Design of 1cm2 coils for HF RFID instruments tracking with detection range improvement

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***Abstract* — This paper concerns an application of magnetic coupling RFID technology at 13.56 MHz (HF band) for tracking devices such as instruments. The tag size is defined to be ergonomically small compared to the hand, and fixed inside a maximum surface of 1 cm². The case of multiple detections is considered, and consequently the reader surface of control is considered wide enough to include several instruments at the same time during a logistic control process. The use of such a small RFID tag is almost impossible using a large reader loop of 15x30 cm², as chosen for the tests. The key idea of the paper is then the addition of a resonator that enables to create the mandatory physical link by means of magnetic coupling between the tag coil and the resonator coil and between the resonator coil and the reader loop. Finally the detection range is highly improved by the presence of this resonator and results demonstrate that it is possible to detect these small RFID "1 by 1 cm² tags" at a distance of 1.5 cm to 3 cm, depending on their orientations.**

Keywords— HF RFID, coil, magnetic coupling

I. INSTRUMENT DETECTION IN A VOLUME

RFID (Radio Frequency Identification) is a fruitful technology that improves many applications of tracking in various contexts such as market or medicine [1][2]. The tracking process can concern persons, animals or devices in various scenarii in which some routing errors can be avoided by using RFID tags [3][4][5]. Additionally, the RFID tags can perform a history back-up memory that can be used for managing the life-cycle of the tagged device and optimize the logistic flux. Currently, technological locks, in RFID projects, are determined by specific cases constraints such as the electromagnetic environment (metal, water…), the problem geometry (e. g. limited volume) and the ability (and/or allowance) to use a radiating (in UHF) or a magnetic coupling (in LF and HF) mode of communication. To reduce routing errors by tracking the devices, the choice of the RFID technology must be customized regardless the whole system use and the ergonomic of the detection method. An example of project tackled in this paper concerns the tracking of surgical instruments with RFID tags [3][4][5][6]. In such project, the goal is to fix some small tags, compared to the size of the instruments and the human hand, and to perform a detection of multiple tags for reconditioning surgical kits before the sterilization process. The management of each instrument life-cycle and its routing represents potential errors of (i) logistics flux, when surgical kits are incorrect, and (ii) nosocomial infection risks, because some specific sterilization process can be mandatory in function of the instrument use by the surgeon in the operating room. This tracking is fruitful if it can provide fast and reliable detection of several instruments, at the same time, and, if possible, inside a limited volume of control. Some optical solution, needing line of sight control process, by engraving Datamatrix or barcode were proposed [3][4][5]. Nevertheless, the use of RFID technology brings the possibility to detect several tags without manipulating the instrument or involving the constraint of visibility. Additionally, the chip memory in RFID tags is an interesting possibility to re-write and store data about the use of the instrument. In this paper, the project consists in tagging surgical instruments with HF RFID technology. The choice of HF (13.56 MHz) is due to the presence of metal (avoid UHF) and in the idea to be compliant with NFC equipment (HF band rather than LF). The constraints of the project are to provide a detection of multiple RFID tags by using anti-collision protocol and to define a volume of detection in which tens of instruments can be routed. In this paper, we focus on the ability to detect, by means of small RFID tags, these instruments put down on a large surface of control (detection), i. e. the reader loop surface. The key idea is to create a magnetic coupling between the tag and an additional resonator and a second magnetic coupling between this resonator and the reader loop, because the direct coupling between the small tag and the reader loop is too weak. In Figure 1, the theoretical maximization of the mutual coupling between the tag and the reader loop is proposed by means of a geometrical similarity (see Neumann formula and [6][7][8]). This solution evolves from a sub-loop to a separate loop and towards the use of a resonator by addition of a tuning capacitor, which increases the induced current in the resonator loop. Mainly, the resulting magnetic field is the sum of the magnetic field generated by the current in the reader loop and the one generated by the current in the resonator. As the magnetic field distribution is more optimized for the tag loop in the vicinity of the sub-loop, the spatial mutual coupling ability is increased. However, the feeding current of the reader is impacted by the presence of such a resonator and implies to tune the reader loop in consequence. A key factor is that the resonator tuning load (mainly the capacitor) defines the current induced in the resonator, especially its phase.

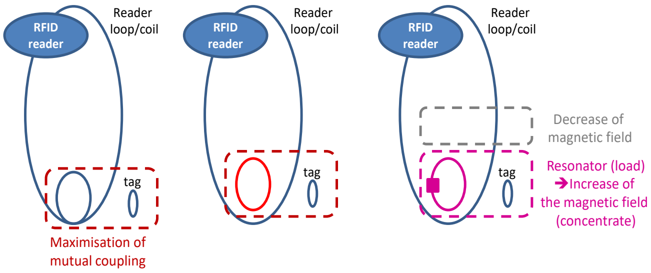


Figure 1 : principle of increasing magnetic coupling by geometrical similarity, and evolution of the solution using a resonator. Physical principle is to feed (left) or to induce (middle or right, thanks to resonance) a current in the small (sub-)loop whose size is in the range of the tag loop, and optimized for a targeted distance of detection

In this paper, we present firstly the design of a small coil dedicated for the instruments tag. This coil is included inside a surface of 1 cm² and adapted to the RFID IC SL2002 ICODE SLI-X, from NXP. Secondly, the coil is measured in presence of a resonator, which is a tuned printed coil with an average diameter of 6 cm, chosen for a detection distance of 4 cm (see the part below and [6][7][8]). Finally, tests of detection are performed with a wide reader loop to demonstrate the improvement due to the presence of the resonator.

II. SMALL COIL DESIGN FOR HF RFID TAGS

In order to tag surgical instruments for the ARTIC project, a coil is designed on a PCB and solder with the SL2002 ICODE SLI-X IC from NXP which is a HF RFID chip. The maximum size of the coil is limited to 1 cm² for ergonomic consideration [3][6] as the tag should not disturb the manipulation of the instruments. The RFID chip includes HF harvesting and has an equivalent capacitance of 23.5 pF, which must be tuned with a coil of 5.86 µH. We designed, with CST electromagnetic calculator, and realized a two faces spiral coil on FR4 substrate with dedicated corner plots for soldering the IC without matching capacitor. The coil parameters are given in Figure 2.

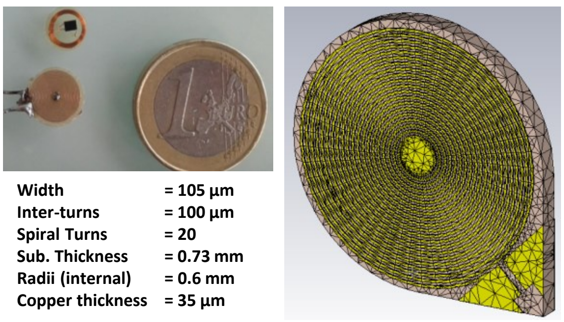


Figure 2 : designed coil (left) and meshing under CST (right)

The coil was realized by micro-etching and its impedance was measured with an impedance analyzer at the RFID operating frequency (13.56 MHz). Comparison between simulations and measurements are in good agreement, as shown in Table 1. It can be noticed that the quality factor is in the range of 35-40 because of the numerous number of turns (20 on each of the two faces) and consequently the total length of the spiral line. Moreover, reducing the number of turns would have increased this quality factor but this implies the addition of an external capacitor which has not been considered inside the 1 cm² surface at the moment.

Table 1: simulation and measurements of the small coil at 13.56 MHz

	CST	measurements
L (µH)	5.93	5.84
Rs (Ω) / Q	12.7 / 39.78	14.3 / 34.8

The tag coil is magnetically coupled with the resonator at a distance in the range of 3 to 5 cm [3][6]. To design the resonator as a tuned coil on PCB, we evaluate the optimum size thanks to a simple computation under MATLAB. The tag coil is supposed to be an equivalent single turn of 1 cm diameter and we calculate the magnetic induction thanks to (1).

$$\begin{cases} B_r = \dfrac{I\mu_0 y}{2\pi\left[(R+r)^2+y^2\right]^{1/2} r}\left[\dfrac{R^2+r^2+y^2}{(R-r)^2+y^2}E(k)-K(k)\right] \\ B_\theta = 0 \\ B_y = \dfrac{I\mu_0}{2\pi\left[(R+r)^2+y^2\right]^{1/2} r}\left[\dfrac{R^2-r^2-y^2}{(R-r)^2+y^2}E(k)-K(k)\right] \\ k^2 = \dfrac{4Rr}{(R+r)^2+y^2} \end{cases} \qquad (1)$$

The magnetic induction expressed in (1) corresponds to the schematic in Figure 3, in which the mutual inductance value is evaluated by numerically integrating (sum) the orthonormal component of the magnetic field, given by (1), over a delimited surface (length parameterized), at different distance.

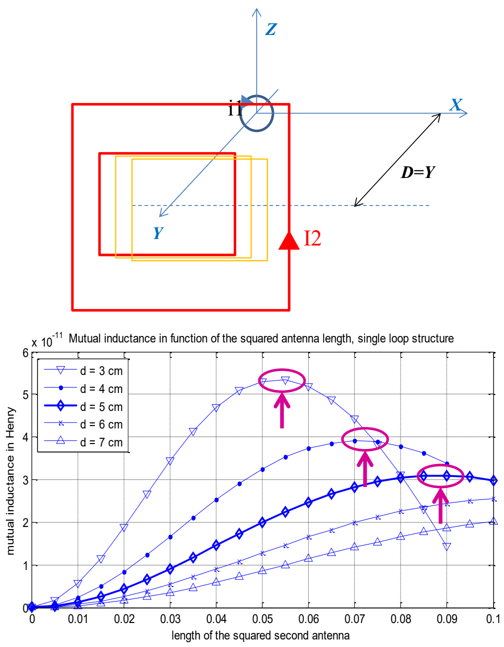


Figure 3 : MATLAB simulation for a single turn coil of 1 cm diameter, in function of the reader loop size at different distance

Results in Figure 3 show an optimum reader loop length (and consequently surface size) in function of the distance for a given surface size of the tag. This drives us to define the resonator loop diameter to be in the range of 6 cm for a distance between 3 and 4 cm.

III. USING A RESONATOR FOR IMPROVING THE DETECTION

A resonator is designed by means of a hexagonal spiral coil of value 1.3 µH (by measurements). This value enables us to adapt the tuning with a variable capacitor (hundred of pF) in order to be able to adapt the resonator tuning in future tests if the environment is disturbed by metal, ferrite, or by another resonator. The resonator impedance is measured in Figure 4 and its quality factor is in the range of 30, which is high enough for powering the tag by magnetic coupling and low enough for the mandatory bandwidth of such RFID systems (several kHz) [1][2].

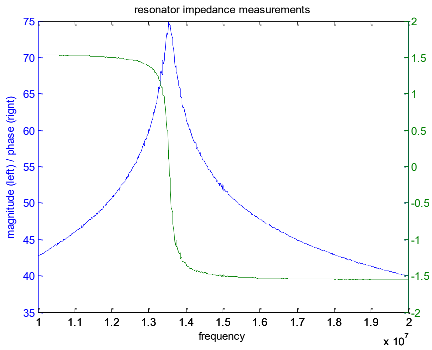
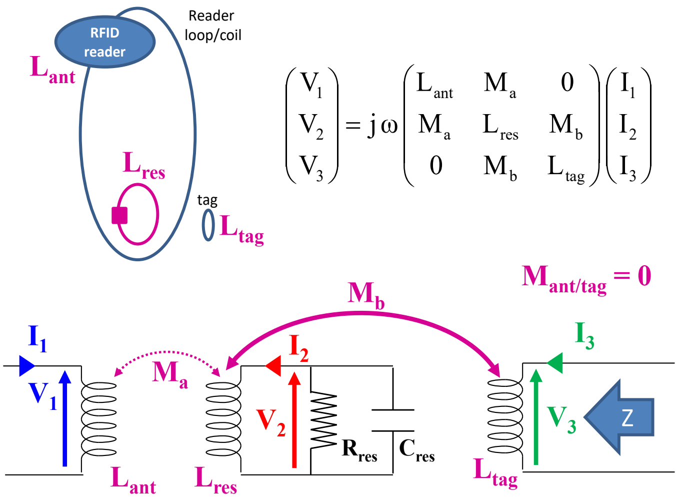


Figure 4 : Impedance measurements of the resonator tuned at 13.56 MHz (magnitude in dB at left/blue, phase in radians at right/green)

To model the resonator influence, we define the equivalent system in Figure 5, in which the magnetic coupling between the tag coil and the reader loop is considered to be insufficient and negligible ($M_{ant/tag} = 0$).



$$\begin{pmatrix} V_1 \\ V_2 \\ V_3 \end{pmatrix} = j\omega \begin{pmatrix} L_{ant} & M_a & 0 \\ M_a & L_{res} & M_b \\ 0 & M_b & L_{tag} \end{pmatrix} \begin{pmatrix} I_1 \\ I_2 \\ I_3 \end{pmatrix}$$

Figure 5 : Equivalent model of the tag coil coupled with the resonator coil, and the resonator coil coupled with the reader loop antenna

The impedance seen by the RFID tag IC is function of the spiral coil designed coupled with the resonator. We expressed this impedance as Z, as given by (2)

$$Z(\omega) = \left.\frac{V_3}{I_3}\right|_{M_{ANT/TAG}=0}$$

$$= j\omega L_{tag} + \frac{\omega^2 M_b^2}{(R_{Res}//C_{Res}) + j\omega L_{res}}$$

$$\approx j\omega L_{tag} + \frac{\omega^2 M_b^2}{(r_s + C_{Res}) + j\omega L'_{res}}$$

$$with \begin{Bmatrix} R_{res} = r_s\left(1+Q_{res}^2\right) \\ L_{res} = L'_{res}\left(1+Q_{res}^{-2}\right) \approx L'_{res} \end{Bmatrix}$$

$$Z\left(\omega_0 = \frac{1}{\sqrt{L_{Res}C_{Res}}}\right) \approx j\omega_0 L_{tag} + \frac{\omega_0^2 M_b^2}{r_s} \qquad (2)$$

In (2), we expressed Z under the hypothesis of a resonator perfectly tuned at the operating frequency (f_0 = 13.56 MHz) and with a sufficiently high quality factor value that enables to use the equivalent series resistance r_s while keeping the same inductance L_{res} in serie or parallel. Theoretically, the impedance seen by the IC is supposed to stay tuned at the operating frequency and its resistive part is increasing with the (square of the) mutual inductance value. This is emphasized when the resonator has a high quality factor (i.e. a low r_s value). In practice, there is a modification of the reactive part of Z if the resonator is mistuned and/or if the resonator is disturbed by its environment, including the presence of another resonator [9][10]. We measure the variation of Z with a VNA, in order to be able to move the spiral coil, as reported in Figure 6. We chose two positions for the spiral coil to illustrate the horizontal mode (position 2) and the vertical mode (position 1) [6][8][10], at a distance of 2 cm, as seen in Figure 6.

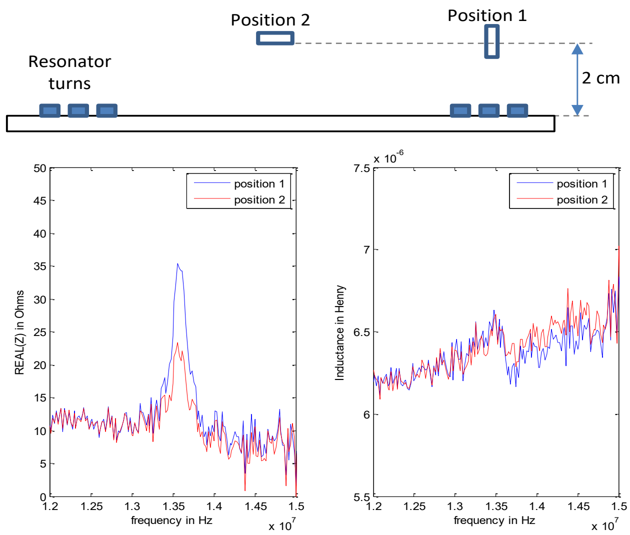


Figure 6 : Measurements of Z (real part /imaginary part) for two positions of the small spiral tag coil (schematic on top).

It can be noticed that the inductance value measured, in Figure 6 (right), are slightly higher with the VNA than with the impedance-meter because the measurements are influenced by the soldered connector, cable, and by the fact that loads measured on VNA ports have a high reflection coefficient magnitude. Moreover, the measurements show the increase of the real part of Z, emphasized for the position 1 in which the coupling is higher, as predicted by (2). The variation of the reactive part of Z (inductance) is noticeable, as mentioned above to be due to the realization.

The spiral coil is impacted by the presence of the resonator but the variation of its equivalent inductance value is low enough to test the detection of a tag. This tag is composed by the RFID IC soldered on the designed PCB of the spiral coil.

IV. TESTS OF DETECTION

The RFID detection test is performed thanks to a RFID reader from Ib technology (RFID-UNI-EVAL with 13.56 MHz ICODE SLI-X chip module) that can be connected toward an external tuned reader loop. We choose a loop with dimension 32x16 cm², as represented in Figure 7, and arbitrarily positioned the resonator center at coordinates (X=26 cm,Y=5 cm), as shown in the Figure 7. The reader loop is realized with thin adhesive copper tapes.

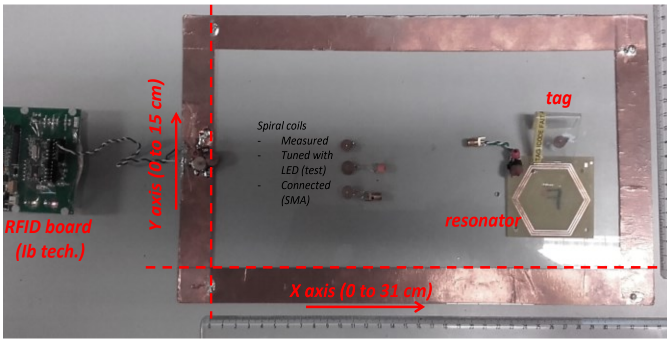


Figure 7 : RFID reader, loop, and coordinates axis for the detection tests

As it can be seen in the figure, the different spiral coils used for the measurements and for the tag are considered small compared to the large reader loop. This is confirmed by the fact that it is impossible to detect the tag without the resonator, except at the edges of the reader loop where the maximum detection range are, respectively, 1 cm and 0.5 cm for the horizontal and vertical modes. These modes correspond to the orientation of the reader loop surface in relation to the tag coil surface.

The detection tests (and range), with the resonator, are reported in Figure 8 for the horizontal and vertical modes. Maximum distances of tag identification show that the resonator highly improves the detection performances in horizontal mode (above the resonator itself) towards 3 cm. In vertical mode, the tag is rotated in the plane and the detection distance can reach 1.5 cm above the edges of the resonator. This is due to the magnetic field distribution (field lines).

However, it is important to notice that the detection range is also improved in the space in-between the loop and the resonator (for example into the delimited area from X = 28 to 30 cm and from Y = 0 to 7 cm). This is due to the coupling of the resonator with the reader loop which modifies non-uniformly the magnetic field distribution. Moreover, a too wide resonator would drives to a too strong coupling with the reader coil which can affect the tuning of the reader loop and penalize the detection performances.

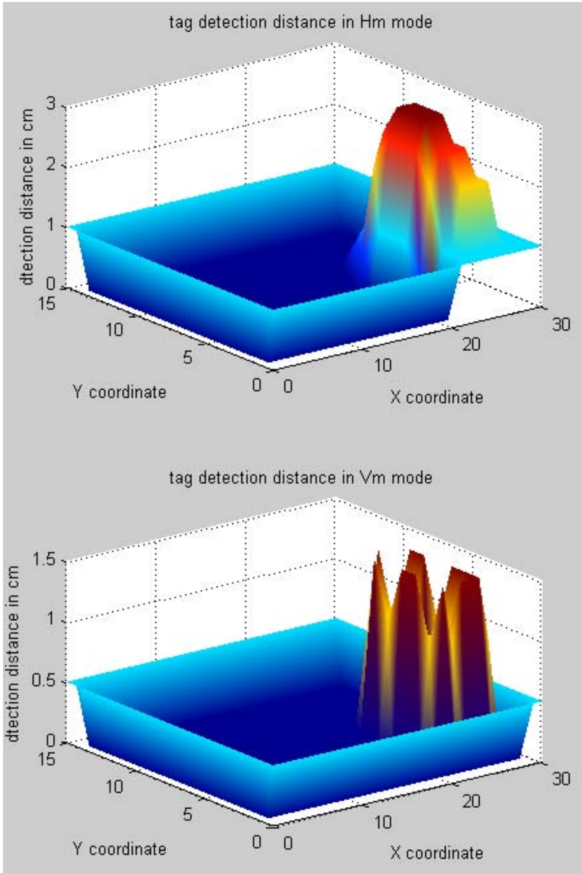


Figure 8 : Detection distance corresponding to Figure 7 configuration for Hm (top) and Vm (bottom) orientation of the RFID tag. Vm corresponds to any position orthonormal with XY plane.

V. CONCLUSION

In this paper, we presented the possibility to simulate and design a small tag coil, inside a surface of 1cm², for tracking multiple devices with RFID. The detection ability is possible over a wide surface if using additional tuned resonators.

This key idea is demonstrated in the case of using a single resonator, and based on the assumptions that both (i) the tag coil is weakly coupled with the resonator coil, and (ii) the resonator coil is also weakly coupled with the reader loop. If one of these coupling factors is too strong, additional works are necessary to overcome the tuning frequency shifting. This is the perspectives of this work because the context drives us to use several resonators over the wide reader loop surface, consequently generating multiple and additional magnetic coupling factors.

Acknowledgment

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