Design of Multi-Antenna System for UMTS Clamshell Mobile Phones with Ground Plane Effects Considerations

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Abstract. *In this paper, the influence of the ground plane dimensions on the port-to-port isolation of two closely-spaced Universal Mobile Telecommunications System (UMTS) Planar Inverted-F Antennas (PIFAs) with and without neutralization line is first presented. Parametric studies show the existence of an optimal size of the ground plane allowing optimizing the isolation and the efficiency of the considered antenna system. The results obtained with this study are used in the second part to develop an efficient neutralized multi-antenna system for clamshell-type mobile phones.*

The obtained results, in terms of isolation, matching and diversity for the two possible configurations of the clamshell system in use namely the open and the closed states, show that good performance are obtained in the open state and preserved in the closed state. Prototypes of these two configurations are realized and measurement results are in good agreement with the simulations.

Keywords

Clamshell system, multi-antenna system, diversity and MIMO, ground plane effect.

1. Introduction

In wireless mobile radio communications, there is an endless quest for increasing the capacity and improving the quality of the RF link. The two techniques which make possible to manage this are diversity and Multiple Input Multiple Output (MIMO) [1]-[4].

A multi-antenna system is a good candidate for increasing diversity and MIMO performance [5], [6]. However, to design realistic multi-antenna systems dedicated to mobile devices, engineers must take into account the limited allocated volume for these radiators. In such systems, the isolation between antennas is a very important parameter, especially for total efficiency performance. Improving this isolation remains a big challenge to ensure that less radiated power coming from the fed radiator is lost in the other one.

Based on intuitive or original techniques, several solutions have been developed to increase the port-to-port isolation of antennas placed on the same small ground plane.

Optimization of positions and orientations of the antennas [7], insertion of EBG cells between the radiators to suppress surface waves [8], [9], insertion of slots or slits in the ground plane, the use of defected ground planes [10]-[13], decoupling networks [14] and neutralization technique [15]-[18], have been proposed to enhance the isolation between the feeding ports of the antennas.

Neutralization technique is promising well-established technique to enhance the isolation of multi-antenna systems, because of its simplicity compared to the other techniques; for example, with the EBG technique, some part of the energy is trapped in the EBG's and therefore not useful for the total radiation mechanism of the antenna-system, despite that this technique is satisfactory in terms of isolation. Defected ground plane techniques are difficult in terms of manufacturing, and may have lower radiation efficiency in addition to the problems encountered during the packaging and the sensitivity to the user. In the case of the decoupling network technique, due to the reactive components generally used, additional losses appear compared to the neutralization technique. Furthermore, this last one is easier to use in the case of non-planar and/or no-substrate antennas, by performing a simple parametric study.

The neutralization technique is now well known and used. It has been established for two closely spaced PIFAs positioned over a typical bar phone [15]-[18] and validated for other antenna types [19], [20].

The isolation level is conditioned by the complex mutual coupling between the antennas, and the currents flowing over the ground plane. Both are difficult to handle, as the ground plane is generally an active part of the radiating system, depending of the operating frequency. As a result, not only the port-to-port isolation but all the radio electrical performance of mobile phone antennas (especially their impedance bandwidth) depend not only on the geometrical characteristics of the radiator, but are also largely defined by the antenna-chassis combination [21]-[23]. However, to our best knowledge, the case of a multi-antenna system for a clamshell-type mobile phone has never been studied [24], [25].

In this paper, we propose to study the evolution of the port-to-port isolation of two UMTS PIFAs placed on a same Printed Circuit Board (PCB) when the size of this one is modified. To validate this study, we designed and optimized a neutralized two antennas system for a clamshell-type phone. Diversity performance of the optimized system is also computed for the open and close states of this clamshell. For all electromagnetic simulations and the design optimizations, the ANSYS HFSS software package has been used. The measured results obtained from a realized prototype are compared to the simulated results.

2. Multi-antenna System on a Single Ground Plane

2.1 Design Considerations

We started to design a single PIFA placed on a finite size ground plane dedicated to operate in the entire UMTS band, the goal being to obtain the desired bandwidth of 250 MHz for a -6 dB matching criteria. Several broadband techniques can be used to increase the matching bandwidth of a simple PIFA as for example the addition of parasitic elements and the use of slots [26]. Another way consists in designing thicker feeding strips, or simply by modifying their shapes [27]. By using this technique, a new architecture was optimized with both the feeding and the shorting strips of the PIFAs shaped as vertical bowtie pin. The height of the optimized bowtie-feed PIFA was set to 8.5 mm and the dimensions of the PCB $L_{gnd} \times W_{gnd}$ to 100×40 mm^2. The obtained dimensions for the metallic plates are 27×12 mm^2 and the dimensions of the bowtie are 14×2 mm^2. The obtained $|S_{11}|$ parameter is depicted in Fig. 1.

A second PIFA is introduced close to the first one. The distance D between the two antennas was chosen equal to 16 mm ($0.11\lambda_0$). The isolation between the two radiating elements was really poor, despite a good matching (Fig. 1).

To increase the port-to-port isolation, the neutralization technique consists in inserting a suspended line between the PIFAs shorting points. The configuration of the considered neutralized multi-antenna system and the resulting scattering parameters ($|S_{11}|$ and $|S_{21}|$) are depicted in Fig. 2. The insertion of the neutralization line decreases the matching level, but increases strongly the isolation between the two antennas. The neutralization line has been meandered to reach the optimized length giving the desired performance.

2.2 Parametric Study for the Single Ground Plane Multi-antenna System

In this part, our aim is to investigate the influence of the dimensions of the ground plane on the port-to-port isolation (Fig. 1, Fig. 2) and to verify the robustness of the neutralization technique when the dimensions of the ground plane are modified. To achieve this, neutralization line and PIFAs dimensions were fixed while the length and the width of the ground plane were modified. In the considered configuration, the width of the PCB is enlarged symmetrically on each side of the two PIFAs.

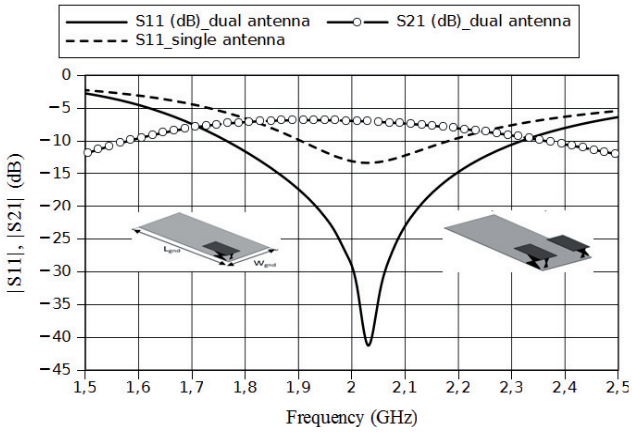


Fig. 1. Simulated scattering parameters of the single and dual antenna system.

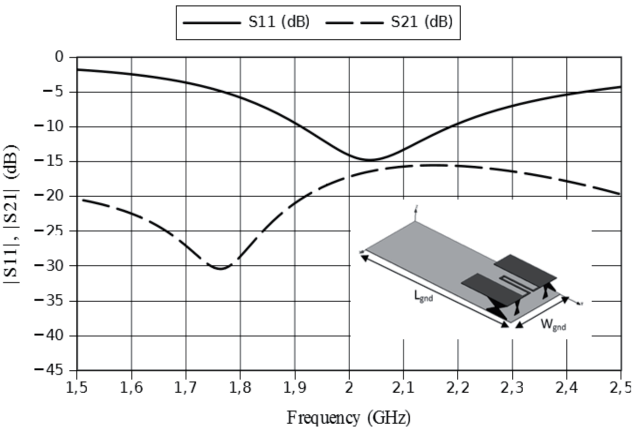


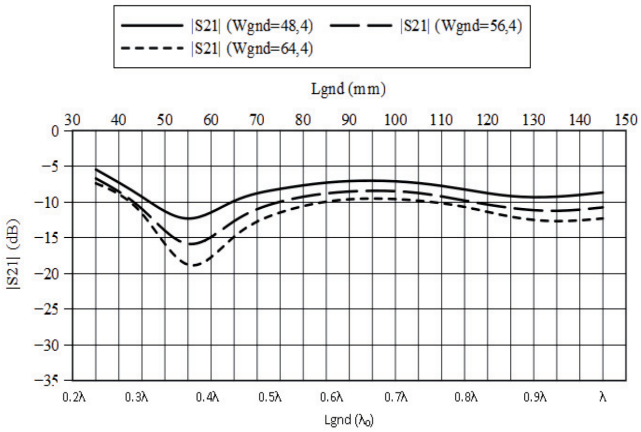
Fig. 2. Simulated scattering parameters of the neutralized dual antenna system.

Fig. 3 (a), (b) show the simulated results of the $|S_{21}|$ parameter, at the central frequency of the UMTS band (2.045 GHz), versus the length L_{gnd} (35 to 145 mm) for the initial system (without neutralization) and for the neutralized one, for different ground plane widths W_{gnd} (from 48.4 to 65 mm). For the same value of W_{gnd}, a "pseudo-periodic" variation versus the length L_{gnd} can be observed.

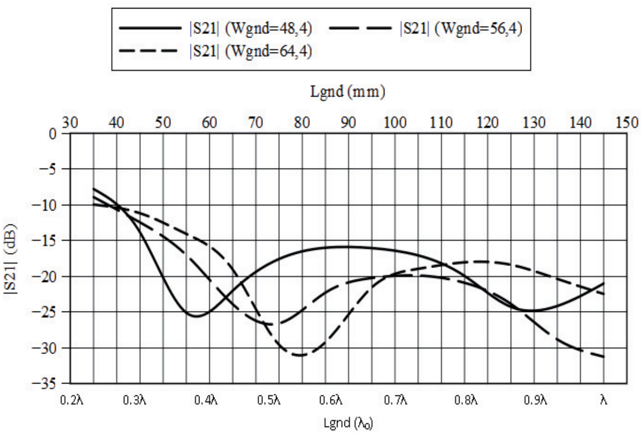
As shown in Fig. 3 (a), a minimum of coupling appears for $L_{gnd} = 55$ mm ($0.38\,\lambda_0$). This deep increases

($|\Delta S_{21}| = +7$ dB) when the width of the ground plane increases ($\Delta W_{gnd} = +16$ mm), for the same length of the ground plane $L_{gnd} = 55$ mm. The best results in terms of isolation are about 19 dB for a width $W_{gnd} = 64.4$ mm, which is the highest ? value investigated in this study. Beyond this value, $|S_{21}|$ parameter is less critical.

For the neutralized multi-antenna system in Fig. 3 (b), a minimum of insertion loss also appears. The value is lower than before and for some configurations of lengths and widths of the ground plane, the level of $|S_{21}|$ can reach very low values, up to -30 dB for example for W_{gnd}= 64.4 mm. However, unlike the previous configuration, the position of the first deep depends now on the width of the ground plane. A variation of 25 mm of the position of these deep (from $L_{gnd} = 55$ mm to $L_{gnd} = 80$ mm) can be observed when W_{gnd} varies from 48.4 to 64.4 mm. These notches periodically appear for each multiple length of $\lambda_0/2$ whatever the value of W_{gnd}.



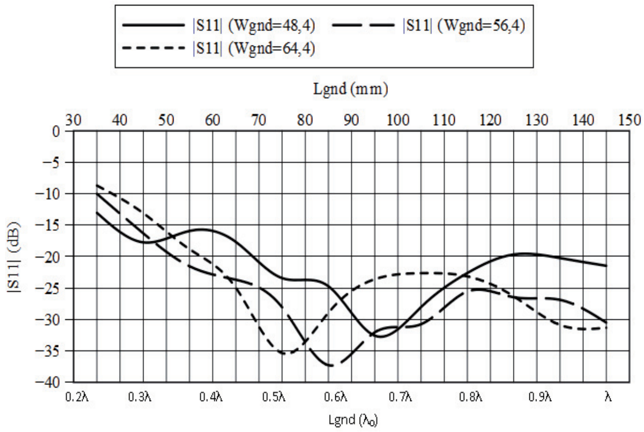
(a)



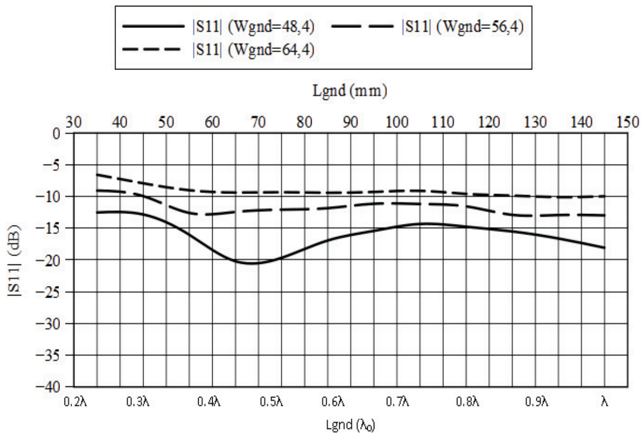
(b)

Fig. 3. $|S_{21}|$ evolution of the single ground plane systems versus L_{gnd}: (a) initial (without neutralization) multi-antenna system, (b) neutralized multi-antenna system.

For the matching $|S_{11}|$ parameter, Fig. 4 (a) and (b) also reveal periodic variations versus L_{gnd} for the two considered configurations. This periodicity is more apparent when the minimum of the matching parameter is more pronounced.



(a)



(b)

Fig. 4. $|S_{11}|$ evolution of the single ground plane systems versus L_{gnd}: (a) initial (without neutralization) multi-antenna system, (b) neutralized multi-antenna system.

The variation of the total efficiency, not presented here, calculated using (1), at the center frequency of the desired UMTS band for different values of L_{gnd}, shows that the influence of the ground plane size length is much more important for the lower values of L_{gnd}.

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

A ground plane of length 35 mm for example, exhibits a total efficiency greater than 78 %, and extending this length beyond 55 mm allows a total efficiency greater than 90 %.

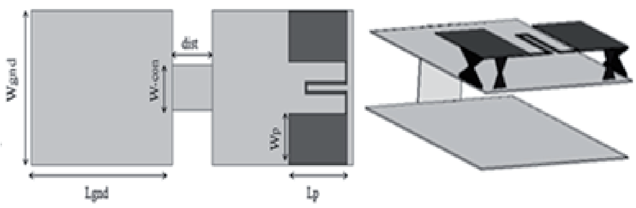
According to this study, we can conclude that the neutralization technique remains robust even if the dimensions of the PCB L_{gnd} and W_{gnd} change. However, the results of these parametric studies show that the best performance in terms of bandwidth (covering all UMTS band), matching and isolation are obtained for small values of L_{gnd} (between 50 to70 mm) which cannot be used in a realistic candy bar mobile phone. To successfully combine performance and dimensions we decide to investigate the clamshell configuration, i.e. two smaller ground planes connected by a small and short metal strip.

In the next section, the influence of the dimensions of this three parts ground plane over the performance of the system is revisited in the clamshell configuration.

3. Clamshell System Antenna Design Consideration and Ground Plane Effect on the Performance of the System

3.1 Design Considerations

In this part, the same kind of study is conducted dealing with the dimensions of the ground plane of a clamshell mobile phone multi-antenna-system in order to optimize its performance. For this kind of application, the design of such antenna systems is even trickier because both open and closed states of the phone have to be considered and they are definitely completely different. Fig. 5 shows the 3D view of the two-element antenna system.



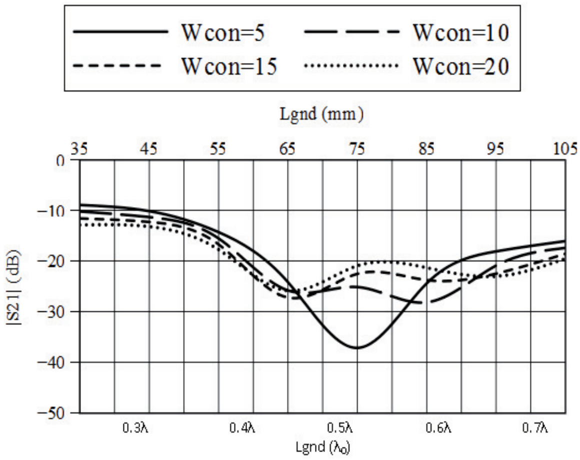
(a) (b)

Fig. 5. Neutralized two antenna system integrated in a clamshell phone: (a) open state, (b) closed state.

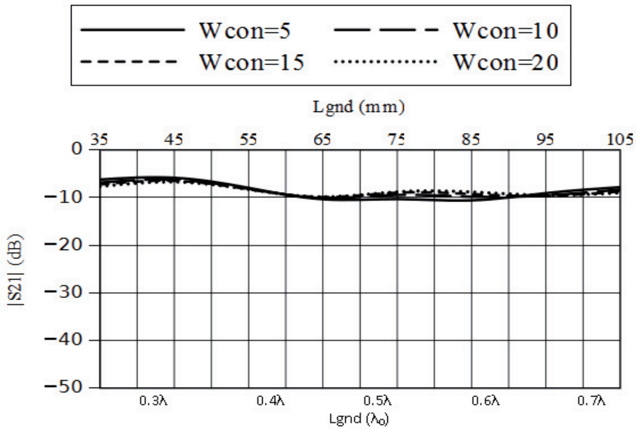
3.2 Parametric Study for the Clamshell Multi-antenna System

Fig. 6 shows the variations of the $|S_{21}|$ parameter versus L_{gnd}, for a W_{gnd} equal to 48.4 mm and for different values of W_{-con} for the initial and the neutralized system. For the neutralized system (Fig. 6a), the level of the isolation between the two antennas increases for some values of W_{-con}. For example, for W_{-con} = 5 mm the isolation level reaches 37.5 dB, (for L_{gnd} = 75 mm ($0.5\lambda_0$)), which means an improvement $\Delta|S_{21}|$ of 30 dB compared to the lower isolation obtained for other values of L_{gnd}. We can also see for W_{gnd} = 48.4 mm, that the effect of W_{-con} on the isolation parameter is more important when the value of L_{gnd} stays within 65 mm ($0.45\lambda_0$) to 95 mm ($0.65\lambda_0$). For the initial system, as shown in Fig. 6b, the effects of the length of the ground plane and the width W_{-con} are much less important than in the neutralized antenna system case. The variation of $|S_{21}|$ is only of few dB (a maximum of 5 dB) when L_{gnd} varies and of 1 or 2 dB versus W_{-con}. The same conclusions can be done concerning the effects of the parameter *dist* on the isolation parameter versus L_{gnd}. The results are shown in Fig. 7(a), (b) for W_{gnd} = 48.4 mm.

Based on this parametric study an optimized system was designed. The optimized dimensions of the proposed neutralized multi-antenna system are listed in Tab. 1 (all parameters are shown in Fig. 5 (a), and H is the height of the two PIFAs).



(a)



(b)

Fig. 6. $|S_{21}|$ evolution of the clamshell phone in open state versus L_{gnd} when W_{gnd} = 48.4 mm, *dist* = 5 mm: (a) neutralized system, (b) initial multi-antenna system.

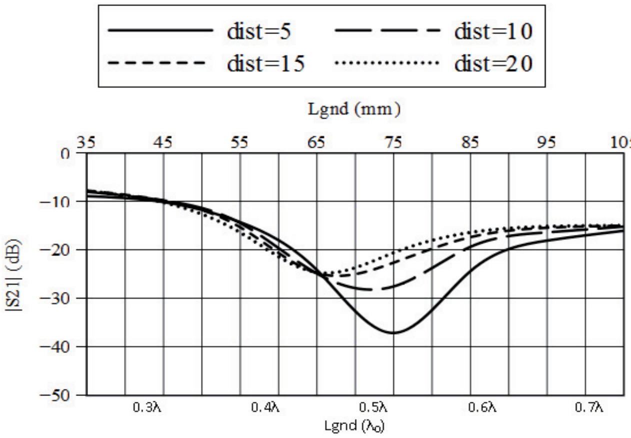
In the next step, we are going to consider the second possible state of our clamshell system namely the closed state (Fig. 5b).

Parameters	L_{gnd}	W_{gnd}	*dist*	W_{con}	L_p	W_p	H
Value (mm)	70	48.4	20	14	29	16	8.5

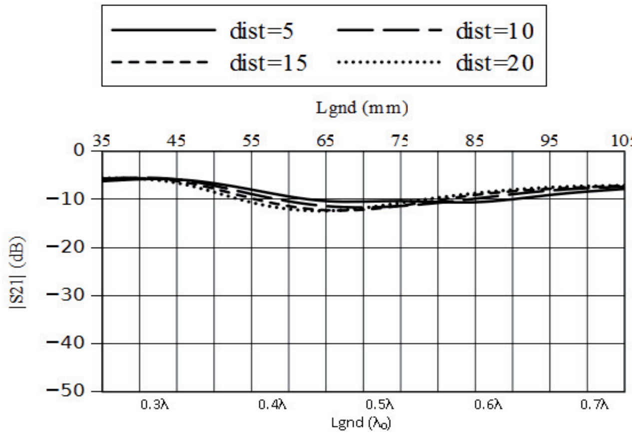
Tab. 1. Dimensions of the optimized clamshell system.

We first compare the matching and the isolation of the system between the closed and the open states. According to the simulated results reported in Fig. 8a, the difference for the $|S_{11}|$ parameter is very insignificant and both configurations have good matching performance ($|S_{11}|$ < -8 dB). Dealing with the $|S_{21}|$ parameter, the open and close states present a level of isolation respectively higher than 30 dB and 22 dB in the entire UMTS band which is really satisfactory. It is seen that the performance in terms of isolation obtained in the closed state is lower to the one obtained for the open state but they both remain acceptable.

To explain this behavior, the surface current distribution of the two operating states is shown in Fig. 8b. It can be observed that there is a low current transfer between the two feeding ports of the system which explains the good isolation level obtained. In the case of the non-neutralized system, this current is much more important, due to a $|S_{21}|$ close to an average value of -8 dB in both states.



(a)



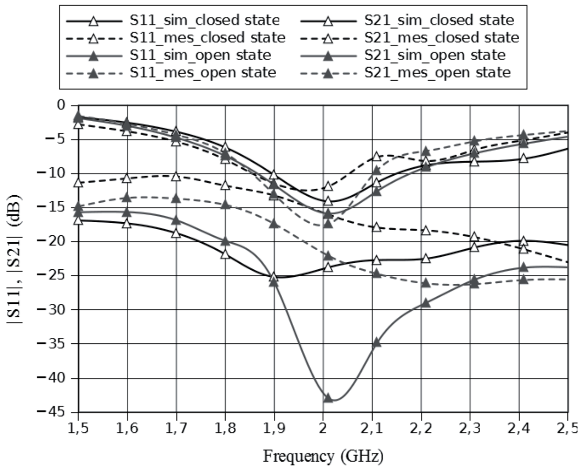
(b)

Fig. 7. $|S_{21}|$ evolution of the clamshell phone in open state versus L_{gnd} when $W_{gnd} = 48.4$ mm, $W_{\_con} = 5$ mm: (a) neutralized system, (b) initial multi-antenna system.

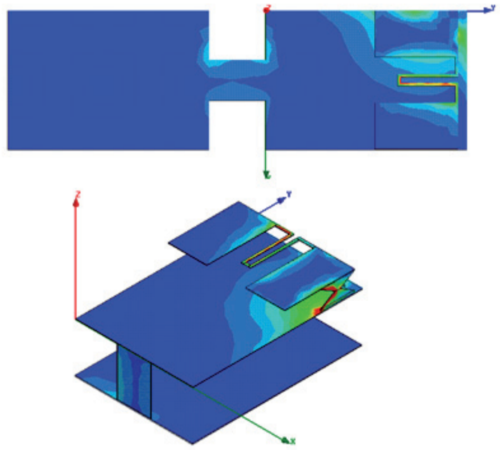
Two prototypes (open and closed states) have been fabricated and measured in order to experimentally validate the proposed design. The measured S-parameters for the two configurations are presented in Fig. 8a.

We can observe a very good agreement in terms of matching for both states. Dealing with the $|S_{21}|$ parameter, there is a slightly worse agreement attributed to the fabrication tolerance and measurements uncertainties. The $|S_{21}|$ values are always below -15 dB in the open state and below -13 dB in the closed one. Note that, the presence of the cables makes difficult the maintaining of the horizontal linearity between the antennas and the neutralization line because of the mechanical pressure created on the ground plane, in addition to their electrical effects on the measurement results.

The simulated total efficiencies for the closed and the open states at the center frequency of the UMTS band are respectively 92 % and 98 % (Fig. 9). For the whole UMTS band, the efficiency is better than 85 % for the closed state



(a)



(b)

Fig. 8. Simulated and measured: (a) $|S_{11}|$ and $|S_{21}|$ parameters and (b) current distribution for the open and closed states of the optimized clamshell antenna system.

and 90 % for the open state. The Wheeler cap method was used to measure the radiation efficiency for the closed state. A small difference is observed between simulated and measured results due to additional losses of the Wheeler cavity. The open state could not be measured because the dimensions of the multi-antenna system exceed the dimensions of the Wheeler cap in this case.

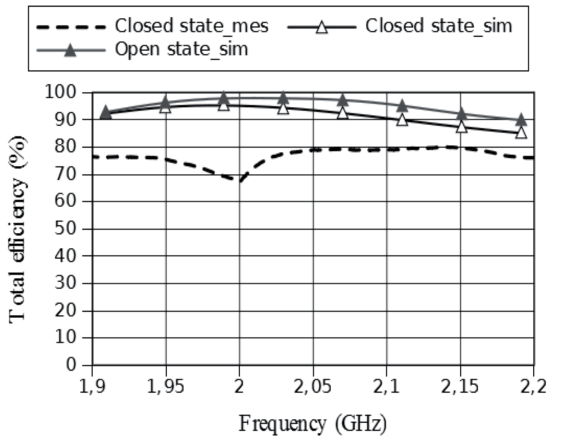


Fig. 9. Total efficiency for the closed and open states of the optimized clamshell antenna-system.

4. Diversity Performance of the Proposed Clamshell System

The diversity performance of the clamshell system for the open and closed states has been evaluated and is presented in this section. The considered parameters are the envelope correlation (ρ_c), the Diversity Gain (*DG*) and the Diversity System Gain (*DSG*), calculated in indoor environment by using an elliptical model following equations (2), (3), (4) and (5) [28], [29]:

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

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

where
$G_\theta = E_\theta(\Omega) * E^*_\theta(\Omega)$,
$G_\varphi = E_\varphi(\Omega) * E^*_\varphi(\Omega)$,
$E_{\theta 1}(\Omega), E_{\theta 2}(\Omega), E_{\varphi 1}(\Omega), E_{\varphi 2}(\Omega)\quad P_{\theta,\varphi}(\Omega)$

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.

The second parameter taken into account is the *DSG* (3) where 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 (4).

$$DSG\,(\mathrm{dB}) = DG\,(\mathrm{dB}) + \eta_{tot}\,(\mathrm{dB}), \tag{3}$$

$$DG = [\frac{\gamma_c}{\Gamma_c} - \frac{\gamma_1}{\Gamma_1}] P(\gamma_c < \gamma_s / \Gamma). \tag{4}$$

In (4), 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 simultaneously on the number *M* of the branches of the system and the envelope correlation. The elliptical distribution model (5) of the incident waves was chosen because the power spectrum is more directional in the indoor case and this model has already proven to give an interesting realistic use-case situation. In this model, space is divided into several beams, fixed by the user, and all the diversity parameters are calculated for each of these beams.

$$\left.\begin{aligned} P_\psi(\alpha) &= \sqrt{A_\psi}\,\frac{S^2_{\psi\alpha}}{S^2_{\psi\alpha} + (\sin\alpha)^2} \\ P_\theta(\varphi) &= \sqrt{A_\theta}\, a_{\theta 0} \\ P_\varphi(\varphi) &= \sqrt{A_\varphi}\,(a_{\varphi 0} - b_\varphi |\varphi|) \end{aligned}\right\} \tag{5}$$

In (5), $S_{\Psi\alpha}$ is a measurement of the angular spread in the sinα- domain for both elevation and azimuth of the polarized wave distributions; $a_{\theta 0}$ and $a_{\varphi 0}$ are the relative amplitude of the uniformly distributed low energy scatters in azimuth; b_φ is the linear decay factor for the horizontal polarized wave distribution in the azimuth plane.

Fig. 10 shows the variation of the DSG for these six beams for the closed and the open states. It is seen that the open state presents a good DSG for all the beams, but the variation of the DSG between the different beams for the closed state is relatively important (2.5 dB).

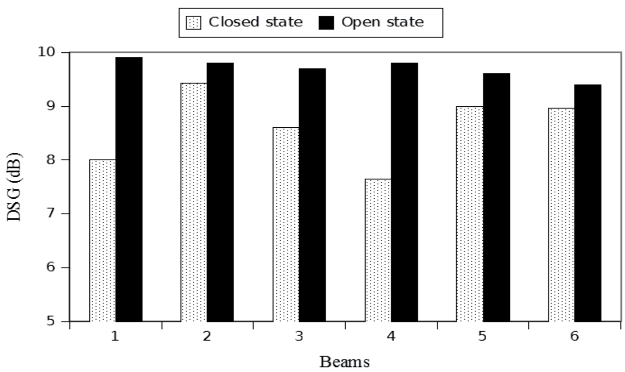


Fig. 10. Comparison of the calculated DSG for the open and closed states versus the considered beams.

Tab. 2 shows the obtained values of the previous parameters for six beams (60° for each) which represent the total space around the clamshell. To estimate the real performance of our system, the averages of the obtained values are also listed in Tab. 2. It is seen that our system gives a good diversity performance in the two closed and open configurations.

	Env_corr		DG		DSG	
	closed	open	closed	open	closed	open
0°-60°	0.4	0.02	8.59	10.1	8	9.9
60°-120°	0.02	0.09	10	10	9.43	9.8
120°-180°	0.16	0.11	9.18	9.94	8.6	9.7
180°-240°	0.17	0.07	8.23	10	7.64	9.8
240°-300°	0.01	0.17	9.61	9.78	9	9.6
300°-360°	0.25	0.25	9.55	9.58	8.96	9.4
Averages	0.17	0.12	9.2	9.9	8.6	9.7

Tab. 2. Diversity performance of the optimized clamshell system.

5. Conclusion

In this paper, the effect of the ground plane dimensions on the isolation and the efficiency performance of a two-antenna system designed for UMTS application were first studied. The two antennas are initially connected by a neutralization line to enhance their port-to-port isolation. Parametric studies have shown the possibility to obtain better performance with optimal dimensions of the ground plane, but also the fact that the neutralization technique was still robust if we have to modify the dimensions of the PCB. In the second part, the design of an efficient multi-antenna system for clamshell-type mobile phone with high port-to-port isolation between the antennas in the entire UMTS band and for the two possible operation configurations (open and closed states) was proposed. The optimized clamshell system was fabricated and measured. A good agreement was observed between simulated and measured results for both configurations. All these results can be used to enhance the design of neutralized systems. A model based on the artificial neural network is developed for the neutralization technique. It gives instantaneously the physical parameters of a multi-antenna system and the neutralization line for a desired performance in terms of isolation, bandwidth and matching level fixed by the user [30].

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