Compact planar antennas with multiple ports for MIMO and diversity applications

M. Cabedo[1], E. Antonino[1], M.Ferrando[1], V. M. Rodrigo[1], A. Vila[1], J. M. Molina[2], and L. Juan[2]
[1] Instituto de Telecomunicaciones y Aplicaciones Multimedia, Universidad Politécnica de Valencia,
8G Building - access D. Camino de Vera s/n - 46022 Valencia (Spain)
[2] Grupo Sistemas de Comunicaciones Móviles
Dpto. Tecnologías de la Información y las Comunicaciones Universidad Politécnica de Cartagena
Antiguo Hospital de Marina, E-30202, Cartagena (Spain)
Corresponding author: marcafab@dcom.upv.es

Abstract

This paper summarizes the research that has been developed by the authors for the last years, concerning the design of compact planar antennas with multiple ports for MIMO and diversity applications. Several designs based on two-port planar monopole antennas are proposed for WiFi and WiMAX frequency bands. All these monopoles present two highly isolated feeding ports in order to provide diversity, and hence capacity increase. A planar multimode MIMO antenna for Wireless Body Area Networks is also presented. This antenna uses multimode diversity, a combination of pattern and polarization diversity, to obtain uncorrelated channel impulse responses for MIMO systems. Prototypes of all the antennas have been fabricated and characterized at iTEAM's facilities. Measurements of the prototypes have been made at Universidad Politécnica de Cartagena using a MIMO channel sounder based on a multiport network analyzer.

Keywords. MIMO systems, diversity antennas, monopole antennas, multimode antennas.

1. Introduction

Multiple Input Multiple Output (MIMO) systems are a very up-to-date solution to face the growing capacity demand for new wireless communication systems. By using multiple antennas at the transmitter and at the receiver, significant improvement in the system capacity is achieved when working at rich scattering environments [1]. Since this kind of environment makes signals from each transmitter highly uncorrelated at each receiver, very high data rates may be reached opening parallel spatial data channels within the same frequency band at no additional power expenditure [2]. Alternatively, MIMO systems can also be used to improve the performance by decreasing the effect of the multi-path propagation. To achieve high performances, good isolation between the antennas is required. To obtain the required isolation, the multiple antennas that constitute the system need to be spaced half wavelength or more. The problem is that the volume occupied by multiple antennas is often prohibited, especially for modern compact handsets.

Recent studies have demonstrated that multiple antennas can be replaced by a single antenna, using different techniques. First approach consists in using compact integrated diversity antennas, like the one described in [3], that incorporate two antennas into one, and uses two isolated feed ports to provide diversity signals. Another alternative is to use a multimode antenna, like the biconical antenna proposed in [4], or the archimedian spiral presented in [5]. This kind of antennas radiate different modes depending on the excitation, so different radiation patterns can be generated simultaneously at the same frequency band, in order to obtain uncorrelated signals.

In this paper the above described techniques are applied to design compact planar antennas with multiple ports for MIMO and diversity applications. In Section 2 several designs based on two-port planar monopole antennas are proposed. All these monopoles present two highly isolated feeding ports in order to provide diversity, and hence capacity increase at WiFi or WiMAX frequency bands. The different techniques applied to achieve the required isolation between ports are explained in detail. Prototypes of the proposed antennas are shown, as well as experimental results.

In section 3 a planar multimode antenna for MIMO applications at Wireless Body Area Networks (WBANs) is presented. MIMO systems not only have demonstrated to be a perfect choice for capacity increase, but also have proven to be an attractive option for WBAN, as they counteract the signal fading produced by the presence of the human body [6]. The proposed antenna is a capacitive loaded metallic ring that exhibits a multimode characteristic. The multimode behaviour is obtained using four feeding ports excited with specific phase configurations.

2. Compact Planar Monopoles for MIMO and Diversity Applications

In this section three very simple, yet effective diversity antennas based on planar monopoles are proposed. Planar monopoles are very well-known antennas that have long been used in mobile communications due to their remarkable properties such as wide impedance bandwidth, omnidirectional radiation pattern, simple structure, small size, and low cost. Because of the broad bandwidth they provide, planar monopole antennas are extremely attractive to be used in emerging ultra-wideband (UWB) applications [7]. Moreover, they are also considered excellent candidates to face up the increasing demand for wireless communication services, which require multi-band or broadband antennas capable of operating at different standards.

In last years, a lot of work has been focused on the determination of the planar monopole shape which provides the wider impedance bandwidth. As a result, a great number of different planar monopole geometries have been characterized experimentally [8]-[9], and automatic design methods have been developed to achieve the optimum planar shape [10]. However, other strategies to improve the impedance bandwidth which do not involve a modification of the geometry of the planar element have been investigated.

In a previous work, a thorough study of the properties of the current modes in planar monopoles, based on the Theory of Characteristic Modes [11], led the authors to the conclusion that the bandwidth performance of monopole antenna would improve if only the presence of the dominant vertical current mode was allowed in the structure. This was accomplished with the double feed planar monopole, proposed by the authors in [12] for UWB applications. This monopole exhibited a novel feeding configuration that consisted of a splitting network connected to two symmetrical ports on its base. The symmetry of the ports prevented the excitation of horizontal currents and assured that only the dominant vertical current mode was present at the structure. As a result, an improvement in the polarization properties and impedance bandwidth of the square monopole was achieved.

But let us suppose now, that the correlation between the two ports of this double fed monopole were small. This would mean that the two ports could be fed independently providing diversity, the same way as the Y-patch proposed in [3]. In section 2.1 and 2.2, it is demonstrated that a long slit cut along the symmetry axis of the monopole is a possible solution to get the isolation between ports required for a two-port antenna diversity system. In section 2.3 it is shown that the isolation between ports can also be obtained by exciting a higher order mode of the monopole with an appropriate current distribution

A long slit cut along the symmetry axis is a possible solution to get the isolation between ports required for a two-port antenna diversity system.

2.1 Planar monopole with isolating slit for Wifi frequency band.

Fig. 1 shows a planar monopole valid for diversity applications that is derived from the double fed square monopole described above. To obtain the required isolation between the ports and guarantee the only presence of vertical currents on the structure, a long slit is cut along the symmetry axis of the antenna. The dimensions of the antenna have been optimized to operate at 2.4 GHz. The location and size of both ports have been adjusted to match the connectors' impedance (50Ω). The feeding ports are symmetrically placed on both sides of the isolating slit.

A prototype of the monopole is presented in Fig. 2. The monopole has been fabricated on a cooper sheet over ROHACELL foam, and it is perpendicularly mounted above a metallic ground plane.

Fig. 3 illustrates the simulated and measured S parameters for the antenna prototype. Simulations have been performed using electromagnetic software Zeland IE3D. As observed, both results are in fairly good agreement. The structure presents a S_{11} parameter less than -10 dB in a range of frequencies of about 1 GHz. Besides, the S_{12} parameter takes values below -35 dB at

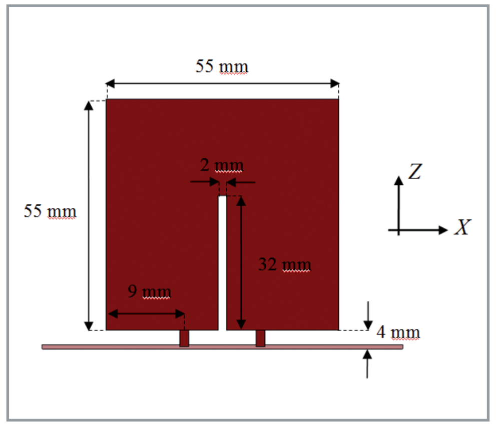


Figure 1. *Geometry of the planar square monopole with isolated ports.*

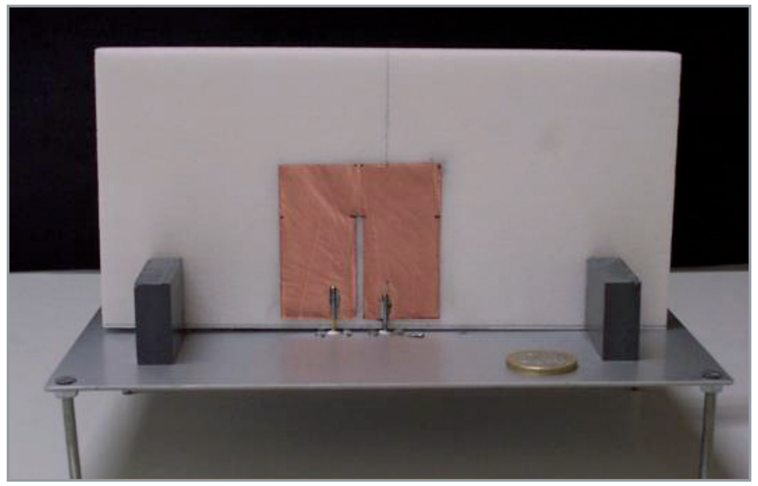


Figure 2. *Prototype of the square monopole with isolated ports for WiFi frequency band.*

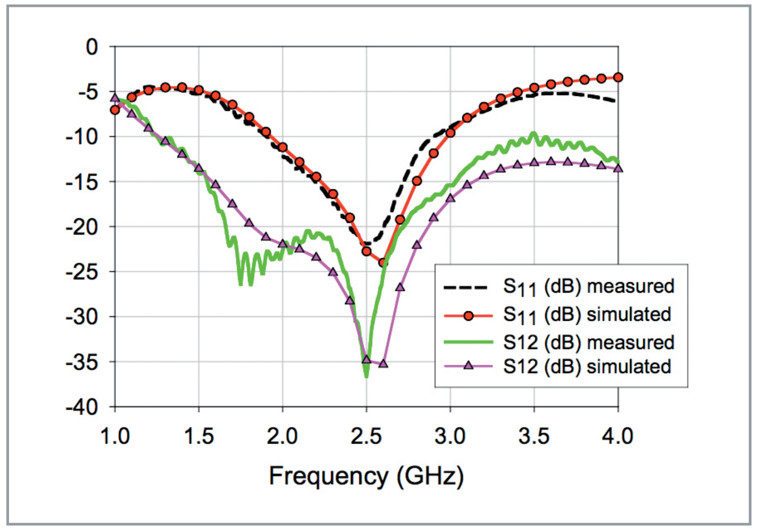


Figure 3. *Simulated and measured S parameters for the antenna prototype shown in Fig. 2.*

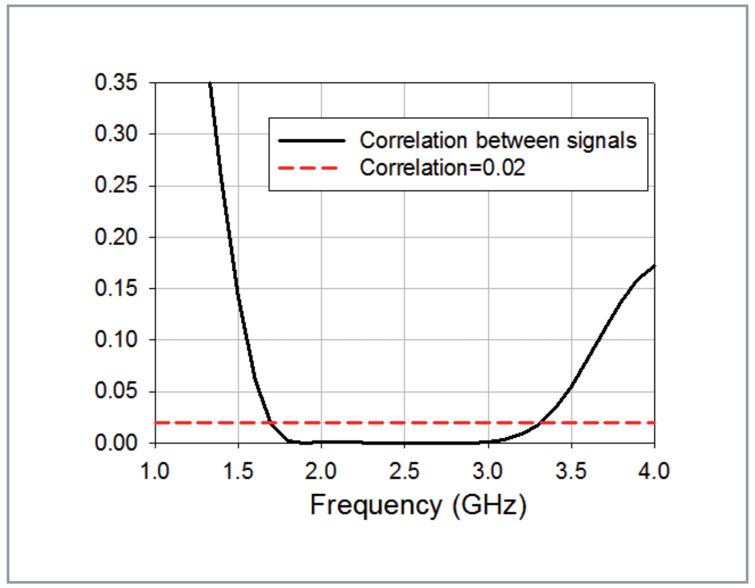


Figure 4. *Envelope correlation between ports obtained from the S parameters of the prototype shown in Fig. 2.*

the design frequency. Therefore, the required isolation between ports for a two-port antenna diversity system is achieved

To characterize port isolation in a more precise way, the envelope correlation has been calculated from measured S parameters, as described in [13]. Using this definition good diversity gain is said to be possible when the correlation is below 0.02. As observed in Fig. 4, the prototype provides correlation values that stay below 0.02 in all the bandwidth of interest. This means that the antenna could be also utilized as a duplexer, allowing the received and transmitted signals to have separate signal paths with more than 20 dB isolation.

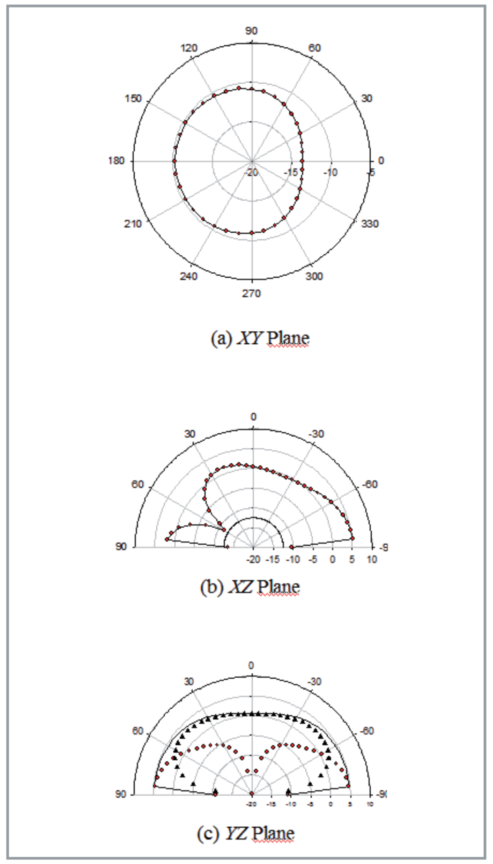


Figure 5. *Simulated radiation patterns at 2.4 GHz: (a) XY Plane, (b) XZ Plane, (c) YZ Plane.*

Fig. 5 shows the radiation patterns computed at 2.4 GHz for the antenna using IE3D. These patterns have been obtained by exciting port 1 and terminating port 2 with a 50 Ω load. As observed, the XY plane presents omnidirectional characteristic. Due to the symmetry of the system, the radiation patterns for port 2 are exactly the same but reflected in the plane of symmetry in the XZ plane.

To verify the suitability of this new design for MIMO applications, the antenna has been measured from 2 GHz to 3 GHz at Technical University of Cartagena. Fig. 6 shows a schematic of the channel sounder used for the measurement. As explained in [14], this MIMO channel sounder, that is based on a multiport network analyzer (Agilent ENA) and a fast switch, have been used to measure the frequency response in an indoor environment with LOS conditions. The multiport network analyzer (ENA) plays the role of transmitter and receiver simultaneously. This simplifies enormously synchronization problems (frequency sweep triggering and 10 MHz synchronization). The control of the measurements is automatically done by a Laptop, which is connected to the fast switch via GPIB and to the ENA via a WLAN. It is possible to use 2.4 GHz WLAN or 5 GHz WLAN. For the 4x4 MIMO system depicted in Fig. 6, the four receiving antennas are connected directly to the ENA ports. Another port acts as the transmitter, and it is connected to a 30 dB low noise amplifier, to a low losses 50 metres cable and to a fast switch, in order to increase to four the number of transmitting antennas. The antennas are mounted on a 1.5 m mast equipped with two guides to vary the spacing between the antennas up to 2λ at 2.4 GHz.

For the characterization of our antenna, a 1x2 SIMO (Single Input Multiple Output) system has been implemented, using a Cisco Aironet omnidirectional mast mount antenna (AIR-ANT2506) with 5 dBi gain as the transmitter, and the two port planar monopole as the receiver. The distance between the transmitter and the receiver has been fixed to 3 m. Measurements have been taken in 1601 frequencies, with an intermediate frequency of 1 KHz. During the measurements, there has been no movement in the lab, so the channel has been supposed quasi-static.

The performance of other 1x2 SIMO systems has been studied for comparison purposes. In all these SIMO systems, the planar monopole has

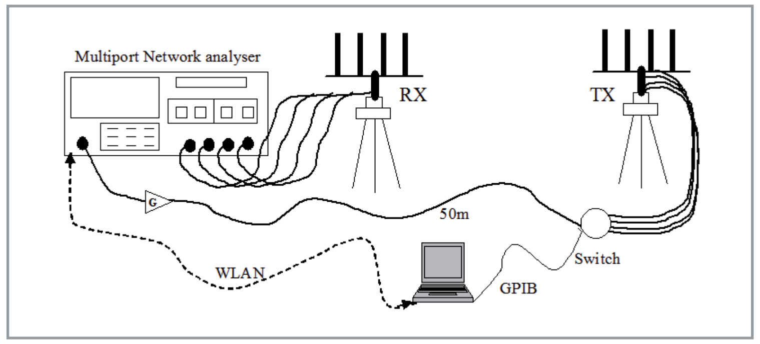


Figure 6. *Diagram of the channel sounder based on one multiport network analyzer and a fast switch.*

been replaced at reception by two Cisco Aironet monopoles with different spacing d. Fig. 7 shows the relative power measured at each receiving antenna, for the two ports of the planar monopole, and for the two vertical Cisco monopoles with different spacing. As observed, in every SIMO system, the power received by each antenna at reception is similar. Obviously, the Cisco monopoles present higher gain than the planar monopole, so they receive a higher power. It can also be noted that high power is received at the WiFi band (around 2.4 GHz) since the monopoles are tune in to that frequency.

Fig. 8 shows the correlation for the two antennas at reception for this environment. In general, the correlation decreases when the distance between the two receiving antennas increases. As observed, the behaviour of the planar monopole resembles that of the two Cisco monopoles with λ/2 spacing. According to these results, the two port planar monopole could be considered equivalent to two vertical Cisco monopoles with λ/2 spacing at 2.4 GHz. Therefore, it seems that

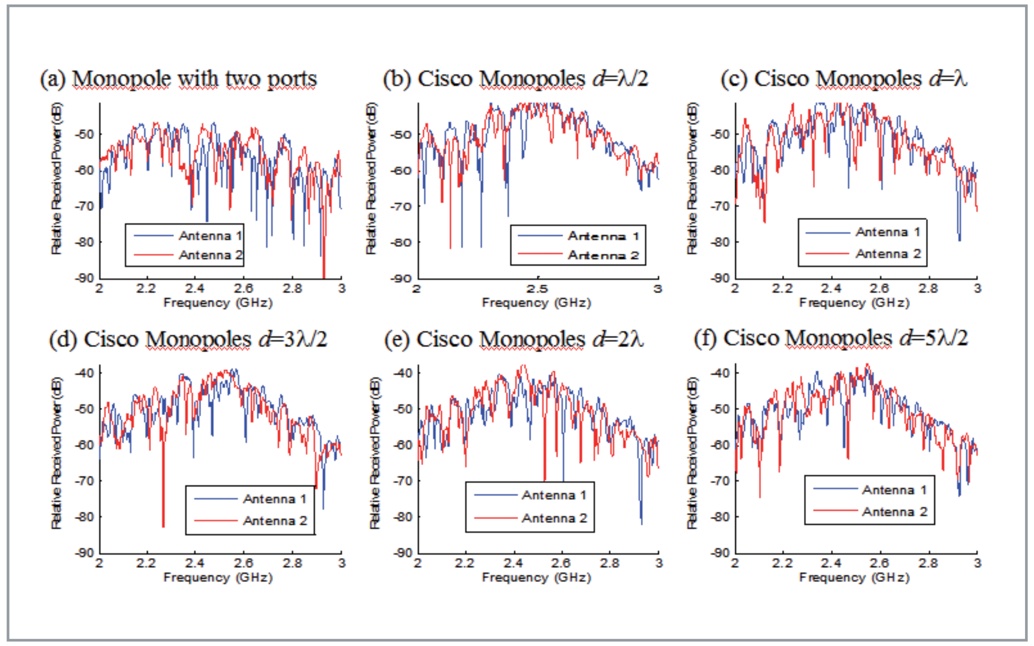
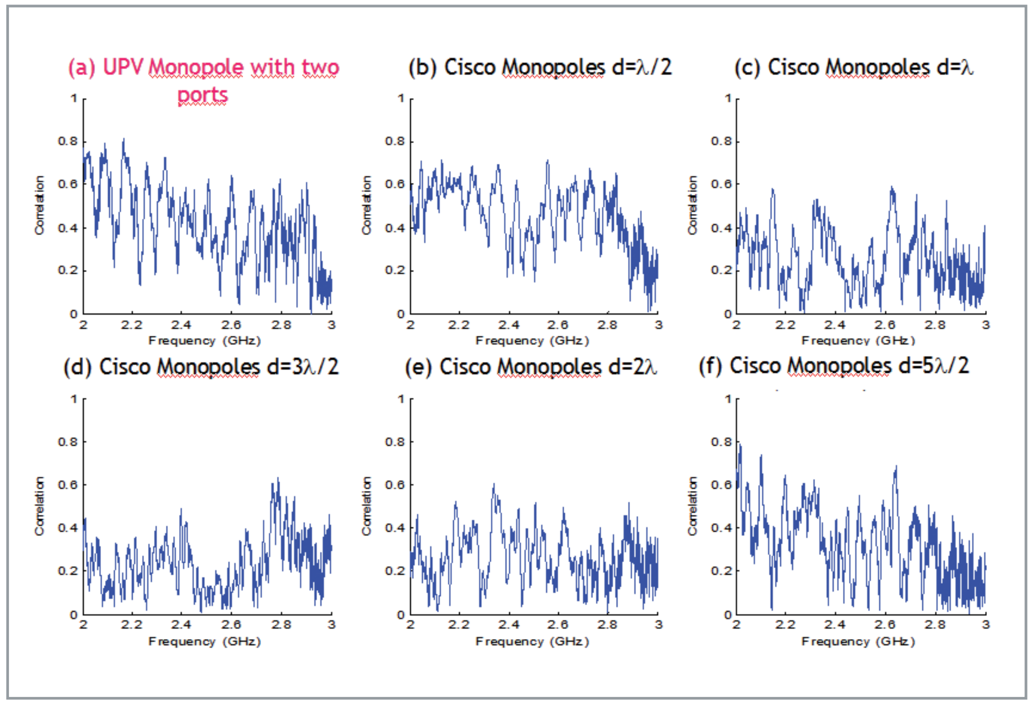


Figure 7. *Power measured at each receiving antenna as a function of frequency, for the two port planar monopole, and for the array of two vertical Cisco monopoles with different spacing d.*



■ **Figure 8.** *Correlation between the two antennas at reception, for the two port planar monopole, and for the array of two vertical Cisco monopoles with different spacing d.*

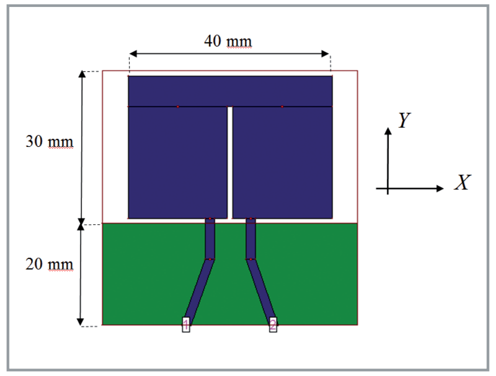
the proposed antenna meets the requirements for achieving diversity, and hence to increase the system's capacity, while it presents compact size and wide impedance bandwidth.

2.2. Printed monopole with isolating slit for WiMAX at 3.5 GHz frequency band.

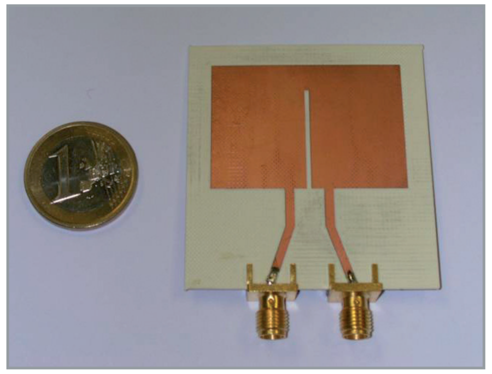
In order to obtain a compact antenna with MIMO behaviour appropriate for a WiMAX system, the dimensions of the monopole previously presented have been scaled and optimized to operate at 3.5 GHz. A printed design, with the radiating element at the front side, and the ground plane at the backside of a printed circuit board (PCB), has been chosen since it constitutes a more compact solution than the one proposed in section 2.1. The dimensions of the antenna which are detailed in Fig. 9, have been adjusted to match the size of a common PCMCIA card. Again, port isolation is achieved by inserting a decoupling slit between the excitation ports. Fig. 10 shows a prototype of this antenna fabricated in microstrip technology, on a GML 2031 substrate of height h=0.76 mm and relative permittivity ε_r=3.2.

Fig. 11 confirms that at 3.5 GHz, both the measured and simulated S parameters are below -20 dB. Moreover, it is observed that measured S parameters for the prototype are in close agreement with the simulations performed with IE3D. In Fig. 12 it can be verified that the prototype also provides envelope correlation values lower than 0.02 in the bandwidth of interest.

Fig. 13 shows the radiation patterns computed at 3.5 GHz for port 1 of the antenna using IE3D. As observed, the XY plane presents omnidirectional characteristic. Due to the symmetry of the system, the radiation patterns for port 2 are exactly the same but reflected in the plane of symmetry in the YZ plane. It should be noted that although the magnitude of the patterns from port 1 and 2 are similar, their phases are different enough to produce low cross-correlation.



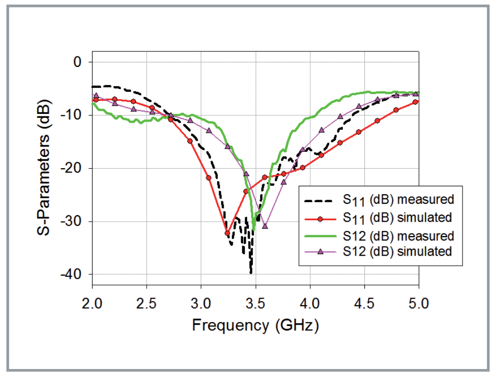
■ **Figure 9.** *Geometry of the printed square monopole with isolated microstrip ports.*



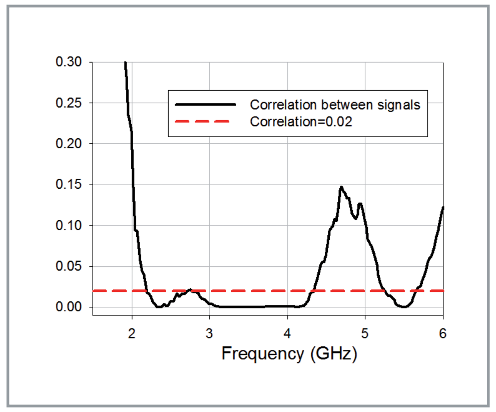
■ **Figure 10.** *Prototype of the printed monopole with isolated ports for WiMAX at 3.5 GHz.*

Once again, the prototype of the antenna has been measured in the lab of the Technical University of Cartagena. In this case, a 2x2 MIMO system has been implemented. As observed in Fig.14, in this system the transmitter is the printed monopole that behaves as two antennas due to the high isolation between its ports. The receiver is formed by two omnidirectional UWB antennas, EM-6116 with 1dBi gain that are spaced s=2λ at 3.5 GHz. A photograph of these antennas can be seen in Fig. 15. Measurements have been taken at 801 frequencies from 3 GHz to 4 GHz, with an intermediate frequency of 1 KHz, in a rich scattering indoor environment with LOS condition. The measurement has been made for different distances d between the transmitter and the receiver. The result at each measurement point is a 3-D channel matrix $G_{2x2x801}$, whose dimensions correspond with the number of receiving antennas, transmitting antennas and analyzed frequencies.

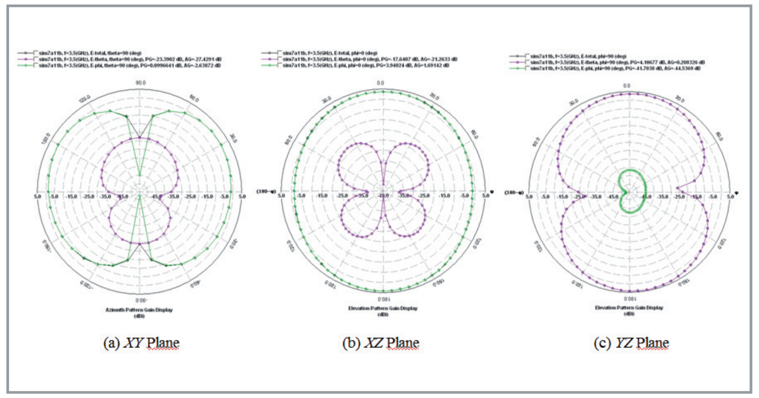
For a MIMO system with M transmitting antennas and N receiving antennas, the maximum theoretical capacity for a uniform distributed transmitted power with a signal to noise ratio of SNR can be expressed as [1]:



■ **Figure 11.** *Simulated and measured S parameters for the antenna prototype shown in Fig. 10.*



■ **Figure 12.** *Envelope correlation values between ports obtained for the prototype of Fig. 10.*



■ **Figure 13.** *Simulated radiation patterns at 3.5 GHz: (a) XY Plane, (b) XZ Plane , (c) YZ Plane*

$$C_{\mathrm{MIMO}}(f) = \log_2\left(\det\left[\mathbf{I}_N + \frac{SNR}{M}\mathbf{H}(f)\mathbf{H}^H(f)\right]\right) \text{ in bit/s/Hz} \tag{1}$$

where I_N is the identity matrix NxN, $()^H$ is the complex conjugated function, and $\boldsymbol{H(f)}$ is the Frobenius normalized transfer function of $\mathbf{G}$, using all the realizations of one measurement. Normally, the capacity is averaged over the measured bandwidth.

For the sake of comparison, the capacity of a reference 2x2 MIMO system that uses EM-6116 antennas at both transmission and reception has also been calculated. A schematic of this system is shown in Fig. 16. At reception the antennas are spaced s=2λ at 3.5 GHz, whereas at transmission different spacing s between the antennas has been considered.

Table 1 shows the channel capacity of the reference system for distances between the transmitter and the receiver d of 1m, 2m and 3m. A fixed SNR of 10 dB at the receiver has been assumed in all calculations. Surprisingly, the greatest capacity values are obtained for d=3m. This happens because the higher the distance d is, the closer the receiving antennas are to the lab's left wall. Reflections due to the left wall of the lab, lead to higher multipath richness and time delay increase. As a result, the capacity rises. In contrast, high capacity values are obtained for shortest spacing s=λ/2. This occurs because with this spacing there is a strong spatial correlation and a strong coupling between the transmitting antennas. As explained in [15] when spatial correlation is strong, the mutual coupling is beneficial, leading to MIMO capacity enhancement.

Table 2 shows the channel capacity achieved with the compact 2x2 MIMO system of Fig. 14 that uses the printed monopole with two ports as transmitter. The difference between this capacity and the mean value obtained in Table 1 for the reference system is also included in Table 2. As observed, for a fixed SNR of 10dB, the differences in capacity for the two systems are not large.

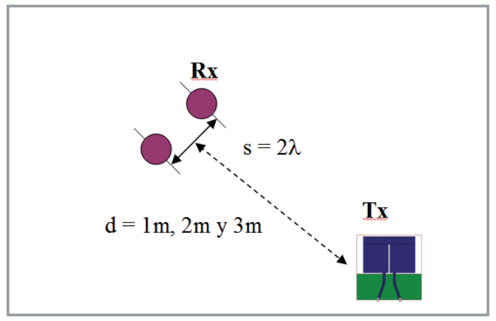


Figure 14. *Schematic of a 2x2 MIMO system that uses the printed monopole with two ports as transmitter and two EM-6116 UWB antennas spaced s=2l as receiver.*

Figure 15. *Two omnidirectional UWB antennas EM-6116, with 1dBi gain.*

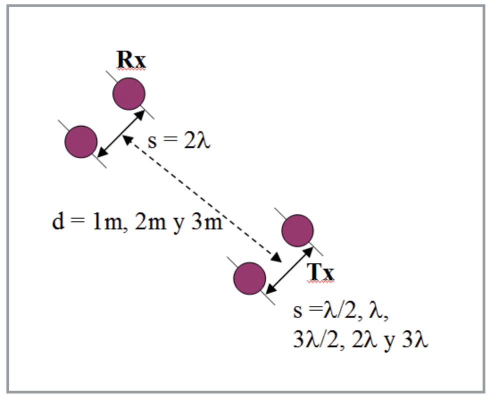


Figure 16. *Schematic of the reference 2x2 MIMO system that uses EM-6116 antennas at both transmission and reception.*

Let us calculate the channel capacity again, considering now real values of SNR. SNR is computed from the mean received power, supposing a noise level of -70 dBm. Results for the channel capacity obtained using the real SNR are presented in Table 3 for the reference 2x2 MIMO system and for the compact 2x2 MIMO system that uses the printed monopole as transmitter. As observed, the mean power received when the printed monopole is used as transmitter is 7 dB lower than the mean power received by the reference system. This is logical, because the EM-6116 antennas are considerably bigger, and present higher gain than the printed monopole. Since the radiation efficiency, is directly dependent on antenna size, it is normal that the EM-6116 radiate higher power than the printed monopole. Note however that in spite of the received power difference, for distances between the transmitter and the receiver d=2 m and d= 3m, a richer scattering environment is obtained, and the capacity values given by the two systems are quite similar.

In conclusion, it has been demonstrated that in rich scattering environment the proposed printed monopole with two highly isolated ports behaves as two independent antennas, but occupying much less space. Of course, the performance of this monopole that has been fabricated in microstrip technology is lower than that of two EM-6116 antennas. Nevertheless, due to its compact size and low profile, the printed monopole can be easily integrated in handheld terminals, and constitutes an interesting solution for a mobile 2x2 MIMO system.

2.3 Dual polarized printed monopole for WiMAX at 3.5 GHz frequency band.

Let us consider now a dual polarized printed monopole with two isolated feed ports. This monopole provides polarization diversity, and it is suitable for MIMO applications at WiMAX 3.5 GHz frequency band. The main differences with the design already presented in section 2.3 are that this new monopole uses polarization diversity, and that the isolation between ports is not obtained now by means of a decoupling slit.

Fig. 17 shows a schematic of the proposed design. It consists in a square planar monopole with orthogonal polarization microstrip ports, and a corner ground plane printed at the back side of the PCB. In a rich multipath environment the two orthogonal ports are expected to work as two independent antennas. The required isolation between ports is obtained by exciting a higher order mode, whose current distribution at 3.5 GHz is depicted in Fig. 18. The current of this mode that has been calculated with IE3D, is very low along the diagonal that connects the upper left corner of the square with the lower right one. This diagonal current null divides the structure in two independent antennas, and provides low coupling between the ports, so there is no need of an isolating slit.

Fig. 19 shows a photograph of a prototype of the antenna, fabricated on a ROGERS4003 substrate of height h=0.813 mm and relative permittivity ε_r=3.38. As observed in Fig. 20, the input matching requirements are accomplished, and the isolation between the ports is higher than 20 dB at 3.5 GHz. In addition, there is good agreement between simulated and measured S parameters. It has also been verified that the envelope correlation is below 0.02 in the operating band.

The 3D radiation patterns computed at 3.5 GHz for port 1 and port 2 of the antenna using IE3D can be seen in Fig. 20. As observed, the patterns present orthogonal polarization.

	d = 1m	**d = 2m**	**d = 3m**
s = λ/2	5.3941	5.0482	5.9738
s = λ	5.0303	4.9546	5.9576
s = 3λ/2	4.9861	4.9775	5.9911
s = 2λ	5.0135	4.9864	5.9975
s = 3λ	4.7917	4.9497	5.9040

Table 1. *Channel capacity (bit/s/Hz) of the 2x2 MIMO reference system for different distances d between the transmitter and the receiver, and for different spacing s between the antennas used at transmission.*

	d = 1m	**d = 2m**	**d = 3m**
Channel capacity	*4.7170*	*5*	*5*
Difference with the mean capacity of the reference system.	*-0.3261*	*0.0167*	*-0.9648*

Table 2. *Channel capacity (bit/s/Hz) for the 2x2 MIMO system that uses the printed monopole with two ports as transmitter, and difference with the mean capacity obtained in Table 1 for the reference system.*

		d = 1m	**d = 2m**	**d = 3m**
Reference 2x2 MIMO system	*Mean received power*	-35.01 dBm	-40.98 dBm	-44.7 dBm
	SNR	24.99 dB	19.02 dB	15.31 dB
	Capacity	15.19 bit/s/Hz	10.71 bit/s/Hz	8.1 bit/s/Hz
2x2 MIMO system with the planar monopole as transmitter	*Mean received power*	-43 dBm	-48.41 dBm	-51.7945 dBm
	SNR	17.0176 dB	11.0176 dB	8.2522 dB
	Capacity	7.7963bit/s/Hz	11.6220bit/s/Hz	8.2522bit/s/Hz

Table 3. *Mean received power, real SNR, and channel capacity (bit/s/Hz) for the reference 2x2 MIMO system, and for the 2x2 MIMO system that uses the printed monopole as transmitter.*

In a rich scattering environment the proposed monopole with two highly isolated ports behaves as two independent antennas, but occupying much less space.

The prototype of the antenna has been experimentally characterized at Technical University of Cartagena. A 2x2 MIMO systems has been implemented, using the printed monopole with dual polarization ports as transmitter. As in section 2.2, the receiver is formed by two EM-6116 antennas with 1dBi gain that are spaced s=2λ at 3.5 GHz. Measurements have been taken at 801 frequencies from 3 GHz to 4 GHz, with an intermediate frequency of 1 KHz, The measurement has been made for different distances d between the transmitter and the receiver. Table 4 summarized the channel capacity achieved with this 2x2 MIMO system that uses the printed monopole with dual polarization as transmitter. The difference between this capacity and the mean value obtained in Table 1 for the reference 2x2 MIMO system is also included. It can be noticed that for a fixed SNR of 10dB, similar capacity values are obtained for the two systems.

Table 5 compares the channel capacity obtained using a real SNR for the reference 2x2 MIMO system and for the compact 2x2 MIMO system that uses the printed monopole with double polarization as transmitter. Calculations have been made considering a noise level of -70 dBm. As observed, the mean power received when the printed monopole is used as transmitter is 6 dB lower than the mean power received by the reference system. This happens not only because the printed monopole presents lower radiation

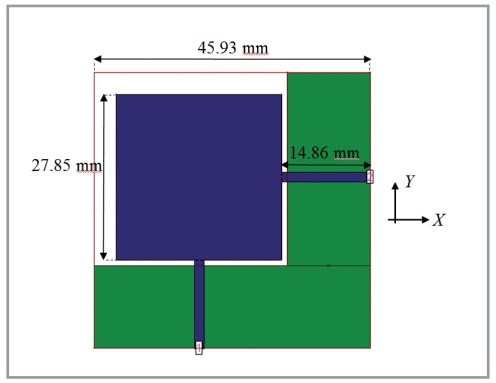
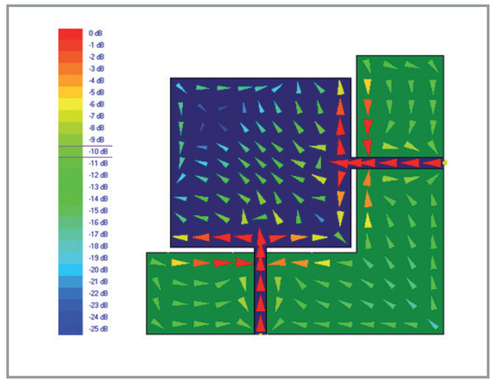
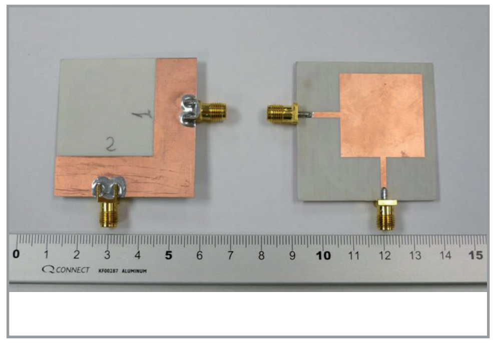


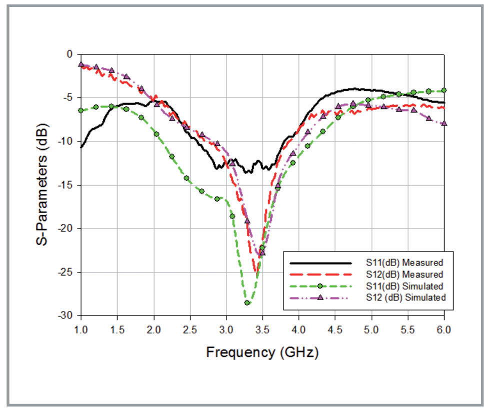
Figure 17 *Geometry of the printed square monopole with orthogonally polarized microstrip ports.*



■ **Figure 18** *Current distribution at 3.5 GHz computed with IE3D.*



■ **Figure 19** *Prototype of the printed monopole with orthogonally polarized microstrip ports.*



■ **Figure 20** *Simulated and measured S parameters for the antenna prototype shown in Fig. 19.*

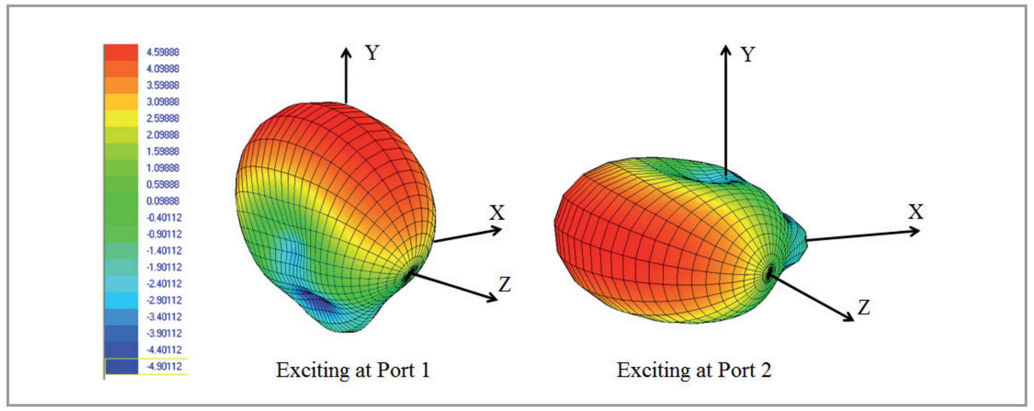
efficiency than the EM-6116 antennas, but also because the channel matrix elements are unbalanced. It should be note that EM-6116 antennas only receive vertical polarization, whereas the printed monopole transmits with horizontal or vertical polarization depending on the port. As a result, there is a XPD (Cross Polarization Discrimination) [16] of 7 dB, which is the mean difference between the power received at co-polar and cross-polar elements. Evidently, this 8 dB difference reduces the mean received power and also de system capacity. However, the low capacity values obtained when using the double polarized monopole as transmitter, could also be due to the non-perfect orthogonality between the radiation patterns at the two ports that yields an unwanted signal cross-coupling.

According to these results, it can be concluded that further investigation needs to be performed to increase the polarization purity at the orthogonal ports of the antenna in order to reduce this unwanted cross-coupling.

3. Multimode MIMO Antenna for Wireless Body Area Networks

MIMO systems have recently proven to be an attractive option for Wireless Body Area Networks, in which body shadowing and user motion lead to multiple rapid changes in the channel characteristics. In this kind of networks, multiple antennas can be used in combination with space-time coding, to save transmit power or to reduce the probability of link failure due to body shadowing [6]. However, the integration of multiple antennas in the personal sphere is not easy, due to the usually limited available space. A possible solution for this scenario is to implement the MIMO system using multimode antennas.

A multimode antenna is an antenna where several modes are excited separately on the same antenna structure at the same temporal frequency. [4] This results in multimode diversity, a combination of pattern and polarization diversity to obtain uncorrelated channel impulse responses for MIMO systems.



■ **Figure 21** *Simulated 3D radiation patterns at 3.5 GHz when exciting at port 1 and port 2.*

	d = 1m	*d* = 2m	*d* = 3m
Channel capacity	*5.0032*	*5.2066*	*5.3442*
Difference with the mean capacity of the reference system.	*-0.0339*	*-0.2233*	*-0.626*

■ **Table 4.** *Channel capacity (bit/s/Hz) for the 2x2 MIMO system that uses the printed monopole with dual polarization as transmitter, and difference with the mean capacity obtained in Table 1 for the reference system.*

		d = 1m	*d* = 2m	*d* = 3m
Reference 2x2 MIMO system	Mean received power	-35.01 dBm	-40.98 dBm	-44.7 dBm
	SNR	24.99 dB	19.02 dB	15.31 dB
	Capacity	15.19 bit/s/Hz	10.71 bit/s/Hz	8.1 bit/s/Hz
2x2 MIMO system with the double polarized monopole as transmitter	Mean received power	-40.35 dBm	-45.91 dBm	-48.99 dBm
	SNR	19.65 dB	14.09 dB	11.01 dB
	Capacity	9.87 bit/s/Hz	7.20 bit/s/Hz	5.83 bit/s/Hz

■ **Table 5.** *Mean received power, real SNR, and channel capacity (bit/s/Hz) for the reference 2x2 MIMO system, and for the 2x2 MIMO system that uses the printed monopole with double polarization as transmitter.*

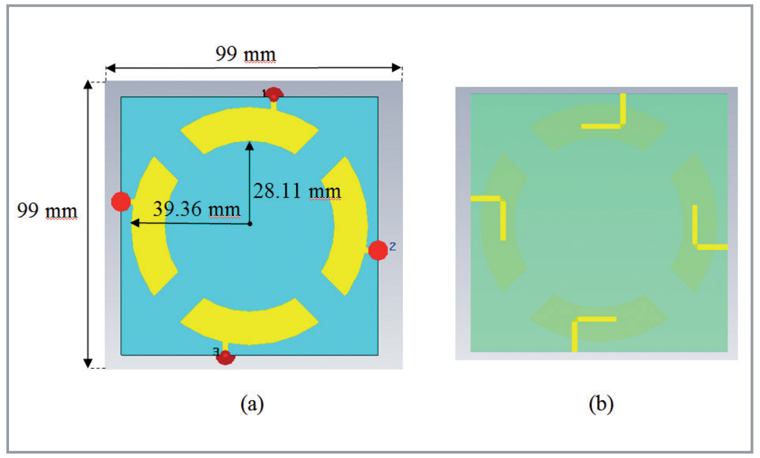
The antenna offers characteristics similar to an antenna array through multiple modes using a single antenna element with four ports.

In this section a planar multimode antenna for WBAN is presented. This antenna offers characteristics similar to an antenna array though multiple modes using just a single antenna element with four ports. The multimode behaviour is obtained exciting the four feeding ports with specific phase configurations. Since only one antenna element is needed, the multimode antenna is more compact than traditional arrays, and it is an interesting solution for MIMO systems working in the Personal Area Network at 2.4 GHz.

Fig. 22 (a) shows the geometry and dimensions of the proposed MIMO antenna. The antenna consists in a metallic circular ring with four slots placed at ϕ=±45° and ±135°, that act as capacitive loading. As explain in [18], these slots allow the control of the resonances of the orthogonal modes that will provide the desired multimode operation, so all of them would resonate at the same frequency band. In this case, the dimension of the slots has been chosen in order to fix the operation bandwidth of the desired modes close to 2.4 GHz. The multimode operation is accomplished by exciting the antenna with the four L-shaped microstrip lines shown in Fig. 22 (b). As observed, these feeding lines are symmetrically distributed along the structure.

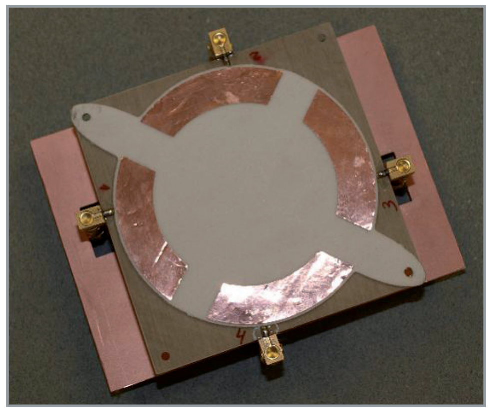
A prototype of the antenna fabricated at iTEAM's facilities can be seen in Fig.23. The capacitive loaded ring has been etched on a cooper sheet over ROHACELL foam. The microstrip lines have been printed on a ROGERS4003 substrate of height h=0.813 mm and relative permittivity ε_r=3.38. The hybrid microstrip network shown in Fig. 24 has been designed in order to obtain the desired phase configurations at the different ports. Future work will focus on obtaining a more compact solution for the feeding network.

Tab. 6 summarizes the different distribution of phases that can be employed at the four ports in order to excite characteristic modes J_0, J_1, $J_{1'}$ and J_2. Further information about the radiating behaviour and current distribution of these characteristic modes can be found in [17]. Note that

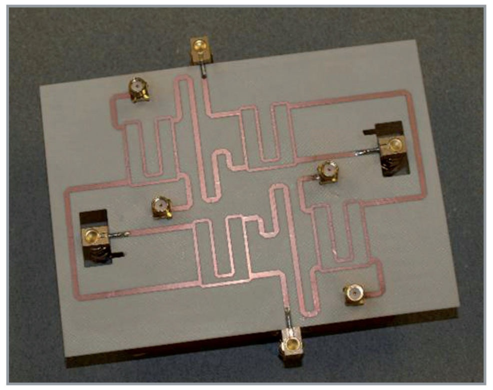


■ **Figure 22** *Geometry of the multimode antenna: (a) Radiating ring with four excitation ports. (b) Microstrip feeding lines.*

The pattern associated to the modes excited by each feeding configuration are orthogonal in order to provide MIMO behaviour by multimode operation.

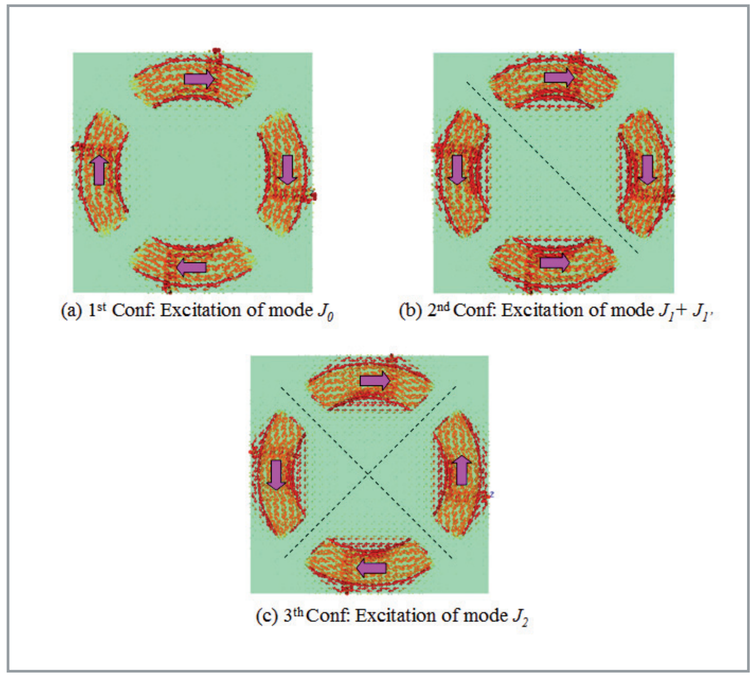


■ **Figure 23.** *Prototype of the multimode antenna with four excitation ports.*



■ **Figure 24** *Hybrid microstrip network used to obtain the desired phase configurations.*

due to the orthogonality properties of characteristic modes over both the surface of the body and the enclosing sphere at infinity, they radiate power independently of one another [11].



■ **Figure 25.** *Simulated current distribution at 2.4 GHz for the feeding configurations proposed in Tab. 1.*

Fig. 25 shows the current distributions obtained at 2.4 GHz with CST Microwave Studio when using the three feeding configurations described in Table 6. Arrows have also been included to facilitate the visualization of the current flow. The use of the first feeding configuration results in the excitation of mode J_0 which presents currents forming a close loop around the ring. The second configuration excites degenerated modes J_1 and J_1' simultaneously, resulting in a current distribution with nulls at 45º. Finally, the third configuration excites the higher order mode J_2 which exhibits four current nulls ±45º and ±135º.

Fig. 26 depicts the return loss measured at each

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

■ **Table 6.** *Feeding configurations (amplitude and phase) for the excitation of different characteristic modes of the antenna.*

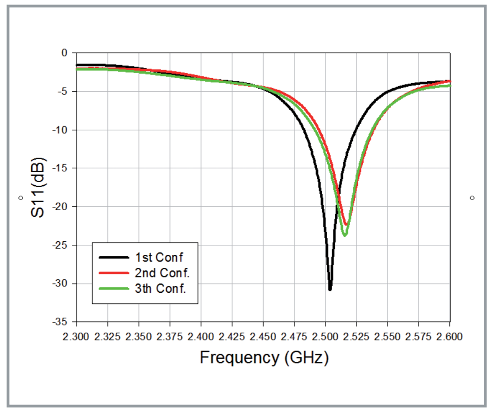
port of the prototype when using the three feeding configurations of Table 6. Because of the symmetry of the structure, the return loss obtained at every port is exactly the same. Considering a reference value of -6 dB for the return loss, a bandwidth (BW) of 2.6% is obtained for the proposed design. Notice however that the central frequency of the operating band is not 2.4 GHz, but 2.5 GHz. This means that the dimensions of prototype need to be slightly scaled in order to shift the operating band towards 2.4 GHz.

Finally, Fig. 27 shows the radiation pattern exhibited by the antenna for each feeding configurations, at 2.5 GHz. These 3D patterns have been simulated with CST Microwave Studio. As expected, the pattern associated to the modes excited by each feeding configurations are orthogonal in order to provide MIMO behaviour by multimode operation.

Although capacity measurement for this antenna are not available yet, all the results presented here seem to confirm that the capacitive loaded ring antenna with four excitation ports behaves as a multimode antenna, and consequently, it is suitable to operate with different orthogonal modes in a MIMO system.

4. Conclusions

Several designs of compact planar antennas with multiple ports for MIMO and diversity applications have been presented. These designs, that can replace antenna arrays traditionally used in MIMO systems, are formed by a single radiating element with multiple ports. Due to its compact size and low profile, the proposed designs are a



■ **Figure 26.** *Return loss measured for the antenna prototype using the three feeding configurations.*

very interesting solution to provide MIMO operation at mobile handsets. The first designs proposed are based on two-port planar monopole antennas, and they have been optimized to work at WiFi and WiMAX frequency bands. Capacity values obtained for the prototypes of these antennas at Universidad Politécnica de Cartagena confirm that, at rich scattering environment, the monopoles with two isolated feeding ports provide capacity gain, as they yield better performance than a single antenna element. A planar multimode MIMO antenna has also been proposed for Wireless Body Area Networks. This antenna presents multimode operation, and uses a combination of pattern and polarization diversity, to obtain uncorrelated signals for MIMO systems. A prototype of this antenna has been fabricated, and although capacity values are not available yet, measurements performed at iTEAM's lab seem to confirm the suitability of the design to operate in a MIMO system.

Acknowledgments

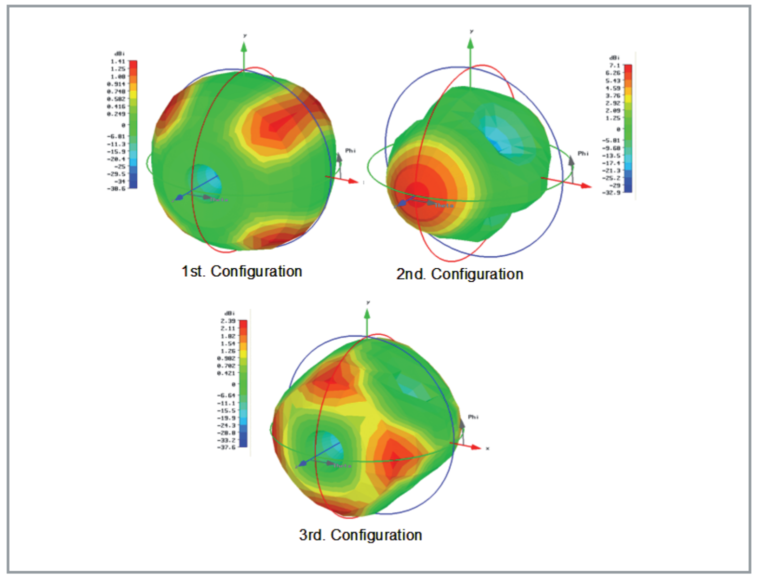
This work has been supported by Spanish Ministry of Education and Science under project TEC2007-66698-C04-03/TCM, and by Generalitat Valenciana under project GVPRE/2008/392.

References

[1] G. J. Foschini and J. Gans, "On Limits of Wireless Communications in a Fading Environment when Using Multiple Antennas", Bell Labs Technical Journal, vol. 1, no. 2, Lucent Technologies, pp 41- 59, 1996.

[2] D. Gesbert, M. Shafi, D-S Shiu, P. Smith and A. Naguib, "From Theory to Practice: An Overview of MIMO Space-Time Coded Wireless Systems", IEEE Journal on Selected Areas in Communications, vol. 21, no. 3, April 2003.

[3] S. C. K. Ko and R.D. Murch, "Compact Integrated Diversity Antenna for Wireless Communications," IEEE Transactions on Antennas and Propagation, vol. 49, no 6, pp. 954-960 June 2001.



■ **Figure 27.** *Simulated radiation patterns obtained for the capacitive loaded antenna using the three feeding configurations.*

[4] T. Svantesson, "An Antenna Solution for MIMO Channels: The Multimode Antenna," in Conf. Record 34th Eur. Microwave Conf., vol. 2, 2000, pp.1617-1621.

[5] C. Waldschmidt, and W. Wiesbeck, "Compact Wide-Band Multimode Antennas for MIMO and Diversity," IEEE Trans. Antennas Propagat., vol. 52, no. 8, pp. 1963-1969, August 2004.

[6] D. Neirynck, C. Williams, A. Nix and M. Beach, "Exploiting multiple-input multiple-output in the personal sphere", IET Microwaves, Antennas and Propagation, vol. 1, Is. 6, pp. 1170-1176, Dec. 2007.

[7] H. Schantz, "The Art and Science of Ultrawideband antennas," Artech House 2005.

[8] M. J. Ammann, "Impedance bandwidth of the square planar monopole", Microwave and Optical Tech. Letters, vol. 24, no. 3, February 2000.

[9] J. A. Evans, M. J. Ammann, "Planar trapezoidal and pentagonal monopoles with impedance bandwidths in excess of 10:1", IEEE Antennas and Propagation Society International Symposium, vol. 3, pp. 1558 – 1561, July 1999.

[10] A. J. Kerkhoff, R. L. Rogers, H. Ling, "Design and Analysis of Planar Monopole Antennas Using a Genetic Algorithm Approach", IEEE Trans. Antennas Propagat., vol. 2 , pp. 1768 – 1771, June 2004.

[11] R. F. Harrington and J. R. Mautz, "Theory of Characteristic Modes for Conducting Bodies", IEEE Trans. Antennas Propagat., AP-19, 5, September 1971, pp. 622-628.

[12] E. Antonino, M. Cabedo, M. Ferrando, A. Valero, "Wideband double-fed planar monopole antennas", Electronics Letters, vol. 39, no. 23, pp. 1635-1636, November 2003.

[13] S. Blanch, J. Romeu and I. Corbella, "Exact representation of antenna system diversity performance from input parameter description", Electronics Letters, vol. 39, no. 9, May 2003, pp. 705-707.

[14] J. M. Molina-García Pardo, J.V. Rodríguez and L. Juan Llácer "Indoor MIMO Measurements for WiFi", in COST 273, TD(05)081, Leuven, Belgium, June 2005.
[15] V.P. Tran and A. Sibille, "MIMO Channel Capacity and Mutual Coupling in Circular Arrays of Monopoles", Tech. Rep. COST 273 TD (03) 099, Paris, France, 22-23 may 2003.
[16] T. Taga, "Analysis for mean effective gain of mobile antennas in land mobile radio environments", IEEE Trans. on Vehicular Technology, vol. 39, nº2, pp. 117-131, 1990..
[17] E. Antonino, M. Cabedo, M. Ferrando, M. Gallo "Design of a Multimode MIMO Antenna Using the Theory of Characteristic Modes ", Radioengineering, vol. 18, no. 4, pp. 425-430 December 2009.

Biographies

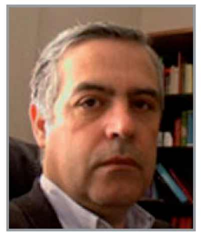
Marta Cabedo-Fabrés was born in Valencia, Spain, on June 8, 1976. She received the M.S. and Ph.D. degrees in electrical engineering from Universidad Politécnica de Valencia, Spain, in 2001 and 2007, respectively.

In 2001, she joined the Electromagnetic Radiation Group at Universidad Politécnica de Valencia (UPV), as a Research Assistant. In 2004, she became a Lecturer in the Communications Department, Universidad Politécnica de Valencia. Her current scientific interests include numerical methods for solving electromagnetic problems, and design and optimization techniques for wideband antennas for mobile terminals, and MIMO antennas for Personal Area Networks.

Eva Antonino-Daviu was born in Valencia, Spain, on July 10, 1978. She received the M.S. and Ph.D. degrees in electrical engineering from the Universidad Politécnica de Valencia, Valencia, Spain, in 2002 and 2008, respectively.

In 2002 she joined the Electromagnetic Radiation Group, Universidad Politécnica 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 Department 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" from the Universidad Politécnica de Valencia in 2008.



Miguel Ferrando-Bataller was born in Alcoy, Spain, in 1954. He 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.

Vicent Miquel Rodrigo Peñarrocha was born in Valencia, Spain, on September 29, 1966. He received the Ingeniero de Telecomunicación degree from the Universidad Politécnica de Madrid (UPM), Madrid, Spain, in 1990, and the Ph.D. degree in electrical engineering from the Universidad Politecnica de Valencia in 2003.

He joined the Departamento de Comunicaciones at the Universidad Politécnica de Valencia in 1991 as a Lecturer. His current interests include radio-wave propagation over the sea, instrumentation, and any educational activity.

Antonio Vila Jiménez was born in Valencia, Spain on June 18, 1981. He received the degree in Telecommunications Engineering, specialising in Telecommunication Systems from the Polytechnic University of Valencia, Valencia, Spain, in 2007.

He has been with the Institute of Telecommunications and Multimedia Application of the Polytechnic University of Valencia since 2007. His main research interest includes field antenna measurement and antenna fabrication.

Jose Maria Molina-Garcia-Pardo was born in Orihuela, Spain, in 1977. He received the B.S. degree in Telecommunications engineering from the Universidad Politécnica de Valencia, Valencia, Spain, in 2000, the M.Sc. degree in communication and signal processing from the University of Newcastle, Newcastle, U.K., in 2001, and the Ph.D. degree in telecommunications engineering from the Universidad Politécnica de Cartagena, Cartagena, Spain, in 2004. In 2000, he was with the Department of Communications and Signal Processing, University of Newcastle, where he was involved with blind source separation. In 2001, he joined the Department of Information Technologies and Communications, Universidad Politécnica de Cartagena, where he is currently an Associate Professor. His research activities have been centered on the propagation studies for multiple-input and multipleoutput systems, measurement campaigns in special environments, and ray launching in the area of mobile personal communications systems.

Leandro Juan-Llacer was born in Albatera, Alicante, Spain, in 1967. He received the B.S. degree in Telecommunications engineering from the Universitat Politècnica de Catalunya, Barcelona, Spain, in 1993 and the Ph.D. degree in communications engineering from the Universidad Politécnica de Valencia (UPV), Valencia, Spain, in 1998. In 1994, he was with the Department of Signal Theory and Communications, UPV, where, from 1995 to 2000, he was an Associate Professor of electromagnetics. He is currently an Associate Professor with the Department of Information Technologies and Communications, Universidad Politécnica de Cartagena, Cartagena, Spain. He has also been participating in COST actions 259, 273, and 2100. His research activities have focused on the characterization and the modeling of radio wave propagation in mobile communication systems. Dr. Juan-Llacer was a recipient of the Doctoral Prize given by the Telecommunications Engineering Association of Spain for his Ph.D. dissertation on urban wave propagation and channel characteristics, particularly for mobile communications.