Design of a Multimode MIMO Antenna Using Characteristic Modes

E. Antonino-Daviu[#1], M. Cabedo-Fabres[#1], M. Gallo[#2], M. Ferrando-Bataller[#1], and M. Bozzetti[#2]

[#1] *Instituto de Telecomunicaciones y Aplicaciones Multimedia (iTEAM),*
Universidad Politécnica de Valencia, Edificio 8G, Camino de Vera, s/n 46022 Valencia (Spain)
[1]`evanda@upvnet.upv.es`
[*] *Politecnico di Bari, via Orabona 4, 70125 Bari, Italy*
[3]`gallo@deemail.poliba.it`

Abstract— **In this communication, the design procedure of a multimode Multiple-Input Multiple-Output (MIMO) antenna is presented. The antenna consists of a metallic ring antenna operating with different orthogonal modes, whose performance in a MIMO system is similar to traditional antenna arrays. Thus, a compact MIMO antenna is obtained, which is very suitable for mobile terminals. A modal analysis of the antenna is carried out first by means of the Theory of Characteristic Modes, in order to identify the different radiating modes of the antenna. Then a set of feeding configurations is proposed so as to excite these modes. As the modes must operate in the same frequency band, a loading technique is used in the antenna in order to shift the resonance frequency of the modes to the proper band.**

I. INTRODUCTION

The use of Multiple-Input Multiple-Output (MIMO) systems has emerged as a very interesting strategy to increase the throughput and capacity of wireless systems in rich scattering environments [1]. Moreover, MIMO systems have recently proven to be an attractive option for on-body sensor networks, as they can counteract the signal fading produced by the presence of the human body [2].

Traditionally, MIMO systems employ multiple antennas spaced half wavelength or more to send or receive signals. The integration of multiple antennas in mobile handsets or sensors is not easy, due to the usually limited available space. Thus, in order to achieve high performances, good isolation and decoupling between antennas are required. To suppress mutual coupling, several methods have been proposed in the available literature [3]-[5].

Nevertheless, a more attractive option, that allows to compact even more the size of the MIMO antenna consists of using the different radiation patterns produced by different modes of an antenna. Therefore, using a single antenna different radiation characteristics can be obtained, which exhibit a similar behaviour to those MIMO systems based on multiple antennas or arrays [6].

Some multimode antennas for MIMO systems can be found in the literature. In [6], a biconical antenna is proposed for MIMO applications, while multimode spiral antennas are presented in [7].

In this paper, a new multimode MIMO antenna is proposed, which consists of a simple metallic ring excited at four points with specific phase configurations.

The objective of this paper is to present a design procedure of multimode MIMO antennas, based of the use of the Theory of Characteristic Modes (TCM), that allows to identify the different radiating modes of any antenna. By properly choosing the excitation mechanism for each mode, a simple compact antenna can be designed for MIMO applications. The design procedure can be applied to other types of antennas, whose current modes can also be computed with the TCM.

II. MODAL ANALYSIS OF A RING ANTENNA

A. Theory of Characteristic Modes

The TCM, first developed by Garbacz [8] and later refined by Harrington and Mautz in the seventies [9], can be used to obtain the radiating modes of any arbitrarily-shaped metallic structure. This Theory has been already used for the design of diverse wire and planar antennas, obtaining excellent results [10].

Characteristic modes (J_n) can be defined as a set of orthogonal real surface currents associated to any conducting object, which depend of its shape and size, and are independent of any excitation source. By definition, modes are related to the power that can be radiated by the conducting body [9].

Associated to characteristic currents, a set of characteristic fields can be computed (E_n). Therefore, the field radiated by the antenna can be expressed as a superposition of these characteristic fields or modal fields. Moreover, since characteristic far-fields are orthogonal, they provide orthogonal radiation patterns, what is very interesting for their use in MIMO systems.

A set of eigenvalues (λ_n) is also associated to characteristic modes. Each eigenvalue determines the weight of each mode in the total surface current [9]. The variation of eigenvalues with frequency allows to determine the resonance frequency and radiating bandwidth of the different modes, as it will be shown in next section.

B. Characteristic Modes of a Metallic Ring

The geometry of the proposed MIMO antenna is shown in Fig. 1. As observed, the antenna consists of a metallic ring in free space, with 31 mm outer radius and 21 mm inner radius. The antenna has also four slits located at φ=0º, 90º, 180º and

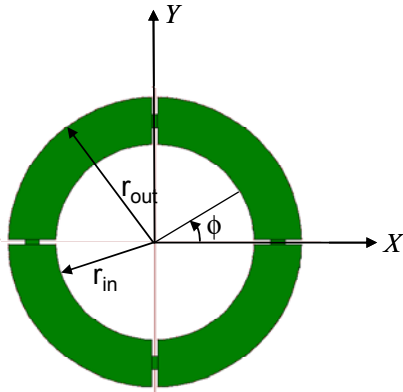270º, that accounts for the points where the excitation ports will be placed.

Fig. 1 Geometry of the proposed ring antenna (r_{in}=21 mm; r_{out}=31 mm)

Mode J_0
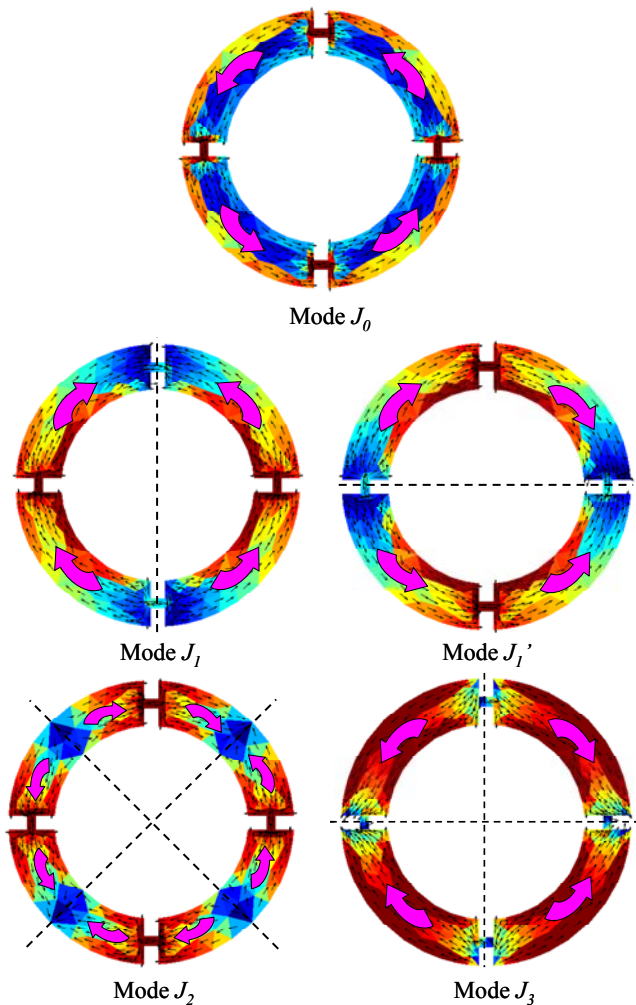
Mode J_1 Mode J_1'

Mode J_2 Mode J_3

Fig. 2 Normalized current distribution at 2.4 GHz of the first five characteristic modes (J_n) of the ring antenna shown in Fig. 1

Next, the TCM has been used to compute the characteristic modes of this structure. Fig. 2 shows the normalized current distribution (J_n) at 2.4 GHz, associated to the first five characteristic modes of this antenna. Arrows have also been included in the figure, so as to facilitate the visualization of the current flow.

As observed, mode J_0 presents currents forming a close loop around the ring, and as it will be demonstrated later, it is a special non-resonant mode with inductive contribution at all frequencies. Because of the symmetry of the ring, the first two resonating modes, J_1 and J_1', are degenerated modes that present exactly the same current distribution, but with 90º phase difference. Mode J_1 presents two current nulls at $\phi=\pm90°$, while current nulls in mode J1' are at $\phi=0°$ and 180º. Finally, modes J_2 and J_3 are higher order modes with four current nulls. Nulls of mode J_2 are at $\phi=\pm45°$ and $\pm135°$, whereas nulls of mode J_3 are at $\phi=0°$, 180º and $\pm90°$.

The resonance frequency of the current modes already described can be determined using the information provided by its associated characteristic angles (α_n). Characteristic angles can be defined as

$$\alpha_n = 180° - \tan^{-1}(\lambda_n)$$

where λ_n are the eigenvalues associated to each characteristic mode [9]. From a physical point of view, the characteristic angle models the phase angle between a characteristic current $\boldsymbol{J_n}$ and the associated characteristic field $\boldsymbol{E_n}$. Hence, a mode is at resonance when its characteristic angle α_n is 180º. The closer the characteristic angle is to 180º, the better radiating behavior presents the mode.

Fig. 3 illustrates the variation with frequency for the characteristic angles associated to the first five characteristic modes of the ring antenna. As shown, degenerated modes J_1 and J_1' resonate at 2.1 GHz, mode J_2 resonates at 3.5 GHz, and mode J_3 at 4 GHz. Note that since the ring does not present rotational symmetry, modes J_2 and J_3 are not degenerated. It can also be observed that characteristic angles associated to mode J_0 remain below 180º at all frequencies. This means that mode J_0 does not resonate and presents inductive behaviour in the range of frequencies considered.
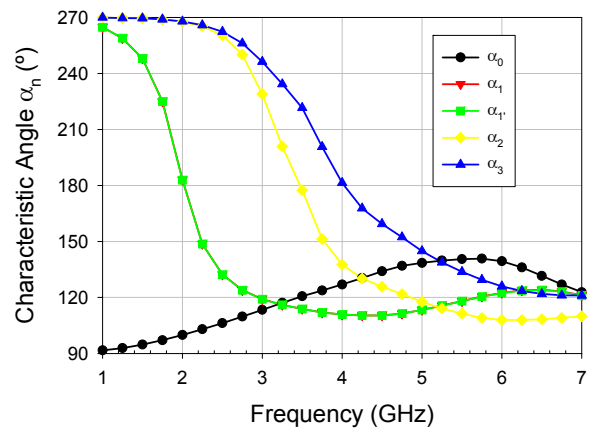

Fig. 3 Variation of the characteristic angle with frequency, for the first five characteristic modes of the ring antenna shown in Fig. 1

III. EXCITATION OF MULTIPLE MODES IN THE ANTENNA

Once the modes have been extracted, next step is to find optimum feeding schemes to excite the different modes existing on the antenna. In this case, multimode operation can be achieved by using four feeding ports symmetrically distributed along the structure, as shown in Fig. 4. Table I shows the different distribution of phases that can be employed at the ports in order to excite modes J_0, J_1, J_1' and J_2. Due to the orthogonality properties of characteristic modes over both the surface of the body and the enclosing sphere at infinity, these modes radiate power independently of one another.
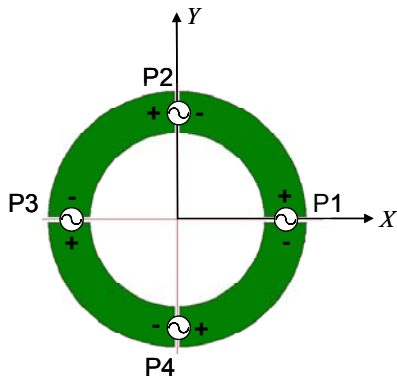

Fig. 4 Geometry of the antenna fed with four sources

TABLE I
FEEDING CONFIGURATIONS (AMPLITUDE AND PHASE) FOR THE EXCITATION OF DIFFERENT MODES IN THE ANTENNA

	P1	P2	P3	P4	Excited modes
1st Conf.	$1_{\angle 0°}$	$1_{\angle 0°}$	$1_{\angle 0°}$	$1_{\angle 0°}$	J_0
2nd Conf.	$1_{\angle 180°}$	$1_{\angle 180°}$	$1_{\angle 0°}$	$1_{\angle 0°}$	J_1, J_1'
3rd Conf.	$1_{\angle 0°}$	$1_{\angle 180°}$	$1_{\angle 0°}$	$1_{\angle 180°}$	J_2

Fig. 5 shows the current distributions obtained at 2.4 GHz with the electromagnetic simulator Zeland IE3D when using the three feeding configurations described in Table I. As observed, the use of the first feeding configuration results in the excitation of the non-resonant mode J_0, whereas the second configuration excites degenerated modes J_1 and J_1' simultaneously, and the third configuration excites the higher order mode J_2. Due to the location of the sources, mode J_3 is not excited with any of the feeding configurations.

Considering these three feeding configurations, return loss computed at each port of the antenna is depicted in Fig. 6. Because of the symmetry of the structure, the return loss obtained at every port is exactly the same. As observed, the first configuration only provides good matching for frequencies higher than 7 GHz. This is because mode J_0, which dominates at lowest frequencies, presents high inductive nature and it is not well matched at lower frequencies. In contrast, the second and third feeding

configurations yield broad matching bands at 2 GHz and 4 GHz, respectively.

Nevertheless, it is observed that each mode operates in a different frequency band, which is centred near the resonance frequency of each mode. In a MIMO system, modes must operate in the same range of frequencies, being then necessary to modify the geometry of the antenna for that purpose.
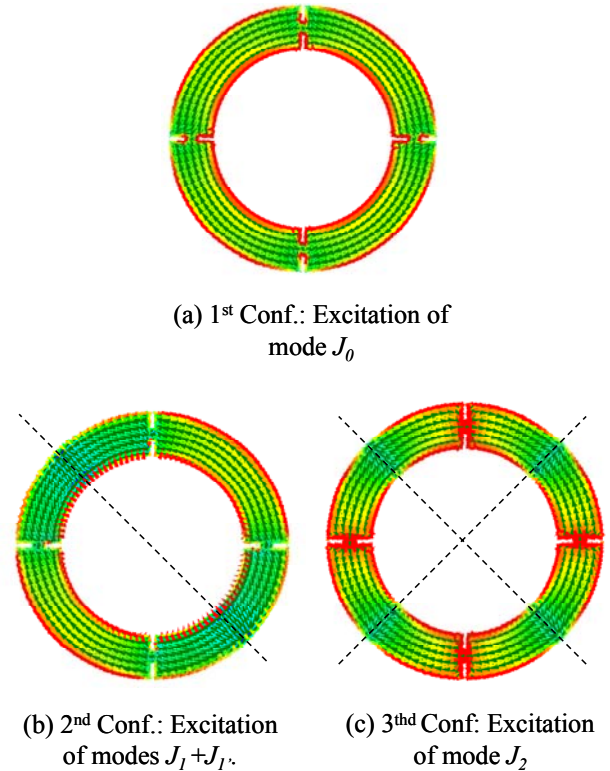

(a) 1st Conf.: Excitation of mode J_0

(b) 2nd Conf.: Excitation of modes J_1 +J_1'.

(c) 3thd Conf: Excitation of mode J_2

Fig. 5 Simulated current distribution at 2.4 GHz using the feeding configurations shown in Table I
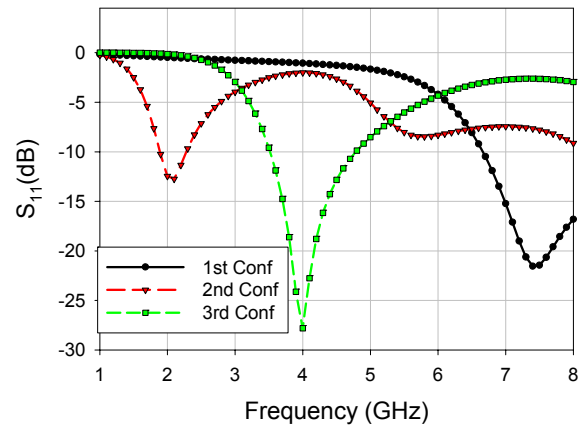

Fig.6 Return loss computed for each of the feeding configurations shown in Table I

IV. RING ANTENNA WITH CAPACITIVE LOADING

A possible solution to obtain multimode operation by combination of four orthogonal modes working at the same frequency band would consist of inserting capacitive loading

in the antenna. The use of inductive or capacitive loading allows to control the resonance frequency of each mode, and hence the frequency band of operation [11].

Due to the inductive behavior of mode J_0, the insertion of four capacitive loads has been considered. This loading has been implemented by inserting four slots in the antenna at $\phi=\pm45°$ y $\pm135°$. Fig. 7 shows the new geometry of the ring antenna with four capacitive loads. From the current distribution associated to the modes of the original antenna (see Fig. 2), it is inferred that the location decided for these loads will change the resonance frequency of modes J_0, J_1 and J_1'. In contrast, mode J_2 would not be really influenced by the presence of the capacitive loading since it presents very small current amplitude at the loading allocation.

Fig. 8 Variation of the characteristic angle with frequency, for the first five characteristic modes of the ring antenna with capacitive loading
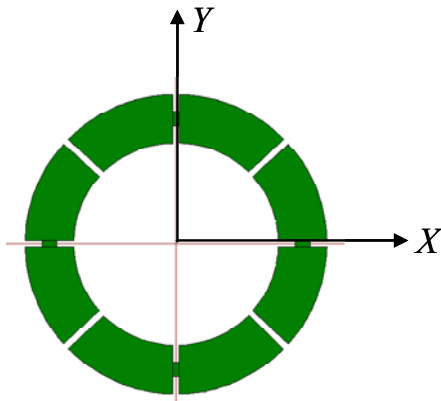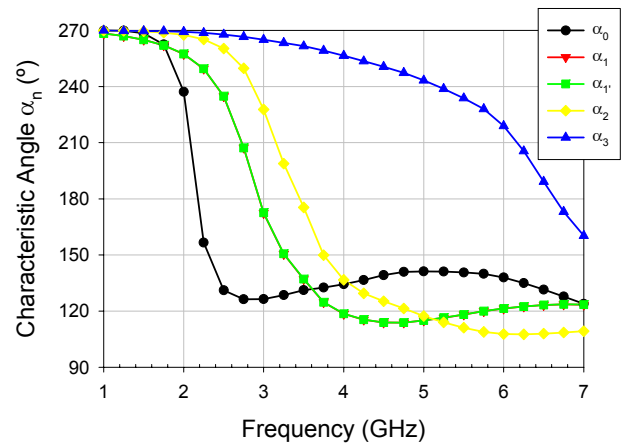

Fig. 7 Geometry of the ring antenna with capacitive loading

The current distributions associated to the characteristic modes of the antenna with capacitive loading are very similar to those shown previously in Fig. 2. However, characteristic angles associated to the modes of this new antenna change as expected. Fig. 8 represents the variation of the characteristic angle versus frequency for the ring antenna with capacitive loading. As it can be observed, if we compare these new characteristic angles with those depicted in Fig. 3 for the antenna without reactive loading, it can be seen that resonance frequency of lower modes has been shifted up. Thus, it can be observed that characteristic angle associated to mode J_2 does not change, whereas for the degenerated modes J_1 and J_1' the curve of the characteristic angle has shifted towards higher frequencies. The resonance frequency of modes J_1, J_1' and J_2 is now very close. Moreover, the insertion of capacitive loads has compensated the inductive effect exhibited by mode J_0, making this mode to become a resonant mode. Resonance frequency of mode J_0 is around 2.1 GHz, which is also very close to the resonance frequencies of the other three modes.

Then, in order to excite the four different modes in the loaded antenna, the same feeding configurations shown in Table I have been used. Fig. 9 shows the return loss obtained at each input port in this case, for each one of the feeding configurations.
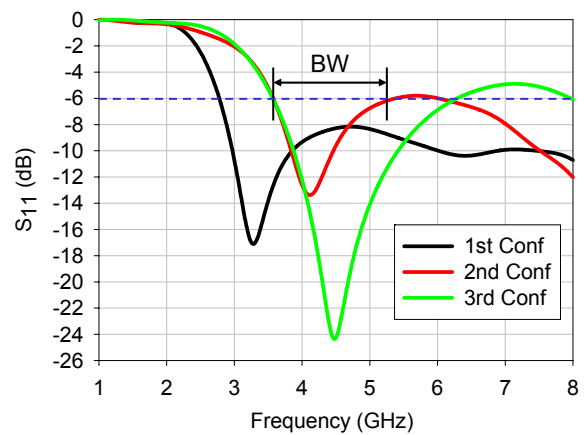
Fig. 9 Return loss obtained for the loaded antenna for the three feeding configurations

1st. Configuration   2nd. Configuration
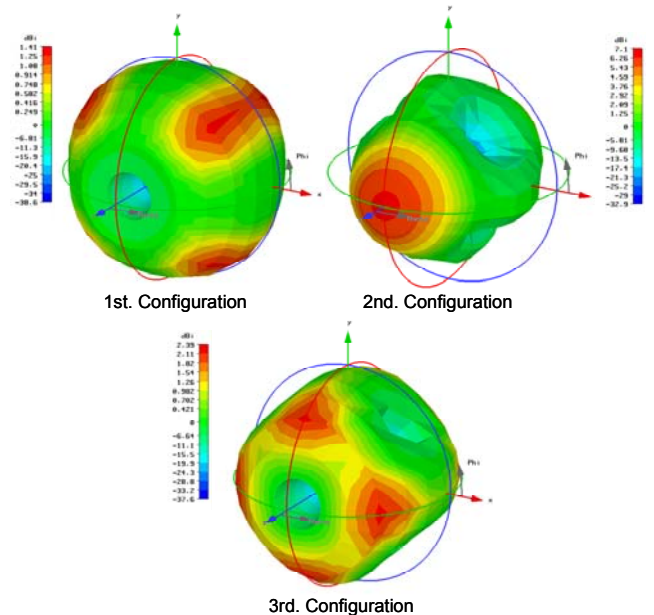
3rd. Configuration

Fig. 10 Simulated radiation patterns obtained for the loaded antenna with the three feeding configurations

As observed, by adjusting the capacitance value of the load, modal resonances have moved closer in frequency. As it can be seen in the figure, a bandwidth (BW) of 43.55% is obtained with the proposed design, if we consider a reference value of -6 dB for the return loss. As observed, the central frequency of the operating band is 4.1 GHz, which can be shifted to other frequencies by simply scaling the antenna dimensions.

Finally, Fig. 10 shows the radiation pattern exhibited by the antenna for each of the three feeding configurations, at 4.1 GHz. As expected, the pattern associated to the mode excited by each of the feeding configurations is obtained.

V. CONCLUSIONS

In the present paper the design procedure of a multimode MIMO antenna has been presented. The design of the antenna starts from the modal analysis of a metallic structure with a ring shape, in which the modes computed exhibit orthogonal radiation patterns. After analyzing the current distribution of each mode, the optimum feeding mechanism to excite these modes is chosen. Thus, three different feeding configurations have been considered to excite four orthogonal modes in the antenna. In order to make these modes to operate simultaneously in the same frequency band, the antenna has been capacitively loaded, obtaining a new geometry. Therefore, a multimode antenna has been finally obtained, which is suitable to operate with four orthogonal modes in a MIMO system.

ACKNOWLEDGMENT

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