Comparison of Different Electromagnetic Solvers for Modeling of Inkjet Printed RFID Humidity Sensor

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Abstract: This paper focuses on the EM modeling of an inkjet printed humidity sensor for UHF RFID systems originally presented in [1]. EM modeling is used to predict the sensor readings as well as to design the tag for certain operating frequencies. Therefore accurate EM modeling is crucial. This paper presents a comparison between three different types of EM solvers in modeling of the humidity sensor; ADS Momentum, Ansoft HFSS and CEMS. As a result, the ADS Momentum managed to predict the impedance matching of the tag most accurately. This suggests that Momentum, whose solving method is based on the method of moments, is best suited for modeling such thin and complex RFID tags.

Keywords: Radio frequency identification, RFID, Electromagnetic modeling

1. Introduction

Radio frequency identification (RFID) is traditionally used only for identification and tracking applications. However, the recent academic and commercial development of RFID systems is aiming to increase the amount of possible RFID applications by integrating sensor functions into RFID tags [2].

RFID tags with sensor functions have many benefits over regular RFID tags. In logistics, the integration of identification and sensor functions into a single RFID tag enables the monitoring of transportation conditions and the tracking for a single item or lot. This is very beneficial especially for sensitive goods such as medicines and groceries. RFID tags with integrated sensor functions have special properties which make them ideal for long term monitoring of numerous environmental parameters as in [3]. The long term monitoring is achieved through the fact that an RFID sensor can be made totally passive i.e. the tag doesn’t need any power supply. This removes the need for any maintenance such as battery replacement. Thus RFID sensors could be used as hidden sensors for structural monitoring of humidity inside walls and floors for several years [4].

We have developed a passive humidity sensor for UHF RFID systems in [1]. Through recent work involving the sensor we have manufactured the first prototype samples using modern inkjet printing. The developed sensor has undergone extensive testing and
measurement stages which have included basic characterization of the tag in terms of basic operation and humidity sensitivity. During these experiments we have noticed the difficulty of accurate electromagnetic (EM) modeling of such a complicated structure.

This kind of difficulty is common for all inkjet printed RFID tags since conductors printed with inkjet printers are usually very thin. The thickness of such conductors is in the range of 0.8 µm to 5 µm depending on the amount of printed conducting layers. To accurately model such conductors, the solution requires high density of mesh cells leading to large problem size. Inkjet printed conductors are usually very uneven and the conductivity varies significantly depending on the manufacturing methods.

Therefore the purpose of this paper is to compare three different EM analysis methods to find out which one is suited best for these kinds of simulations and design challenges.

2. Simulation model of the passive RFID humidity sensor

This section presents the structure of the sensor and impedance model for the used RFID integrated circuit (IC).

A. Simulation model

The sensor is a two-sided design printed onto 125 µm thick Kapton polyimide film using conductive silver ink. The structure of the sensor tag can be divided into three different components: IC, sensor element and radiating element.

The sensor elements form effectively twelve plate capacitors which are used for the actual humidity sensing. The humidity sensing is explained thoroughly in [1]. The radiating element of the tag is a half wavelength dipole which will enable omni-directional reading of the tag. The tag is designed for Higgs 3 IC which is manufactured by Alien Technology [5].

B. Impedance model for Higgs 3 IC

In modeling of RFID tags the main parameter to examine is the power transfer between the IC and the antenna. Therefore it is vital to have as accurate impedance model for the IC as possible to achieve maximum power transfer by means of complex conjugate matching. Alien provides a simple RC equivalent model for the input impedance of the IC which can be formulated into the following form [6]

\[
Z_{\text{input}}(f) = \frac{1}{1/R_e + j2\pi f C_e}.
\]  

(1)

However, this model becomes quite inaccurate as the IC is attached to the antenna using the strap. Therefore we have added the resulting stray capacitance and inductance to the
provided model to improve the accuracy

\[ Z_{\text{Strap--Higgs}}(f) = \frac{1}{j2\pi C'} + \frac{1}{j2\pi L' + Z_{\text{Input}}} \]  \hspace{1cm} (2)

Table 1 includes the explanations and numerical values of the improved impedance model presented in (2).

<table>
<thead>
<tr>
<th>Quantity</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Equivalent parallel input resistance ( R_e )</td>
<td>1500 ( \Omega )</td>
</tr>
<tr>
<td>Equivalent parallel input capacitance ( C_e )</td>
<td>0.85 pF</td>
</tr>
<tr>
<td>Stray capacitance added by the strap ( C' )</td>
<td>0.25 pF</td>
</tr>
<tr>
<td>Stray inductance added by the strap ( L' )</td>
<td>0.45 nH</td>
</tr>
</tbody>
</table>

As shown by (2) the impedance model of the RFID IC is heavily frequency dependent. Therefore the impedance matching of the antenna structure has to be made carefully to enable the tag operation for specific operating bands. In Europe the RFID systems utilize a center frequency of 866 MHz whereas in the US the corresponding center frequency is 915 MHz.

3. EM solvers for modeling inkjet printed humidity sensors

The sensor tag in [1] was designed using Ansoft High Frequency Structure Simulator (HFSS) [7] which is a computer aided EM solver based on the Finite Element Method (FEM). The measurements conducted on the sensors revealed a significant difference between the simulated results acquired with HFSS and measured results. The difference was especially visible in the impedance matching of the sensors.

Due to the facts that the sensor tag will undergo more development steps in the near future and the need is increasing for an accurate and fast EM solver for other inkjet printed tag designs, this paper will now compare the accuracy and performance of three different types of EM solvers in the modeling of the existing design of inkjet printed humidity sensor.

The additional two EM solvers compared against the measured and simulated values from HFSS are the Advanced Design System (ADS) Momentum from Agilent and the Computational Electromagnetic Simulator (CEMS) based on the Finite Difference Time Domain (FDTD) program in [8] developed by Veysel Demir and Atef Z. Elsherbeni.

ADS Momentum is based on the Method of Moments (MOM) [9]. The MOM is based on the Maxwell’s integral equations and Green’s functions which means that only the metallic parts of the simulated structure need to be modeled in the solver. This also means that the 3D problem can be discretized into a 2D problem. Therefore the calculation matrix can be made significantly smaller than the FEM equivalent matrix. This technique promises to be very beneficial over the FEM especially in the case of thin inkjet printed structures. CEMS allows the user use the graphics processing unit (GPU) to calculate the fields. This promises huge time savings over the use of central processing unit (CPU) for the calculations.
The most significant simulation result when designing RFID tags is the impedance matching between the IC and antenna. The impedance matching dictates the power transfer between the two components which can be used to predict the behavior of the tag as a function of frequency and threshold power. This helps the designer to match the impedances over a specific frequency and achieve tag operation which meets the design goals. It is therefore very crucial to have accurate simulation models to shorten the design process as the amount of needed prototyping stages is lowered through gained simulation accuracy.

The way to predict the impedance matching is to run the simulations and extract the Z-parameters from the results. After the port impedances are acquired the power transfer between the antenna and IC can be expressed in the means of power reflection coefficient

\[
\Gamma = 1 - \tau = 1 - \frac{4R_A R_L}{[Z_A + Z_L]^2} = 1 - \frac{4R_A R_L}{(R_A + R_L)^2 + (X_A + X_L)^2}.
\]

In (3) the subscript \(A\) stands for antenna and subscript \(L\) for load i.e. IC. The power reflection coefficient expresses how much power is reflected back from the load.

**A. Comparison of simulation accuracy using lossless materials**

We have simulated the sensor tag by plotting the power reflection coefficient as a function of frequency using the three different EM solvers in Fig. 2 as per the simulation model presented in section 2. The conductors were modeled as infinitely thin perfect conductors (PEC). The substrate was modeled as lossless dielectric with a relative permittivity of 3.3. This corresponds to a relative humidity level of 30 % at 23 °C at which the measurements were made.

Fig. 2 shows a comparison between the simulated values against the measured value of power on tag. The power on tag measurement result is the most accurate way to estimate the state of impedance matching on a fabricated tag since it describes the minimum power required to activate the tag’s IC as a function of operating frequency.

This simulation in HFSS used 300 000 tetrahedrons and it took 24 minutes on a personal computer (PC), later referred to modeling computer 1, equipped with a dual Intel Xeon X5460, 16 GB of random-access memory (RAM) and Nvidia GeForce GTX 285. CEMS used 4.5 million mesh cells and 20 000 time steps on which took 13 minutes on the same PC using the GPU. ADS Momentum used 7100 mesh cells using adaptive solving which took 32 minutes on a PC, later referred to modeling computer 2, equipped with a Intel Core 2 6200 and 2 gigabytes of RAM.

![Fig. 1. Comparison between the simulated power reflection coefficients and the measured power on tag using lossless materials.](image_url)
The estimated center frequency of the best impedance matching i.e. lowest power reflection coefficient is 890 MHz judging from the power on tag measurements. Table 2 shows the accuracy comparison between the different EM solvers in terms of percentage error from the measured value.

Table 2. Comparison of simulation accuracies against measured results using lossless materials.

<table>
<thead>
<tr>
<th>Type of result</th>
<th>Center frequency of best impedance match [MHz]</th>
<th>Percentage error against measured impedance match [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Measured power on tag</td>
<td>890</td>
<td>0</td>
</tr>
<tr>
<td>HFSS simulation</td>
<td>874</td>
<td>1.8</td>
</tr>
<tr>
<td>CEMS simulation</td>
<td>881</td>
<td>1.0</td>
</tr>
<tr>
<td>Momentum simulation</td>
<td>890</td>
<td>0</td>
</tr>
</tbody>
</table>

Amazingly, ADS Momentum predicts exactly 890 MHz as the frequency point of lowest power reflection coefficient. This value matches the measured power on tag center frequency. HFSS falls last in the accuracy comparison.

B. Comparison of simulation accuracy using lossy materials

The second simulation round was conducted using lossy materials. By using lossy conductors i.e. using finite conductivity for the conductors, the EM solvers will also model the internal properties of the conductors which could improve the simulation accuracy.

A conductivity value of 33 MS/m was used for the conductors made of silver ink. Additionally the conductors were thickened to 2 μm which corresponds to conductor thickness of the fabricated sensor sample. Also, the Kapton substrate was set to have a frequency constant loss tangent of 0.0025, the relative permittivity value was unchanged. The simulated power reflection coefficients are shown in Fig. 3 along with the measured power on tag result.

![Fig. 3. Comparison between the simulated power reflection coefficients and the measured power on tag using lossy materials.](image)

As one can see from the results there is very little difference against the results acquired with lossless materials. Clearly, the biggest difference is in the magnitude of the simulated power reflection coefficients. However, there is some frequency shift in the simulation results from HFSS and ADS. The percentage errors are listed in Table 3.

In this simulation HFSS used 305 000 tetrahedrons and it took 32 minutes on the modeling computer 1. CEMS used the same amount of cells and time for this simulation as it did in the lossless simulation using the modeling computer 1. ADS Momentum used 7100
cells, but this time the calculation was finished in 15 minutes using the modeling computer 2.

Table 3. Comparison of simulation accuracies against measured results using lossy materials.

<table>
<thead>
<tr>
<th>Type of result</th>
<th>Center frequency of best impedance match [MHz]</th>
<th>Percentage error against measured impedance match [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Measured power on tag</td>
<td>890</td>
<td>0</td>
</tr>
<tr>
<td>HFSS simulation</td>
<td>872</td>
<td>2.0</td>
</tr>
<tr>
<td>CEMS simulation</td>
<td>881</td>
<td>1.0</td>
</tr>
<tr>
<td>Momentum simulation</td>
<td>886</td>
<td>0.5</td>
</tr>
</tbody>
</table>

By using lossy materials the simulation accuracy of HFSS suffers even more. Accuracy of CEMS remains intact since the only difference against lossless simulations was a slight magnitude difference. ADS Momentum predicted the center frequency of the impedance matching perfectly by using lossless materials, by using lossy materials the results became more inaccurate.

7. Conclusions

This paper presents a comparison of three different types of EM solvers for modeling of thin complex inkjet printed humidity RFID sensor tag. The purpose of this study was to find out the most accurate EM solver for such demanding modeling applications. The study involved the simulation of a novel inkjet printed humidity sensor, originally introduced in [1] and comparing the results against real measurement data. The comparison was made using Ansoft HFSS, CEMS and Agilent ADS Momentum EM solvers. As a result of this study we conclude that the most accurate simulator to model thin complex inkjet printed RFID tags is ADS Momentum which is based on the Method of Moments. The fastest simulator was CEMS, thanks to its ability to use the GPU card’s 240 cores for the matrix calculations.

References


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