

Planar Compact Array with Parasitic Elements for MIMO Systems

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Abstract—A compact planar array with parasitic elements is studied to be used in MIMO systems. Classical compact arrays suffer from high coupling which makes correlation and matching efficiency to be worse. A proper matching network improves these lacks although its bandwidth is low and may increase the antenna size. The proposed antenna makes use of parasitic elements to improve both correlation and efficiency. A specific software based on MoM has been developed to analyze radiating structures with several feed points. The array is optimized through a Genetic Algorithm to determine parasitic elements position in order to fulfill different figures of merit. The proposed design provides the required correlation and matching efficiency to have a good performance over a significant bandwidth.

Index Terms—MIMO, compact array, mutual coupling, capacity, correlation, impedance matching, MoM, optimization.

I. INTRODUCTION

The development of new communication systems and services has led to a notorious increase in the needs of bandwidth and capacity. Multiple-Input Multiple-Output (MIMO) systems make use of spacial or polarization diversity to rise the binary rate. The important limitations in the available spectrum has made the MIMO systems to become a suitable solution to overcome present and future requirements.

MIMO systems are formed typically by electrically large radiating structures with several elements in transmission and reception. Therefore, capacity improvement is achieved at the expense of enlarging the antenna dimensions. The fact that the communications devices tend to have a smaller size has constrained the popularization of MIMO systems.

The design of compact antennas which are adequate for MIMO systems has special interest. The analyzed solutions in the literature are fundamentally of two kinds: antennas with an only multi-mode radiating element and compact arrays with several elements. The structures with only one radiating element use the different radiated modes to establish a MIMO channel. In [1], a spiral antenna with 4 legs and 2 working modes is proposed; the modes have different polarizations and radiating diagram. [2] shows a multi-layered antenna that works with several modes and provides radiation diagram diversity. The other alternative is based on compact arrays which make use of spatial diversity. The mutual coupling between the array elements has influence on the radiating diagram and affects to the correlation [3]. Moreover, it modifies the elements input impedance provoking power mismatching [4].

These lacks can be solved with a proper matching network [5], [6]. However the matching network is usually complex and provides a low bandwidth [7].

In this paper, a compact planar array of $2 \lambda_0/2$ dipoles with parasitic elements is proposed to be used in 2×2 MIMO systems. The studied design performance is comparable to the obtained with the use of an optimal matching network and shows a less selective frequency response. Section II describes the employed model to study the MIMO system with the scattering parameters. In Section III, the considered figures of merit are described. Section IV summarizes the main characteristics of the developed software tool to analyze electromagnetically the array through Method of Moments (MoM) and address the design through an optimization procedure. Finally, in Section V, the proposed design and the achieved results are shown.

II. MIMO SYSTEM MODEL

Fig. 1 shows a schematic view of a 2×2 MIMO communication system. The transmitter is an array of 2 elements which are connected to the sources through a matching network. The receiver is analogous to the transmitter. A Non-line-of-sight (NLoS) channel with random uniform field is considered between the transmitter and receiver.

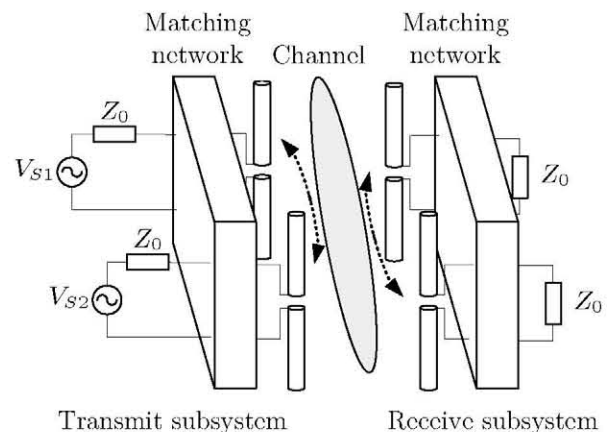


Figure 1. Schematic view of a 2×2 MIMO communication system.

The transmitter and receiver can be characterized in terms of their S-parameters matrix. For simplicity, the transmitter antenna is only considered as shown in Fig. 2. The S-parameters

matrix can be obtained from the impedance matrix Z with the transformation $S = \mathcal{F}(Z) = (Z + Z_0 I)^{-1}(Z - Z_0 I)$, where Z_0 is the reference impedance, typically 50 Ω . S_S is the source S-parameters matrix, which is diagonal in this case, and $S_{TT} = \mathcal{F}(Z_{TT})$ is the array S-parameters matrix.

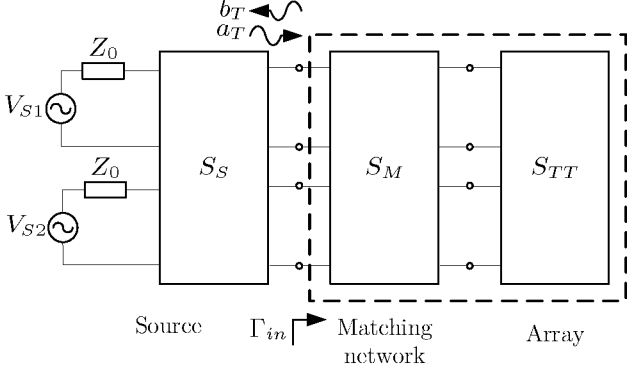


Figure 2. Transmitter block diagrams with the array connected to the sources through a matching network.

The matching network is a 4-port device. The matrix S_M can be written by blocks with 2×2 matrices as follows

$$S_M = \begin{pmatrix} S_{11} & S_{12} \\ S_{21} & S_{22} \end{pmatrix}, \quad (1)$$

where S_{11} is the S-parameters matrix of the ports connected to the sources and S_{22} is the one corresponding to the ports connected to the array. The S-parameter matrix Γ_{in} for the cascade of S_M and S_{TT} is given by

$$\Gamma_{in} = \begin{pmatrix} r_{11} & r_{12} \\ r_{21} & r_{22} \end{pmatrix} = S_{11} + S_{12}(I - S_{TT}S_{22})^{-1}S_{TT}S_{21}. \quad (2)$$

III. FIGURES OF MERIT IN MIMO SYSTEMS

A. Matching efficiency

In the antenna of Fig. 2, the reflected signal can be determined as a function of the incoming signal a_T and Γ_{in} , which is given by (2)

$$b_T = \Gamma_{in}a_T. \quad (3)$$

If the conductor losses are assumed to be negligible, the instantaneous power delivered to the array is [6]

$$P_{inst} = a_T^H a_T - b_T^H b_T = a_T^H (I - \Gamma_{in}^H \Gamma_{in}) a_T. \quad (4)$$

With zero-mean signals, the average power delivered to the antenna can be obtained as [6]

$$P_T = E\{P_{inst}\} = \text{tr}\{R_{aT}(I - \Gamma_{in}^H \Gamma_{in})\}, \quad (5)$$

where $R_{aT} = E\{a_T a_T^H\}$ is the correlation matrix of the incoming signal.

The matching efficiency [7] of a MIMO antenna is then defined with (5) as

$$\eta_T = 1 - \gamma_T = \frac{\text{tr}\{R_{aT}(I - \Gamma_{in}^H \Gamma_{in})\}}{\text{tr}\{R_{aT}\}}, \quad (6)$$

which expresses the relation between the power that is delivered to the array and the provided power by the sources. If a_{T1} and a_{T2} have the same average power, (6) can be expanded as

$$\eta_T = \frac{(2 - |r_{11}|^2 - |r_{12}|^2 - |r_{21}|^2 - |r_{22}|^2)}{\text{tr}\{R_{aT}\}} - \frac{2\text{Re}[E\{a_{T1}a_{T2}^*\}(r_{11}^*r_{12} + r_{21}^*r_{22})]}{\text{tr}\{R_{aT}\}}. \quad (7)$$

And assuming that a_{T1} and a_{T2} are uncorrelated, η_T turns into

$$\eta_T = \frac{(2 - |r_{11}|^2 - |r_{12}|^2 - |r_{21}|^2 - |r_{22}|^2)}{2}. \quad (8)$$

Throughout the rest of the paper, this figure of merit is named equivalently matching efficiency or matching losses ($\gamma_T = 1 - \eta_T$).

B. Correlation coefficient

This parameters measures the correlation between the transmitted or received signals by the antenna. Under the channel described in Section 1, the correlation coefficient absolute value ρ can be calculated from the S-parameters as $|\rho| \approx \sqrt{\rho_e}$, where the envelope correlation ρ_e is given by [8]

$$\rho_e = \frac{|r_{11}r_{12}^* + r_{21}r_{22}^*|^2}{(1 - |r_{11}|^2 - |r_{21}|^2)(1 - |r_{22}|^2 - |r_{12}|^2)}. \quad (9)$$

IV. ELECTROMAGNETIC ANALYSIS OF THE RADIATING STRUCTURE

A. Numerical method description

A specific simulation software has been developed to study metallic planar structures with several feed points to address the design through an optimization procedure. The Electrical Field Integral Equation (EFIE) is solved by applying MoM [9]. The solution of the EFIE determines the current distribution over the metallic surface $\vec{J}(\vec{r})$. The electromagnetic analysis involves the following tasks:

- *Structure mesh*: the antenna geometry is meshed with triangular elements satisfying constrained Delaunay conditions [10]. The primary mesh is refined by applying Rupert's algorithm [11]. $\vec{J}(\vec{r})$ is calculated as a linear combination of vectorial basis functions Rao-Wilton-Glisson (RWG) [12], that are defined between adjacent mesh triangular elements

$$\vec{J}(\vec{r}) = \sum_i I_i \vec{f}_i. \quad (10)$$

- *Impedance matrix calculation*: MoM impedance matrix Z characterizes the antenna electromagnetic behaviour of the antenna. In order to improve results accuracy, a mixed analytical-numerical integration procedure has been implemented. Z diagonal elements, which are likely to be the more critical, can be calculated practically analytically [13]. The rest of the matrix elements are obtained numerical and analytically [14]. The numerical integration is performed by Gaussian quadrature. MoM

equation related the coefficients I_i with the voltages at the feed points V through the following matricial equation

$$V = ZI. \quad (11)$$

- *Input impedance calculation:* the antenna input voltage is approximated with the delta-gap model [15]. Once (11) is solved, $\vec{J}(\vec{r})$ is determined and the impedance at the feed point is calculated. With $\vec{J}(\vec{r})$, other parameters like the radiated field or the radiation diagram can be computed.

B. Validation

The developed software tool has been validated against the software 4NEC2, that is able to simulate wire antennas with MoM. The reference array is composed of $2 \lambda_0/2$ dipoles at a distance of $0.1\lambda_0$ and a radius of $0.04\lambda_0$. A plane dipole can be approximated by a cylindrical one with an equivalent radius given by [16]

$$r_{eq} = \frac{W}{4}, \quad (12)$$

where W is the plane dipole width.

Fig. 3 shows a comparison of the $S_{11} = S_{22}$ obtained with 4NEC2 and our tool between $0.7f_0$ and $1.3f_0$. There is a good similarity over the whole bandwidth and the same resonance frequency.

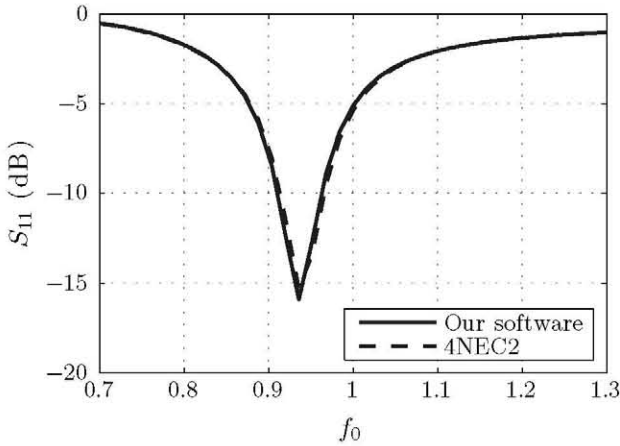


Figure 3. Comparison of the S_{11} obtained with the developed tool and 4NEC2.

V. RESULTS

A. Optimal matching network

Multipoint conjugate (MC) matching [6] is able to provide quasi-optimal correlation and matching efficiency [7]. Fig. 4 shows a possible implementations to build a MC matching network with transmission lines [17]. It is formed by 7 transmission lines and 4 open stubs. Transmission lines length and characteristic impedance are adjusted to get optimal correlation and matching efficiency at f_0 with the reference array.

If the matching network is assumed to be symmetrical with respect to the axis depicted in Fig. 5, odd-even excitation method can be applied to determine analytically the S-parameters

matrix. Optimal values for the parameters of the MC matching network can be found out by an optimization procedure such as evolutionary algorithms or even analytically under certain hypothesis.

Table I
TRANSMISSION LINE PARAMETERS IN THE MC MATCHING NETWORK.

Element	Kind	$Z_0(\Omega)$	$l(\lambda_0)$
1, 2	Open stubs	50	0.235
3, 4	Transmission lines	50	0.619
5	Transmission lines	17.4	0.863
6, 7	Transmission lines	50	0.738
8, 9	Open stubs	50	0.179
10, 11	Transmission lines	50	0.406

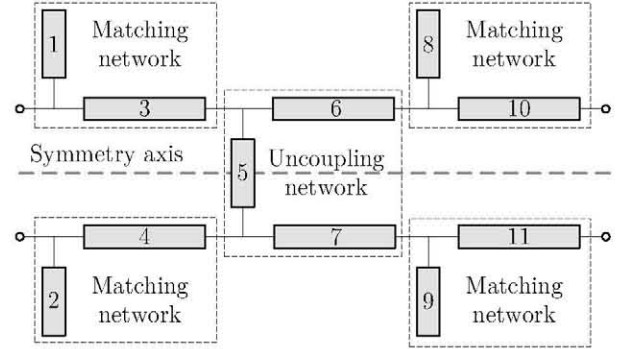


Figure 4. MC matching network built with transmission lines.

Fig. 5 shows correlation and matching losses with and without the designed MC matching network. With the MC matching network, matching losses of -33.3 dB and a correlation coefficient of -80.9 dB are obtained at f_0 . The MC matching network provides a -6 dB bandwidth ($\eta_T = 75\%$) of 3% in matching losses and a -3 dB bandwidth ($\rho_e = 0.5$) of 7% in correlation.

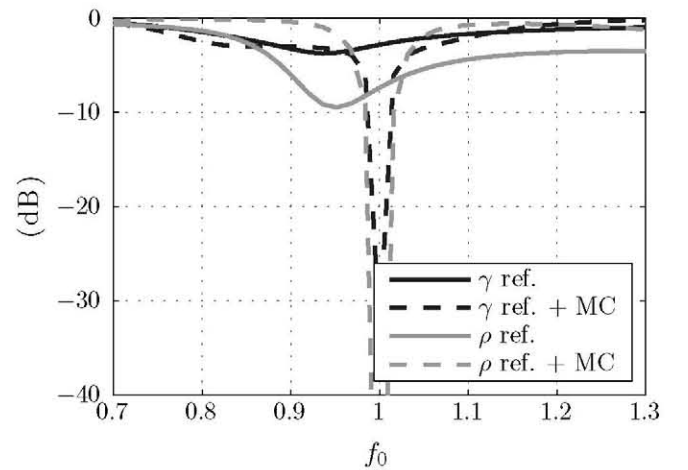


Figure 5. ρ and γ frequency response without the MC matching network (continuous line) and with it (dashed line).

B. Design of a compact array with parasitic elements

The design under study consists of the reference array close to some additional parasitic dipoles. The 2 array dipoles are oriented in the \hat{x} direction, with 2 feed points located at $x = 0$, $y = -0.05\lambda_0$ and $x = 0$, $y = 0.05\lambda_0$. The parasitic dipoles have a width of $0.02\lambda_0$ and are disposed also in the \hat{x} direction. In the optimization, their position is constrained to be in the rectangle $-0.3\lambda_0 \leq x \leq 0.3\lambda_0$ and $-0.1\lambda_0 \leq y \leq 0.1\lambda_0$.

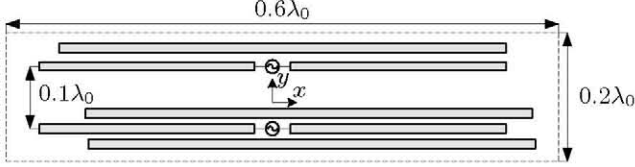


Figure 6. Feasible region for the parasitic dipoles.

In order to decide the optimal parasitic dipoles position, a Genetic Algorithm (GA) [18] has been applied with a population of 100 individuals, tournament selection, crossover probability of 50% and mutation probability of 1%. The fitness function g to be minimized in the GA takes into account both average figures of merit in a band of interest

$$g = \alpha_\rho \frac{1}{N} \sum_{i=1}^N \rho_e(f_i) + \alpha_\eta \frac{1}{N} \sum_{i=1}^N [1 - \eta_T(f_i)], \quad (13)$$

where η_T and ρ_e are given respectively by (8) and (9). The two figures of merit are computed in N frequencies within the band $0.95f_0 \leq f \leq 1.05f_0$. The weights α_ρ y α_η are introduced to ponderate the average values.

Several parametric analysis have been carried out varying the number and length of parasitic dipoles. Dipoles width has hardly any influence on the figures of merit. Table III shows the -3 dB correlation in matching losses and table II, the -6 dB bandwidth in correlation. Best results are obtained with 4 parasitic dipoles. Parasitic dipoles length appears to be very critical. The optimal design is achieved with 4 $0.4\lambda_0$ parasitic dipoles whose position is summarized in Table IV. Fig. 7 shows the frequency response in the figures of merit. The -6 dB bandwidth in matching losses is of 10% and the -3 dB bandwidth in correlation is of 48%.

Table II

-6 DB BANDWIDTH IN MATCHING LOSSES WITH THE OPTIMIZED DESIGNS.

Length (λ_0)	Number of parasitic dipoles			
	1	2	3	4
0.400	0%	0%	0%	10%
0.425	0%	0%	9%	9%
0.450	0%	8%	6%	0%
0.475	0%	0%	0%	0%
0.500	0%	0%	0%	0%

Table III

-3 DB BANDWIDTH IN CORRELATION WITH THE OPTIMIZED DESIGNS

Length (λ_0)	Number of parasitic dipoles			
	1	2	3	4
0.400	0%	0%	47%	48%
0.425	0%	31%	31%	36%
0.450	25%	24%	23%	24%
0.475	15%	32%	0%	15%
0.500	0%	>48%	0%	20%

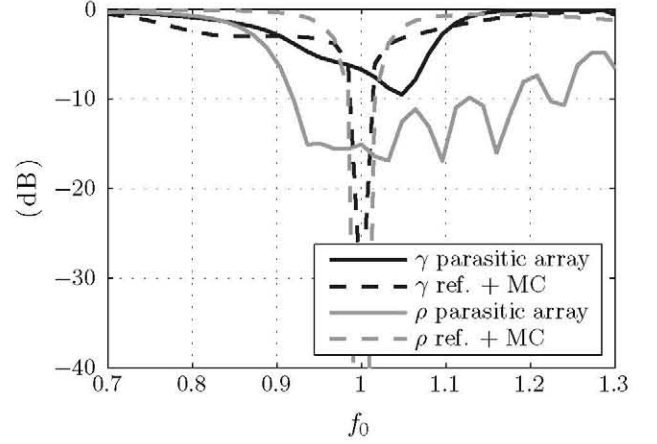


Figure 7. ρ and γ frequency response with the proposed design (continuous line) and the solution with the MC matching network (dashed line).

Table IV

PARASITIC DIPOLES CENTER POSITION WITH THE OPTIMAL DESIGN.

Parasitic dipole	$x(\lambda_0)$	$y(\lambda_0)$
1	-0.058	-0.095
2	0.027	-0.077
3	-0.027	0.094
4	0.066	0.079

In order to assess the proposed antenna in terms of capacity, a frequency-flat fading 2×2 MIMO channel with additive white Gaussian noise (AWGN) is used. The channel matrix H is characterized by the Kronecker model. If mutual coupling is neglected, H is calculated as follows

$$H = R_T^{1/2} H_w R_R^{1/2}, \quad (14)$$

where R_T and R_R are respectively the transmit and receive covariance matrices and $H_{w,ij} \sim \mathcal{CN}(0,1)$ and can be estimated from the antenna correlation [19].

To consider the mutual coupling, that may affect significantly to the matching efficiency, a channel model based on Z-parameter analysis has been used [20]. Other alternative is to apply a channel model based on the S-parameters [5], [6]. The MIMO capacity C_{mc} with the channel matrix H_{mc} (than takes into account mutual coupling effect) is given by

$$C_{mc} = \log_2 \det(I_2 + \frac{\rho}{2} H_{mc} H_{mc}^H) \text{ bps/Hz}, \quad (15)$$

where ρ is the signal-to-noise ratio.

The analyzed channel has a working band of 10% and a SNR of 20 dB. The parasitic array acts as transmitter antenna and an ideal array of two elements as receiver. Fig. 8 shows the capacity distribution function (CDF) within the band of the proposed design compared to the reference array with the MC matching network. The parasitic array provides a capacity 24% higher the other one.

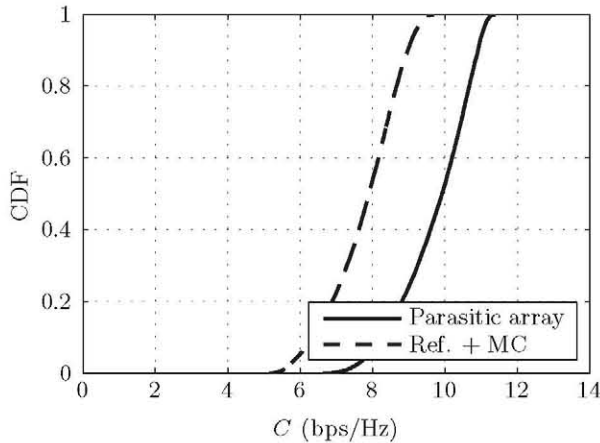


Figure 8. CDF for the parasitic array and the reference array with the MC matching network.

VI. CONCLUSIONS AND FUTURE WORKS

Classical compact arrays suffer from high coupling which degrades significantly the achievable capacity in MIMO channels. MC matching is able to provide optimal correlation and matching efficiency, although it exhibits a reduced bandwidth. The studied antenna is a compact array with parasitic elements for a 2×2 MIMO system. The proposed design has -3 dB bandwidth in matching losses of 10% and -6 dB bandwidth in correlation of 48%. In terms of binary rate, for a working band of 10% and SNR of 20 dB, the array with parasitic elements reaches an average capacity 24% higher than the array with the MC matching network.

At the moment, some prototypes are being manufactured. Some measurements are going to be made for future work.

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