Read range study of energy-harvested implanted NFC sensors with commercial NFC ICs and smartphones

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Abstract
The present work deals about the study of the depth and the read range of implanted sensors based on battery-less Near-Field Communication (NFC) integrated circuits (IC) using as a reader the smartphone with NFC. The performance of NFC ICs with energy harvesting capability from different manufactures is compared. The conventional system based on resonant 2-coils topology, and an improved one based on 3 resonant coils are studied. In the latter a relay antenna is implemented on a patch and attached on the skin. From the experimental results it can be concluded that the system based on 3-coils presents a much better robustness. The measurements have been performed using a prototype of the implanted tag consisting of a 15 ×15 mm antenna with a commercial NFC IC with energy harvesting that is able to read up to 16 mm inside the body using commercial smartphones.

1 Introduction

Lately, there has been a strong development of RFID technology. Low-cost RFID tags to track items have progressively been replacing the traditional barcodes. RFID technologies can be classified depending on their frequency band, such as LF, HF or UHF. One of the technologies which has experienced a great growth is the near-field communication (NFC), which is a short-range RFID that enables the communication between devices using the ISM 13.56 MHz RFID band [1]. Although NFC technology exists for more than a decade [1], it has not become popular until its massive incorporation in payment systems. For this reason, most smartphones have currently incorporated the NFC technology. Thus the interest of NFCs within the IoT scenario and Industry 4.0 is growing [2]. It is also useful in the development of low-cost low-range sensors, since it provides a fast and easy way to obtain data from them, placing the reader near to tag without needing to pair the devices.

NFC integrated circuits (IC) with energy harvesting capability that can provide energy to small sensors and microcontrollers [2-4] are recently available in the market. A couple of the most promising applications of the NFC based sensors are oriented on wearable and biomedical devices [2-5]. For this reason, implantable devices are becoming more powerful. However, they have several challenges towards other green power sources such as the replacement of the batteries. Rechargeable batteries of the implanted devices must periodically be transcutaneously recharged by means of wireless telemetry, while single-use batteries require surgical removal to replace them. In order to increase the biocompatibility (associated with battery toxicity) and the lifetime of these devices, battery-less devices are preferred [5]. Radiofrequency (RF) specifically wireless power transfer (WPT) based on radiofrequency electromagnetic waves, is the most common used communication method in implanted devices. However, the tissues that surround the implant present dielectric losses that heavily attenuate electromagnetic signals. Therefore, WPT is limited to a few MHz range due to the losses. In this paper a comparison of the performance (harvesting range) of different NFC ICs available in the market is made. The aim of this work is to study the viability of working with conventional NFC integrated circuits with energy harvesting capability in implanted devices using the smartphone as a reader. Implanted devices with WPT are often designed using discrete components or specific integrated circuits with embedded sensors. Due to size constraints, the dimensions of the implanted coil have to be as small as possible. However, the maximum coupling is obtained for coils of similar size [2]. But unfortunately, the NFC readers in conventional smartphones are designed to read smart cards rather than miniature implanted coils. Therefore, in medical applications the use of special readers for implanted sensors are required. To this end, a method to increase the read range of implanted NFC sensors with energy harvesting capability using smartphones based on the use of a 3-coil system [4] is presented. A comparison of different NFC IC is provided.

2 System proposed

An implanted NFC sensor which uses a NFC IC must harvest from RF signal to power circuitry and establish the communication with the outside (see the block diagram depict in Figure 1). The rectified voltage provided by the NFC IC is employed to feed the microcontroller and the sensors. The microcontroller transfers the processed sensor data to the internal memory of the NFC IC by using an I2C bus and the message stored as Data Exchange Format (NDEF) is read by the smartphone mobile. The coupling coefficient between the small implanted antenna and the smartphone (originally designed to read smart cards) is low. Therefore, higher magnetic fields are required to feed the system. Consequently, smaller depths of implants or read distances and higher sensitivity to misalignment between coils are produced. For this reason, the 3-coil system proposed [4] allows to obtain higher magnetic fields at higher distances, increasing both the depth of the embedded implants, and the probability of detecting...
sensors. A third relay resonant antenna is manufactured on a flexible substrate attached on the skin. The frequency resonance of the tag and relay antennas is tuned to 13.56 MHz with a shunt SMD capacitor. Figure 2 depicts a proof of concept tag prototype for the read range tests. This tag integrates a microcontroller (ATtiny85 from AVR), a temperature sensor (LM75A from TI) and a LED. The implanted antenna is designed using a 0.8 mm thick FR4 PCB substrate. The antenna is a square (15×15 mm) double-sided loop with 3 turns on each side, a strip width of 0.5 mm and strip spacing of 0.5 mm. The measured antenna inductance is 0.68 µH. The relay antenna used in this study is a square loop (25×25 mm) with 4 turns, a track width of 0.5 mm and spacing between tracks of 0.5 mm, printed on FR4 substrate with a thickness of 0.8 mm.

![Figure 2. Image of the tag prototype for testing: top (left) and bottom view (right).](image2.png)

**Table 1.** Dielectric properties of the layers used in the EM simulations

<table>
<thead>
<tr>
<th>Layer</th>
<th>Dielectric Constant (S/m)</th>
<th>Conductivity (S/m)</th>
<th>Thickness (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Skin</td>
<td>120</td>
<td>0.25</td>
<td>1.5</td>
</tr>
<tr>
<td>Fat</td>
<td>38</td>
<td>0.21</td>
<td>4</td>
</tr>
<tr>
<td>Muscle</td>
<td>138</td>
<td>0.62</td>
<td>25</td>
</tr>
</tbody>
</table>

![Figure 3.](image3.png)

Some electromagnetic simulations with Keysight Momentum have been performed to study the influence of the body. The permittivity and conductivity of the stack of materials to simulate the body are provided in Table 1 and they are taken from [6]. The conventional equivalent circuit (Fig.3a) cannot model correctly the quality factor as a function of the frequency of implanted antennas. Therefore, an improved circuital model to take into account the parasitics introduced by the body (Fig.3b) has been proposed. Implanted devices must be protected with a biocompatible material such as silicone (ε_r=3). In the relay antenna an space made with low permittivity material (Silicone) is considered. This coating and spacer allow to separate the antenna from the loss materials increasing the quality factor. The effect of the coating thickness and the spacer are investigated. Fig.4, which shows a good agreement between the electromagnetic simulations and the circuit model obtained from the optimization for both antennas [4]. When the thickness of the coating layer increases, the frequency response is close to the one presented by the loop antenna in the air. This antenna presents a higher quality factor in the air compared to that achieved in the implanted antenna, but, due to the substrate height in addition to the spacer thickness up to the skin, the quality factor remains approximately constant and close to the air value (around 75) at 13.56 MHz. In the case of the relay antenna the spacer also improves the quality factor.
3. NFC IC performance comparison

Three commercial NFC IC with energy harvesting capability have been chosen for this study: M24LR04E-R and ST25DV from ST Microelectronics, and NT3H11 from NXP. In order to compare the performance of the different ICs, a coil of size close to the smart cards is chosen. Therefore, the read range obtained is representative for general purpose NFC based sensors. A single-side loop antenna of 50×50mm with 6 turns printed over 0.8 mm thick FR4 substrate is chosen. The width of the strips is 0.7 mm and the gap between them is 1 mm. In order to investigate the load effect produced by the power consumption of the sensors and the microcontroller, a simulation with a load resistance connected at the energy harvesting output of the NFC IC is made. The average magnetic field on the loop antenna is measured using the procedure described in [2]. A typical measurement of 3 mA current load is shown in Fig.5. This figure compares the voltage at the energy harvesting output as a function of the distance between the tag and the mobile (Xioami Mi Note 2). The three ICs give a regulated voltage around 3 V that can be used to bias low-power sensors. Fig.5 shows the measured average magnetic field that allows to determine the minimum magnetic field (\(H_{\text{min}}\)) required for the operation of the sensor that depends on the current load. Note that this energy harvesting range is lower than the read range (to read previously saved data in the NFC IC memory), because the ICs do not activate the harvesting output if they do not receive enough power, but can answer to reader commands. Fig.6 shows the maximum distance for a constant energy harvesting voltage as a function of the current load for the compared NFC ICs. These results shows that the sensors can be fed by the NFC ICs up to 5 mA, as long as the high magnetic fields are higher. Therefore, a practical limit of 3 mA constitutes a margin to compensate misalignments between coils or differences between the transmitted power between mobile readers.

![Figure 4](image_url)

**Figure 4.** Simulated (solid line) and modelled (dashed line) quality factor as a function of the frequency for the implanted antenna (a) with different coating thickness, and the relay antenna (b) with different spacer thickness.

![Figure 5](image_url)

**Figure 5.** Measured voltage of the energy harvesting output for the different NFC IC and average magnetic field as a function of the tag to reader distance for a load of 3 mA.

![Figure 6](image_url)

**Figure 6.** Measured maximum distance for constant voltage at the energy harvesting output as a function of the load current.

4. Measurements with implanted tags

The average magnetic field as a function of the distance in the implanted tag in the 2-coils and 3-coils systems is determined with the experimental setup described in [5] (see Fig.7). The tag is covered by a plastic bag (made of PTE, with 0.1 mm thickness) that emulate the protection layer in a real implant. A phantom based on some slices of pork meat is used in this setup. The relay is fabricated in flexible Rogers Ultralam 3000 (\(\varepsilon_r=3.14\), thickness 100 µm) and has a single layer loop with 4 turns and an area 25 mm × 25 mm. The resonance frequency is tuned at 13.56 MHz with the parallel capacitor and verified through the VNA measuring the S11 of a test coil close to the relay. Fig.8 shows the results as a function of the reader-to-skin distance (\(d_{\text{air}}\)) for different depths of the implanted tag depending on 2-coil or 3-coils are used. The threshold magnetic field (\(H_{\text{min}}\)) for the studied NFC ICs has been indicated. The values of \(H_{\text{min}}\) depend on the minimum current to activate the energy harvesting mode but also the inductance and area of the tag antenna. A noticeable improvement of the 3-coil system is observed, especially for NFC IC with higher minimum magnetic field (M24LR).
Figure 7. (a) Schema of the measurement setup, and (b) photograph of the setup for read range measurements, and screenshot of the mobile application [4].

Figure 8. Measured average magnetic field as a function of the reader-to-skin distance ($d_{rs}$) for different depths of the implanted tag in the phantom for the 2-coil system (a) and the 3-coils system (b). The measured threshold $H_{\text{min}}$ is shown as a dashed line for each IC.

5 Conclusions

This work has presented a comparison of different commercial NFC IC with energy harvesting for batteryless sensor applications for first time. An improvement in the threshold minimum magnetic field required for operation has found in the latest generations of NFC IC. One promising application is the powering and reading of implanted devices with NFC. The results demonstrate that implanted sensors up to 16 mm deep can be powered using smartphones. The proposed system based on 3-coils presents higher reliability than those based on 2-coils.

6 Acknowledgements

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7 References