontal plane arrays, this component is the same to all the array elements. It is also considered that the wave is traveling from a far point ($R_i \gg \lambda$) and so, can be referred as planar.

III. COMPACT ANTENNA ARRAY DESIGN

A. Microstrip Patch Antenna Array

Microstrip antennas are one of the most utilised antennas for several applications ranging from military to civilian. Among some of its most remarkables advantages are the low profile, simplicity, low cost, leightweight, conformability, simple manufacturing and mechanical robustness. Moreover, requirements such as dual-polarization or dual-frequency band can be easily achieved.

A microstrip antenna consists of a metalized radiator printed on a grounded dielectric slab as depicted in Figure 1. The size of the metalic radiator defines the antenna resonance frequency and due to element limited electrical size, the frequency bandwidth of a microstrip antenna is usually very narrow. The properties of the dielectric layer play an important role to the radiation performance of the antenna. Thick layers are usually prefered when the objective of frequency bandwidth enhancement, although it will definitely comes with the cost of higher losses within the substrate. The shape of the metalized radiator, hereafter refered to as patch, also influences the antenna efficiency. Rectangular and circular patch antennas are the two most used configurations due to its simplicity although fancier shapes may also be considered for the optimization of the antenna performance.

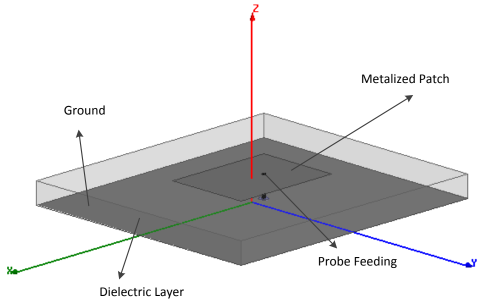


Fig. 1: Six-element planar probe fed microstrip patch array.

The results presented in this publication considered a six-element patch array as depicted in Figure 2. The array is comprised of six microstrip patches, in planar arrangement. The patches of width 40 mm and length 30 mm are printed on a dielectric layer of relative permittivity $\epsilon_r = 2.2$ and 3.2 mm height. The patches are fed by probes located at $(x_f, y_f) = (5\,\mathrm{mm}, 0)$. The patches dimensions are optimized for the frequency of 2.35 GHz and the probe location may be varied for impedance matching.

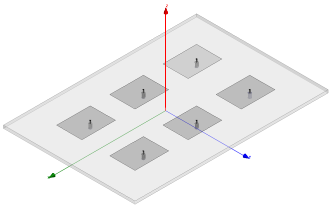


Fig. 2: Six-element planar probe fed microstrip patch array.

B. Decoupling and Matching Network

Since solutions to compensate for mutual coupling in the digital domain are not able to fully restore the degrading effects, we need to employ a technique in the analog domain. In [8], [9], a Decoupling and Matching Network (DMN) comprised of distributed elements is designed based on a decomposition of the antenna array radiation matrix into fundamental modes of radiation. The DMN and the originally coupled radiating elements exchange reactive energy, giving rise to decoupled radiation patterns. The network together with the radiating elements may thus be considered as a "new" antenna array.

The eigenmode decomposition approach, first introduced by Stein [10] and further detailed in [8], describes the antenna as an array of ideally uncoupled ports and orthogonal radiation patterns. Each of the antenna array fundamental modes of radiation presents an efficiency that measures the amount of power radiated to the far field, and defined as eigenefficiency. The array eigenefficiencies complement the S-parameters for the analysis of coupling within the array.

Let us start by defining the antenna array radiation matrix $\boldsymbol{H} \in \mathbb{C}^{M \times M}$ of an antenna array.

$$H_{ij} = \frac{1}{4\pi} \oint \boldsymbol{A}_i^{\mathrm{H}}(\vartheta, \varphi) \boldsymbol{A}_j(\vartheta, \varphi) d\Omega \tag{2}$$

where Ω is the solid angle. Since the matrix $\boldsymbol{H}$ is Hermitian, it is possible to diagonalize it through the following transformation.

$$\boldsymbol{\Lambda} = \boldsymbol{Q}^H \boldsymbol{H} \boldsymbol{Q} \tag{3}$$

where $\boldsymbol{\Lambda} \in \mathbb{R}^{M \times M}$ is a diagonal matrix with each diagonal element λ_m representing the m-th mode eigenefficiency and $\boldsymbol{Q} \in \mathbb{C}^{M \times M}$ is the matrix comprised by the M eigenvectors $\boldsymbol{q}_m$, the eigenmodes. The matrix $\boldsymbol{Q}$ characterizes the fundamental modes of radiation of an antenna array and the matrix Λ comprises the correspondent modal radiation efficiencies, the eigenefficiencies.

We observe that the $\boldsymbol{Q}$ guides into the design of the required decoupling network. In order to decouple the antenna array, the goal is to design a decoupling network that renders the excitation given by the eigenvectors. Considering that the new antenna array is comprised of a decoupling network connected to the antenna array ports, the new array manifold for each mode m, denoted by $\tilde{A}_m(\vartheta, \varphi)$ is:

$$\tilde{A}_m(\vartheta, \varphi) = \frac{1}{\sqrt{\lambda_m}} \boldsymbol{q}_m^{\mathrm{T}} \boldsymbol{A}(\vartheta, \varphi) \tag{4}$$

where $\boldsymbol{q}_m, \in \mathbb{C}^{M\times 1}$ is the m-th eigenvector, corresponding to the m-th column of the matrix of eigenmodes $\boldsymbol{Q}$.

The magnitude and phase of the eigenvectors thus define the magnitude and relative phase of excitation at each port, for effective decoupling. The goal of this paper is to investigate the current distribution that is required at each of the DMN input ports in order to steer the array beam pattern for high performance phased array radars. The phased array antenna is, in our case, not only comprised of radiating elements, but also of the DMN.

IV. SIMULATION RESULTS

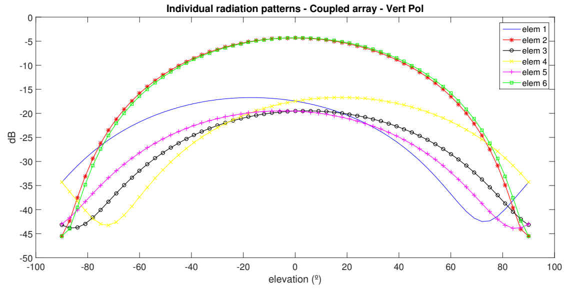
In this section, we present results on the simulation of the six-element microstrip patch array, as detailed in Section III-A, with inter-element spacing of 0.32 λ. Since the element spacing is much smaller than half of the free space wavelength, adverse effects caused by mutual coupling will arise. Please note that we characterized the radiation patterns as full-polarimetric, decomposing it into a vertical polarization component and a horizontal polarization component. However, it is possible to observe, as expected, that the cross-polarization is very small, due to the fact that the array elements are vertically polarized.

With the aim of investigating the performance improvement due to compensation for the degrading effects from coupling, we simulated the behavior of the antenna array connected to a DMN as detailed in Section III-B. Figure 3 depicts the individual radiation patterns of each radiating element in the array depicted in Figure 2, cut in $\varphi = 0°$. With the aim of comparing the radiation characteristics of the decoupled array with the originally coupled array, we present in Figure 4 the radiation patterns of each eigenmode, cut in $\varphi = 0°$, which are observed if we connect the original antenna to the proposed DMN, giving rise to the already mentioned "new" decoupled antenna array.

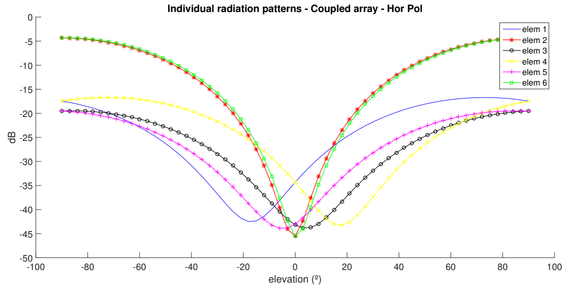
It is possible to observe from Figures 3 and 4 that the gain of the individual radiation patterns for the decoupled array is much higher than for the coupled array. Moreover, the pattern is much wider for the decoupled array. By looking exclusively at the radiation patterns, one would already expect that the performance for phased array will be much higher for the decoupled array, due to the higher individual gains and to the wider beam pattern. At this point we remind the reader that for phased arrays, the wider the individual beam patterns, the more capable the array is to steer the beam in all possible directions.

With the aim of investigating the proposed technique for decoupling and matching the compact array depicted in Figure 2, with inter-element spacing of 0.32 λ, used in a phased array, we worked on the amplitude and phase of the current distribution at the ports of the "new" antenna array for beam steering at specific directions in elevation, for a cut in $\varphi = 0°$. Figure 5 depicts the output of the phased array, using the originally coupled array, when we steer the beam in $0°$, $30°$ and $45°$ in elevation. Figure 5 depicts the output of the phased array, using the decoupled array.

It is possible to observe, from Figures 5 and 6 that the output of the phased array for the decoupled array has a

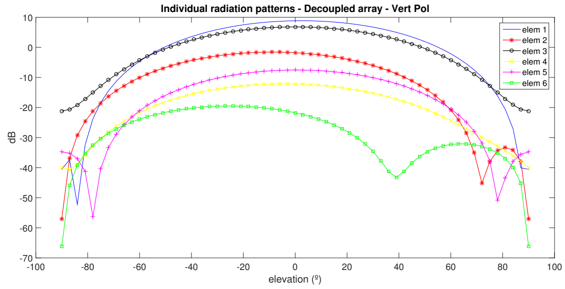


(a) Vertical Polarization Component

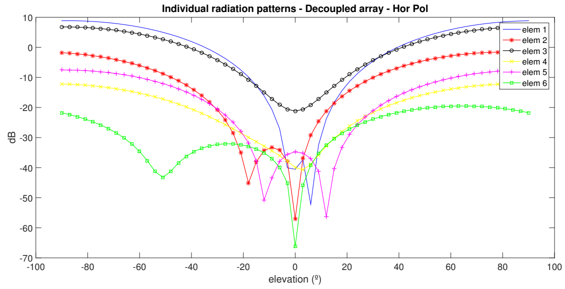


(b) Horizontal Polarization Component

Fig. 3: Individual Radiation Patterns - Coupled Array.

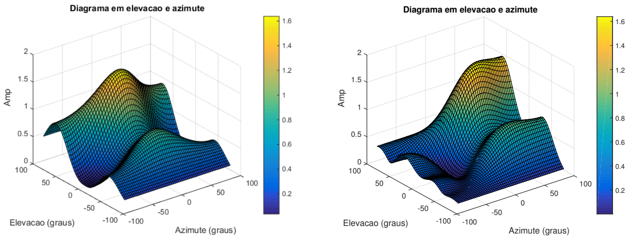


(a) Vertical Polarization Component



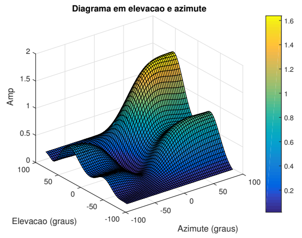
(b) Horizontal Polarization Component

Fig. 4: Individual Radiation Patterns - Decoupled Array.



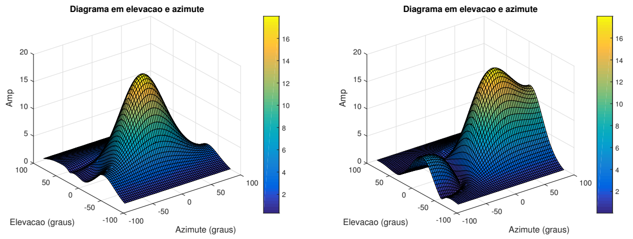
(a) Steered Pattern in 0°

(b) Steered Pattern in 30°



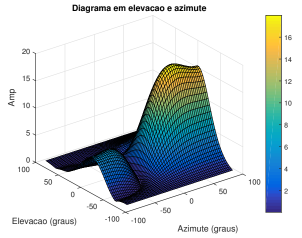
(c) Steered Pattern in 45°

Fig. 5: Steered Pattern - Coupled Array.



(a) Steered Pattern in 0°

(b) Steered Pattern in 30°



(c) Steered Pattern in 45°

Fig. 6: Steered Pattern - Coupled Array.

much higher gain. The total gain at the direction of the maximum is around 2 dB for the coupled array, while the total gain for the decoupled array is around 16dB. Moreover, the decoupled array is able to steer the beam in the desired direction with much lower side lobes. We are able to prove that one is able to benefit from the use of the proposed technique when employing compact antenna arrays with element spacing shorter than $\lambda/2$ to compensate for electromagnetic mutual coupling.

V. CONCLUSION

In this work we proposed a decoupling and matching technique for compact antenna arrays, based on the modal decomposition of the radiation matrix, for phased array radars. We reviewed the design of Decoupling and Matching Networks (DMN) to be connected to an antenna array with inter-element shorter than $\lambda/2$. Moreover, we detailed the antenna array investigated, which is comprised of microstrip patches, and presented the fundamentals of phased arrays.

We compared the radiation characteristics of a coupled microstrip patch antenna array to the radiation characteristics of the decoupled array, and concluded that the gains of the individual radiators are higher if the elements are decoupled. Moreover, the aperture is wider when the degrading effects of electromagnetic coupling are restored with the use of DMN.

Finally, we proved that the performance of the phased array is higher when we want to steer the beam in one specific direction using a decoupled array in comparison with the performance of the coupled array. Besides higher total gain, we were able to observe lower side lobes, which is fundamental in phased array radars, in order to avoid incorrect target detection.

VI. ACKNOWLEDGEMENT

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