Channel Measurements and Simulations with Planar Inverted F-Antennas in an Enhanced Testbed for a Wireless Battery Management System

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Abstract—Under the project IntLiIon, we are investigating a wireless data transmission alternative for the Battery Management System of electrical and hybrid vehicles. In our previous work [1], we introduced the testbed and battery emulator employed for the first radio channel measurements. In this work, we present an enhanced version of this testbed. The connection method between antenna, cable, and battery emulator was changed to avoid the influence of the feed cables in the measurements, allowing more accurate channel measurements. Additionally, we have developed simulation models of the PIFA antennas and the environment. We validated the new testbed as well as the channel transfer function between antennas (point-to-point and point-to-multipoint links) in different positions inside the battery emulator by means of measurements and simulations, showing a good agreement.

Keywords—Antenna Measurement, Antenna Simulation, Planar Inverted F-Antenna (PIFA), Radio Channel Measurement, Battery Management System, Wireless Sensor Network

I. INTRODUCTION

Lithium-ion batteries employed in electric and hybrid vehicles comprise a large number of cells, typically between 100 and 200. In each of them, a Cell Sensor Unit (CSC) measures several physical variables, such as voltage and temperature. All this data is required by the Battery Control Unit (BCU), the device which controls and monitors the battery. Thereby a communication network is established for the data acquisition. The complete system is called Battery Management System (BMS).

In state-of-the-art BMSs, the data transmission inside the battery pack is not carried out directly between CSCs and the BCU. The cells are grouped in modules (typically between eight and 12 cells per module). Each of them counts with a Module Supervision Circuit (MSC), which collects the information from its cells and communicates with the BCU by means of standard wired bus protocols, such as CAN-Bus [2]. This requires the installation of a complex wiring harness, which increases the cost, weight, and construction complexity of the battery. Furthermore, the CAN-Bus limits the maximum data rate to 1 Mbps, which could turn into a bottle neck for the development of future generations of BMSs.

The IntLiIon project (“Intelligent data bus concepts for lithium-ion batteries in electric and hybrid vehicles”) aims to develop novel and smart data transmission techniques for the BMS. Our group is currently studying two novel alternatives for the physical layers: power line communications [3] and wireless (radio based) [1]. We have focused this work on the last one and are expanding our previous work.

This novel wireless proposal consists of installing an antenna in each communication node inside the battery pack, reducing the wiring. Our final target is a direct communication between each CSC and the BCU, in order to avoid the intermediate communication components in the MSC and to ease the assembly of the battery pack. However, we consider the installation of antennas on the MSCs (instead of on the CSCs) as an intermediate step, in order to test the functionality and feasibility of this proposal. In any case, the concept of the communication network will always be a master-slave architecture, where the BCU acts as master and either the MSCs or the CSCs as slaves.

We need a deep understanding of the radio channel inside the battery for the design of the communication system. However, measuring in real batteries would be a complicated and risky task, because of the high voltages and high direct current involved. Hence, we have designed two battery wireless channel emulators with different sizes, already described in [1]. Each of them consists of a metallic rectangular box emulating the environment of the free space between the cells top side and the battery housing, where the electromagnetic waves are mostly propagated. Thereby we measure the channel transfer function between antennas with a Vector Network Analyser (VNA).

We have already presented the first results of these measurements in [1]. However, when we tried to reproduce these measurements with simulations, we observed strong disagreements among them. The main reason was the interaction between the antennas and their feed cables in the measurements. This is a common source of errors in the measurement of small antennas and it has been extensively investigated in the past, as for example in [4], [5], [6] and [7].

Our target has been to enhance the measurement testbed, in order to avoid the effect of the feed cables on the channel under analysis. This allows us to carry out more accurate measurements, which can be later validated by simulations. Other authors have proposed different alternatives, such as the...
use of baluns or cables with better electromagnetic interference suppressant [8]. But in our case, since we are interested in measuring antennas inside our emulator, which is a metallic housing, we are going to take advantage of this situation by using the metallic walls to isolate the antenna from the cable.

In this paper, we focus in the measurement and simulation of antennas above 1 GHz, and we are working only with the so-called “small emulator”, whose dimensions are 80 cm length, 50 cm width and 5 cm height.

The paper is organized as follows: Section II explains how the enhanced testbed differs from the first one. Section III describes how we validated the new method, and how we compared it with the previous one. Sections IV and V show the results of the measurement and simulation of channel transfer functions inside the emulator, first between only one master and one slave, and then between one master and several slaves simultaneously. Finally, the conclusions and the future work are presented in section VI.

II. MEASUREMENT TESTBED

A. Previous testbed

In our previous testbed [1], we fed the antennas directly by coaxial cables and we held them with small plastic bases, always parallel to the emulator floor. In one of the side walls there were five holes, through which the cables were taken out of the emulator and connected to the VNA. As a consequence, long portions of the feed cables (approximately 20 or 30 cm for the small emulator, and more than 50 cm in the big one) remained inside the emulator during the measurements. These cables interact with the antenna, having two main consequences [4]:

- The electromagnetic field produced by the antenna is reflected and scattered by the cable
- Secondary radiation is produced by the feed cable because of the common-mode current that flow on its outer surface

The second effect is particularly strong when the antenna has a electrically small ground plane [4]. This is the case for our antennas, especially the ones for lower frequencies (below 500 MHz). Furthermore, other authors have reported that normally it is more difficult to reach a good agreement between measurements and simulations in these cases [9].

B. Enhanced testbed

In the new testbed, each antenna is held by a SMA-adapter, which is screwed to the emulator floor (figure 1a). At the other end of the adapter (and at the opposite side from the floor, outside the emulator, see figure 1b), the feed coaxial cable is connected. In this way, the cable is shielded from the antenna by the metallic floor of the emulator. The new connection method can be observed in figure 1. The antenna plane is always parallel to the emulator floor (see figure 1a), because in a real battery, the height of free space above the cells is the smallest dimension (as well as the thickness in the planar antenna).

C. Antennas designed for the validation of the enhanced testbed

In order to compare the effectiveness of the previous and the new measurement methods, it is important to compare them with simulations. The designs of the commercial evaluation boards of antennas employed in our previous work are quite complex for a simulation model (e.g., because of the large amount of through-hole vias to interconnect the two layers of ground plane) [10]. Therefore, we designed and manufactured our own antennas, keeping them as simple as possible (e.g., having a single layer). This allows simpler and more accurate simulation models. We employed the software CST Microwave Studio for the simulations.

We designed two Planar Inverted F-Antennas (PIFA), for the frequency ISM-bands of 2.4 GHz and 5 GHz. We used the formulas presented in [11] as a reference for the dimensions of the PIFAs, and then we adjusted the designs by means of simulations in order to get a better performance at the desired frequency ranges (in free space). Figure 2 presents photos of the manufactured antennas, as well as pictures of the designed models for CST.

Figure 4 shows the simulation results. They could not be accurately verified by means of measurements in free space due to the already explained difficulties in section I. However, this is not of major consequence, since we are really only interested in the antenna performance inside a metallic housing.

III. VALIDATION OF THE NEW, ENHANCED TESTBED

In order to prove the reliability of the new testbed, we first tested the designed PIFAs under two scenarios, comparing the results of measurements and simulations. The two scenarios were:
Scenario 1: Only one PIFA with its feed located in the centre of a rectangular metallic plate (290 mm × 390 mm). The largest edge of the antenna board was parallel to the largest edge of the plate. The $S_{11}$ parameter of the antenna was measured and simulated.

Scenario 2: One PIFA in the centre of the same metallic plate, and a second one at a distance of 130 mm (measured parallel to the largest edge of the rectangular plate). The $S_{12}$ parameter, which represents the Channel Transfer Function (CTF) between them, was measured and simulated.

For this first scenario, we measured only the 2.4 GHz PIFA, but using both the previous and the new connection methods. In the second scenario, we measured the CTF with both PIFAs, but only using the new connection method.

Figure 4a shows the comparison of measurement and simulation results under the first scenario by means of the method of our previous testbed. The disagreement among them is clear.

The same comparison in the same scenario but with the new connection method is presented in figure 4b. Here, the results of simulation match the measurement better. The frequency deviation of the resonant frequency is 2.46% between the simulation and the measurement, while the difference in the $S_{11}$ parameter at the corresponding resonant frequencies is 0.45 dB.

The results under the scenario 2 for both antennas are presented in figure 5. For a mathematical comparison of simulations and measurement, we employ the cross-correlation function (XCF). But first, in order to avoid an inappropriate result, both sets of values are normalized by their root mean square (RMS) values. The equation is the following:

$$\varphi_{x_1n,x_2n} = \frac{\varphi_{x_1,x_2}}{x_{1,RMS} \cdot x_{2,RMS}}$$  \hspace{1cm} (1)

Where $\varphi$ represents the XCF, $x_1$ and $x_2$ are the two functions to compare, $x_{1n}$ and $x_{2n}$ represent the same functions but normalised, and $x_{1,RMS}$ and $x_{2,RMS}$ are their corresponding RMS values. The maximum absolute value of the XCF expresses how similar the functions are. The maximum possible value is 1 (100%), because they are normalised respect to the RMS value. This occurs when they are the same function.

$$\text{Max}_{XCF} = \text{maximum} \left( |\varphi_{x_1n,x_2n}| \right)$$  \hspace{1cm} (2)

Employing (2) for the measurements and simulations under the second scenario, the maximum value of cross-correlation is 91% for the 2.4 GHz PIFA, proving an excellent agreement. However, this is only 64% for the 5 GHz PIFA. A possible reason for this difference, is that the substrate material employed in both antennas is FR4, whose main parameters, as for example the dielectric constant, change considerably and are much more sensible at high frequencies [12]. We did not test other specific dielectric materials for high frequencies, because for the real application, keeping the costs low is mandatory, and FR4 is the material already employed for the remaining circuits.
With the results in this section, we proved that it is possible to achieve a better agreement between measurement and simulation by using the new method to interconnect the antenna with the feed cable. This also allows us to analyze the influence of different parameters of our system by varying them in the simulation, and without measuring them each in a different situation, which sometimes requires significant time and money. We present an example of this advantage in the following subsection.

A. Influence of the cable length

We were also interested in the influence of the cable length in the measurements, because in the past we noticed some variation in the results using feed cables of different lengths. Therefore, we repeated the simulations of old and new methods under the first scenario but parametrizing the length of the feed cables, keeping every other scenario parameter constant (e.g. the distance between antenna and metallic plate). In the case of the new connection method, this means only change the length of the cable at the opposite side of the plate.

The results of the simulation are presented in figure 6. They prove that with the new method (figure 6b), the effect of the feed cable is almost negligible when they are at the other side of the metallic plate, because this reflects the electromagnetic waves produced by the antenna and therefore they cannot interact with the feed cable, preventing the common mode current in the cable shield. On the other hand, when the cable is at the same side as the antenna, its length modifies the antenna performance (figure 6a). The effect of the length of the cable was also verified by means of measurements in our laboratory, where we obtained the same conclusion.

IV. MEASUREMENT AND SIMULATION OF POINT-TO-POINT WIRELESS CHANNELS IN THE BATTERY EMULATOR

The main target of this work is to obtain the transfer function between antennas inside the battery emulator for the intra-battery wireless channel. We measured and simulated several pairs of antenna positions inside the emulator. Similar to what we did in [1], we located one antenna always in the center of the emulator (representing the master of the communication system), and we modified the position of the second antenna (representing the slave).

In this work, we present the results of both simulations and measurements of four different slave positions with the PIFA for the 2.4 GHz band. The positions of the master and slave antennas are outlined in figure 7. Their exact values appear in table I, where the positions in the X and Y directions (horizontal and vertical according to figure 7, respectively) are measured considering the center of the emulator floor as origin of coordinates. Thereby, L and W represent length (800 mm) and width (500 mm) of the emulator, respectively.

Figure 8 reveals the results of measurements and simulations of the CTF between the master and the slave antenna at the different positions. A good agreement can be visually observed, because most of the resonant and notch frequencies are nearly coincident. The maximum cross-correlation factors,
which are listed in Table II, also verify this. They are all above 70%. Additionally, the frequency displacement at which occurs the maximum value of the XCF in (2) represents the average frequency deviation between measurement and simulation. This maximum deviation is 8.5 MHz, which represents a deviation of only 0.423% respect to the minimum frequency of interest.

Table II. Results of the point-to-point measurements and simulations.

<table>
<thead>
<tr>
<th>Position</th>
<th>Max XCF</th>
<th>∆f [MHz]</th>
<th>CTF Measurement RMS [dB]</th>
<th>CTF Simulation RMS [dB]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>75%</td>
<td>-5</td>
<td>-9.21</td>
<td>-8.40</td>
</tr>
<tr>
<td>2</td>
<td>86%</td>
<td>-4.5</td>
<td>-10.42</td>
<td>-9.38</td>
</tr>
<tr>
<td>3</td>
<td>78%</td>
<td>-8.5</td>
<td>-11.95</td>
<td>-9.80</td>
</tr>
<tr>
<td>4</td>
<td>76%</td>
<td>-8</td>
<td>-12.19</td>
<td>-10.54</td>
</tr>
</tbody>
</table>

In Table II, we also show the RMS values of the CTF at each position for both measurement and simulation. The maximum difference between them is 2.15 dB. They offer excellent values for a wireless communication channel, with a RMS attenuation value of only about 10 dB in every case.

A. Difficulties with the measurements at high frequencies in our emulator

When we tried to repeat the same experiments from the last section with the 5 GHz PIFA, we observed that there was not a good agreement between measurements and simulations. We repeated the measurements, but the results were considerably different than the first measurements (and still inconsistent with the simulations). Therefore, we carried out two different easy experiments to test the sensibility of the system under small changes.

First, we fixed and connected two antennas inside the emulator. Then we carried out several measurements under this scenario (keeping the antennas always at the same positions) but applying a little pressure with the hand over the cover of the emulator (from the outside) at different positions (for example, in the four upper corners of the emulator cover).

Figure 9 shows the results for both antennas. In both cases, we observe that the CTF remains almost constant for frequencies below approximately 2.8 GHz (it is visually clear...
that the six different CTFs are almost perfect overlapped, therefore only one color is mostly observable). But above this value, it varies widely between the different situations (the CTF curves are not overlapped any more).

The second experiment consisted in measuring again the CTF between two antennas several times, without applying any external pressure but slightly rotating one of the antennas in each measurement (always keeping them parallel to the floor of the emulator). The result is shown in figure 10. As in the previous experiment, for frequencies above 2.8 GHz the variation between measurements increases.

The explanation that we found for these facts is related to the behaviour of the emulator as a rectangular resonant cavity. In this type of structure, the resonant frequencies of the modes can be calculated as follows [13]:

\[ f_{mnl} = \frac{c}{2\sqrt{\mu_r \varepsilon_r}} \sqrt{\left(\frac{m}{x}\right)^2 + \left(\frac{n}{y}\right)^2 + \left(\frac{l}{z}\right)^2} \]  

(3)

where the indices \( m, n, \) and \( l \) indicate the mode numbers in the directions of \( x \) (width, 500 mm), \( y \) (length, 800 mm) and \( z \) (height, 50 mm), respectively; \( c \) is the speed of the light in vacuum; and \( \mu_r \) and \( \varepsilon_r \) are relative permeability and permittivity of the cavity filling respectively, which are approximated as one, since the cavity is filled with air.

Since \( z << x < y \), there would be less density of modes with \( l > 0 \) than with either \( m > 0 \) or \( n > 0 \). With the dimensions of our emulator, the resonant frequency of the first mode with \( l > 0 \) is:

\[ f_{011} = \frac{c}{2\sqrt{\frac{1}{y} + \frac{1}{z}}} = 3.0059 \text{ GHz} \]  

(4)

In general, as in our scenario (the free space available between cells and battery housing) where the height will be always much smaller than length and width, we can approximate the minimum resonant frequency at which \( l > 0 \) as:

\[ f_{\text{min}(l>0)} \approx \frac{c}{2\cdot z} = 15 \cdot \left(\frac{\text{mm}}{z}\right) \text{ GHz} \]  

(5)

This means that for frequencies below \( f_{\text{min}(l>0)} \), there are only plane waves perpendicular to the \( z \) direction, since
\( l = 0 \). But for frequencies above \( f_{\text{min}}(l > 0) \), the density of nodes increases very quickly. The system is therefore much more susceptible to any small change, both on environment (like the one produced by small variations in height by adding pressure over certain points on the emulator top) as well as in the antenna positions or orientation.

For the remainder of this paper we will consider only the frequency range below \( f_{\text{min}}(l > 0) \), since for higher frequencies we are not able to measure in a proper and reproducible way. With our current emulator, \( f_{\text{min}}(l > 0) = 3 \) GHz. However, the effect is already observable from approximately 2.8 GHz.

V. MEASUREMENT AND SIMULATION OF POINT-TO-MULTIPOINT WIRELESS CHANNELS IN THE BATTERY EMULATOR

As we explained in section I, our aim is to communicate the master (the BCU) with the slaves, which will be the MSCs in the first stage of the project. For this reason, we also investigated the consequences of installing several antennas simultaneously, instead of only two as in the previous sections, to know how this affects the system performance.

The real battery that we used as reference for our emulator is composed by eight modules of 12 cells. The modules are distributed in two levels, one above the other. Our emulator represents the free space above each of these module levels. Since it would be almost impossible for one master antenna to communicate with a slave of the other level, we would need one master antenna for each level. Therefore, we propose that in this battery pack each master antenna would need to communicate which four slave antennas. The master antenna of the battery is located at one of the sides of the battery pack, and we determined that the slave antennas would be located in the middle of the modules and parallel to the longest emulator measure. To emulate this situation, we distributed the antennas as shown in figures 11 and 12. Table III outlines the exact position of each antenna.

We wanted to measure the CTF of every pair of master-slave, with the other three slaves “consuming” energy from the electromagnetic field at the same time. As our VNA has only four ports, we measured twice. In each measurement, we kept the master and three slaves connected directly to the VNA, and the fourth slave terminated by a 50 \( \Omega \) impedance. Then we repeated the measurement, but we changed the terminating impedance to another antenna. In that way, we got the four S-parameters between the master and each of the slaves.

Figure 13 shows the results. First, by analysing the channel transfer function and taking into account our application, we observe promising values of CTF. Both in the results of measurements and simulations, there are large regions of the spectrum showing a very good compromise between less attenuation and good bandwidth. The RMS value of the CTF is bigger than -20 dB in every case. These values are lower than in the point-to-point case, because here the transmitted energy that does not leave the emulator is divided between four receivers, instead of only one.

Table IV compares the outcome of our measurements and simulations. We observe a correct agreement among them, specially for the two slave antennas that are closer to the master.

VI. CONCLUSIONS

The target of this work was to improve the testbed employed in our previous work. We modified the connection between antenna and feed cable, in order to increase the accuracy of the measurements. We also created simulation models of the PIFAs and the emulator for the software CST Microwave Studio. The results of these simulations proved the
higher accuracy of the enhanced measurement testbed up to the frequency $f_{\min(>0)}$ (3 GHz in our emulator).

The next step is to continue studying intensely the wireless channel inside the battery pack by means of simulations. This will allow us to analyse different environments (e.g., different battery emulator sizes and positions) much faster than with measurements, and without additional costs in materials. The final aim is to design a proper communication system, according to the channel conditions and project requirements. We are also working on the development of new antenna models to expand our research on frequency ranges below 1 GHz, where there may be better alternatives than the PIFA (e.g., helix antennas).

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References


