

Performance Evaluation of a Novel Animals Tracking System based on UHF RFID Technology

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Original scientific paper

Abstract: The adoption of solutions based on Radio Frequency Identification technology in a wide range of contexts is a matter of fact. In many situations, such as the tracking of small-size living animals, the straightforward use of commercial systems does not ensure adequate performance. Consequently, both the RFID hardware and the software control platform should be tailored for the particular application. In this work, the specific requirements of Near Field Ultra High Frequency RFID reader antennas suitable for small-size animal localization and tracking are identified and a control system in a LabVIEW environment is designed. Afterwards, both hardware and software solutions have been implemented and validated. In particular, an algorithm based on the measured Received Signal Strength Indication, in order to obtain precise localization data, was developed and validated. Finally, the set-up of a first working prototype involving built-in-lab reader antennas has been completed and tested. The achieved results prove the effectiveness of the proposed tracking system.

Index terms: UHF tags, RFID, animal tracking system, performance evaluation, test bed.

I. INTRODUCTION

The cost-effectiveness and ease of use of passive Radio Frequency Identification (RFID) systems in the Ultra High Frequency (UHF) band is promoting an impressive diffusion of such a technology in a wide range of application scenarios, even quite far from the canonical ones related to logistics. Identification of goods containing liquids or metal [1]-[2], RFID-based sensor data transmission [3], RFID-assisted navigation of robots, augmented RFID scenarios [4], item-level traceability [5] are only a few of the many possible examples. A peculiar case study, not yet exhaustively explored [6], consists of the tracking of small-size animals carrying a small-enough RFID tag. The literature in this field proposes

solutions primarily based on Low Frequency (LF) or High Frequency (HF) RFID systems and, consequently, not exploring the powerful of the EPC Class-1 Generation-2 standard, which provides, for instance, anti-collision mechanisms for the concurrent identification of multiple tags. Other reported solutions make use of sophisticated and much more expensive vision systems [7] which, although avoiding the animal to carry or having implanted any kind of device, can be strongly inaccurate, especially when many animals, one indistinguishable from another, must be simultaneously localized and tracked.

In this work, the problem of small-size animal tracking is tackled by means of passive Near Field (NF) UHF RFID technology. More specifically, we designed and validated a novel RFID-based indoor tracking system for laboratory free-range animals, i.e. where the animals are not forced to move in predetermined paths. The idea is simple and effective: the ground of the animal cages are virtually splitted into partially overlapping cells of size comparable with that of the animal. Under the fundamental working assumption that a passive NF UHF RFID tag is implanted in every animal, customized NF reader antennas covering the cells with a confined and uniform magnetic field are then positioned right below the cage and in correspondence of each elementary cell. The design and realization of such antennas is a significant part of this work because the more uniform and confined is the magnetic field, the easier and more effective is the animal tracking algorithm. The whole system comprises both hardware parts (RFID readers and antenna multiplexers) and a smart software platform for the RFID data collection, gathering, and interpretation. The specifications of the NF antennas and their consequent design and realization, along with the software platform, are undoubtedly the two main scientific aspects of this work. The former is attacked by means of segmented loop techniques, which guarantee uniform magnetic field even for loop lengths greater than λ (i.e., wavelength at the operating frequency). The latter is performed by a LabVIEW-based interface which drives the hardware subsystem. Moreover, the software platform implements an effective algorithm which, on the basis of the measured Received Signal Strength Indication (RSSI) of the NF tag signals, extracts reliable information about the animal positions. Thanks to the NF antenna properties, since in most cases only one antenna will detect a given tag, the association animal-cell is straightforward. Vice versa, if more antennas read the same tag (e.g. when the animal is on a border cell), an RSSI

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comparison will be performed to discriminate the correct cell.

The paper is structured as follows. In Section II, the state of the art on animal localization and tracking is summarized. In Section III, the proposed tracking system is described and all its functionalities are presented. Testing procedures to validate the whole system and their results are presented in Section IV. Finally, conclusions are drawn in Section V.

II. RELATED WORKS

The animal tracking is a widely area explored in the literature. In [8], the movement of Antarctic seals is monitored by using GPS technology, providing a positional accuracy of 150 m. Instead, in [9] the tracking system is based on the use of radar technology. Transmitters are fixed at the neckband of the cows, allowing a 2D localization with an accuracy of 25 cm. However, both solutions are not effective for small animals that move in indoor environments because of the poor visibility of the satellites in the case of the GPS technology and the big dimension of transponders in the case of the radar technology. Actually, the problem of poor visibility of GPS satellites in indoor tracking applications is dealt by using pseudolites [10], which however require high costs of installation and calibration. In addition, in pseudolite applications, particularly in indoor positioning, multipath is a major concern, as well as the near-far problem that occurs when the receiver is too close or too far from the pseudolite. Furthermore, GPS and radar technologies do not satisfy stringent accuracy requirements requested in small animals tracking that move in small indoor environments.

A widespread technology for the small laboratory animals tracking is based on the use of complex and expensive vision systems, which often are not very effective, especially in poor visibility conditions and where many similar animals move in the same space.

Other solutions are based on the use of the very well known passive RFID technology, which allows the identification of a tag when it is in the region covered by the antenna of an RFID reader. The widespread use of this technology is due its high performance in critical scenarios [11]-[12]-[13]-[14], that makes possible its use for tracing of particular products, for example drugs, with no deteriorating effects due to thermal and non-thermal effects [15]-[16].

The most significant example of small animals tracking system based on passive RFID technology is presented in [6]. In this paper, LF band is used and a semi-natural environment (SNE) is reproduced in order to study the laboratory mice behaviour. In this way, mice are forced to follow obligatory paths so that their movements can be detected. In addition, LF band does not allow simultaneous reading of multiple tags because it is not compatible with the EPC Class1 Gen2 standard. Furthermore, this frequency band offers a very limited reading range (less than 1 cm distance between tag and reader antenna). Finally, the biggest limitation is that a semi-natural environment can alter the normal animals behavior.

Finally, first results of a study performed by a living laboratory approach on the tracking system proposed in this

paper are reported in [17]. In particular, a feasibility study on the use of RFID technology in UHF band for small animal tracking is performed.

III. THE PROPOSED TRACKING SYSTEM

A. Main system requirements and overall architecture

A tracking system able to correctly track small laboratory animals, in particular mice, should satisfy some essential requirements. First of all, it must be capable to track simultaneously more similar animals that move in small indoor environments, avoiding the ambiguities often introduced by vision systems commonly used in these scenarios. These ambiguities can derive, for example, from the difficulty in distinguishing very similar animals that move in the same environment, especially in the nocturnal visions.

Moreover, this system should not be invasive both for animals and for environments in order not to alter the animal behavior. Low invasivity and freedom of movement are, indeed, key requirements in order to obtain this result.

From the hardware point of view, it is necessary to use reader antennas able to discriminate the exact animals position, ensuring a magnetic field as much as possible localized.

The overall architecture of the proposed tracking system is shown in Fig.1.

The data acquisition and the processing and plotting modules are implemented by using the integrated development environment LabVIEW [18]. In particular, the data acquisition block is responsible for intercepting the reading reports of each reader antenna and for storing these reports in an appropriate table of a relational database, created by using the Relational Database Management System MySQL [19]. These data are used by an algorithm that processes them and extracts information about the animal positions. The processed localization data are stored in another table of the same relational database.

Finally, a plotting module extracts these data and draws the paths followed by the animals in the space of observation and

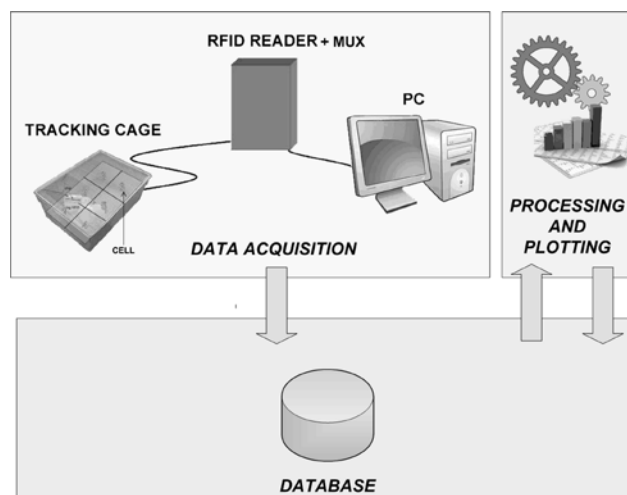


Fig. 1. Proposed tracking system architecture.

in the time window chosen by the user, in the form of both spatial and temporal graphs.

B. Prototype reader antenna design

The most important hardware device enabling a reliable animals tracking is the reader antenna system. Indeed, an antenna specifically designed for a similar purpose should be able to:

- irradiate a magnetic field confined as much as possible in a specific cell in NF conditions;
- ensure an inductive coupling with the RFID tag when the animal is on the cell associated to the reader antenna
- guarantee a uniform magnetic field within the cell in order to minimize the localization uncertainty.

Actually, even though NF UHF RFID reader antennas having good electromagnetic performance are on the market, reader antennas that fully cover all the mentioned requirements are not present yet, hence have to be specifically designed. According to the first specification, among all the possible antennas available in literature [20]-[21], the loop structure seems to be a good solution to implement reader antennas working in the NF zone. Nevertheless, in the conventional loop [21], when the antenna perimeter is comparable with wavelength (λ) at the operating frequency (f), the antenna does not produce a uniform magnetic field because currents are not in phase along the circumference. This aspect does not satisfy the other desired properties. This problem was overcome thanks to the segmentation strategy proposed in [22] and theorized in [23]. The idea is to subdivide the loop into a series of inner and outer segments separated by a small gap. The use of such gaps introduces a distributed capacitance along the loop that leads in-phase the current distribution, thus contributing to the irradiation of the desired uniform magnetic field.

In Fig. 2.a, the layout of our proposed solution based on

such a theory is shown. The antenna is substantially a segmented loop working in the European UHF RFID whose dimensional parameters were optimized to cover a cell of almost 12 cm x 12 cm. Simulation campaigns were carried out by using CST Microwave Studio. Some prototypal samples of the designed reader antenna were realized on a substrate of FR-4 with dielectric constant $\epsilon=3.6$, and thickness $h=1.6$ mm. Moreover, a matching network was employed in order to adapt the antenna impedance to the reader impedance of 50 Ω . For instance, in Fig. 3, the very good agreement between simulated (i.e., solid line) and measured (i.e., dotted line) $|S_{11}|$ scattering parameter is shown, with a peak of -23 dBm (measured) and -29 dBm (simulated) at 866 MHz.

As a result of the simulation and optimization phase, the overall current becomes quite uniform and it flows along a specific direction. In Fig. 2.b, the representation of this phenomenon for the designed segmented loop antenna is reported. The main practical consequence of this current distribution is that the radiated magnetic field becomes both uniform and rather confined in a region slightly larger than the total area of the antenna. For a better clarification, in Fig. 2.c, a slice of the distribution of the radiated magnetic field at 2.5 cm of distance from the antenna is shown.

C. Data acquisition module

The data acquisition module is responsible for configuring the hardware and storing the tag readings performed by reader antennas.

This module was designed and implemented separately from other components (e.g. processing and plotting subsystem) in order to guarantee effectiveness and scalability. In this way, it is possible to have different plotting modules that are able to extract data from the same data acquisition module. Furthermore, this choice relieves the computational load of the acquisition module.

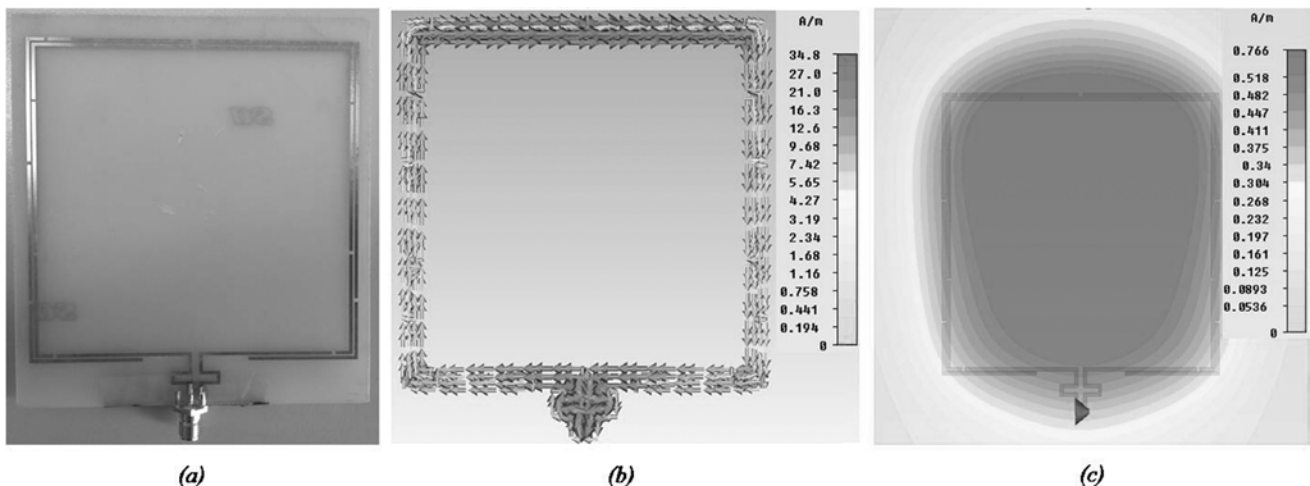


Fig. 2. (a) Prototype of the segmented loop antenna for animal tracking system; (b) current distribution of the segmented loop antenna; (c) magnetic field distribution of the segmented loop antenna for animal tracking system at 2.5 centimeters of distance.

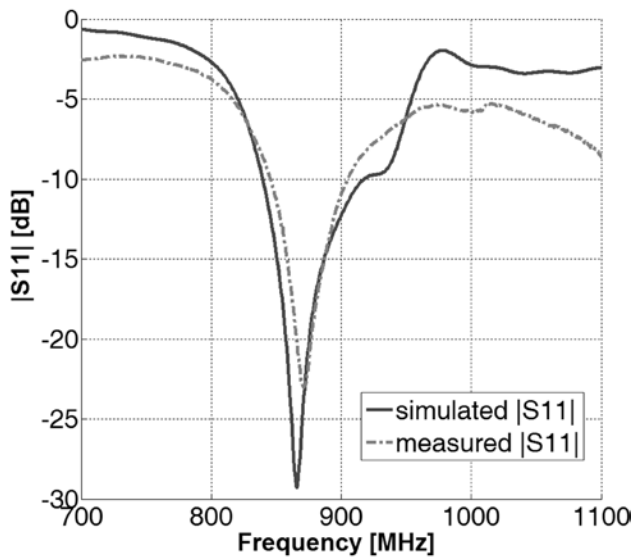


Fig. 3. Performance comparison between measured and simulated $|S_{11}|$ of the proposed segmented loop antenna.

A diagram that reports the main activities needed to carry out the data acquisition phase is shown in Fig. 4.

As previously mentioned, this module allows to manage and configure the whole hardware system. This is possible by exploiting the Low Level Reader Protocol (LLRP), according to which the packets exchanged between RFID reader and application are formatted. In particular, the interface associated to the data acquisition module allows the user to enter some preliminary parameters, such as the transmission power of each reader antenna. In addition, the module allows to couple a string label to the Electronic Product Code (EPC) stored in each RFID tag, in order to identify in a meaningful way every mouse in experimental tests. All string labels are stored in a table of the relational database.

When the application is started, it sends the initial set-up to the reader according to the user requirements; in turn, the RFID reader responds by using a LLRP message that indicates the configuration success or failure. This feedback is directly visible on the application front panel, in addition to the connected/disconnected status of each reader antenna.

Finally, the data acquisition module allows for a preliminary tags acquisition so that only readings of desired tags are intercepted by the system, whereas all the other ones on the reading range are discarded.

Noteworthy that each reader antenna sends to application program a report every 300 ms that is perfectly able to intercept and store all these readings. A so fast rate allows to correctly detects faster movements of mice.

D. Processing algorithm

The algorithm that processes the data provided by the acquisition module consists of three main phases.

Starting from the raw data, this algorithm is repeated for each ID tag stored in the relational database, in order to obtain the animal positions in the cage. In particular, the three phases

are reported as follows:

- *Phase 1*: identification of simultaneous readings and data discrimination based on the RSSI value.
- *Phase 2*: check of adjacent cells based on the Chebyshev distance [24] calculation;
- *Phase 3*: removal of the "ping-pong" effect.

The pseudocode of the proposed algorithm is shown below:

```

for each tag ID{
    for each sampling interval{
        PHASE 1:
        store the sample with max RSSI value and all
        samples with RSSI value in the interval
        (RSSImax - ΔRSSI) in List1.
    }
    PHASE2:
    for each sample in List1{
        if distance [ i , i+1 ] ≤ 2
            add i+1 sample in List2;
    }
}

```

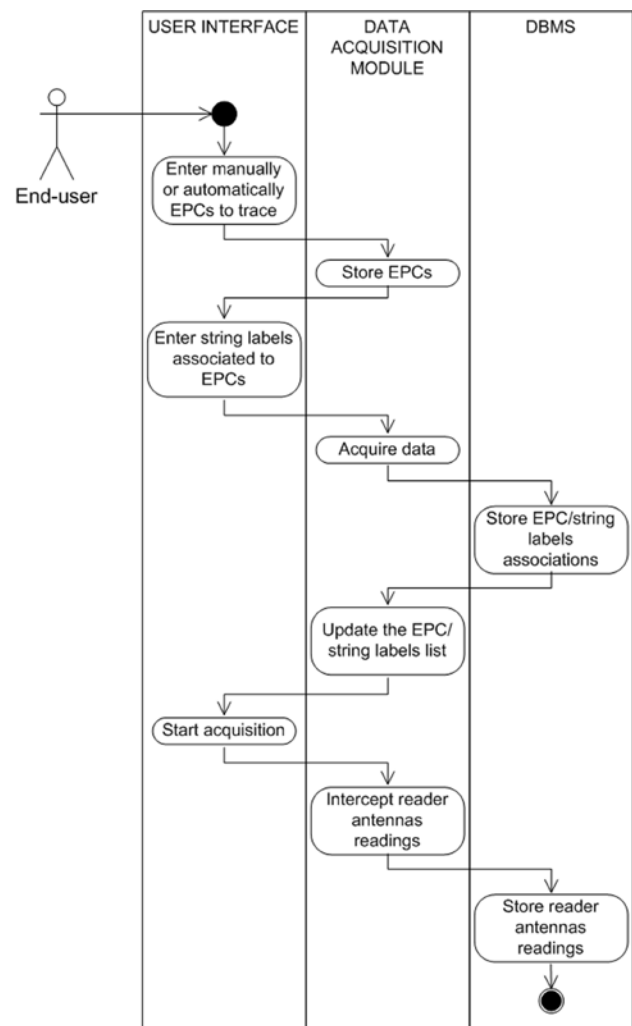


Fig. 4. Activity diagram of the data acquisition module.

```

else if distance [i + 1, i + 2] > 2
    discarded i+1 sample;
else add i+1 sample in List2;
}
PHASE3:
for each sample in List2{
    if i ≠ i+1{
        if i-1=i+1
            discarded i sample:
            ping-pong effect!;
        else add i sample in List3;
    }
    else add i sample in List3;
}
store all sample in List3 in the relational
database
}

```

E. Plotting module

The plotting module is responsible for presenting in a meaningful way the animal positions stored in the relational database to the end-user. Its activity diagram is presented in Fig. 5.

In particular, this module gives the end-user the possibility to choose a time window and a string label (i.e., laboratory animal) on which to concentrate the observations. After these choices, the user interface is able to show both spatial and temporal graphs. In particular, two spatial graphs are

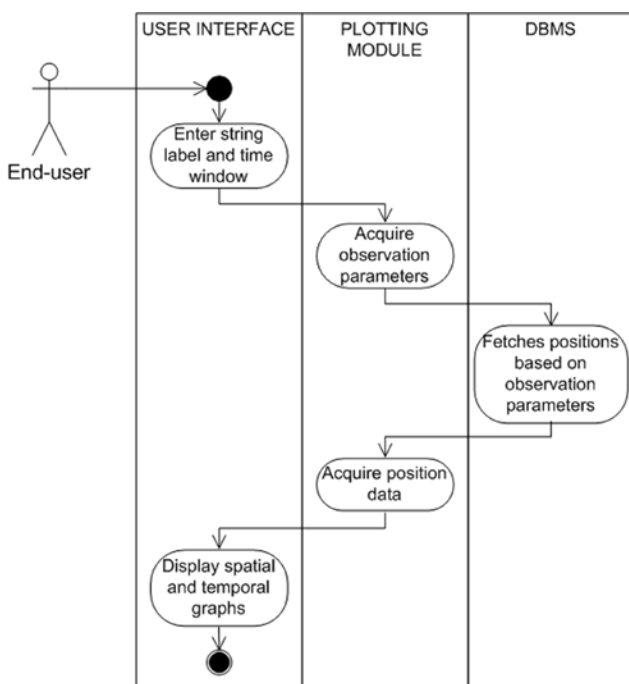


Fig. 5. Activity diagram of the plotting module.

displayed, one concerning the movements of the selected mouse among the cells, without temporal information, and the other that summarizes the movements of all mice in the same time interval.

Furthermore, the temporal graphs, one for each mouse, show how long each mouse remains in each cell. These last graphs have the time on the abscissa axis and the cell labels on the ordinate axis. These temporal graphs are placed one below the other to allow the user to see which mice have simultaneously visited the same cells.

IV. VALIDATION AND RESULTS

A. Test environment

Test environment used to validate the proposed tracking system is shown in Fig. 6.

It consists of an Impinj Speedway Revolution R420 reader [25] with four antenna ports, an Impinj GPIO adapter and one HD15 cable. The GPIO adapter allows to connect up to four Impinj Antenna Hubs [26], each of which accepts up to 8 reader antennas. In this way, up to 32 different antennas can be powered in time division through a single 4-port RFID reader. More specifically, only 4 antennas are contemporaneously powered, thus reducing potential array effects and energy wasting.

Each Antenna Hub is connected to the GPIO adapter by using a straight ethernet cable and to the reader by using a SMA-male to R-TNC-female coaxial cable, whereas each reader antenna is connected to its Antenna Hub by using a SMA-male to SMA-male coaxial cable. Finally, the reader is connected to the computer via a cross ethernet cable. In this way the application, once started, will acquire all reader antennas reports and will store them in a relational database.

The reader antennas system represents a matrix of cells (32 in our case), collocated under the cage in which the mice

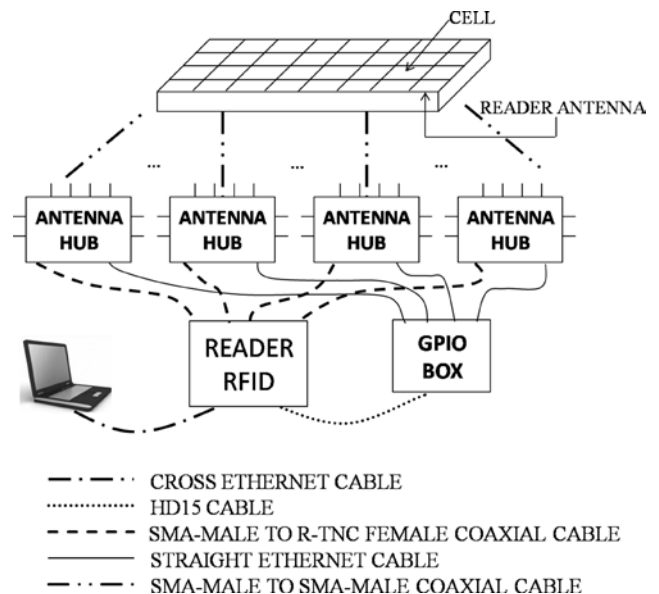


Fig. 6. Test environment used to validate the proposed tracking system.

move, and each cell represents a possible position held by the animal. As this cells system is very large (about 40 cm x 80 cm), it can allow the observation of a mice colony.

The tests were carried out by using plastic test tubes filled with saline solution and on each tube a passive RFID tag was applied. The saline solution is able to simulate with a good approximation the attenuation caused by the animals tissue during the reading of the tag.

The tag type used in the tests is a commercial passive NF UHF RFID transponder characterized by a memory of 32 bits, whose antenna size is 15 mm x 10 mm and the mounted chip is the Impinj Monza4D. Finally, this tag has an inlay composition characterized by aluminium on the top and polyester PET as substrate.

It is important to highlight that, before the validation of all the hardware and software components of the system, the feasibility of the proposed solution, in relation to the tag implant in real animals, was verified, as already mentioned in [17]. This validation phase was carried out in collaboration with the Italian National Institute of Health, Rome, ITALY, and was aimed at confirming that there were no differences in behavior between implanted animals and normal subjects. In this perspective, sham-operated animals underwent the same surgical procedures without being implanted with RFID tag. After the surgery, all mice were placed in the home cage and observed (once a day) in order to study their behavior. Every day activity level (inactivity or hyperactivity), attitude (arousal or awareness of surroundings), behavior (posture, vocalization, self-injury, hiding, aggressiveness), food and water intake, fecal and urinary output, and wound closure was evaluated and recorded. Body weight was recorded four times per month. These observations revealed no changes in gross behaviour in confront to control animals. Body weight and weight gain was in the same order of magnitude in the implanted animal and in the sham-operated animals. Post-mortem examination did not reveal significant signs of inflammatory reaction or granuloma formation in the tissue near the implant site. The research protocol was approved by the Service for Biotechnology and Animal Welfare of the Italian National Institute of Health and authorized by the Italian Ministry of Health, according to Legislative Decree 116/92, which implemented the European Directive 86/609/EEC on laboratory animal protection in Italy. The results of this validation phase were not reported in detail since a more exhaustive study about the animal behavior is object of an ongoing work.

B. Reader antenna testing

Once the NF reader antennas were realized, an electromagnetic characterization aimed at verifying the properties of uniformity of the magnetic field was performed. In particular, a 12 cm x 12 cm matrix of 25 NF RFID tags arranged on a paperboard substrate in 5 rows and 5 columns was used as illustrated in Fig. 7, and was positioned close to the reader antenna. Such antenna was connected to the Impinj Speedway Revolution reader. The tag matrix was placed in

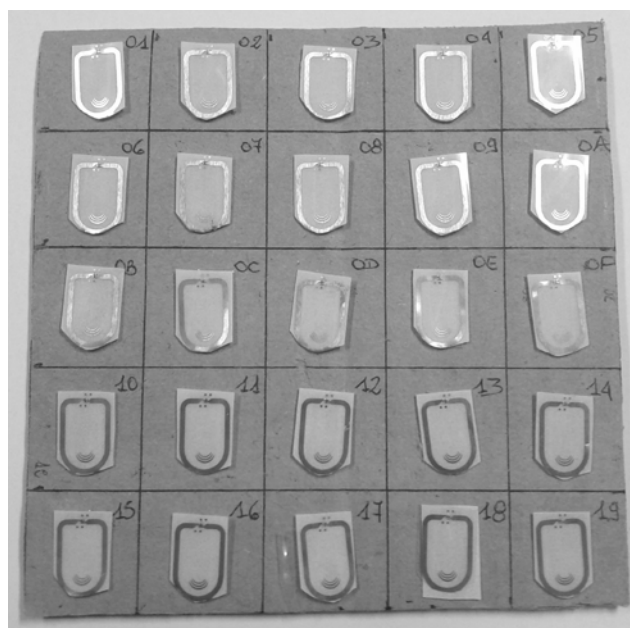


Fig. 7. A 5 x 5 matrix of RFID NF tags.

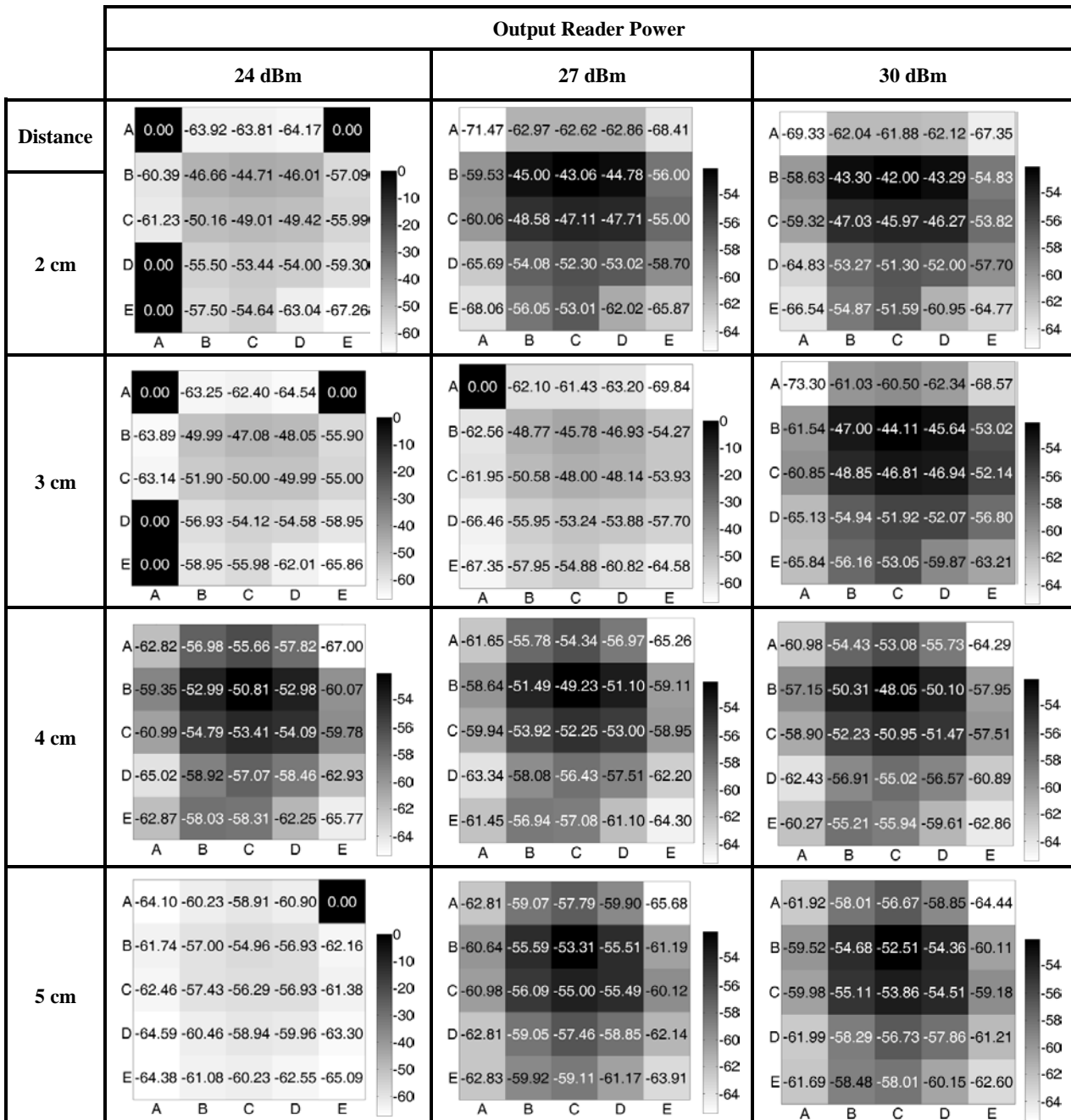
front of the antenna and moved at different distances in the range from 2 cm to 5 cm in steps of 1 cm. For each step the average RSSI of all the 25 tags was evaluated through the reader by varying the reader output power between 21 and 30 dBm in steps of 3 dBm for a test time of 20 seconds per point.

It is worth pointing out that, despite RSSI measurement is not a rigorous characterization approach, in this context it results rather adequate. In fact, in one shot the presence of 25 mice is simulated. Furthermore, differently from what happens by directly measuring the magnetic field, the evaluation of the RSSI for a specific tag also assures that it is properly occurred the communication between tag and reader.

Once the measurements have been done, they were elaborated by using MATLAB [27] tool and graphs reporting the RSSI distribution for different distances and different power levels for all the considered tags of the matrix were obtained. In such a way, the uniformity of the RSSI distribution can be assimilated to the uniformity of the magnetic field distribution and then the antenna behavior in NF can be effectively evaluated. In other words, if the RSSI distribution is quite uniform it can be assumed that the magnetic field distribution in NF is uniform as well.

In Table I, obtained results are summarized. In particular, values of the RSSI distribution of the tag matrix evaluated by varying both the distance from the loop antenna and the output transmission power of the reader are shown. For each block, a single cell shows the average value of RSSI in dBm measured for each tag that composes the matrix and, moreover, a gray-scale has been used to graphically represent the overall RSSI distribution. Let us observe that null values of RSSI are present in some cases, whilst in most cases a quite uniform RSSI distribution can be appreciated. In particular, the best antenna performance in this sense is obtained at a distance of 5 cm and power of 30 dBm. In such a case, RSSI values vary in a rather narrow range between -52.51 dBm and -64.44 dBm

Table I
 GRAPHS OF THE RSSI DISTRIBUTION OF THE TAG MATRIX



and the distribution results fairly uniform.

On the basis of the just discussed results, a second step was performed, aimed at estimating the optimum distance between two segmented loop antennas (antenna I and antenna II). It was carried out by placing the antennas (opportunedly connected to an Impinj Speedway reader) with two sides adjacent between them and by locating a NF tag along the separation line at a distance of 5 cm above the antennas surface. Consequently, the distance between two reader antennas was gradually increased from 0 cm to 2 cm in order to evaluate the minimum distance guaranteeing the correct detection by both antennas simultaneously. More specifically,

the tag was moved in every point around the separation gap between the antennas and the percentage of readings of each antenna was recorded. Finally, in order to evaluate the actual independence between the two antennas, the UHF NF tag was unbalanced towards one of the two antennas (i.e. antenna I) and the the ratio between the overall number of readings of the two antennas and the readings of the antenna I was evaluated. In Table II, results at different distances are reported. As can be observed, optimum values was obtained for gaps of 1 cm and 2 cm, with a percentage of readings of the antenna I greater than 95% highlighting a good independence between the antennas. On such basis a mean gap of 1.5 cm has been

TABLE II
SUCCESSFUL READING PERCENTAGE WITH THE
CHANGE IN READER ANTENNAS DISTANCE

	ANTENNA 1 [Read Percentage]	ANTENNA 2 [Read Percentage]
0 cm	53%	47%
1 cm	95%	5%
2 cm	97%	3%

then set.

Finally, on the basis of the obtained results, the hardware set-up for the animal tracking system has been composed by setting a distance between the reader antennas and the cage of 5 cm, the separation gap between each couples of antennas of 1.5 cm and an output reader power of 30 dBm.

C. Tracking algorithm testing

In order to test the effectiveness of the proposed data processing algorithm, each algorithm phase was separately validate.

In particular, a predetermined path was simulated by using the test tube and the corresponding data were collected. This simulation was carried out a sufficient number of times to

ensure statistically significant results.

Some results obtained in the algorithm validation phase are shown in Fig. 8. In particular, a space of 32 reader antennas according to a 4x8 matrix was considered. In Fig. 8.a, the executed path, and therefore the one that should appear after the processing phase, is indicated by using a continuous line, whereas the path obtained before applying the processing algorithm is indicated by using a dashed line.

The cells correctly identified are indicated in dark grey, whereas the cells that must be neglected are light grey. Finally, the cells between which the ping-pong effect was occurred are indicated with a dotted arc.

In Fig. 8.b, the path obtained after the first algorithm phase is shown. As can be seen, some cells were excluded from the path, because the RSSI value of the corresponding readings was too low compared with the maximum value detected by the algorithm (i.e. the cells number 3, 19, 21, and 30).

In Fig. 8.c, the cells that were at a distance greater than two compared to the previous cell and to the next cell (i.e. cells number 5 and 13) were considered unrelated to the path and eliminated by the second algorithm phase.

Finally, in Fig. 8.d, the ping-pong effect between cell 20 and cell 29 was eliminated after the third phase of the processing algorithm and the final results are shown.

The resulting path coincides with the path simulated in test

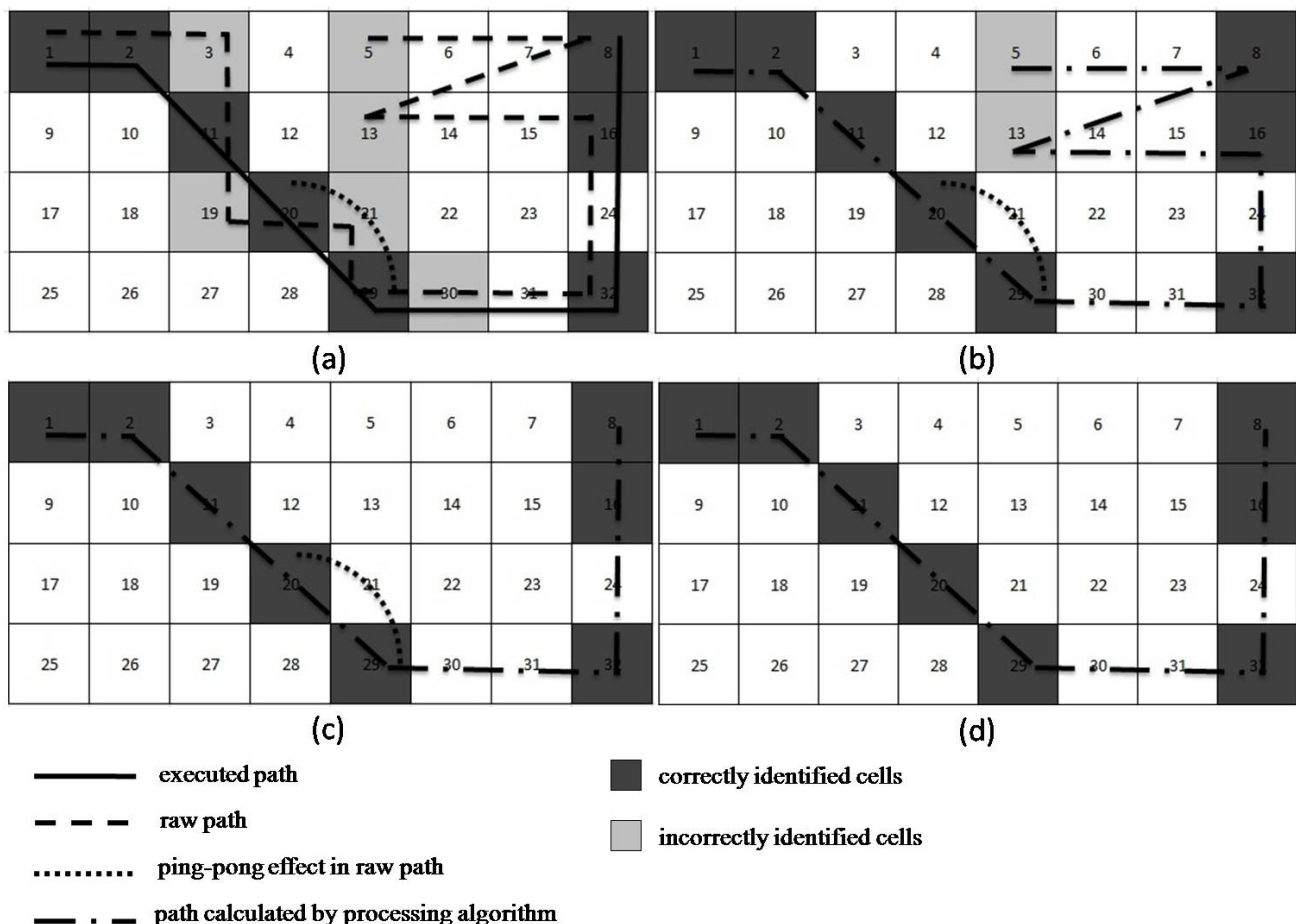


Fig. 8. Results of the processing algorithm validation: (a) Initial situation; (b) result after the first algorithm phase; (c) result after the third algorithm phase; (d) final result, after the third algorithm phase.

phase and this result proves how the algorithm is perfectly able to reproduce the path followed by a tag ID (mouse) inside the cage.

V. CONCLUSIONS

In this work, the problem of the tracking of small laboratory animals, by using passive UHF RFID technology is afforded. More specifically, a complete hardware and software system has been designed, implemented and tested. The hardware component mainly consists of one UHF RFID reader and particular built-in-lab NF reader antennas capable to guarantee uniform and confined magnetic field in a desired region. The software sub-system consists mainly of three modules able to guarantee both the data acquisition and the processing and plotting. They are implemented by using the LabVIEW graphical language.

This system is designed to overcome the drawbacks of traditional approaches for animal tracking. Usually, in fact, animals localization and tracking through wireless technologies are addressed to big animals that move in outdoor environments and which may leverage on technologies such as GPS and radar communications. On the contrary, the tracking of small animals in indoor environments is often based on expensive optical vision systems which have several problems in critical conditions like presence of many animals or poor visibility.

The proposed animal tracking system has been exhaustively tested on phantoms emulating the animal dielectric properties, with encouraging results. In fact, exploiting the benefits of the proposed and implemented algorithm based on RSSI, the movement of the phantoms is perfectly reconstructed in each working condition, thus demonstrating the effectiveness of the proposed framework, now ready for a validation through a living animal approach. Moreover, in the next future, further tests will be performed in order to optimize power radiation. In conclusion, both from the cost and performance point of view, the developed system can represent a valuable alternative to commonly adopted animal tracking systems.

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