

Analysis of the discrepancies between simulation and measurement of an antenna

Erik Mezzomo
Polytechnic School
Unisinos University
São Leopoldo, Brazil
erikmzz@edu.unisinos.br

Sandro Binsfeld Ferreira
Polytechnic School - itt-Chip
Unisinos University
São Leopoldo, Brazil
sbinsfeld@unisinos.br

Abstract—With the increased use of wireless communication devices for applications of the Internet of Things, adequate characterization of the antenna, which is the main interface with the environment, becomes necessary. To achieve the system requirements and ensure efficiency, accurate measurement methods, characterization, and simulation steps are required. Electromagnetic simulation is an important tool that allows for faster and cheaper tests, but good input parameters are needed. In this work, the operating conditions of a PCB fractal geometry antenna have been analyzed. This antenna showed different results between simulation and measurement, and the discrepancies are discussed here. Two possible errors are evaluated. First, the difference between the substrate parameters used in the simulation and the fabricated prototype is considered. Thus, two parameters were analyzed and experimentally determined: the loss tangent and the relative dielectric constant. Secondly, transmission lines and connectors are included in the measurements. Finally, the antenna was re-designed and measured. Measurement results showed good agreement with the simulation after the loss tangent calibration. However, a different resonance frequency was still observed. This work aims to calibrate the measurement process and define a reliable antenna design flow.

Index Terms—measurement calibration, antenna, EM simulation, high frequency

I. INTRODUCTION

The widespread use of radio frequency identification (RFID) systems and the success of the recently developed concept of the Internet of Things wouldn't be possible without the development of high-performance antennas. This component enables the connection between electronic systems through the wireless media access [1]. In the development of antennas, electromagnetic simulation tools prove useful to accelerate the design process and anticipate results when using the correct input parameters.

Several parameters can impact the performance of fabricated antennas. The model development depends on the correct characterization of the printed circuit board substrate, and the correct measurement setup, among others possible issues.

As a consequence of these implementation challenges, an antenna prototype was designed, fabricated, and measured, but the simulated and measured results did not match. The

This work was partially supported by the National Council for Scientific and Technological Development (CNPq) and by the Technological Institute of Semiconductors of Unisinos University (itt Chip)

designed antenna is a miniaturized 50- Ω 902-MHz planar inverted F antenna (PIFA) using fractal geometries to reduce area [2]. The total size of the antenna is 45.5 mm x 21 mm. It was fabricated using a 1-mm thick FR-4 substrate and 0.5-Oz thick copper layer with a UFL SMD connector and simulated using Ansys HFSS [3]. The antenna layout is shown in Figure 1, and the simulated and measured return loss are presented in Figure 2.

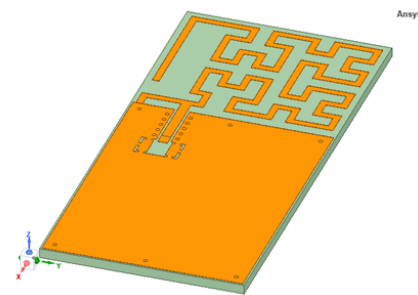


Fig. 1. Analyzed antenna.

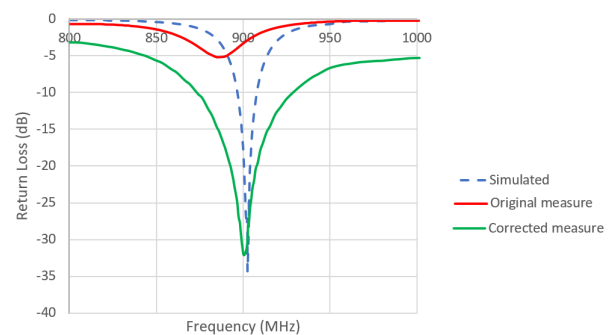


Fig. 2. Comparison of the results of the analyzed antenna.

The PIFA antenna was designed to match exactly the impedance of 50 Ω without additional components to reduce cost. Nevertheless, it was necessary to use impedance matching via discrete components (capacitors and inductors) to enable antenna operation. This procedure caused additional rework and added costs.

Various errors can be associated with antenna characterization. In this work, we explore the differences between the simulated substrate parameters and the printed circuit board (PCB) used in the prototyping. Additionally, the added transmission lines and connectors impact on the measurement results is briefly discussed. Electromagnetic simulations were performed using Ansys HFSS which uses 3-D finite element method [3]. Section II of this paper introduces a theory basis. The adopted methodology is presented in Section III. Simulated and measurement data are presented in Section IV, and conclusions are presented in the last section.

II. SUBSTRATE AND ANTENNA CHARACTERIZATION

Characterization of substrate and antenna is traditionally based on the comparison of Scattering parameters (S-parameters) obtained in simulation against measurement results. The scattering matrix represents an N-port high-frequency linear circuit, hence taking into account not only voltages and currents, but also power and phase of a traveling wave. This way, it is the standard model to measure incident, reflected and transmitted signal waves. (1) represents the S-parameters matrix of a two port linear circuit. Normally, this analysis is done in a wide range of frequencies [4].

$$\begin{bmatrix} V_1^- \\ V_2^- \end{bmatrix} \begin{bmatrix} S_{11} & S_{12} \\ S_{21} & S_{22} \end{bmatrix} \begin{bmatrix} V_1^+ \\ V_2^+ \end{bmatrix} \quad (1)$$

Where $S_{ij} = V_i^-/V_j^+$ where $V_k^+ = 0$ for $k \neq j$. S_{11} and S_{22} correspond to the power reflected at ports 1 and 2, respectively. S_{21} measures the transmitted power from the port 1 to port 2, and S_{12} from port 2 to port 1. The V^+ is the incident voltage and the V^- is the reflected voltage in the port.

For the visualization of the parameters are used graphs. One is the Return Loss graph that relates frequency to S_{11} in dB. Another graph is the Smith chart, a useful tool for impedance matching and transmission line analysis. It is a unitary polar graph of the reflection coefficient overlaid with circles of complex impedance modified through a conformal transformation. It relates in a simple way the impedance and the coefficient of reflection when the frequency or the length of the DUT or both are changed. The reference of the chart is a normalized impedance (in this project 50Ω), the best impedance matching is found in the center of the chart.

A. Relative permittivity(ϵ_r) and loss tangent($\tan\delta$)

The relative permittivity and loss tangent are two parameters related to the complex permittivity of a medium (ϵ), the insulator substrate used in the printed circuit board (PCB) process in this case. The permittivity of a medium is given by (2) [4]

$$\epsilon = \epsilon' - j\epsilon'' \quad (2)$$

Where real and imaginary parts of ϵ are related to $\epsilon_r = \epsilon'/\epsilon_0$ and the loss tangent $\tan(\delta) = (\omega\epsilon'' + \sigma)/\omega/\epsilon'$. ϵ_0 is

the vacuum permittivity, and ω is the angular frequency of operation.

Relative permittivity is related to the amount and size of the electrical dipoles which internally compose the dielectric material. The influence of ϵ_r can be seen in the formation of the capacitance observed when the substrate is exposed to a differential voltage. The higher the ϵ_r , the higher the observed capacitance. ϵ_r can also vary over frequency. FR-4 is a typical PCB substrate and its ϵ_r varies according to the manufacturing process to which it was submitted [5].

Loss tangent represents the signal power dissipation related to the difficulty to change the spatial orientation of the electrical dipoles as the electric field is travelling along the substrate. This difficulty also increases with signal frequency [5].

An accurate representation of both parameters is required in the simulation environment to correctly model the substrate for the electromagnetic simulations.

B. De-embedding

De-embedding consists of moving the reference plane in the RF measurement to remove the unwanted accessories which are not part of the circuit, hence measuring only the DUT (Device under test) [6]. The VNA (vector network analyzer) used to measure the S-parameters, can practically eliminate measurement errors up to the termination of the probes with specific calibration kits. However, many circuits have additional transmission lines, cables, and connector lengths that need a different treatment. VNA's also measure these distances and losses to some extent by using compensation methods [7]. In figure 3, it is possible to see a representation of the de-embedding application, where the reference measurement plane is moved to the DUT. All the unwanted behaviors are included in the fixture compensations.

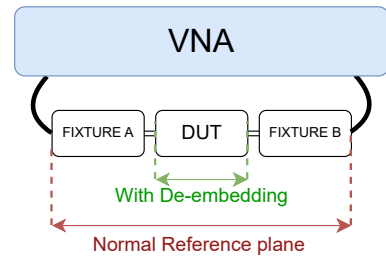


Fig. 3. De-embedding concept.

A typical method used in these cases is the TRL method (thru-line-reflect) which can be implemented using PCBs and two VNA ports. It is based on the use of different test structures: short/open connections, through connection (which is a straight connection between two PCB connectors), and transmission lines with different lengths [8]. By calculation, it is possible to separate the S-parameter of the DUT and the fixture. The fixture obtained data effect can be removed from the next simulations and measurements.

III. METHODOLOGY

In the characterization process of the antenna and its substrate, the following steps were taken. Initially, simulated and measurement results presented in [2] were compared. Following, a method was specified to: adjust the loss tangent and the relative permittivity of the substrate, and to include the S-parameters of the fixtures used in the measurement setup.

Based on the response curve of the initial antenna prototype (prototype 1), the simulation can be adjusted to match the measured results. Through an iterative process, it was observed that when the loss tangent is increased in simulation, the S_{11} results on the Smith chart move from the green-color simulated plot towards the blue-color measured result, as shown in Figure 4. In contrast, the resonance frequency identified by a red dot moves when the relative permittivity is changed in simulation.

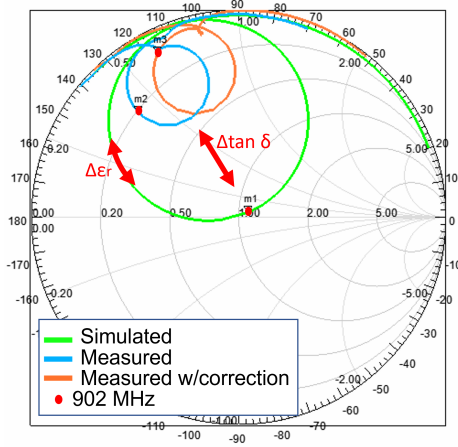


Fig. 4. Analysis of the ϵ_r and $\tan \delta$ variation in prototype 1.

To approximate the loss tangent, the simulated curve was compared with the measurement presented in Figure 4. From the difference between the two, an approximation of the real value could be achieved.

The relative permeability was calculated based on the phase difference between two coplanar-waveguide-with-ground (CPWG) transmission lines are shown in Figure 5.

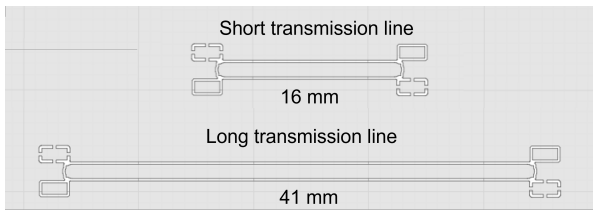


Fig. 5. Calibration transmission lines.

These lines were designed for a characteristic impedance of 50Ω on a PCB from the same manufacturer as the antenna prototype. Through the lengths of the CPWG lines, the effective permittivity is achieved using (3) and (4) according to [9].

$$TD_{\Delta L} = \frac{\Theta_u(S_{21, long}) - \Theta_u(S_{21, short})}{360^\circ f} \quad (3)$$

$$\epsilon_{eff} = \left(\frac{c}{\frac{\Delta L}{TD_{\Delta L}}} \right)^2 \quad (4)$$

Θ_u is the unwrapped phase of the signal S_{21} , meaning the reconstruction of the signal phase without discontinuity, $TD_{\Delta L}$ is the time delay difference between both analyzed lines, ϵ_{eff} is an effective value that takes into account the ϵ_r of all the elements in the analyzed region and also considers the geometry of substrates and conductors. ϵ_{eff} is usually obtained by simulation or by mathematical approximation for transmission lines.

As we are using well-defined transmission lines, it was possible to obtain the ϵ_r through the ϵ_{eff} with the help of the transmission line calculation tool available in the QucsStudio software [10].

Based on the updated values of ϵ_r and $\tan \delta$, the antenna layout was modified so that it would match 50Ω at the designed frequency. De-embedding was applied through the compensation function of the VNA.

IV. SIMULATION AND MEASUREMENT RESULTS

The first step was the modification of the loss tangent which was initially simulated with a default value of 0.02, and then increased to 0.12, reaching a curve similar to what was measured. The relative permittivity was changed from 4.4, to 4.3 after applying the proposed method. In Figure 6, we can verify the simulation of the antenna with the updated parameters, between the measured values with and without the VNA compensation.

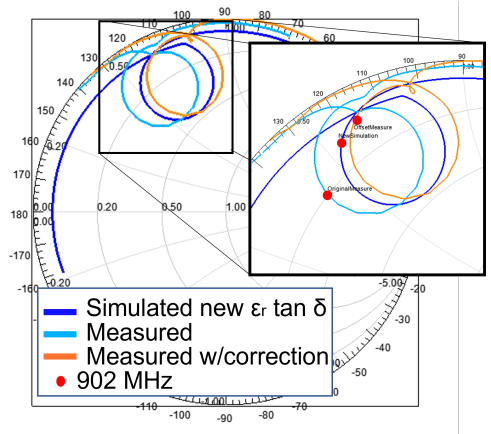


Fig. 6. Correction of relative permittivity and loss tangent.

Using the new values, the antenna layout was adjusted to achieve the center frequency of 902 MHz without changing its total area. For the reassignment, the total length of the antenna was changed and also the distance between the short and the feed. The new layout is presented in Figure 7.

The new antenna prototype was fabricated using the same PCB characterized substrate. Figures 8 and 9 present Smith

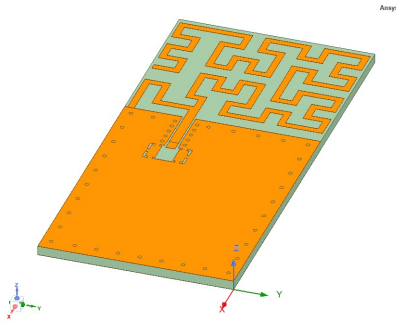


Fig. 7. Optimization of the layout of antenna.

chart and return loss in dB for simulated and measured results. Traces in blue color present simulation results with updated PCB parameters, where an impedance very close to 50Ω at 902 MHz is expected. Traces in green show the original antenna prototype results, presented for reference. Finally, traces in red show the measurements for the new antenna. Table I presents a comparison between simulated and measured parameters of the new antenna.

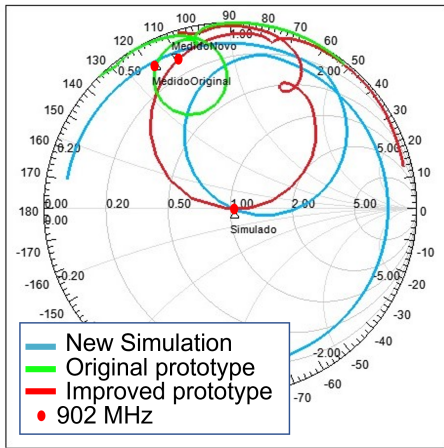


Fig. 8. New simulation and new measurement.

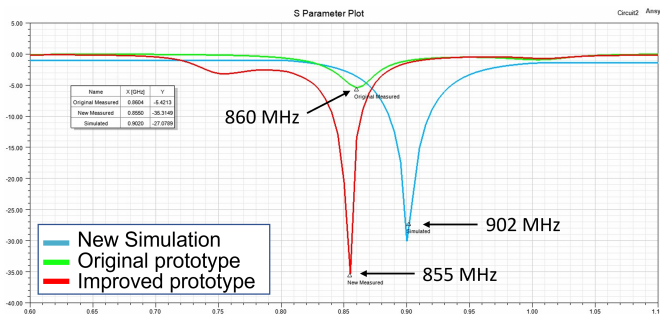


Fig. 9. Return loss of the optimized antenna.

TABLE I
COMPARISON OF SIMULATED AND MEASURED RESULTS

Parameter	Simulated	Original Prototype	Improved Prototype
Phase difference	0°	25°	10°
Frequency	902 MHz	860 MHz	855 MHz
Bandwidth	22 MHz	-	30 MHz
Return Loss	-27 dB	-5.4 dB	-35 dB

V. CONCLUSION

In this work, a fractal planar inverted F antenna was fabricated and measured. Calibration of relative permittivity and loss tangent parameters of the substrate was performed using measurement and simulation procedures. After calibration of the loss tangent, it was possible to significantly approximate the simulation and measurement of the antenna. Return loss has been improved by 29 dB when compared to the antenna designed before the calibration step. Additional work is required to match resonance frequency at simulation, since 47-MHz shift was observed after measurement. This difference can be related to the adopted de-embedding process that may require refinements. A standard VNA de-embed was implemented here.

With the correct characterization of the antenna and its substrate, it is possible to accelerate the development process and avoid the use of passive components for matching the antenna impedance, reducing costs and manufacturing time.

REFERENCES

- [1] C. A. Balanis, *Antenna Theory: Analysis and Design*, (3RD ED.). LTC, 2009.
- [2] M. C. RIBEIRO, "Desenvolvimento de uma antena de microfita sub-ghz encapsulada com dimensões reduzidas," pp. 0–87, 2021.
- [3] Ansys hfss — 3d high frequency simulation software. [Online]. Available: <https://www.ansys.com/products/electronics/ansys-hfss>
- [4] D. Pozar, *Microwave Engineering*, 4th Edition. Wiley, 2011. [Online]. Available: <https://books.google.com.br/books?id=JegbAAAAQBAJ>
- [5] E. Bogatin, *Signal and Power Integrity - Simplified*, 2nd ed. USA: Prentice Hall PTR, 2009.
- [6] scikit rf. (2023) De-embedding. [Online]. Available: <https://scikit-rf.readthedocs.io/en/latest/tutorials/Deembedding.html#>
- [7] rohde schwarz. (2022) Offset parameters and de-embedding. [Online]. Available: https://www.rohde-schwarz.com/webhelp/ZNL_ZNLE_HTML_UserManuals_en/Content/869fae7fce084a05.htm
- [8] N. INSTRUMENTS. (2023) Through-reflect-line (trl) calibration. [Online]. Available: https://www.ni.com/docs/en-US/bundle/ni-vna/page/vnahelp/calibration_trl.html
- [9] E. Bogatin, K. Quillen, G. Duenas, and D. Heckmann, "Become an expert in measurement-simulation correlation for highspeed serial data links," pp. 0–49, 12 2022. [Online]. Available: <https://go.teledynelecroy.com/l/48392/2022-12-07/8mpfhh>
- [10] QucsStudio. (2023) Qucsstudio homepage. [Online]. Available: <http://qucsstudio.de/>