Design of a Multimode MIMO Antenna Using the Theory of Characteristic Modes

Eva ANTONINO-DAVIU [1], *Marta CABEDO-FABRÉS* [1], *Miguel FERRANDO-BATALLER* [1], *Michele GALLO* [2]

[1] Instituto de Telecomunicaciones y Aplicaciones Multimedia (iTEAM), Universidad Politécnica de Valencia, Edificio 8G, Camino de Vera, s/n, 46022 Valencia, Spain
[2] Politecnico di Bari, via Orabona 4, 70125, Bari, Italy

evanda@doctor.upv.es, marcafab@dcom.upv.es

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.*

Keywords

Antenna design, multimode antenna, MIMO, multiple feed, capacitive loading.

1. 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 behavior 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 communication is to present a design procedure of multimode MIMO antennas, based on the use of the Theory of Characteristic Modes (TCM) which allows identifying 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.

2. Theory of Characteristic Modes

The Theory of Characteristic Modes, 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. These radiating modes, known as characteristic modes, not only present really attractive orthogonality properties, but also bring physical insight into the radiating phenomena taking place on the antenna.

Because of these advantages, TCM is extremely useful for systematic analysis and design of antenna. Recently, TCM has been used for the design of diverse wire and planar antennas, obtaining excellent results [10]. In this communication, it will be demonstrated that using TCM a controlled design of MIMO antennas can be performed on a clear and rational basis.

Characteristic modes (J_n) can be defined as a set of orthogonal real surface currents associated to any conducting object, which depend on its shape and size, and are independent of any excitation source. As characteristic modes form a set of orthogonal functions, they can be used to expand the total current J on the surface of the antenna as follows:

$$J = \sum_n \frac{V_n^i J_n}{1 + j\lambda_n} \qquad (1)$$

where J_n are the eigencurrents or characteristic modes, λ_n are the eigenvalues and V_n^i is the modal excitation coefficient.

The modal excitation coefficient can be obtained as:

$$V_n^i = \left\langle J_n, E^i \right\rangle = \oiint_S J_n \cdot E^i ds \,. \qquad (2)$$

The product $V_n^i J_n$ in (1) models the coupling between the excitation and the nth mode, and determines which modes will be excited by the antenna feed or incident field (E^i).

Note however that the total current in (1) also depends on λ_n, the eigenvalue associated to the nth characteristic current mode. As it will be shown in next section, the variation of eigenvalues with frequency gives information about the resonance frequency and radiating bandwidth of the different current modes. In general, eigenvalues range from -∞ to +∞. Considering a mode is at resonance when its associated eigenvalue is zero, it is inferred that the smaller the magnitude of the eigenvalue is, the more efficiently the mode radiates when excited. Additionally, the sign of the eigenvalue determines whether the mode contributes to store magnetic energy (λ_n >0) or electric energy (λ_n <0).

Finally, associated to characteristic currents, a set of characteristic fields can be computed. 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.

3. 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.

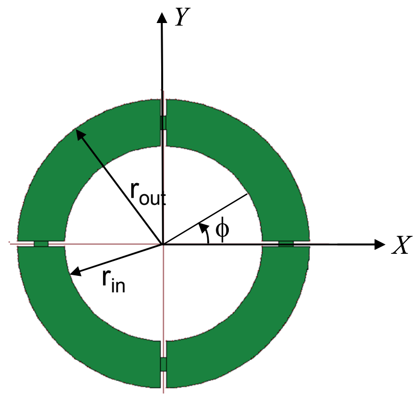


Fig. 1. Geometry of the proposed ring antenna (r_{in}=21 mm; r_{out}=31 mm).

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.

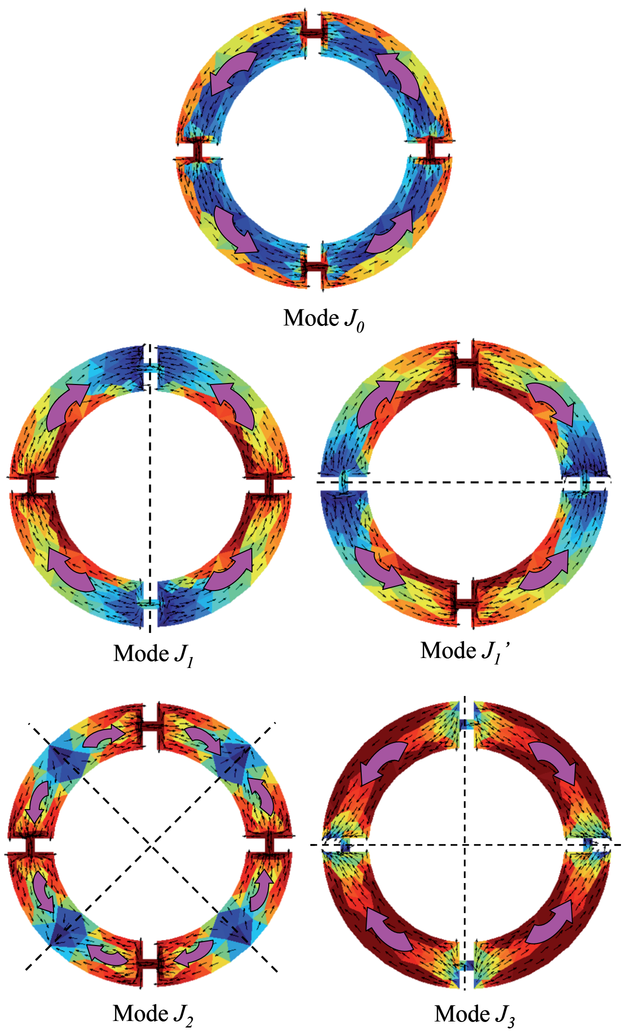


Fig. 2. Normalized current distribution at 2.4 GHz of the first five characteristic modes (J_n) of the ring antenna shown in Fig. 1.

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 ϕ=±90º, while current nulls in mode $J_1{}'$ are at ϕ=0º and 180º. Finally, modes J_2 and J_3 are higher order modes with four current nulls. Nulls of mode J_2 are at ϕ=±45º and ±135º, whereas nulls of mode J_3 are at ϕ=0º, 180º and ±90º.

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

$$\alpha_n = 180^\circ - \tan^{-1}(\lambda_n) \qquad (3)$$

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 J_n and the associated characteristic field 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 behavior in the range of frequencies considered.

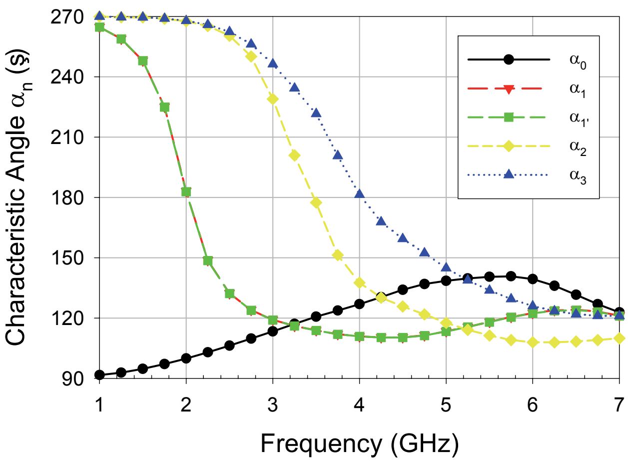


Fig. 3. Variation of the characteristic angle with frequency, for the first five characteristic modes of the ring antenna shown in Fig. 1.

4. 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. Tab. 1 summarizes 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.

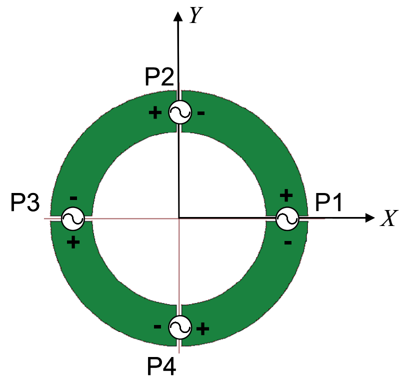


Fig. 4. Geometry of the antenna fed with four sources.

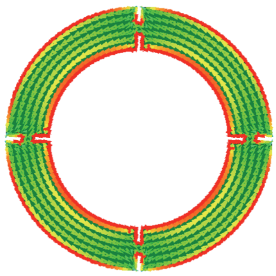
	P1	P2	P3	P4	Excited modes
1st Conf.	$1\angle 0^\circ$	$1\angle 0^\circ$	$1\angle 0^\circ$	$1\angle 0^\circ$	J_0
2nd Conf.	$1\angle 180^\circ$	$1\angle 180^\circ$	$1\angle 0^\circ$	$1\angle 0^\circ$	J_1 , $J_1{}'$
3rd Conf.	$1\angle 0^\circ$	$1\angle 180^\circ$	$1\angle 0^\circ$	$1\angle 180^\circ$	J_2

Tab. 1. Feeding configurations (amplitude and phase) for the excitation of different modes in the antenna.

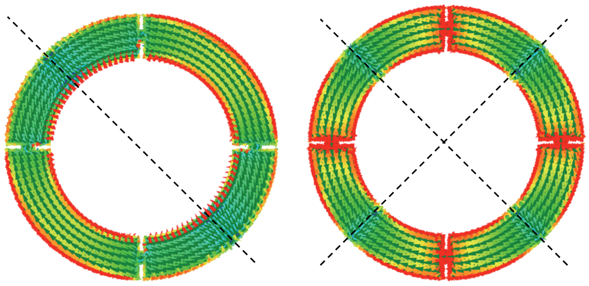
Fig. 5 shows the current distributions obtained at 2.4 GHz with the electromagnetic simulator Zeland IE3D when using the three feeding configurations described in Tab. 1. Standard ports have been used in the simulation. As observed, the use of the first feeding configuration results in the excitation 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.

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 fre quencies. 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 centered 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 proposed in Tab. 1.

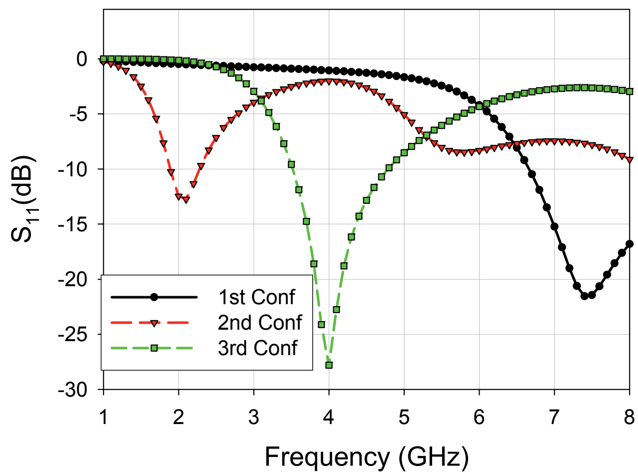


Fig.6. Return loss computed for each of the feeding configurations shown in Tab. 1.

5. 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 ϕ=±45º and ±135º. 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.

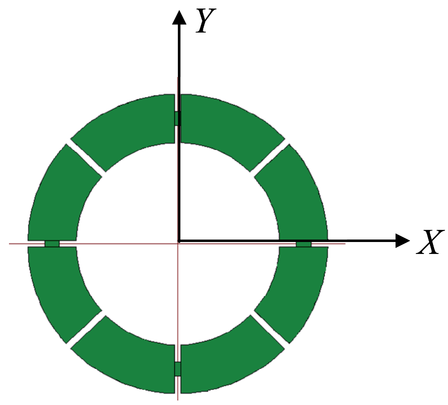


Fig. 7. Geometry of the ring antenna with capacitive loading.

The current distributions associated to the characteristic modes of the antenna with capacitive loading are presented in Fig. 8. As observed these current 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. 9 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. Degenerated modes J_1 and J_1' resonate at 2.9 GHz, and mode J_2 still resonates at 3.5 GHz. 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 close to the resonance frequencies of the other three modes.

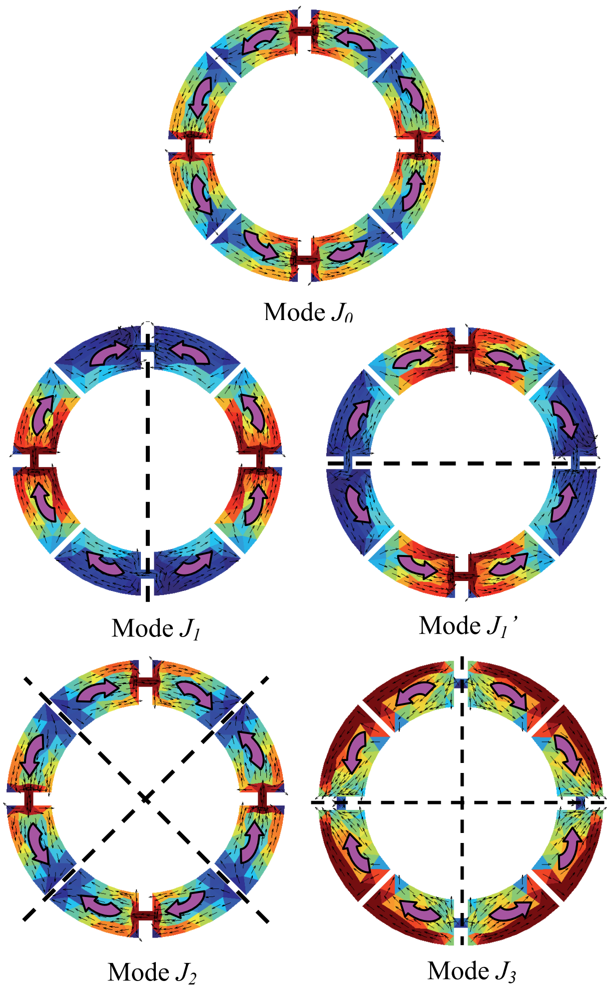


Fig. 8. Normalized current distribution at 2.4 GHz of the first five characteristic modes (J_n) of the ring antenna with capacitive loading shown in Fig. 7.

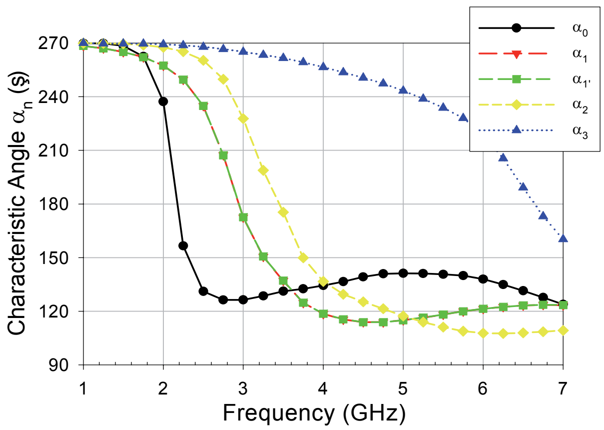


Fig. 9. Variation of the characteristic angle with frequency, for the first five characteristic modes of the ring antenna with capacitive loading.

Then, in order to excite the four different modes in the loaded antenna, the same feeding configurations shown in Tab. 1 have been used. Fig. 10 shows the return loss obtained at each input port in this case, for each one of the 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 Fig. 10, 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. It can also be noticed, 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. 11 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. Furthermore, all radiation patterns are orthogonal in order to provide MIMO behavior by multimode operation.

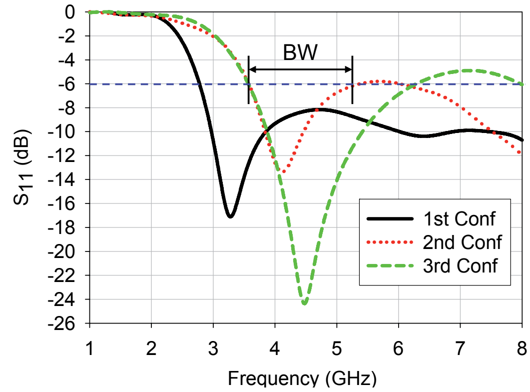


Fig. 10. Return loss obtained for the loaded antenna for the three feeding configurations.

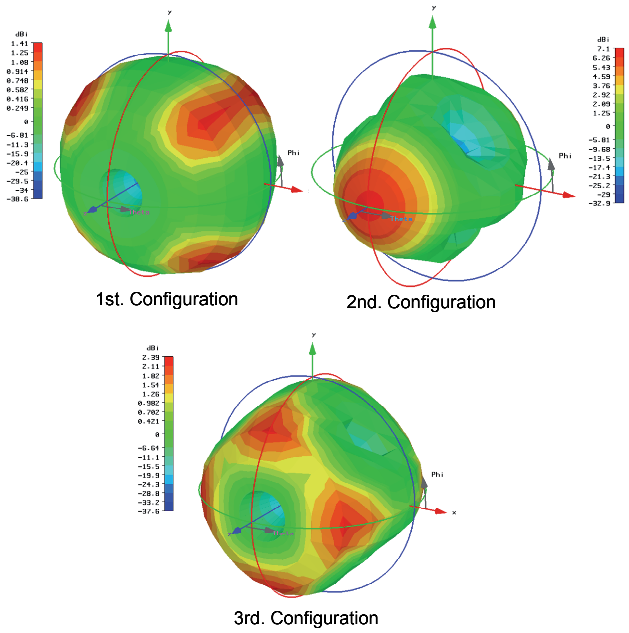


Fig. 11. Simulated radiation patterns obtained for the loaded antenna with the three feeding configurations.

6. 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 analysis 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.

Acknowledgments

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About Authors ...

Eva ANTONINO-DAVIU (*1978 Valencia, Spain) received the M.S. and Ph.D. degrees in electrical engineering from the Universidad Politécnica de Valencia, Spain, in 2002 and 2008, respectively. In 2002 she joined the Electromagnetic Radiation Group, Universidad Politecnica de Valencia, and in 2005 she became a Lecturer at the Escuela Politécnia Superior de Gandia, Gandia, Spain. During 2005 she stayed for several months as a guest researcher at the Dept. of Antennas & EM Modelling of IMST GmbH, in Kamp-Lintfort, Germany. Her current research interests include wideband and multi-band planar antenna design and optimization and computational methods for printed structures. Dr. Antonino-Daviu was awarded the "Premio Extraordinario de Tesis Doctoral" (Best Ph.D. thesis) from the Universidad Politécnica de Valencia in 2008.

Marta CABEDO-FABRÉS (*1976 Valencia, Spain) received the M.S. and Ph.D. degrees in electrical engineering from Universidad Politécnica de Valencia, Spain, in 2001 and 2007, respectively. In 2001, she joined the Electromagnetic Radiation Group at Universidad Politécnica de Valencia (UPV), as a Research Assistant. In 2004, she became an Associate Professor in the Communications Dept., Universidad Politécnica de Valencia. Her current scientific interests include numerical methods for solving electromagnetic problems, and design and optimization techniques for wideband and multi-band antennas.

Miguel FERRANDO-BATALLER (*1954 Alcoy, Spain) received the M.S. and Ph.D. degrees in electrical engineering from the Universidad Politecnica de Catalunya, Barcelona, Spain, in 1977 and 1982, respectively. From 1977 to 1982, he was a Teaching Assistant with the Antennas, Microwave, and Radar Group, Universidad Politécnica de Catalunya, and in 1982 he became an Associate Professor. In 1990, he joined the Universidad Politecnica de Valencia, Valencia, Spain, where he is a Professor. His current research activities include numerical methods, antenna design, and e-learning activities.

Michele GALLO (*1979 Bari, Italy) received the M.S. and Ph.D. degrees in electronic engineering from the Politecnico of Bari, Italy, in 2004 and 2008, respectively. In 2005 he joined the Electromagnetic Field Group at the Politecnico di Bari where he is currently working as a post-doc researcher. From February 2006 to February 2007 he joined, as a guest researcher, the Communications Engineering Group at the University of Birmingham (UK) and, from October 2007 to March 2008 he stayed in the Electromagnetic Radiation Group, Universidad Politecnica de Valencia, Spain. His research interests include wideband and MIMO antennas, antenna for wireless on-body communications and antenna diversity.