Multiport Multiband Coupling Minimization for Miniature Antennas

R. Serrano, S. Capdevila, A. Aguasca, J. Romeu and L. Jofre

Departament de Teoria del Senyal I Comunicacion, Universitat Politècnica de Catalunya

Jordi Girona, 1-3, Barcelona, Spain.

www.tsc.upc.edu

raquel.serrano@tsc.upc.edu

***Abstract*— The equations governing the multiport multiband antennas are analyzed in this paper with the objective of drawing the design guidelines for low coupling small antennas. Those guidelines have been applied in the design and optimization of a dual band two-port small antenna of size around $\lambda_0/13$ x $\lambda_0/13$. The antenna geometry is shown together with coupling minimization results.**

I. Introduction

The evolution towards minimization due to increase of mobility of communication devices and their pervasive incorporation in the environment leads to high degree of integration of the antenna with the rest of the circuitry. New applications require multiband operation, implying multiband multiport antenna designs. All this imposes specific restrictions to the antenna: it needs to be thin enough to be compatible with the multilayer integration technologies; its radiation towards circuitry must be low and the total size of the antenna must be kept as small as possible. In addition to the worsening of the radiation properties (radiation efficiency and bandwidth) when reducing the size of an antenna, as it has been formulated in many publications, such [1] and [2], one of the backbones of the small multiport antennas is the strong port coupling, which can become very unfavourable from the point of view of the efficiency for certain applications.

There have been a lot of studies focused on the coupling minimization techniques for single band multiantennas composed by radiating elements working at the same frequency f_i, which are positioned at very short distance ([3], [4]). However, those techniques are quite complicated to be applied when the antenna is very small and there is no symmetry in the radiating structures or when the different structures share the same radiating metallic layer. Taking the advantage of the multiband multiport operation, we can think of other techniques to minimize coupling by imposing certain working conditions to the antenna ports not only at its own resonating frequency (at which the condition would be the perfect matching), but also at the rest of the operation frequencies. At a certain port *i*, matching requirements are fulfilled at f_i, and some coupling condition could be imposed in addition at every f_j (being $i \neq j$).

The aim of this work is the deep study of those equations governing the multiport multiband small antennas, in order to have designs criteria for optimum antennas.

II. Analytic Analysis

Considering the multiband multiport antenna as a multiport network (Fig. 1), each port *i,* will be required to radiate energy at a certain frequency f_i. f_j. In multiport multiband antennas, the total efficiency at f_i, η_{total}^{fi}, can be divided in three main contributions: reflections (due to mismatching, η_{ref}^{fi}, ohmic losses, η_l^{fi}, and coupling to other ports, η_c^{fi}:

$$\eta_{total}^{fi} = \eta_{ref}^{fi}.\eta_l^{fi}.\eta_c^{fi} \qquad (1)$$

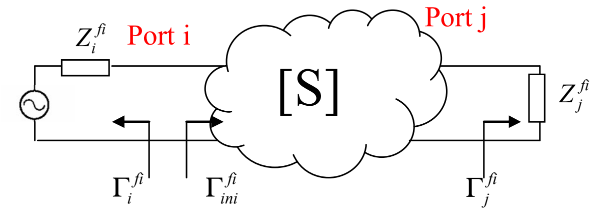


Fig. 1 Dual-port dual band antenna two-port network model at f_i

In this way, one of the conditions for a high antenna efficiency, is a good matching at port *i* at its corresponding operating frequency f_i (approximating η_{ref}^{i} to 1). In the same way, the power which is transferred from port *i* to port *j* must be minimized, achieving high η_c^i. Therefore, the objective is to find a condition at the ports *i, j* to minimize the coupling between them.

The relation between the power coupled from port *i* to port *j* at f_i (P_j^{fi}) with respect to the available power at port *i* $P_{av_i}^{fi}$ can be expressed as in (1),

$$C_{ji}^{fi} = \frac{P_j^{fi}}{P_{avi}^{fi}} = 4.\mathrm{Re}(Z_i^{fi}).\frac{|S_{ji}^{fi}|^2}{|1-S_{jj}^{fi}\Gamma_j^{fi}|^2\,|1-\Gamma_{ini}^{fi}\Gamma_i^{fi}|^2}.\frac{|Z_{0i}^{fi}|}{|Z_{0i}^{fi}+Z_i^{fi}|^2}\left(1-|\Gamma_j^{fi}|^2\right) \qquad (2)$$

being Z_i^{fi} and Z_{0i}^{fi} the input impedance and reference impedance at port *i* at f_i, Γ_i^{fi} the reflection coefficient looking into the port *i* at f_i, Γ_{ini}^{fi} the input reflection coefficient looking towards network port i at f_i and Γ_j^{fi} the reflection coefficient of the load at port j at f_i. The, coupling and efficiency are related according to the expression (3):

$$\eta_c^i = 1 - C_{ji}^{fi} \quad (3)$$

The trivial solution to minimize the coupled power is to make $\left|S_{ji}^{fi}\right|$ close to 0, which will be extremely difficult to achieve, in case of very close radiating elements, or small multiband antennas, where the resonant structures share the same radiating metallic element.

Assuming matching conditions at port i at working frequency f_i, then $\Gamma_i^{fi} = 0$ and $Z_i^{fi} = Z_{0i}$, the expression for the coupling is simplified to (4):

$$C_{ji}^{fi} = \frac{P_{L_j}^{fi}}{P_{avi}^{fi}} = \frac{\left|S_{ji}^{fi}\right|^2}{\left|1 - S_{jj}^{fi}.\Gamma_j^{fi}\right|^2}.\left(1 - \left|\Gamma_j^{fi}\right|^2\right) \quad (4)$$

The condition to minimize expression (4) is expressed as follows:

$$S_{jj}^{fi}.\Gamma_j^{fi} = -1 \quad (5)$$

Therefore, when the product $S_{jj}^{fi}.\Gamma_j^{fi}$ equals -1, the transferred power from port i to port j at f_i is minimized.

Then, there are two design options: either the antenna S parameters ($[S]$) or the load RF circuitry (Γ_j) should be adjusted to fulfil the coupling minimization condition:

- If we choose to modify the antenna, a first design condition will be imposed to θ_{Sjj}, the S_{jj}^{fi} parameter phase: it should fulfil the expression (6).

$$\theta_{S_{jj}^{fi}} + \theta_{\Gamma_j^{fi}} = 180^\circ \quad (6)$$

Once condition (6) is assured, the maximum reduction will be obtained when the S_{jj}^{fi} amplitude, $\left|S_{jj}^{fi}\right|$ equals 1. However, this would imply having reactive load (radiating element) at port 2. Having $\left|S_{jj}^{fi}\right| = 1$ would lead again to the trivial solution $\left|S_{ji}^{fi}\right| = 0$, since there will not be dissipated power in load at port j. The condition for $\left|S_{jj}^{fi}\right|$ to minimize the coupling in (4) will be bounded by the power balance expression (7) in case of lossy networks:

$$\left|S_{ji}^{fi}\right|^2 + \left|S_{jj}^{fi}\right|^2 \leq 1 \quad (7)$$

meaning that, considering lossless antennas, we can assume $\left|S_{ji}^{fi}\right|^2 + \left|S_{jj}^{fi}\right|^2 + P_{radj}^{fi} = 1$. If we achieve a high $\left|S_{jj}^{fi}\right|$, this will imply either a reduction of $\left|S_{ji}^{fi}\right|$ or a reduction of the radiated power at f_i at port j (P_{radj}^{fi}), which is also advantageous, since port j is required to work only at f_j.

The S-parameters depend on the antenna geometry, so, the way of modifying S_{jj}^{fi} is to play with the geometry or the feeding points, which will have also certain effects on the rest of the parameters (S_{ii} amplitude and phase and S_{ji} phase at all the frequency bands) that are difficult to analyse and may not be advantageous for other antenna characteristics such us radiation efficiency or port matching.

- However, if we choose to impose the coupling minimization condition to the load RF circuitry, Γ_j^{fi}, the problem is reduced to the design of a port load fulfilling certain conditions at f_j: According to (5), the reflection coefficient is tuned to approximate -1:

$$\theta_{\Gamma_j^{fi}} = 180^\circ - \theta_{Sjj} \text{ and } \left|\Gamma_j^{fi}\right| \approx 1 \quad (8)$$

These coupling minimization criteria must be applied keeping Γ_{ini} as low as possible.

In sum, each port (i.e. port i) should fulfil the design criteria:

a) at its corresponding operating frequency f_i should present the proper impedance to maximize matching conditions ($\Gamma_i^{fi} = \left(\Gamma_{ini}^{fi}\right)^*$),

b) at the rest of the operating frequency bands (f_j), the impedance at port i should fulfil $\Gamma_i^{fj} = -1, (\forall f \neq i)$.

In order to manage and meet the different conditions at different frequency bands for the ports reflection coefficients, $\Gamma_i^{fi,fj}$, optimization methods based on genetic algorithms may be used, [5]. Eventually, genetic algorithms can be also applied in the antenna design process, if we chose to impose the coupling conditions to the S parameters (S_{jj}^{fi}).

III. Miniature Dual port Dual band Antenna Design

The previous analytic analysis has been applied to a dual band dual port miniature antenna. Its design has been done following the minimization coupling requirements.

A. *Minimum coupling Dual band dual port antenna application*

The miniature antenna is thought to work for self-powered miniature wireless sensor nodes, which means that the node must generate its own energy to keep functioning without any external battery. In other words, the node must be able to harvest the sufficient energy from the ambient sources to feed all the subsystems of which is composed. From all the possible energy sources, the ambient RF power is a convenient option in case of indoor short range wireless applications. In this way, when using RF ambient energy to power the node circuitry, two radiating structures are needed:

one of the structures will be in charge of collecting energy from the external source, at a certain frequency band f_1, and the other structure is used for the data communication at frequency f_2. In this kind of applications, the energy received to be harvested is very low, and therefore, the scavenging circuitry and the antenna should be designed for the maximum efficiency. In this context, a high coupling between both ports would mean that a significant amount of the received power is not used for the powering of the node system but it is lost through the communication port.

B. Design

The miniature antenna system, which should fit in 25x25mm, since it is the space occupied by the sensor node die, is required to collect energy at f_1=950MHz and transmit and receive data at f_2=2.45GHz. The 950MHz antenna port is connected to a 50ohm single-ended port rectifier, whereas the 2.45GHz resonating structure is directly fed by a 50 ohm balanced output.

Having chosen a patch type antenna as radiating structure at 950MHz, the need for using downsizing techniques is obvious, since the resonant length at 950MHz is 157.9mm, which equals half wavelength in free space ($\lambda_0/2$). The proposed antenna has transversal dimensions (*l, w*) of 25x25mm ($\approx\lambda_0/13$ x $\lambda_0/13$) and 1.5mm thickness, t, ($\approx\lambda_0/200$). The use of low loss substrate (ε_r= 3.55, tg(δ)=0.0027), a shorting edge on one side of the patch antenna, which lowers the dimension to $\lambda/4$, and the lateral folding of the structure, leads to sufficient size reduction of the antenna for on-chip integration with an acceptable cost in efficiency and bandwidth. The active layer of the patch is fed by a conductive via which, passing through the ground plane, is connected to the rectifier that is placed on the circuitry layers, which are located bellow. In Fig 2 a complete v3D view of the whole node architecture is shown. In Fig 3 a 3D view of the 950 MHz resonant structure is drawn.

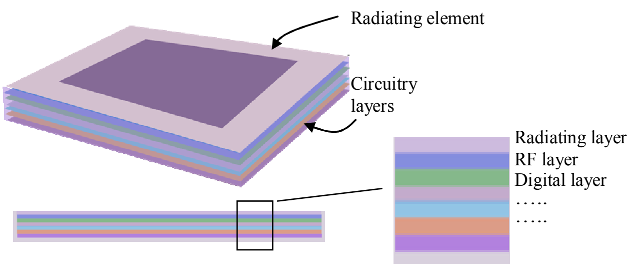


Fig. 2 Node integrated architecture

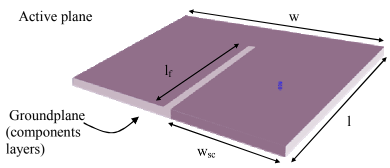


Fig. 3 950 MHz antenna design

The resonant structure at 2.45GHz is to be connected to a balanced port, which leads to think of a structure with a balanced feeding, such as dipoles or slots, which are suitable for direct integration with differential transceivers. Taking advantage of the active plane of the 950MHz patch antenna, the most convenient solution seems to be to etch a slot on it, of the 2.45GHz resonant length. This resonant length in free space is 61.2mm ($\lambda_0/2$), which is too large to fit in 25x25mm, consequently downsizing techniques need to be also applied in this case. The symmetry presented by the field distribution of a $\lambda/2$ a slot antenna allows to place a PMC in the symmetry axis, which is right in the middle, at $\lambda/4$. Therefore, an open circuited $\lambda/4$ has the same performance as the $\lambda/2$ slot. Considering the dielectric constant of the patch substrate, a sufficient length reduction is achieved ($\lambda/4$ is around 17mm) fitting on 25x25mm. The location of the 2.45GHz slot on the top conductive plate follows isolation optimization criteria, being placed on a foreseeable low current zone of the 950MHz patch (surface density current at 950MHz shown in Fig. 4). Fig. 5 presents the complete structure for the two-port dual band miniature antenna.

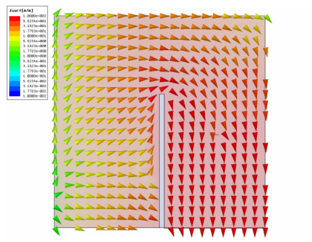
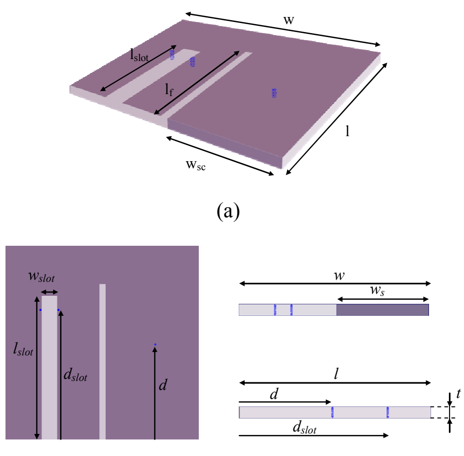


Fig. 4 Surface density current for the one-port patch antenna



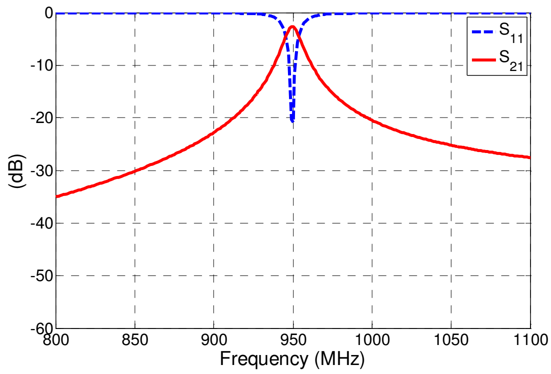
(b)

Fig. 5 Two-port dual band small antenna. (a) 3D view. (b) top and lateral views

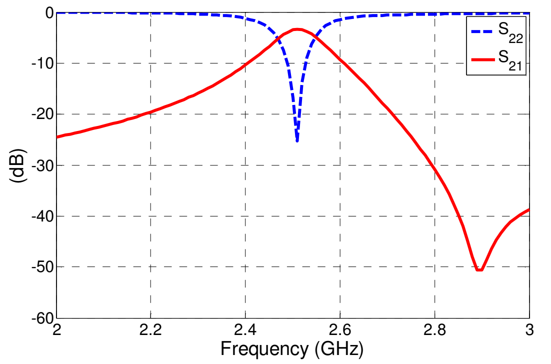
C. Coupling Minimization

In order to adjust the physical parameters for the proper performance of the antenna, a series of simulations have been done using the simulation tool HFSS10.1.2, which is based on the finite element method.

First, the S parameters are calculated and, as it was foreseeable and can be seen in Fig. 6, the S_{21} parameter is too high to achieve low coupling considering that both ports are load with 50Ω at both frequencies, then, in expression (2), $\left|\Gamma_i^{fi}\right| = \left|\Gamma_j^{fi}\right| = 0$



(a)



(b)

Fig. 6 Dual band two-port small antenna. S-parameters at (a) 950MHz and (b) 2.45GHz

However, having already the antenna S-parameters, we can play with the load reflection coefficient in order to achieve low coupling.

According to previous discussion, Γ_2^{f1} should fulfil the conditions defined in (8) : $\Gamma_2^{f1} \approx -1$

Fig. 7 shows the variation of coupling with $\theta_{\Gamma_2^{f1}}$ for different amplitudes $\left|\Gamma_2^{f1}\right|$ at frequency f_1=950MHz, achieving lower coupling for $\theta_{\Gamma_2^{f1}} \approx 29^{\circ}$, which is remarked in red, (θ_{S22} at f_1=950MHz is 151º approx.) and for $\left|\Gamma_2^{f1}\right|$ close to 1.

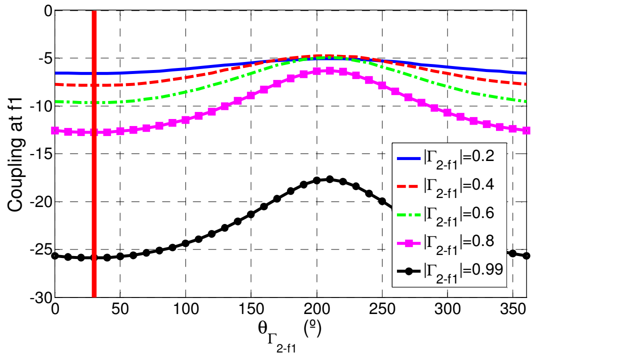


Fig. 7 Variation of coupling with $\theta_{\Gamma_2^{f1}}$ for dual band two-port small antenna at f_1=950MHz for different values of $\left|\Gamma_2^{f1}\right|$

Therefore, the design solution will resides in the load circuitry, requiring the above-mentioned values at f_1 and perfect matching at f_2=2.45GHz ($\Gamma_2^{f2} \approx 0$).

The optimum load impedances at the different ports depend on frequency, fulfilling the previous design conditions.

IV. Results

In order to test our two-port dual band small antenna design, once optimized for minimum coupling, some simulation results are shown hereby. In low power applications, it is especially critical to keep efficiency as high as possible. Scavenging is one of those low power applications, and therefore the efficiency at port 1 or scavenging port will be maximized, reducing the power which is coupled to the port 2 at f_1=950MHz . According to criteria described previously, we have to design a frequency dependent load for port 2, $Z_2^{f1,f2}$. The design of the variable load has been done with the software tool ADS (Advanced Design System) from Agilent. These loads behave like filters, meaning that $Z_2^{f1,f2}$ will be composed by some extra lumped components. Here we confront a compromise between the space we have for extra components if needed, which determines de order of the filter, and the improvement of the coupling. Results of the improvement of the coupling are shown in Fig. 8, where figures for minimum coupling are presented together with the initial coupling figures. According to (3), when coupling is minimized to -30dBm, the improvement in efficiency would be around 70%.

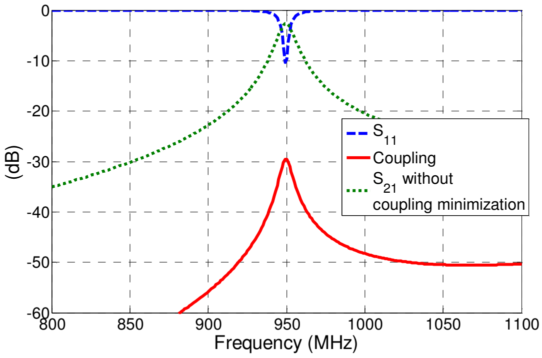


Fig. 8 Dual band two port antenna optimized for minimum coupling. Results for 950MHz.

Further improvement could be done by reducing also the coupling from port 2 (communication data at 2.45GHz) to port 1 (scavenging at 950MHz) following the same procedure: a frequency dependent load would be designed for port 1 (Z_1). Fig 9 shows the coupling optimization at 2.45GHz band.

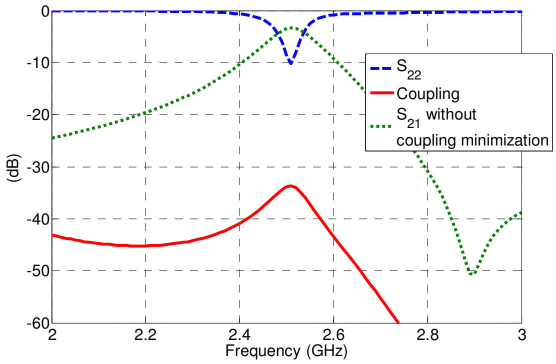


Fig. 9 Dual band two port antenna optimized for minimum coupling. Results for 2.45 GHz.

The final two port network model for the optimized antenna is presented in Fig 10. Z_2 and Z_1 are different at f_1 and at f_2

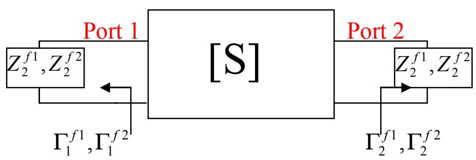


Fig. 10 Dual band two-port optimized antenna model

V. Conclusions

Coupling between ports in multiport multiband antennas increases significantly when the size of the antenna shrinks. However, by analysing the equations governing the port coupling, we have found the conditions to be applied to the port loads in order to minimize the amount of coupled power from one port to the others.

Achieving port impedances fulfilling certain design conditions at certain frequencies, the coupling is minimized, achieving an efficiency improvement of 70%.

The use of Genetic Algorithms to find the optimum impedances may improve the optimization process, reducing the number of extra components and making it more accurate.

The design criteria have been proved for a two port dual band miniature antenna.

Acknowledgements

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References

[1] Chu, L.J. “Physical Limitations of omni-directional Antennas”. *Journal of Applied Physics*, 1948, 19, pp. 1163-1175.

[2] McLean, J.S. “The Radiative properties of Electrically-Small Antennas”, *IEEE International Symposium on Electromagnetic Compatibility*, pp. 320 – 324, Aug. 1994.

[3] Serrano, R., Capdevila, Diallo, A., S., Blanch, Luxey, C., Le Thc, P., Staraj, R., S., Romeu, J., Jofre, L. “Optimal Multiantenna Structures for Maximum Capacity in Wireless Compact Systems” *EUCAP*, Edimburgo, Nov 2007.

[4] Diallo, A. Luxey, C., le Thuc, P., Staraj, R., Kossiavas, G., Franzen M., Kildal P-S., "Evaluation of the performances of several four-antenna systems in a reverberation chamber" in *Proc International Workshop on Antenna Technology 2007 (iWAT07)*, 21st-23rd March 2007, Cambridge.

[5] Rahmat-Samii, Y. and Michielssen, E. *Electromagnetic Optimization by Genetic Algorithms*, Ed. Wiley, 1999