A Systematic Method to Design Broadband Matching Networks

Aurora Andújar[1], Jaume Anguera[1,2], Carles Puente[1,3]

[1] *Technology and Intellectual Property Rights Department, FRACTUS S.A., C/ Alcalde Barnils nº64, 08174 Barcelona, Spain*
aurora.andujar@.fractus.com, jaume.anguera@fractus.com

[2] *Electronics and Telecommunications Department, Universitat Ramon Llull, 08174 Barcelona, Spain*

[3] *Signal Theory and Communications Department, Universitat Politècnica de Catalunya, 08174 Barcelona, Spain*

***Abstract*—The narrow bandwidth (BW) associated to small antennas featured by a high quality factor (Q) can be enhanced by the addition of a matching network. However, the impedance matching is a difficult and time-consuming process since it depends on the ability of the designer for selecting that suitable matching architecture that achieves the best trade-off between BW, complexity and implementation. In this paper, a systematic method for broadening the BW of handset antennas is proposed. The method is focused on those antennas whose input impedance near the first resonance can be modeled as an RLC series circuit. In order to develop the proposal, a mathematical analysis is carried out using a simple electrical model and the theoretical results are validated through simulations and by an experimental process. As a result, a systematic method for designing matching networks with a good balance between complexity and BW enhancement is obtained. Thus, the method described herein ensures one half of Fano's limit BW increment through a simple and methodic matching design.**

I. INTRODUCTION

Small antennas are featured by a high Q, which traduces in narrow bandwidth BW [1]. The addition of a matching network becomes an efficient method for enhancing the BW limitations associated to small antennas [2]. However, the matching network design is not a methodical process, since it must be customized according to the input impedance of the antenna under study. At the same time, it becomes a very time-consuming task, usually based on trial and error methods. Furthermore, it depends on the abilities of the matching network designer on finding the suitable solution, ensuring the requirements of BW increment, low complexity and integration facilities, between a great number of alternatives. This research overcomes the aforementioned shortcomings introducing a systematic method to design a matching network that increases the bandwidth about one half the Fano's limit [5]. The method is focused on antennas with an input impedance that can be modeled as an RLC series circuit, such as dipoles or monopoles in their first resonances.

The bandwidth enhancement obtained with a double-tuned matching is demonstrated in [2]. However, it fails to mention which are the values of the inductor and the capacitor required for a double-tuned antenna impedance matching circuit.

In [3], several matching stages are presented for increasing the BW of conventional microstrip patch antennas using distributed elements.

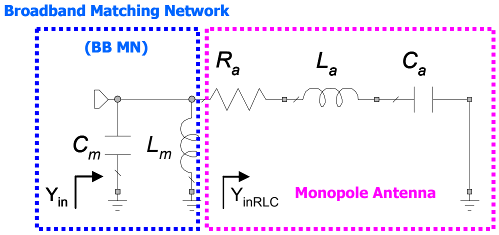
A simpler method to design broadband microstrip patch antennas is disclosed in [4]. The values obtained are restricted to situations where the antenna presents an input impedance that can be modeled as an RLC parallel circuit, such as microstrip patch antennas.

Hence, the aim of this paper is to determine the values of the inductance and the capacitor required in a double-tuned matching network to increase the BW of an antenna featuring an input impedance close to an RLC series circuit. The values are obtained through a mathematical analysis carried out using a simple electrical model.

The paper is divided in the following sections. Firstly, a mathematical analysis using an equivalent electric circuit of the antenna structure is developed in (II). The accurate analysis allows determining the values of the matching network required for bandwidth enhancement. Secondly, the effectiveness of the proposal is evaluated through simulations using the software IE3D based on MoM (III). In a third stage, a prototype is built for the sake of validating the simulations with the experimental results (IV). Finally, the conclusions are presented (V).

II. MATHEMATICAL ANALYSIS

Monopoles and dipoles are antennas whose input impedance near their first resonance can be associated to the input impedance of a RLC series circuit. As stated in [2] the addition of an LC resonator as a matching network allows bandwidth improvements. However, the values of this LC resonator are not disclosed in [2].



$$Y_{in}(f) = Y_{inRLC}(f) + j2\pi f C_m + \frac{1}{j2\pi f L_m}$$

Fig. 1 Equivalent circuit regarding a specific antenna featuring an RLC series input impedance and a two stages matching network

During this section a mathematical analysis is carried out using the equivalent electrical circuit associated to this type of antennas (Fig. 1). It allows determining the exact expressions that give the values of the matching network components (C_m y L_m) required for BW optimization.

The BW is enhanced by fulfilling the conditions that force the impedance locus of the Smith Chart to be inscribed inside a circle of VSWR=S (Fig. 2).

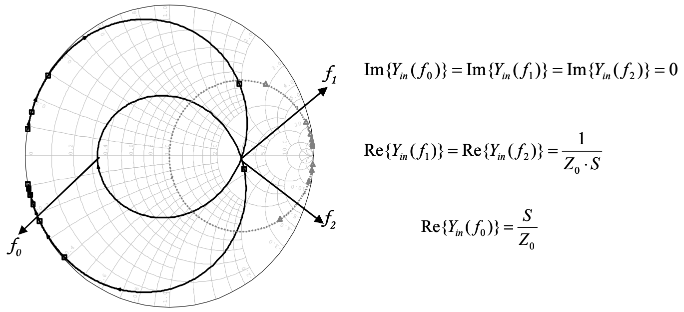


Fig. 2 Graphical representation in the Smith chart of the conditions required to achieve BW enhancement

As aforementioned, the mathematical analysis carried out along this section provides the numerical expressions that determine the exact values of the reactive components required to attain a BW enhancement of approximately one half of Fano's limit. Besides the reactive values, the method also determines the input impedance of the antenna that allows tuning the impedance locus at the center of the Smith chart (Fig. 2). Thus, the matching network process is simplified, since the antenna designer is able to know in advance the values of these components, avoiding, at the same time, the annoying trial and error methods.

Following the teachings of [4] and applying duality it is possible to obtain the values that will improve the bandwidth of an antenna featuring an RLC series input impedance. The admittance of this kind of circuits can be written as:

(1) $$Y_{inRLC}(f)=\frac{R-jRQv}{R^2+(RQv)^2}$$

(2) $$v=\frac{f}{f_0}-\frac{f_0}{f}$$

(3) $$f_{0(RLC\_resonance)}=\frac{1}{2\pi\sqrt{L_aC_a}}$$

As previously stated, the inherent BW of an antenna, with the characteristics described above, can be increased if the correct matching network is chosen. In order to correctly match the RLC series circuit that models the impedance behavior of the antenna, a parallel capacitor and inductor is used. An accurate mathematical analysis applied using the electrical model of Fig. 1 leads to the values of these reactances that satisfy the condition given in (Fig. 2).

The admittance related to the electrical model associated to Fig. 1 is defined as follows:

(4) $$Y_{in}(f)=Y_{inRLC}(f)+j2\pi fC_m+\frac{1}{j2\pi fL_m}$$

Hence, the imaginary and real part of the input admittance is:

(5) $$\mathrm{Im}\{Y_{in}(f)\}=\frac{-R_aQ_av}{R_a^{\,2}+(R_aQ_av)^2}+\omega C_m-\frac{1}{\omega L_m}$$

(6) $$\mathrm{Re}\{Y_{in}(f)\}=\frac{G_a}{1+(Q_av)^2}$$

It is important to note that if the imaginary part of the antenna admittance is equated to 0, three resonance frequencies appear (f_0, f_1 and f_2). In order to maximize the BW, the input impedance locus has to be forced to fulfill the following requirements (also illustrated in Fig. 2) that will condition the L_m and C_m values.

(7) $$\mathrm{Im}\{Y_{in}(f_0)\}=\mathrm{Im}\{Y_{in}(f_1)\}=\mathrm{Im}\{Y_{in}(f_2)\}=0$$

(8) $$\mathrm{Re}\{Y_{in}(f_1)\}=\mathrm{Re}\{Y_{in}(f_2)\}=\frac{1}{Z_0\cdot S}$$

(9) $$\mathrm{Re}\{Y_{in}(f_0)\}=\frac{S}{Z_0}$$

The first solution to the equation (5) gives the relationship required between L_m and C_m (10). At the same time, the value of L_m can be easily obtained substituting equation (10) into equation (5).

(10) $$C_m=\frac{1}{\omega_0^{\,2}\cdot L_m}$$

(11) $$L_m=\frac{(f_1^{\,2}-f_r^{\,2})\cdot Z_0\cdot(1+(Q_a\cdot v_1)^2)}{S\cdot Q_a\cdot(f_1^{\,2}-f_r^{\,2})\cdot 2\cdot\pi\cdot f_r}$$

Where f_1 is computed according to equation (8):

(12) $$f_1=\frac{-f_0\cdot\sqrt{G\cdot Z_0\cdot S-1}+f_0\sqrt{G\cdot Z_0\cdot S-1+4\cdot Q^2}}{2\cdot Q}$$

And at the same time, f_2 follows the expression (13):

(13) $$f_2=\frac{f_0\cdot\sqrt{G\cdot Z_0\cdot S-1}+f_0\sqrt{G\cdot Z_0\cdot S-1+4\cdot Q^2}}{2\cdot Q}$$

Therefore,

(14) $$BW_f=\frac{f_2-f_1}{f_0}=\frac{\sqrt{S^2-1}}{Q_a}$$

Which coincide with the result obtained in [4] associated to parallel RLC resonators.

III. SIMULATED RESULTS

The effectiveness of the solution presented is evaluated through a simulation process by means the software IE3D based on MoM. In order to demonstrate the feasibility of the proposal, a handset monopole antenna has been designed for resonating in the central frequency (1940 MHz) of the frequency region (1710-2170MHz) that comprises the communication standards (DCS, PCS, and UMTS). The dimensions of the handset monopole antenna are adjusted for satisfying the equation (9). In this sense, the input impedance at said central frequency presents the correct value for achieving and impedance locus centered in the smith chart and inscribed inside a circle of VSWR=S.

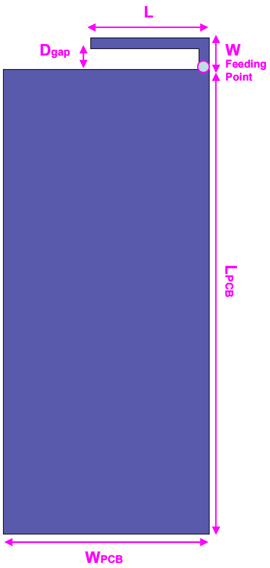


Fig. 3 Monopole handset antenna and PCB dimensions. The dimensions of the monopole antenna are L=23mm and W=6mm with a strip width of 2mm and it is located in the shorter edge of a PCB at a distance D_{gap}=4mm from the ground plane. The PCB dimensions are L_{PCB}=90mm and W_{PCB}=40mm

The handset monopole antenna (Fig. 3) is located in the shorter edge of a PCB. Both, handset antenna and ground plane are etched over a 1mm FR4 piece (εr=4.15, tanδ=0.013).

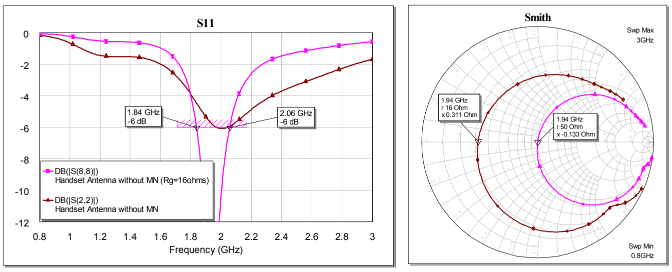


Fig. 4 Input impedance and reflection coefficient related to the simulated monopole handset antenna referred to 50Ω. Input impedance and reflection coefficient associated to the simulated monopole handset antenna referred to 16Ω, which is the impedance at the resonant frequency (1.94 GHz).

The handset monopole antenna features an insufficient BW for covering the communication standards located in the frequency region (DCS, PCS and UMTS) (Fig. 4).

The Q_a of the structure (Fig. 5) and its inherent BW_0 can be calculated from its input impedance according to equations (15) and (16) derived in [6].

$$Q_a(\omega) = \frac{\omega}{2R(\omega)} \sqrt{\left[\frac{dR(\omega)}{d\omega}\right]^2 + \left[\left[\frac{dX(\omega)}{d\omega}\right] + \left|\frac{X(\omega)}{\omega}\right|\right]^2} \tag{15}$$

$$BW_0 = \frac{f_2 - f_1}{f_0} = \frac{S-1}{Q_a \cdot \sqrt{S}} \tag{16}$$

The well-known equation (16) is valid either for a series-resonant or parallel-resonant RLC circuits.

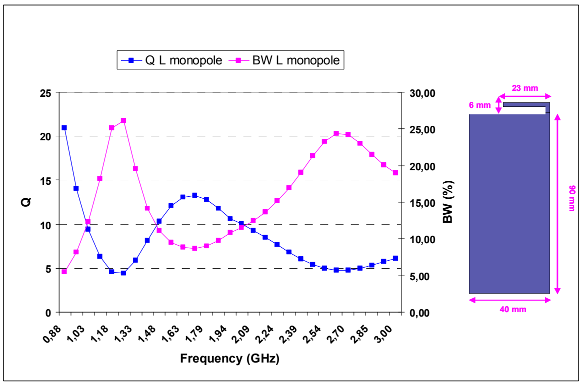


Fig. 5 Q_a and inherent BW_0 calculated from the input impedance of the handset monopole antenna according to [6]

Once the Q_a of the structure is known from (15), the suitable values of C_m and L_m for achieving the expected BW enhancement (Fig. 6) can be derived following expressions (10) and (11) and regarding, in this case, S=3.

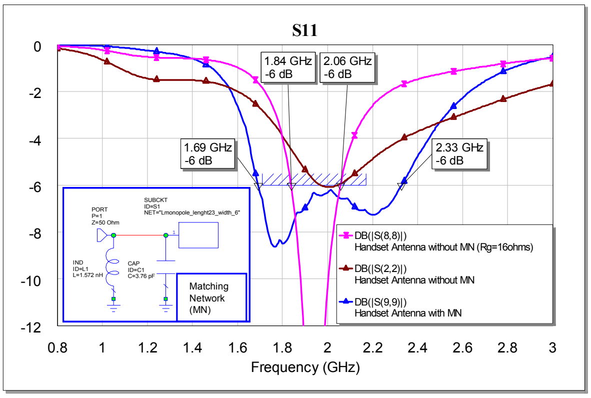


Fig. 6 Reflection coefficient related to the simulated monopole handset antenna referred to 50Ω; Inherent BW_0 (Rg=16Ω) and BW_f enhancement (L_m=1.6nH, C_m=3.8pF) obtained with the addition of the two stages matching network

The designed matching network allows centering the impedance loop in the center of the Smith chart maximizing the BW (Fig. 7).

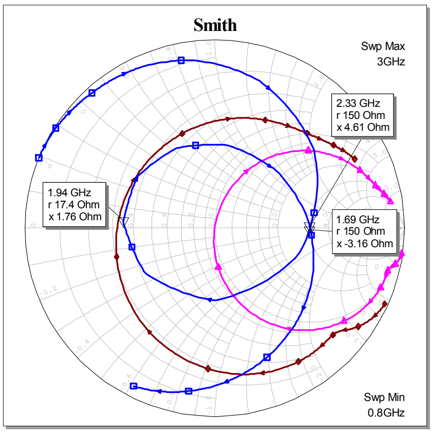


Fig. 7 Smith chart representation of the input impedance related to the simulated monopole handset antenna referred to 50Ω; Inherent BW_0 (Rg=16Ω) and BW_f enhancement (L_m=1.6nH, C_m=3.8pF) obtained with the addition of the two stages matching network

The enhancement factor (F) is calculated as the ratio between the inherent BW_0 ($Rg=16\Omega$) of the structure and the potential BW_f that can be achieved with the addition of the two stages matching network.

In this sense, F can be defined as:

$$F=\frac{BW_f}{BW_0}=\frac{\left(\sqrt{S^2-1}/Q_a\right)}{S-1/Q_a\cdot S}=\frac{\sqrt{S^3-S}}{S-1} \tag{17}$$

The simulated results are aligned with the analytic results (Table 1) and a BW enhancement around 2.82 is obtained by simulation with the addition of a simple two stages matching network composed by a parallel capacitor (C_m=3.8pF) and a parallel inductor (L_m=1.6nH).

TABLE 1 SIMULATED RESULTS VS THEORETICAL RESULTS

BW from Q_a (Equation (16))	BW with $Rg=16\Omega$ (Simulation)
$BW=\frac{3-1}{10.89\cdot\sqrt{3}}=10.60\%$	$BW=\frac{2.06-1.84}{1.95}=11.28\%$
BW with MN (Equation (14))	BW with MN (Simulation)
$BW=\frac{\sqrt{3^2-1}}{10.89}=25.97\%$	$BW=\frac{2.33-1.69}{2.01}=31.84\%$
F (Theoretical)	F (Simulation)
$F=\frac{\sqrt{S^3-S}}{S-1}=2.45$	$F=\frac{31.84\%}{11.28\%}=2.82$

NOTE: (MN: Matching network)

Finally the radiation efficiency has been computed. The structure does not present significant losses although it is etched over a 1mm FR4 piece since the radiation efficiency remains around 80% for all the frequency range under study. In the same way the antenna efficiency is calculated taken into account the two stages matching network shown in Fig. 6.

This section demonstrates that the insufficient initial BW_0 (Fig. 4), is enhanced in a factor around 2.82 by the addition of a simple resonant matching network with the specifications derived from the mathematical analysis developed during the first stage of this work (II). In this sense, this part states that it is possible to increase the inherent BW_0 of a specific structure systematically through the addition of a two stages matching network.

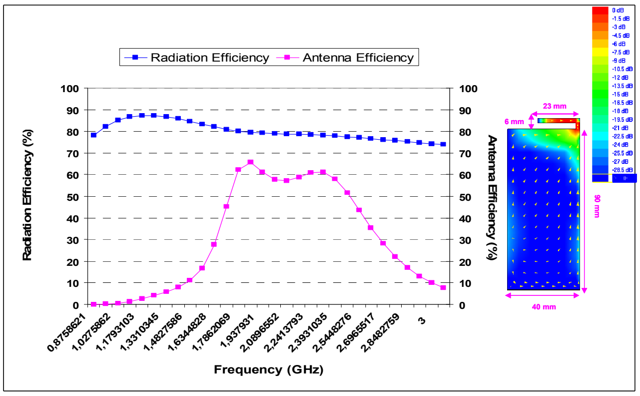


Fig. 8 Radiation efficiency (η_r), antenna efficiency (η_a) and current distribution associated to the monopole handset antenna at f_0=1.94GHz. The antenna efficiency takes into account the matching losses since it is defined as $\eta_a=\eta_r(1-|S_{11}|^2)$

IV. EXPERIMENTAL RESULTS

The simulated results are validated through an experimental procedure. In this sense, a prototype is built by means of an etching process using FR4 substrate, with the characteristics previously cited.

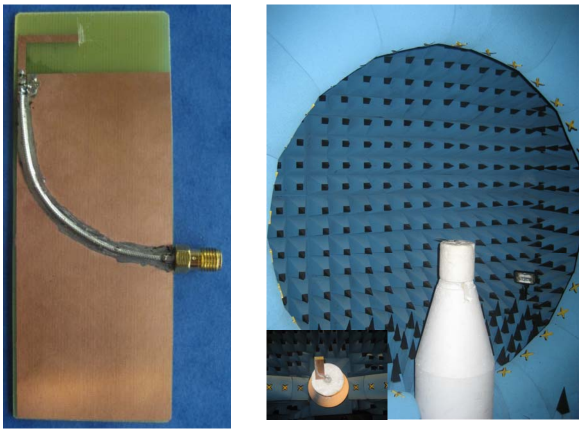


Fig. 9 a) Handset monopole antenna prototype; b) Anechoic chamber Satimo Stargate32 located in Fractus Lab where the efficiency of the prototype has been measured

The characteristic antenna parameters with and without the matching network have been measured in order to evaluate not only the benefits of the reactive components over the impedance BW but also their effect over the performance of the monopole handset antenna. A single port network analyzer has been used for measuring the reflection coefficient. At the same time, the antenna efficiency has been measured using 3D integration pattern with the Satimo StarGate32 chamber located at Fractus-Lab.

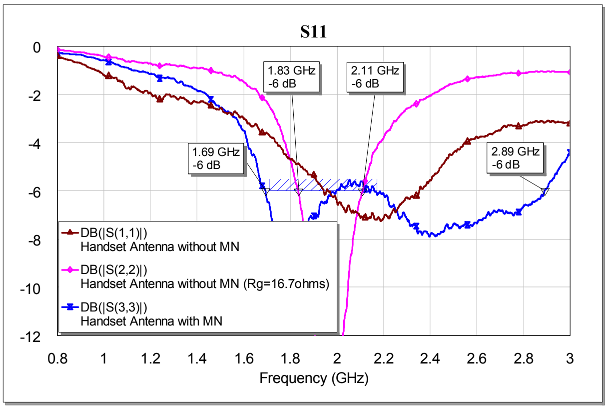


Fig. 10 Reflection coefficient related to the simulated monopole handset antenna referred to 50Ω; Inherent BW_0 ($Rg=16.7\Omega$) and BW_f enhancement (L_m=3.3nH, C_m=1.3pF) obtained with the addition of the two stages matching network

The experimental results depict a BW enhancement around 3.7 for the prototype under study (Fig. 10) and (Table 2). This value exceeds the theoretical BW enhancement factor (Table 1). The explanation resides in the nature of the input impedance curve of the prototyped handset antenna, which can be only approximated to an RLC series circuit for a limited range of frequencies (Fig. 11).

TABLE 2 MEASURED RESULTS

BW with Rg=16.7Ω	BW with MN	F
$BW=\dfrac{2.11-1.83}{1.97}=14.21\%$	$BW=\dfrac{2.89-1.69}{2.29}=52.40\%$	3.7

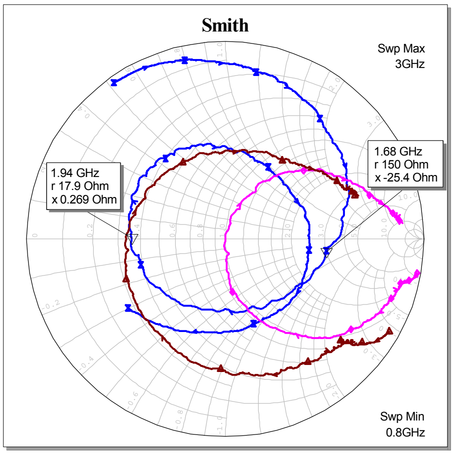


Fig. 11 Smith chart representation of the input impedance related to the simulated monopole handset antenna referred to 50Ω; original BW_0 (Rg=16.7Ω) and the BW_f enhancement (L_m=3.3nH, C_m=1.3pF) obtained with the addition of the two stages matching network

If the equivalent circuit featuring the same Q_a and resonant frequency of the prototyped antenna is regarded (exact approximation to an RLC series circuit), the suitable L_m and C_m values as well as F, are perfectly aligned with the theoretical results (Fig. 12).

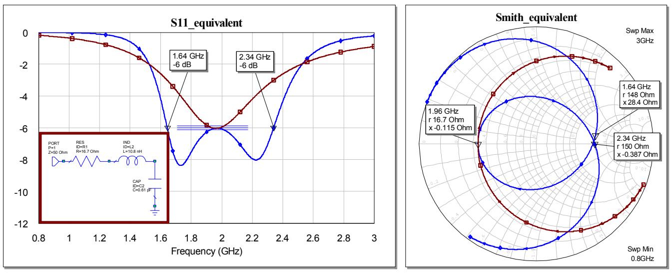


Fig. 12 Equivalent RLC series circuit of the handset monopole antenna prototyped

In this sense and as aforementioned, the BW increment above the theoretical value in the measured case as well as the difference between the values of C_m and L_m, is just a result of the input impedance curve of the handset antenna, which favors the compactness of the locus in the Smith chart. This fact can be easily demonstrated through the Q_a calculation over the input impedance following equation (15). In the measured case the Q_a value, especially in the frequency region over the resonant frequency, is lower than the Q_a associated to the RLC series circuit. The measured BW allows covering not only DCS, PCS and UMTS but also other communication standards such as Bluetooth and Wi-Fi with a single coplanar handset antenna and a two stages matching network.

In order to complete the antenna characterization, the efficiency of the whole system has been also evaluated. The radiation efficiency of the handset monopole antenna without regarding the two stages matching network is weakly reduced with respect to the simulated case mainly due to the fact that in practice, the dielectric seems to present higher losses than those considered in the simulation. In the same way, the reactive components do not introduce significant losses since the radiation efficiency regarding matching network slightly differs from the radiation efficiency obtained when no matching network is considered.

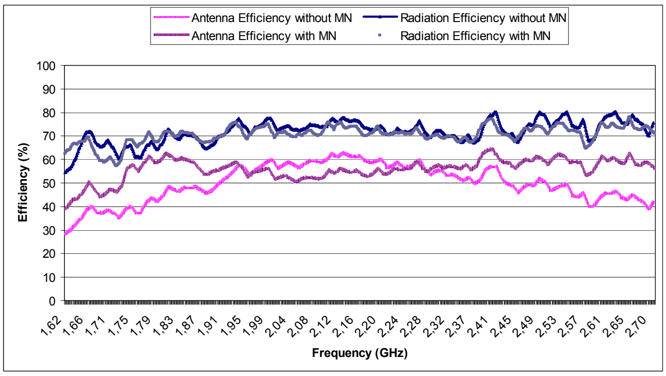


Fig. 12 Radiation efficiency (η_r) and antenna efficiency (η_a) of the handset monopole antenna with and without the addition of the two stages matching network. The antenna efficiency takes into account the matching losses since it is defined as $\eta_a=\eta_r(1-|S_{11}|^2)$

Thus, not only the simulation but also the experimental results reveal that the analytical study presented in this communication provides a simple and a systematic method to enhance the BW of those antennas that can be modeled as RLC series circuits.

V. CONCLUSIONS

A systematic method for calculating the component values for a matching network of two stages is presented. The method is focused on antennas featuring input impedance comparable to an RLC series circuit. The proposal allows not only simplifying the matching network design process but also ensuring the best solution. As a result, a BW enhancement of at least one half of Fano's limit is achieved with a simple two stages matching network. As a practical example a monopole with an inherent BW_0 of 14.21% SWR≤3 has been improved to achieve a BW_f of 52.4% SWR≤3.

REFERENCES

[1] L. J. Chu, *Physical limitations on omni-directional antennas*, J. Appl. Phys., vol. 19, pp. 1163-1175, Dec. 1948.

[2] A. R. Lopez, *Wheeler and Fano Impedance Matching*, IEEE Antennas and Propagation Magazine, vol. 49, nº 4, August 2007, p. 116-119.

[3] H. F. Pues, A. R. Van de Capelle, *An Impedance-Matching Technique for Increasing the Bandwidth of Microstrip Antennas*, IEEE Transactions on Antennas and Propagation, vol. AP-37, nº11, Nov. 1989, pp. 1345-1354.

[4] J. Anguera, C. Puente, C. Borja, G. Font, J. Soler, *A systematic method to design single-patch broadband microstrip patch antennas*, Microwave and Optical Technology Letters, vol. 31, nº3, November 2001, p. 185-188.

[5] R. C. Hansen, *Fano Limits on Matching Bandwidth*, IEEE Antennas and Propagation Magazine, vol. 47, nº 3, June 2005, p. 89-90.

[6] Steven R. Best, *The Inverse Relationship between Quality Factor and Bandwidth in Multiple Resonant Antennas*, IEEE Antennas and Propagation Society International Symposium, 2006, 623-626.