Design of an AMC-based antenna for mobile communications applications

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Abstract. The use of metamaterials has grown in interest in recent years. Their usefulness and the benefits they offer have broadened the number of applications where metamaterials can be used. This Master Thesis aims to make use of a certain metamaterial structure in order to improve the performance of a monopole structure used as an antenna for mobile communications. Moreover, the design and fabrication of said structure comprising an AMC -Artificial Magnetic Conductor- is intended, as well as the analysis of a real mobile device, used to compare its performance to that of the designed AMC-based structure.

Keywords: AMC, monopole, mobile communications, metamaterial

1. Introduction

In this Master Thesis the benefits of structures made out of metamaterials are assessed. Metamaterials essentially comprehend those kind of materials which present certain properties unachievable for materials of common use[1]. They can be organized in different groups, to name some: artificial dielectrics, artificial magnetic materials, materials with negative refractive index, materials with artificial anisotropy, etc. The inclusion of a particular AMC -Artificial Magnetic Conductor- into a previous antenna design with the aim of creating an antenna at mobile communication frequencies is studied[2][3][4]. Simulations are run with IE3D software in order to evaluate the theoretical behavior of said structure when it is built step by step.

Once the effects of including an AMC structure in this kind of design[5] have been evaluated, a prototype of the simulated assemblage is fabricated to prove the feasibility of including such entity into a mobile device structure. To this end, the passive behavior of the fabricated model, such as $S_{11}$ parameter, is measured. For the sake of comparison, a real mobile phone is analyzed.
2. Simulations

2.1. Impedance matching of the design

One important aspect of constructing and developing antennas is the need for a matching network, i.e. a bunch of components strategically set into a board so that the input impedance of the entire structure is matched to that of the measurement equipment -the standard value for such matching impedance is $50\Omega$. To this end, the AWR Design Environment, a practical software to design matching networks for particular modules, is used.

The reason for including such matching networks lies in the fact that when the input impedance of the analyzed structure is the complex conjugate of the input impedance of the measurement equipment the transfer of power is maximum, as remarked in equation 1:

$$P_d = |V_s|^2 \frac{1 - |\Gamma_l|^2}{1 - \Gamma_g \Gamma_l}$$

with:

$$\Gamma_l = \frac{Z_l - Z_0}{Z_l + Z_0}, \Gamma_g = \frac{Z_g - Z_0}{Z_g + Z_0}$$

where $P_d$ stands for the dissipated power at the load, $V_s$ for the generated wave of the source, $\Gamma_g$ is the reflection coefficient looking back into the generator, $\Gamma_l$ is the reflection coefficient looking forward to the load, and it is also named return loss parameter $S_{11}$, $Z_g$ is the input impedance of the generator and $Z_0$ is the characteristic impedance of the system, $50\Omega$ in this case.

The proper matching networks which match the whole structure to $50\Omega$ to have maximum transfer of power have been sought.

2.2. Antenna studied without AMC

One of the most important aspects of antenna design is the dependance of the antenna size on the wavelength. However, the performance of an antenna does not only depend on its size (height, width...), but also on the geometry of the whole structure.

In this Master Thesis, a planar monopole antenna is studied (figure 2). In [6], a semi-circular umbrella-like shape structure is presented, showing remarkable features in a vast range of frequencies. This monopole has been chosen because of its wide-band
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2.3. Having a ground plane below the antenna

If an antenna has to be placed above a ground plane it does not work properly; as can be observed in figure 3, where the real and imaginary parts of the structure are compared for both the case without ground plane below the monopole—named first approach—and the case of a 60 x 22 mm ground plane placed below the monopole—named second
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Figure 3: Real and imaginary parts of the input impedance of the first (figure 3a) and second approaches (figure 3b).

Whereas in the first approach values for the impedance equal to $53.1 - j114.6\Omega$ are obtained at 900MHz, after placing the pernicious ground plane eventually approximately $0.8 - j30\Omega$ are attained (see figure 3), which means that there is no resonance anymore.

Antenna and radiation efficiency are important parameters in order to assess the performance of a good antenna considering mobile communications applications. Their mathematical expressions are shown in equations 3 and 4:

\[
\eta_R = \frac{P_{\text{radiated}}}{P_{\text{input}}},
\]

\[
\eta_A = M_L \cdot \eta_R,
\]

where $\eta_R$ and $\eta_A$ stand for the radiated and antenna efficiencies respectively, $P_{\text{radiated}}$ and $P_{\text{input}}$ are the radiated and input power respectively and $M_L$ is the antenna loss due to impedance mismatch, and can be calculated as

\[
M_L = 1 - \Gamma^2_i.
\]

It is worth noticing that since $M_L$ only takes values between 0 and 1, the maximum value for the antenna efficiency at a certain frequency is the value of the radiated efficiency at that same frequency.

In figure 4 the inclusion of the ground plane placed right below the monopole shows its detrimental effect in terms of efficiency.

2.4. Antenna with an AMC structure

Benefits of using metamaterials are visible when studying the inclusion of an AMC between the antenna and the ground plane. In [8], a complete analysis to determine and characterize an AMC structure has been done. Such AMC structure is characterized
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Figure 4: Antenna and radiation efficiencies simulated for the case of the first approach -without ground plane below the monopole- and the case of the second approach -with ground plane below the monopole-.

Figure 5: AMC structure disposed below the umbrella-shaped monopole to reduce the effect of the ground plane seen in 2-D (5a) and 3-D (5b).

by the dimensions specified in figure 5a, with an AMC resonance frequency \( f_{\text{AMC}} \) equal to 866.7MHz and supported by a Rogers dielectric (\( \epsilon_r = 10.2 \) and height \( h_{\text{AMC}} \) equal to 1.28mm). The monopole-shape structure described in section 2.2, with the dimensions specified in figure 2 except for the value of \( C_r \), which has been varied to 21mm, is employed. Thanks to the metamaterial structure it is possible to reduce the height at which the monopole is placed from the ground plane, or said in other words, the AMC allows the monopole to be placed at a distance close to the ground plane without losing its resonance. Some simulations have been run to assess the effect of changing the dimensions of the monopole. However, the final dimensions used are, as shown in figure 5a, \( C_r = 21\text{mm} \), \( S_l = 10.5\text{mm} \) and \( S_w = 4\text{mm} \).

Simulations have been launched in order to observe the advantages of placing the AMC below the monopole, being now the distance between them that of the monopole dielectric \(-h_{\text{dil}-}\) and equal to 3mm (see figure 5b). As mentioned before, one of the advantages of including an AMC is the fact that the antenna does not lose its resonance (see figure 6), in this case particularly in the range of 0.8 – 0.9GHz. \(|S_{11}|\) is displayed in
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Figure 6: Input impedance (6a) and $|S_{11}|$ parameter (6b) in dB of the structure including an AMC.

Figure 6b to show the bandwidth performance of the antenna, which now includes the AMC structure.

Moreover, as it is explained in section 2.1, a matching network can enhance the performance of an antenna. With such a goal, a matching network is added to the whole structure. Thanks to that, the structure is able to cover the mobile frequency band compressed between 0.791 and 0.821 -LTE800 downlink- with a value of the $|S_{11}|$ parameter equal to $-4.5\text{dB}$, equivalent to a value of the SWR equal to 4, as can be seen in figure 6b.

3. Prototype fabrication

3.1. Change of the AMC dielectric

Unfortunately, it has not been possible to dispose of a Rogers dielectric with dielectric constant equal to 10.2. This is why FR-4 dielectric ($\epsilon_r = 4.15$ and $\tan\delta = 0.013$), at disposal, has been used instead. As it is shown in figure 7a, the use of FR-4 material instead of the Rogers dielectric causes a large frequency shift towards high frequencies.

In order to fix this displacement, a scale of the AMC dimensions is done taking into account that the displacement factor is, approximately $D = \frac{f_1}{f_2}$. As the frequency of resonance of any antenna depends inversely on its size, an increase of the size of the AMC structure is expected in order to compensate the upwards frequency displacement caused by the inclusion of FR-4 dielectric instead of the Rogers dielectric. The new AMC dimensions are shown in figure 7b.

3.2. AMC scale and viability of fabricating with available materials

The new structure has been scaled in order to evaluate the viability of fabricating a prototype with the available material in the lab. To this end, two experiments have
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Figure 7: 7a shows the $S_{11}$ parameter for the case of the structure with FR-4 not scaled -blue line- and the cases of the structure already scaled -red line for $h_{\text{died}} = 3\text{mm}$ and black line for $h_{\text{died}} = 1.6\text{mm}$-. In both cases $h_{\text{AMC}} = 1.6\text{mm}$. 7b shows the new dimensions of the AMC once it has been scaled.

been carried out: in the first one, the height of the AMC dielectric $h_{\text{AMC}}$ is set to $1.6\text{mm}$ and the height of the monopole dielectric $h_{\text{died}}$ has been maintained to $3\text{mm}$; and in the second experiment, the heights of the two employed dielectrics are equal to $1.6\text{mm}$, instead of the $h_{\text{AMC}} = 1.28\text{mm}$ and $h_{\text{died}} = 3\text{mm}$ previously employed.

In figure 7a the new $|S_{11}|$ parameter obtained with both experiments is also provided. For both experiments, the dimensions of the AMC structure are the ones shown in figure 7b.

3.3. Matching the scaled designs

Since the ground planes have to be supported by a substrate, experiments have been run in order to assess the impact of placing such substrate below the ground planes.

After placing such substrate, the design with dielectric height equal to 3mm covers the LTE900 downlink -0.88GHz to 0.915GHz-. $|S_{11}|$ values below $-4.5\text{dB}$ are found between 0.863GHz and 0.915GHz. On the other hand, the model with monopole dielectric height equal to 1.6mm covers entirely the LTE850 band -0.824GHz to 0.894GHz- at $-4.5\text{dB}$, providing better performance in terms of $|S_{11}|$ parameter. Hence, this last model is the one whose performance is shown in figure 8. Furthermore, this is the design which has been fabricated.

Once the prototype has been fabricated and the matching network in figure 9a has been added to it -such matching network differs slightly from the simulated case-, $|S_{11}|$ parameter has been measured with the analyzer from Rohde&Schwarz model 1127.8551, able to measure frequencies from 400KHz to 4GHz and shown in figure 9b. Unlike simulation results, where the design covers LTE850 band, the fabricated prototype covers the band from 0.901GHz to 1.021GHz, including the LTE900 downlink. For
Figure 8: \( S_{11} \) parameter (8a) and Smith Chart (8b) of the design with a dielectric substrate of height \( h_{\text{diel}} \) equal to 1.6mm.

Figure 9: Real matching network added to the prototype with dielectric height equal to 1.6mm (9a). Figure 9b shows the \( |S_{11}| \) parameter in dB measured for the fabricated prototype.

this reason, some adjustments should be done on the monopole in order to compensate the frequency shift if LTE850 was sought in particular. Radiation patterns measured for the fabricated prototype are shown in figure 10 together with a photo of said prototype.

4. BQ Aquaris E5 Cellular Phone Measurements

4.1. Mobile phone measurements

TRP-TIS or active measurements are useful for the study of the overall behavior of a cellular phone in terms of transmitted and received power. To compute them, the mobile phone has been set inside an anechoic room at disposal, as shown in figure 11.

Passive measurements are shown in figure 12, where it can be observed that at low frequency range -0.824GHz to 0.960GHz- an average of approximately 10% of efficiency
Figure 10: Comparison between the radiation patterns of the prototype at 0.95GHz and the radiation patterns of the mobile phone analyzed at 0.9GHz -10a- and photo of the fabricated prototype -10b-.

Figure 11: Setup for TRP-TIS (active) measurements. In 11a, the horn antenna is set to feed the phone with horizontal polarization.

is achieved whereas at high frequency range -1.710GHz to 2.170GHz- efficiencies around 30% are obtained. In figure 12a it can be observed that unlike other devices, this particular mobile phone does not cover LTE850 and LTE900, which implies that the fabricated prototype is still offering promising results. Radiation patterns of the prototype at 0.95GHz are depicted in figure 10a in order to compare them to the radiation patterns -at 0.9GHz- measured for the fabricated prototype.

5. Conclusions

In this Master Thesis a design of an AMC-based antenna for future mobile applications has been done. Simulation work has started with the design of a umbrella-shape monopole and its performance. Due to the importance of ground planes in real mobile devices, simulations taking into account such ground planes have been run, obtaining deteriorated results. An AMC structure has been inserted between the umbrella-shape monopole and the ground plane, obtaining improved performance. Due to fabrication reasons, a dielectric is included below the ground planes, varying the previous results. Two models are simulated: one with $h_{\text{diele}}$ equal to 3mm and another one with $h_{\text{diele}}$ equal to 1.6mm. Their return losses parameters are compared, resulting the model
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Figure 12: $|S_{11}|$ parameter in dB (12a) and radiation and antenna efficiencies for the measured BQ Aquaris E5 (12b). The vertical lines in 12b are at the same frequencies than the markers in 12a.

with $h_{\text{dielectric}} = 1.6\text{mm}$ of better performance, obtaining promising results in terms of $S_{11}$ parameter. Such results are verified by fabricating this latter design. Finally, for the sake of comparison, a BQ Aquaris E5 mobile phone has been analyzed in terms of return loss parameter and efficiency to compare them with the fabricated structure, which is offering promising results in terms of bandwidth $-|S_{11}|$ parameter.-

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References

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