Anchorless Indoor Localization and Tracking in Real-Time at 2.45 GHz

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***Abstract*—This paper introduces a custom portable RFID (Radio-Frequency IDentification) reader, performing bi-dimensional beam-steering in real-time by means of the radar monopulse principle. The system is able to simultaneously track the angular position of multiple tagged entities (objects or people), static or dynamic, with respect to the azimuth and elevation planes. Furthermore, a simple signal processing algorithm, running on board of the reader, is used to derive an estimate of the tags-to-reader distances, thus allowing a 3D-position assessment of the tracked entities. This portable device can be exploited in Ambient Assisted Living (AAL) applications to perform a tri-dimensional scanning of a room and detect potential falls of the monitored people. The scanning data, collected during the device tracking operations, can further provide various feedbacks regarding the tagged people behaviour; for this purpose, a procedure to remotely control the whole system is introduced making use of a Raspberry Pi 3B directly connected to the reader output and wirelessly communicating with the environment monitoring platform. In this way, a seamless link of the portable reader to a software architecture, able to control several devices and processes at the same time, is obtained.**

***Keywords*—indoor localization, RFID, Ambient Assisted Living (AAL).**

I. Introduction

Recently, there has been an increasing number of new RF systems developed to provide solutions for monitoring everyday life spaces, in order to guarantee not only smart ambient but also smart facilities. This need is particularly significant for Ambient Assisted Living (AAL) applications where solutions for monitoring human activities should be at the same time agile, non-invasive and highly reliable. Various perspectives have been recently proposed, most of them making use of the doppler radar technique [1]–[3], and tentative solutions to derive human activities have been demonstrated. Recently, a novel passive UWB tag has been implemented for real-time localization and tracking [4], which is particularly interesting due to the exploitation of a very large range of frequencies which mitigate the possible fading and shadowing effects. One drawback of many solutions is the need for the employment of reference nodes, for their delicate synchronization and set-up process.

In this work, an alternative system, that gets rid of reference nodes, is designed and realized: it is anchor-free and based on a custom RFID reader system using a beam-steered two-dimensional antenna array. The array is composed of four ground-aperture fed patch antennas driven in such a way to perform a fully bi-dimensional electronic beam steering. In this way, in a given room, the reader not only identifies the tags present in the ambient but also finds their angular position both in the azimuth and in the elevation planes. By further estimating the distance of the active tags from the reader, through a suitably weighted evaluation of the tags Received Signal Strength Indicator (RSSI) values, a short-range 3D localization is made available. In Fig. 1, an illustrative example of the targeted scenario is represented. This portable device can be exploited as an agile system for monitoring not only a human static or moving condition, but also his/her elevation, being a possible solution for remote fall detection. Some preliminary demonstrations of the system operation in a reference private room are presented.

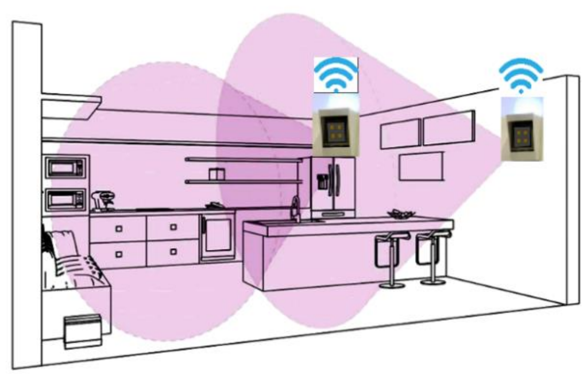

Fig. 1. Envisioned indoor scenario for people localization and tracking. In this case, two readers are present in the same room and can be embedded in everyday life objects and furniture (i.e., a wall lamp).

II. Antenna Array and RF Front-End Design

In order to achieve a successful localization of tagged people and objects in indoor environments in the most transparent and non-invasive way, a RFID reader able to exploit the monopulse radar technique [5], [6], and to achieve a bi-dimensional electronic beam steering [7] has been designed, realized and validated.

The antenna array consists of four squared patch antennas (Fig. 2a) fed by microstrip lines overlapping the resonant slots

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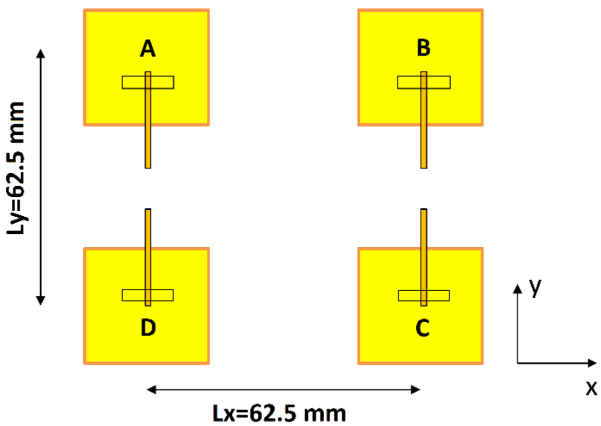
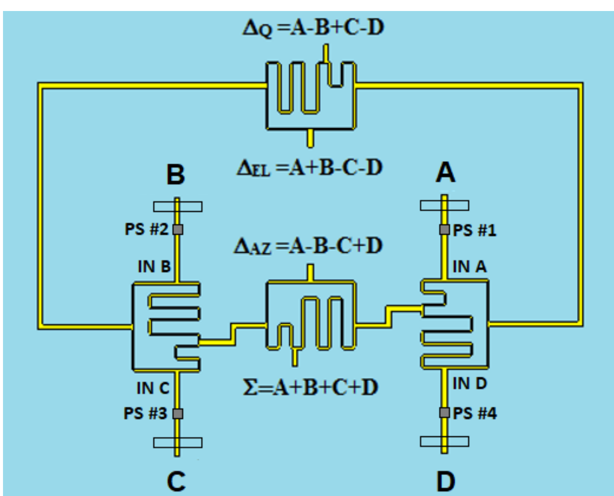
placed in the ground plane [8]. In this case, the selected working frequency is 2.45 GHz, belonging to the Industrial, Scientific and Medical (ISM) Band going from 2.4 GHz up to 2.4835 GHz.

Some of the most important design specifications in order to obtain the desired resonant frequency are certainly the slot dimensions, the stub length, the position of the slot with reference to the patch and primarily the dimensions of the squared patches: after the optimization accomplished thanks to the electromagnetic (EM) simulations, the optimal length for the patch has ultimately turned out to be 21.6 mm.



(a)



(b)

Fig. 2. (a) Antenna array front view; (b) the slots in the ground plane and the RF and digital circuitry in the bottom layer (microstrip antenna feeding lines, phase shifters (PS) and monopulse comparator system, or Rat Race System) are here represented all together.

The whole multi-layer stack-up of the reader is shown in Fig. 3: two layers of the substrate Taconic RF-60A (Inner Layer #1 and #2: thickness: 0.635 mm, with ε_r=6.15) are attached together through a FR-4 film (Prepreg: thickness: 0.120 mm, ε_r=4.5). The external copper foils L1 and L4 represent, respectively, the upper face of the board hosting the four squared patch antennas (Fig. 2a), and the lower face containing the microstrip feeding lines, the RF and the digital circuits and components (Fig. 2b).

Copper	(L1)	Thickness: 0.035 mm
Taconic RF-60A	(Inner Layer #1)	Thickness: 0.635 mm
Copper	(L2)	Thickness: 0.035 mm
FR-4	(Prepreg)	Thickness: 0.120 mm
Copper	(L3)	Thickness: 0.035 mm
Taconic RF-60A	(Inner Layer #2)	Thickness: 0.635 mm
Copper	(L4)	Thickness: 0.035 mm

Fig. 3. Stack-up of the entire board of the RFID reader.

The microstrip lines width (W_f=0.9 mm) has been chosen in order to realize a 50-Ω input impedance that matches perfectly with the output impedance of the feeding line of the selected transceivers.

Each internal copper layer L2 and L3 presents four slots that are required for the antennas feeding and the dimensions of these apertures have also been optimized by means of EM simulations in order to have the best matching at 2.45 GHz.

The other key element for the overall architecture of the RF system is the combination of four bended rat race hybrid couplers (represented in Fig. 2b) which provide the in-phase and the out-of-phase received signals both in the azimuth and in the elevation planes and an auxiliary signal [9], respectively at the Σ, Δ_{AZ}, Δ_{EL} and Δ_{Q} ports, namely sum, difference in azimuth and elevation planes, and the auxiliary signal ports.

At the same time, the monopulse comparator is connected to the four microstrip lines feeding the antennas (A, B, C, D).

III. Hardware Architecture and Principles of Operation of the Radar

The selected microcontroller unit (MCU or μC) is CC2530 from Texas Instruments (TI), a System on a Chip (SoC) that enables radio communication at the 2.4 GHz Band and therefore acts as a transceiver: each of the four abovementioned ports is connected to its own CC2530.

The communication between the four MCUs is based on the Master-Slaves logic: there is one CC2530 Master, that controls and receives information from the other three CC2530 Slaves through the Slave Select (SS) signals.

The two-planar detection of the tags is enabled by the electronic beam-steering over two orthogonal planes of the Σ and Δ radiation patterns of the antenna array. The proper phase shifts of antennas excitations are controlled by four digital phase shifters (Macom MAPS-010164) that are inserted along the microstrip antenna feeding lines.

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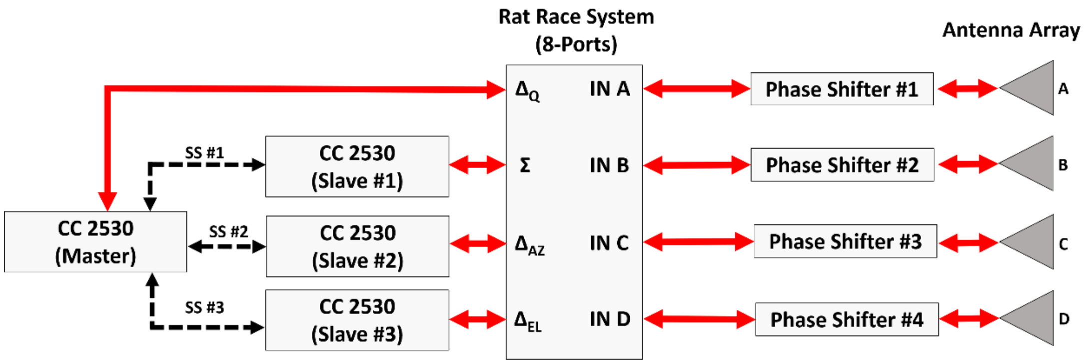


Fig. 4. Block diagram of the hardware architecture and principles of operation (digital I/O and control signals are represented with black dotted lines, while the solid red ones represent the RF signals).

The basic hardware architecture, from which the principles of operation of the whole system can be deducted, is schematically illustrated in Fig. 4.

Through the phase shifters placed in the array feeding network layer, it is possible to electronically vary the absolute phase (ϕ_i) at each port, so that proper phase shifts (ϕ_x and ϕ_y) between each couple of antennas are obtained. In this way, the electronic steering of the array radiation patterns is performed in real-time: depending on the relative phase shifts, the scanning of both the xz and yz planes is possible.

In order to localize the angular positions of the tags, both in the azimuth and elevation planes, the RSSI values at the sum (Σ_{AZ} and Σ_{EL}) and differences (Δ_{AZ} and Δ_{EL}) ports are adopted.

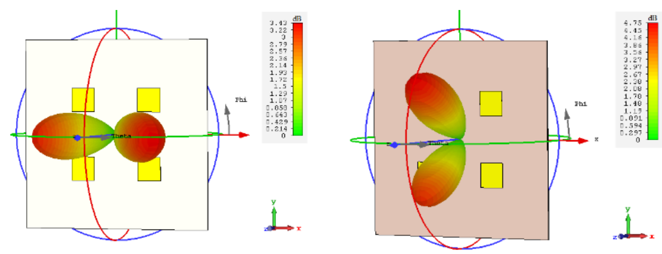
Figs. 5 show the EM simulated radiation surfaces resulting from the out-of-phase feeding of the antenna array, for the azimuth (Fig. 5a) and the elevation (Fig. 5b) planes respectively, in the field of view of the reader. The differences (in dB) between the RSSI power values at sum and difference ports, called MPR (Maximum Power Ratio), are computed as follows:

$$MPR_{AZ} = \Sigma_{AZ} - \Delta_{AZ} \quad (1)$$

$$MPR_{EL} = \Sigma_{EL} - \Delta_{EL} \quad (2)$$

where MPR_{AZ} and MPR_{EL} are assumed as figures of merit for the angular localization of tags in the azimuth and in the elevation planes, respectively: the MPR peaks give the angular positions of the tracked tags. This allows to monitor not only people movements but also their elevation, through the height detection of the worn tags.

A further data processing has been designed in order to estimate the tags distance from the reader, in addition to the already demonstrated estimation of their angular position. This ensued assessment is based on the evaluation of the power of the signals received from the reader (RSSI). For this purpose, a preliminary calibration of the reader inside the specific room must be carried out: it consists in an initial reference detection of the maximum Σ-RSSI received from tags placed in different positions, spanning the [-45°, 45°] reader aperture: in this way the room can be sectorized into three or more calibration zones.



(a) (b)

Fig. 5. Δ-radiation surfaces for (a) the azimuth and (b) the elevation planes.

After the calibration and the real-time measurement of the referenced RSSI signals [10], [11], the tag distance from the reader can be estimated as:

$$d = 10^{\frac{P_{0i,j} - P_{Rm}}{10 \cdot n_{i,j}}} \quad (3)$$

where $P_{0i,j}$ is the maximum RSSI measured (at Σ-Port) after calibration at 1 meter, P_{Rm} is the instantaneous maximum RSSI measured (at Σ-Port), $n_{i,j}$ is the path-loss exponent that has to be regulated depending on the environment radio channel under consideration (typically values are: from 2.7 to 4.3 for urban areas, 2 for free space, and 1.6 for harsh indoor scenarios) with $i=1,\ldots,N_{AZ}$ and $j=1,\ldots,N_{EL}$, where N_{AZ} and N_{EL} are the numbers of different calibration zones in which the room is sectorized, for azimuth and elevation planes, respectively.

Examples of 3D localization measurements for different human positions are reported in Fig. 6: they reveal that the average error for the (x,y) coordinates is 12.82 cm for reader-tag distances up to 3.50 m, whereas the average error in detecting the tag height is 14.85 cm moving the tag to higher and lower elevations with respect to the RFID reader, that for the present case was positioned at a height of 125 cm. Finally, the averaged tri-dimensional percentage error results to be 12.80%, and has been calculated as follows:

$$\text{3D\_Err}\ (\%) = 100 \cdot \frac{\sqrt{(x_0-x_m)^2+(y_0-y_m)^2+(z_0-z_m)^2}}{\sqrt{x_0^2+y_0^2+z_0^2}} \quad (4)$$

where (x_0, y_0, z_0) are the real positions, and (x_m, y_m, z_m) are the measured ones.

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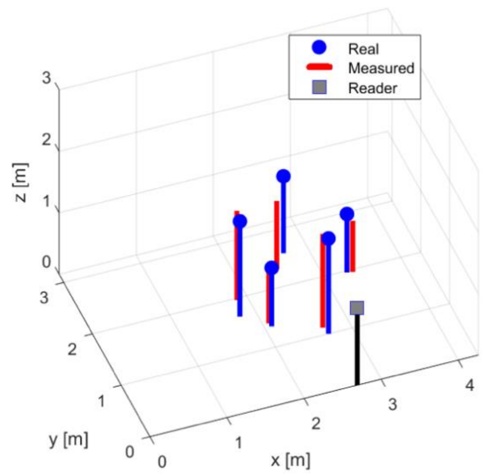

Fig. 6. 3D plot for five averaged real and estimated points evaluated during the measurements in an indoor scenario.

The reader transmitting antennas polarization is vertical (coherent with the microstrip feeding lines represented in Figs. 2), thus it is required that the receiving tags show the same polarization in order to make the localization as much effective as possible.

As future development, work is being done on the integration of the tag antennas in flexible textile materials, with the aim of having fully wearable receivers, as well as the study of a circular polarization able to tolerate unwanted displacements of the tags worn by the users.

This should lead to a clear improvement of the localization accuracy, along with a deep enhancement of both angular position and distance retrieval formulas, also using specific filters and software techniques.

IV. Reader Remote Control and Data Analysis

To enable a fully portable implementation of the proposed localization system, the necessary signal processing algorithms of the RFID reader have been included into an application running on an on-board controller. In this way, the RFID reader plays the role of an IoT device generating raw data that can be further fused with other information in the framework of an IoT platform. For the present demonstration, a Raspberry Pi 3B is wired to the reader hardware through an UART (Universal Asynchronous Receiver-Transmitter) serial communication, and wirelessly connected to a customized server that can control several devices and processes at once. The scheme of the application is divided into four classic steps: in the first step, the hardware circuit performs the measurement resulting in a stream of bytes coming from the MCU; in the second step, the bytes are transformed in a set of human-intelligible objects (i.e., numbers, strings, graphs). Then, in the third step, the data aggregation is started, i.e. the real application logic deployment. This phase is responsible for the storage of data, the detection of relevant sequences within the present and the previous information, and the identification of the better way to perform actuation. Actuation, finally, allows the IoT application to react to changes in the environment.

V. Conclusion

In this work, a novel anchor-free, portable and remotely controllable RFID reader operating at the frequency of 2.45 GHz with real-time tracking capabilities, has been presented and exploited to identify the dynamic position, with respect to both the horizontal and the longitudinal planes, of people and objects that are present in a given indoor environment. Moreover, a simple algorithm has been developed to retrieve the tag distance from the reader and its height, based on the calibration data of the scenario under test and on the information derived by the RSSI coming from the tracked tag. In this way, a well-approximated 3D localization of tagged people in an indoor environment is feasible. The effectiveness of the reader operations has been demonstrated by detecting tags position in indoor scenarios that are typically electromagnetically harsh.

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