Multi-band multi-antenna system for diversity and/or MIMO applications

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ABSTRACT

In this paper, a tri-band multi-antenna system, consisting of two pairs of Planar Inverted-F Antenna operating at 1.92-2.17GHz, 2.4-2.485GHz and 2.5-2.7GHz bands and placed on a small ground plane, with high ports to ports isolation is proposed. The proposed isolation solution is based on a specific orientation of these antennas and the insertion of an optimized slot on the ground plane. The diversity performance of the proposed isolated system are calculated and discussed in 1.92-2.17GHz frequency band. The size and performances of this antenna system make it a good candidate for hand-held devices with diversity and/or Multiple Input Multiple Output applications.

Keywords: Diversity, Isolation techniques, MIMO, Multi-band.

CONCLUSION

First, a multi-antenna system with a minimum isolation of 26dB operating in the UMTS (1.92-2.17GHz) band is proposed. This good isolation is obtained by the optimization of a slot inserted on the ground plane and placed between the two identical UMTS PIFAs, and with a specific orientation of these PIFAs. The diversity performance of this system in terms of envelope correlation, Mean Effective Gain (MEG) and Diversity System Gain (DSG) calculated using a home code and the obtained results show that this system is desirable for diversity and/or MIMO applications.

Thereafter, the same techniques are used to develop another system operating at the WIFI (2.4-2.5GHz) and LTE (2.5-2.7GHz) bands and placed at the other top of the ground plane. Good isolation performance are obtained for the global system (UMTS, WIFI and LTE), which shows the interest of the chosen orientation of the PIFAs but also the insertion of the slots. The manufacturing of the proposed systems and the simulation of the effect of the users on their performance is in progress, and the estimation of the diversity and MIMO performance for the tri-band system (and UMTS system for the MIMO) are planned shortly to complete this work.

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I. INTRODUCTION

To satisfy the demand of the today's emerging wireless technologies, high data transmission rates have become increasingly necessary. By increasing the SNR (Signal to Noise Ratio) or the signal bandwidth the data transmission rate can be increased but without improving the spectral efficiency. To overcome this limit, it was proved that the use of multi-antenna system (MAS) is more effective especially for rich multipath environment which is the case of the propagation in a real environment [1], [2]. Multi-antenna systems are used effectively on different kinds of applications, such as handsets, mobile units, sensors etc.

With the trend of the miniaturization of mobile communicating devices, the placeholder for antennas is more and more reduced. The use of multiple antennas on the same ground plane and located at a little distance from one another creates therefore additional difficulties compared to single antenna system to maintain or obtain desired performances. A half-wavelength separation distance is required to reduce signal correlation and obtained the maximum of isolation, this is difficult to reach in increasingly small modern communication devices.

Indeed, to take advantage of MAS, the antennas must be isolated which ensure that the received signals are uncorrelated. Coupling between antennas induces high signal correlation thus reducing the antenna efficiency, the diversity and MIMO (Multiple Input Multiple Output) performances of the system and consequently the data transmission rate [3].

The development of next-generation wireless communication systems requires broadband and multiband devices for multi-functionality and faster data transfers, while maintaining good efficiency, low weight, low cost, and easy manufacturing. In this context, antenna isolation or decoupling has become a real challenge for antenna designers. Based on intuitive solutions or original solution, several decoupling techniques have been developed. In [4] antenna position and orientation optimization are used to enhance isolation. Electromagnetic band-gap (EBG) cells have been used to suppress surface waves and enhance isolation [5]. Slot insertion in the PCB [6], the use of defected ground plane structure [7], neutralization technique [8], and decoupling networks [9] has been proposed to enhance the isolation between the feeding ports of the antennas. Most of these techniques cannot be readily transposed to enhance the isolation of a bi-band or multi-band multi-antenna system.

In this paper, a novel solution based on the specific orientation of antennas and the insertion of slots in the ground plane is proposed. This solution is applied to a miniature tri-band multi-antenna system with high isolation of the antennas in the desired frequency bands: UMTS (1.92-2.17GHz), WIFI (2.4-2.5GHz) and LTE (2.5-2.7GHz). The distance between the antennas can be as little as 5 mm.. The diversity performance in terms of envelope correlation, MEG (Mean Effective Gain) and DSG (Diversity System Gain) are also calculated and discussed.

This paper is organized as follows. In section II, a multi-antenna system operating in the UMTS (1.92-2.17GHz) band with high port-to-port isolation is developed, and its diversity performance is calculated. In section III, a second multi-antenna system placed at the other top of the mobile standard ground plane, and covering the WIFI (2.4-2.5GHz) and LTE (2.5-2.7GHz) bands is developed following the same steps design of the UMTS antenna. The multi-band multi-antenna system presents a good performance in terms of isolation, matching and efficiency.

II. UMTS MULTI-ANTENNA SYSTEM

A. Antenna design consideration

We have started the design of our system by placing a Planar Inverted-F Antennas (PIFAs) on a top of a ground plane of dimension $L_{GND}\times W_{GND}$ = 120×50mm^2, which is the standard dimension of a mobile phone ground plane. PIFAs are used because they are regarded as good alternatives for wireless applications for their advantages such as bandwidth, low profile and low cost.

Because the PIFA is positioned over a finite small ground plane which is an important radiating body at the UMTS frequency band, the positioning and then the orientation of the antenna or antennas on the PCB may have a significant effect on the behavior and the performance of the system.

The dimensioning of the single PIFA is done such that it resonates in the UMTS (1.92-2.17GHz) band. Positioned at a distance of D=3.5mm relative to the top of the PCB and S=3mm with respect to the side, the optimized dimensions of this single PIFA operating in the UMTS band is $L_{PIFA}\times W_{PIFA}$=20×10mm^2, the distance between the feed strip and the short strip is about 3mm, and placed at a height of 8mm from the PCB (Fig 1). The performance of this optimized single PIFA in terms of the matching parameter ($|S_{11}|$) is shown in Fig 2; the desired band (1.92-2.17GHz) is covered with a criterion of $|S_{11}|$<-6dB (VSWR=3).

The multi-antenna system is obtained by the insertion of an identical PIFA to that shown on Fig 1, on the same specific ground plane but rotated by 180° compared to the vertical plane (XY), and placed at a distance of 5mm (0.035λ_0) from the first antenna (Fig 1). Figure 2 shows the performance of the initial multi-antenna system in terms of $|S_{11}|$ and $|S_{21}|$ which represent the matching and the isolation parameters respectively. The desired band is covered with a criterion of $|S_{11}|$<-6dB (VSWR=3).

Low isolation is observed between the two feeding accesses of the multi-antenna system; it varies between 7.7dB and 11.4dB in the desired band (1.92-2.17GHz). This low value of the isolation in the desired band has as effect to deteriorate the total efficiency of the system, and thus the diversity performance. With such results, incorporate a second antenna for obtaining multi-antenna system is useless because the signals received by the antennas will be highly correlated.

To enhance the isolation, a slot is used on the ground plane and placed at the center between the two antennas in order to get the same effect on each of the antennas, and guaranteed then the use of this system for diversity and/or MIMO applications. The dimension (length and width) of the slot, are optimized with the aim of modifying the current paths in order to eliminate the current flowing from the excited antenna to the charged antenna, or to ensure that their phases are in opposition (Fig 3). After optimization, the dimension of the slot that ensure a good performance of the system in terms of matching level, isolation and necessary bandwidth are $L_{slot} \times W_{slot} = 20 \times 2mm^2$.

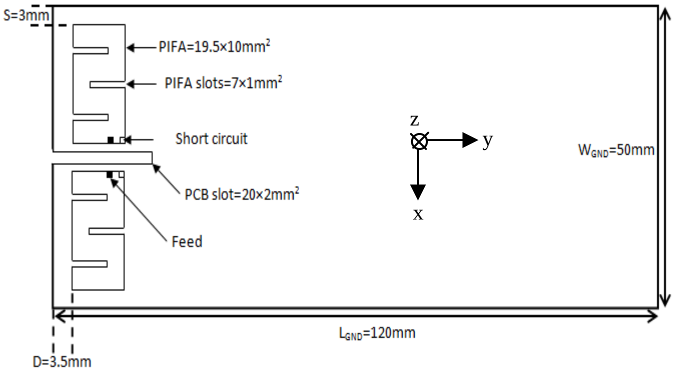


Fig. 1. Top view of the UMTS isolated multi-antenna system.

The system performance in terms of isolation are obtained by the appearance of a dip in $|S_{21}|$ parameter. The existence, depth and position of this dip depend on the dimensions of the slot used on the PCB. Figure 2 show the results obtained by the optimized isolated multi-antenna system.

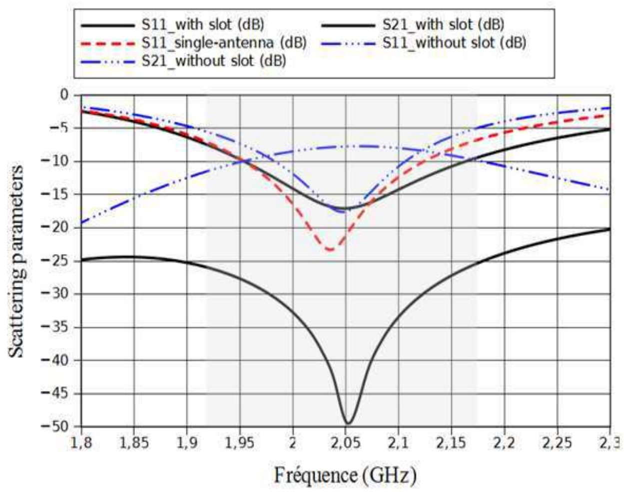


Fig. 2. Simulated scattering parameters results.

The desired bandwidth [1.92-2.17GHz] is covered by a criterion of $|S11| \leq -6$dB and the minimum isolation in this band is about 26dB between the feeding ports of the two antennas. A maximum isolation of 50dB is obtained for the frequency of 2.05GHz which is the center frequency of the UMTS band.

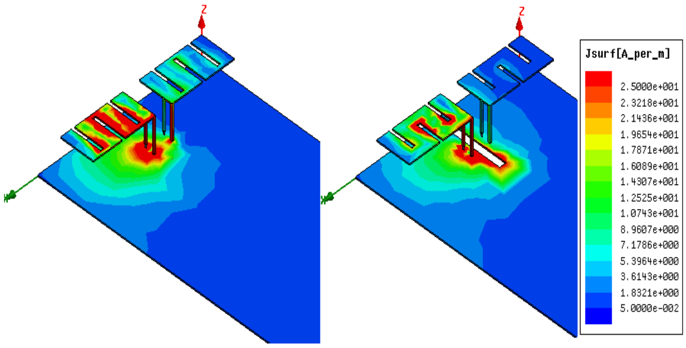


Fig. 3. Surface current distribution for the no-isolated and isolated UMTS multi-antenna system.

The total efficiency is function of the matching and isolation parameters at the considered frequency, and is calculated using equation (1). The significant improvement of the isolation between the two feeding ports of the antennas obtained using the proposed technique and for this configuration of antennas on the PCB has a direct effect on the total efficiency and the diversity performance of the system. For the system with a slot on the PCB (isolated system), the simulated efficiency ranges from 75% to 98% in the [1.92-2.17GHz] frequency band, while it is between 45%-80% for the non-isolated system as shown in figure 4.

$$\eta_{tot} = \eta_{rad} (1 - |S_{11}|^2 - |S_{21}|^2) \qquad (1)$$

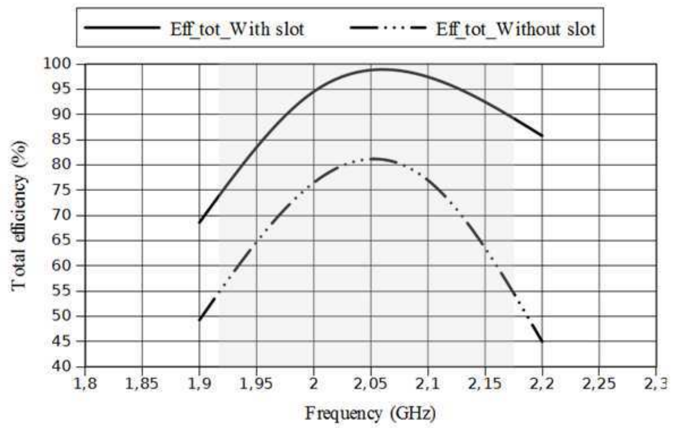


Fig. 4. Comparison of the simulated total efficiency for the system with and without slot.

B. UMTS system diversity performance

The diversity performance of the proposed UMTS multi-antenna system has been evaluated and discussed in this section. The considered parameters are the envelope correlation (ρ_c), the mean effective gain (MEG) and the Diversity System Gain (DSG), calculated in indoor and outdoor environment by using a Gaussian and Laplacian distributions model of the incident waves [10], [11].

Usually, the envelope correlation is presented to evaluate the diversity capabilities of a multi-antenna system. The envelope correlation coefficient of the two prototypes with and without slot is calculated using the radiation patterns formulation (Eq. 2) which gives best results compared to the approximated formula of the envelope correlation given from scattering parameters which requires special circumstances.

$$\rho_c = \frac{A}{B \times C}, \tag{2}$$

with

$$A = (\oint (XPR\, E_{\theta 1}(\Omega) E^*_{\theta 2}(\Omega) P_\theta(\Omega) + E_{\varphi 1}(\Omega) E^*_{\varphi 2}(\Omega) P_\varphi(\Omega)) d(\Omega))^2,$$

$$B = \oint (XPR\, G_{\theta 1}(\Omega) P_\theta(\Omega) + G_{\varphi 1}(\Omega) P_\varphi(\Omega)) d(\Omega))$$

$$C = \oint (XPR\, G_{\theta 2}(\Omega) P_\theta(\Omega) + G_{\varphi 2}(\Omega) P_\varphi(\Omega)) d(\Omega))$$

where:

$$G_\theta = E_\theta(\Omega) * E^*_\theta(\Omega)$$

$$G_\varphi = E_\varphi(\Omega) * E^*_\varphi(\Omega)$$

$E_{\theta 1}(\Omega), E_{\theta 2}(\Omega), E_{\varphi 1}(\Omega), E_{\varphi 2}(\Omega)$, $P_{\theta,\varphi}(\Omega)$ are respectively the vertical (θ) and horizontal (ϕ) polarized complex patterns of the antennas 1 and 2 and the incident power spectrum of the different polarizations. XPR (cross polar discrimination) is the time averaged vertical-to-horizontal power ratio.

As shown in Tab I, the envelope correlation coefficient for the isolated UMTS system is below 0.02 and 0.16 in the indoor and outdoor environment respectively which is very satisfactory, while it can reach 0.58 for the no-isolated system.

TABLE I. ENVELOPE CORRELATION VALUE (IN=INDOOR, OUT=OUTDOOR)

		$\times 10^{-3}$				$\times 10^{-3}$			
		With slot				**Without slot**			
		1.9 GHz	**2 GHz**	**2.1 GHz**	**2.2 GHz**	**1.9 GHz**	**2 GHz**	**2.1 GHz**	**2.2 GHz**
Gaussian	In	3	6.6	23	10	340	190	50	60
	Out	60	134	180	145	560	410	240	240
Laplacian	In	0.04	16	40	23	380	220	80	90
	Out	75	150	200	160	580	430	250	260

The MEG defines the power received by an antenna:

$$MEG = \int_0^{2\pi}\int_0^{\pi} (\frac{XPR}{XPR+1} G_\theta(\Omega) P_\theta(\Omega) + \frac{1}{XPR+1} G_\phi(\Omega) P_\phi(\Omega))(d\Omega) \tag{3}$$

The MEG ratio of the system with slot is computed and it is close to unity which means that the two antennas receive the same amount of power and therefore participate with the same efficiency to the MIMO link. This parameter includes the contribution of the radiation power pattern, the antenna efficiency and the propagation effects.

Diversity system gain (DSG) is another important characteristic of the diversity system; it is calculated by the sum of the DG in dB at 1% CDF (Cumulative Distribution Function) level in our case and the total efficiency in dB:

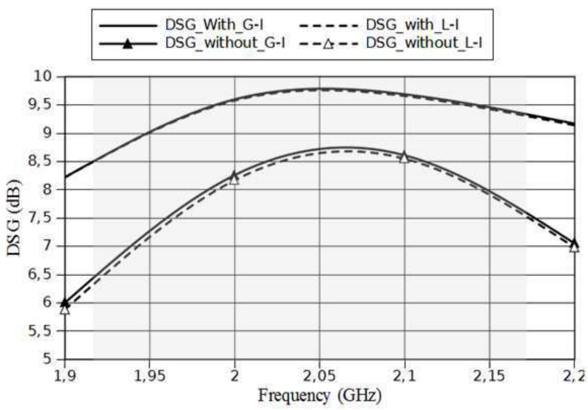
$$DSG(dB) = DG(dB) + \eta_{tot}(dB) \tag{4}$$

The DG is defined as the difference between the Signal-to-Noise Ratio (SNR) of the combined signals and the SNR of the best single antenna of the system:

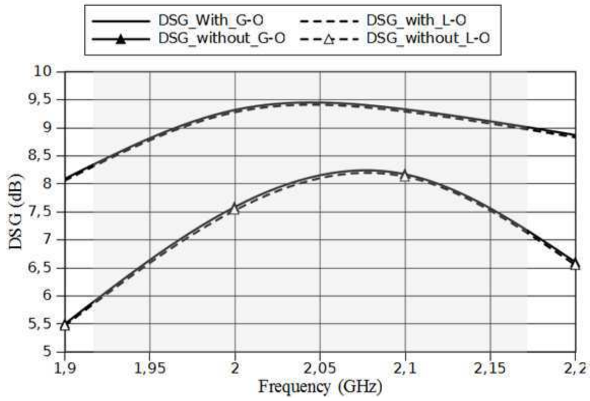
$$DG = [\frac{\gamma_c}{\Gamma_c} - \frac{\gamma_1}{\Gamma_1}] P(\gamma_c < \gamma_s / \Gamma) \tag{5}$$

In Eq. 5, γ_c and Γ_c are respectively the instantaneous and the mean SNR of the combined signals, γ_s/Γ is a preset threshold value and Γ_1 the mean value of the γ_1 of the branch receiving the best signal. The probability P depends at the same time on the number M of the branches of the system and the envelope correlation.

The calculated DSG (dB), using the Gaussian and Laplacian models in indoor and outdoor environments is represented in Fig 5-a and b.



-a-



-b-

Fig. 5. DSG comparison for the UMTS system With and Without slot: (a) Indoor environment, (b) Outdoor environment (G=Gaussian, L=Laplacian, I=indoor, O=outdoor).

O that the minimum value of the DSG in the desired band is of the order of 8.5dB and can go up to 9.75dB. These values are sufficient to fulfill the diversity requirements for MIMO systems.

III. UMTS, WIFI AND LTE MULTI-ANTENNA SYSTEM

In the past few years, users are demanding more and more mobile applications; the dual and multi band characteristics have thus been attracting considerable interest and undergoing rapid development worldwide. This rising demand has induced a need for miniaturized devices with communication systems which can cover multiple frequency bands. The problem in the multi-band multi-antenna system is the difficulty to isolate simultaneously all the feeding ports of the antennas.

The steps taken to design the isolated (with slot) UMTS multi-antenna system in the previous section (mono-antenna system, dual antenna system, use of slot) are used to develop an antenna system which covering the WIFI (2.4-2.5GHz) and the LTE (2.5-2.7GHz) bands. This second system is placed at the other top of the ground plane (Fig 6).

A re-optimization of the dimension of the PIFAs and the slot are then necessary not only to shift the resonant frequency of the identical antennas to the desired bands, but also for better isolation (by creating a dip in the a $|S_{ij}|$ parameter if possible) of the ports of these new two antennas (the dimension of the slot used on the PCB to enhance the isolation depend on the operating frequency of the antennas).

To obtain more degrees of freedom to seek better performance in terms of isolation for all $|S_{ij}|$, two slots are placed in the middle of the PCB as shown in figure 6. Given the current distribution the chosen position of the slots does not affect significantly the matching parameter of the UMTS, WIFI and LTE antennas (low current concentration in this location). However, it alters more or less significantly the $|S_{ij}|$ parameters.

Figure 7 shows the performances in terms of matching and isolation parameters of the proposed four antenna system. According to the results obtained for $|S_{13}|$ ($|S_{24}|$) and $|S_{14}|$ ($|S_{23}|$)) which have a value of $|S_{ij}|$ below -20dB on the desired bands; we can see the interest of the chosen direction (along (X)) for the PIFAs. If PIFAs were oriented along (Y), the coupling between the UMTS and WIFI-LTE antennas would be important compared to the proposed configuration.

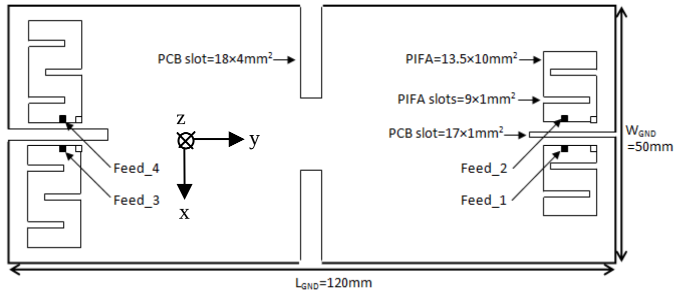


Fig. 6. Top view of the UMTS, WIFI and LTE isolated multi-antenna system.

A minimum of 19dB of isolation is obtained in the UMTS band between all the feeding ports of the four antenna system. In the WIFI and LTE bands the lowest value of the isolation is higher than 16dB.

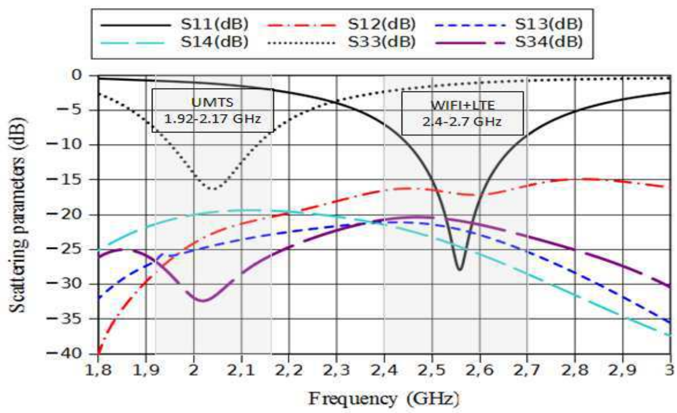


Fig. 7. Simulated scattering parameters results.

The total efficiency in the UMTS, WIFI and LTE bands is calculated using Eq 1. For the UMTS band, we excited the feeding ports number 1 (or 2), and for the WIFI and LTE band we excited the feeding port number 3 (or 4) as shown on figure 6.

A good total efficiency is obtained for all the bands; its value is greater than 80% for the entire UMTS band (with a maximum value of 96%) and higher than 78% for the entire WIFI and LTE bands (with a maximum value of 97%), Fig 8. These results: isolation and efficiency, are very significant for a system with four antennas mounted on a small ground plane, and allow having good diversity performance.

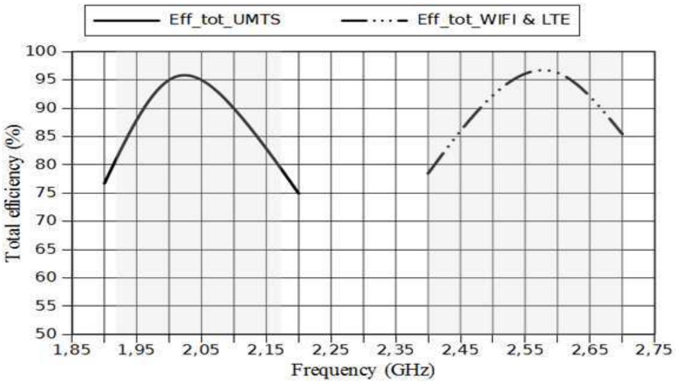


Fig. 8. Simulated total efficiency for the isolated UMTS, WIFI and LTE multi-antenna system.

Figure 9 shows the simulated 3D radiation pattern at the two frequencies 2.05GHz and 2.55GHz corresponding to the center frequencies of the desired bands [1.92-2.17GHz] and [2.4-2.7GHz].

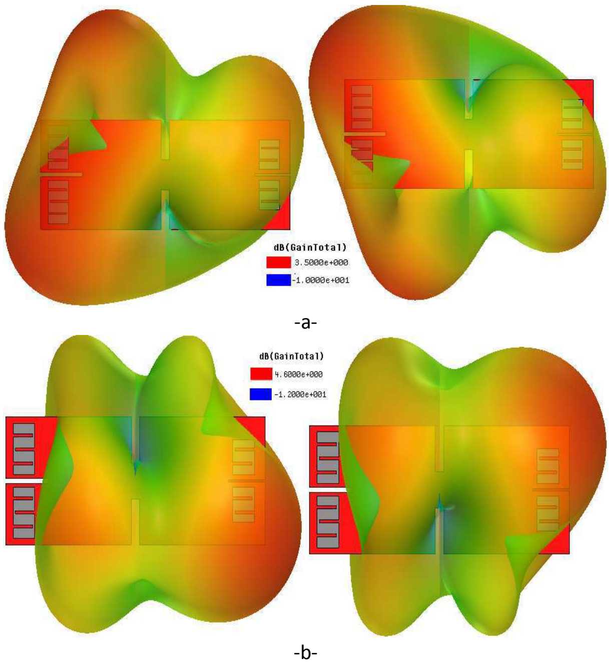


Fig. 9. 3D simulated radiation pattern: (a) left (port 1 excited), right (port 2 excited) at 2.05GHz, (b) left (port 3 excited), right (port 4 excited) at 2.55GHz

These results are obtained by excitation of port 1 (or 2) and terminating the others by a 50ohms load for the UMTS band and by the excitation of the port 3 (or 4) and terminating the others by a 50ohms load for the WIFI and LTE bands. When port 2 (or 4) is excited and port 1 (or 3) terminated by a 50ohms load, the pattern for the UMTS (or WIFI-LTE) band are mirror transformations of those obtained when port 1 (or 3) is excited and port 2 (or 4) terminated to 50ohms; this is due to the symmetry of our multi-antennas system. As a result, the radiation patterns of the two antennas tend to cover complementary space regions, which can provide pattern diversity to overcome the multipath fading problem and enhance the system performance. The maximum simulated total gain is of the order of 3.52dB for the UMTS band and 4.55dB for the WIFI and LTE bands.

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Rafik ADDACI was born in Batna, Algeria. He received his M.Sc. degree in electrical and electronics engineering (2004) and the Magister (BAC+7) degree in microwave for telecommunication (2006) from the University of Batna and Constantine, Algeria. In 2008 and 2011 he received the D.E.A and the Ph.D degrees from the polytechnic school of the University of Toulouse and the University of Nice Sophia Antipolis, France. He is currently working as a researcher at IFSTTAR (Institut Français des Sciences et Technologies des Transports, de l'Aménagement et des Réseaux) with LEOST Team in Villeneuve d'Ascq. He serves as reviewer for several technical journals (Antenna and Wireless Propagation Letters, Transaction on Antenna and Propagation). His studies concerned, multi-antenna design, MIMO systems, miniaturized antennas design, metamaterials, antenna modeling.

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