MICROWAVE RADAR SYSTEMS FOR INDOOR LOCALIZATION AND BIOMEDICAL APPLICATIONS

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Abstract

In this work, a custom 2.45 GHz RFID (Radio-Frequency Identification) reader, designed to simultaneously perform 3-D tracking of multiple tagged entities (objects or people), static or dynamic, in harsh electromagnetic indoor environments, is described. This is obtained by a bi-dimensional electronic beam-steering, implementing the monopulse radar technique, with tags-reader distance estimation based on the Received Signal Strength Indicator (RSSI) values. Experimental results show that the system is able to perform a tridimensional scanning of a monitored room with decimeter-accuracy over the three reference axes. The presented architecture is experimentally demonstrated also to perform a reliable fall detection of tagged people in indoor environments.
Moreover, a wearable device for vital signals detection, in particular human breath sensing, exploiting Self-Injection Locking (SIL) radar at 5.8 GHz, is described. In addition to the respiratory rate, a tentative estimation of the lung capacity is also feasible, with the distinction between normal and deep breath.
Index Terms – Microwave, RFID Reader, Indoor Localization, Fall Detection, Self-Injection Locked Oscillator, Breath Detection.

I. INTRODUCTION

In recent times, the interest on wireless sensor network (WSN) field has grown significantly, and the trend is now addressed to the inclusion of innovative wireless technologies in spaces of everyday life, in order to let them become Smart Spaces including all the relative Internet of Things (IoT) technologies, as shown in Fig. 1.

In particular, Radio-Frequency Identification (RFID) is extremely important with his capability to remotely identify and distinguish objects and people also in crowded and electromagnetically harsh environments, such as department stores, retirement homes or private houses.

As well, the average age of population is meaningfully widening and, as a consequence, also the number of elderly people is increasing and it's proving to be more and more urgent to monitor their movements and consuetudes in order to detect as soon as possible any kind of age-related disease or problematic. For these reasons, this paper shows how these technologies can be proficiently used for helping elderly or impaired people in their everyday life by following them, analyzing their habits in a non-invasive way and monitor their vital parameters during the whole day.

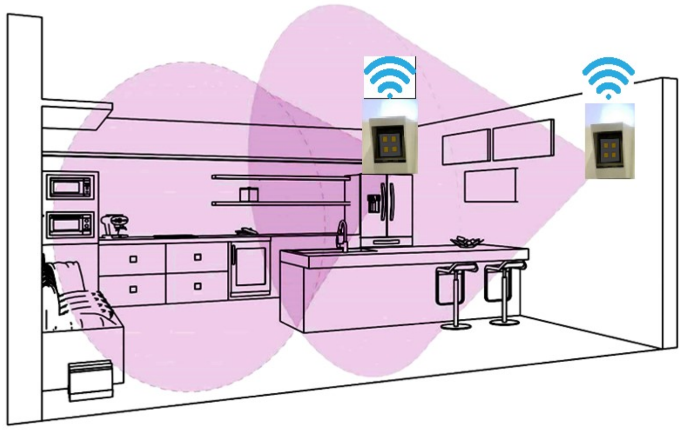


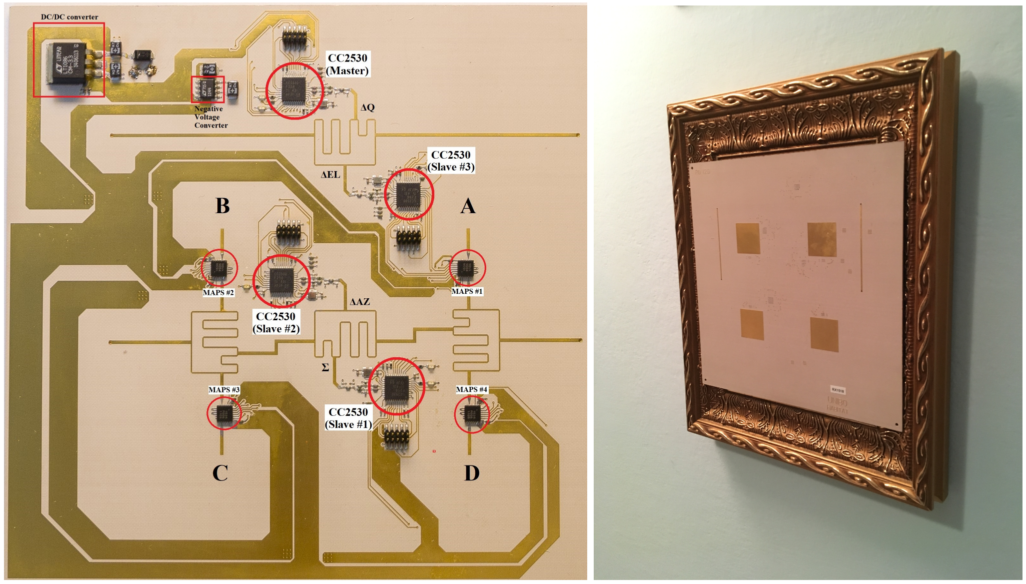
FIG. 1 – Envisioned indoor scenario for people localization and tracking. In this case, two RFID readers are present in the same room and embedded in everyday life objects and furniture (here, wall lamps).

II. RFID READER FOR INDOOR POSITIONING SYSTEM IN HARSH ELECTROMAGNETIC ENVIRONMENTS

The presented 2.45 GHz RFID reader (Fig. 2) exploits the monopulse radar and the bidimensional electronic beam steering techniques with the aim of performing a tridimensional localization of tagged people in electromagnetically harsh indoor environments in the most transparent and non-invasive way [1].

The antenna array is composed of four squared aperture-coupled patch antennas fed by four microstrip lines extended alongside the corresponding resonant slots placed in two ground planes.

The most crucial specifications to consider in order to obtain the desired resonance frequency are mainly the slot dimensions, the stub length, the position of the slot with reference to the patch and the dimensions (length L = width W) of the square patch.



(a) (b)

FIG. 2 – RFID Reader prototype: (a) circuit back view, (b) antenna array layout and a possible solution to include the smart object in everyday life environments (a frame, in this case).

The other key element for the overall architecture of the RF system is the combination of four bended rat race hybrid couplers which should primarily provide the in-phase and the out-of-phase received signals both in the azimuth and in the elevation plane and an auxiliary signal, respectively at the Σ, Δ_{az}, Δ_{el} and Δ_q channels (represented in Fig. 2a), namely Sum, Difference in Azimuth and Elevation plane, and the auxiliary signal channels.

At the same time, the monopulse comparator is connected to the four microstrip lines feeding the antennas (A, B, C, D in Fig. 2a).

The selected microcontroller unit (MCU) is CC2530 from Texas Instruments (TI), a System on a Chip (SoC) enabling radio communication in the 2.4 GHz Band and therefore acting 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, typical of the monopulse radar technique. 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 (shown in Fig. 2a).

III. 3-D Indoor Localization and Fall Detection

In order to localize the tags in their angular positions, both in azimuth and elevation plane, measurements concerning the RSSI values at Sum and Differences ports have been performed.

The main patterns that have been analyzed in order to reach the two appropriate angular detections are Σ_{az} and Δ_{az} for the azimuth scanning and Σ_{el} and Δ_{el} the elevation scanning.

The difference between the RSSI power values in dBm at the Sum and Difference ports is called MPR (Maximum Power Ratio), and is given by:

$$\begin{aligned} MPR_{az} &= \Sigma_{az} - \Delta_{az} \\ MPR_{el} &= \Sigma_{el} - \Delta_{el} \end{aligned} \tag{1}$$

where MPR_{az} and MPR_{el} have been adopted as figures of merit for the angular localization of the tags in the azimuth and in the elevation plane, respectively: the peaks in the MPR patterns determine the angular positions of the active tag under test in both planes.

With the intention of evaluating people movements and the relative altitudes of their worn tags, a suitable data processing has been designed and exploited in order to estimate the distance of the tags from the reader, in addition to the abovementioned estimation of the angular positions. 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 room under test has to 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.

After the calibration and the real-time measurement of the received RSSI signals, the distance of the tag from the reader is given as:

$$d = 10^{\frac{(P_{0\,i,j} - P_{Rm})}{10 \cdot n_{i,j}}} \tag{2}$$

where d is the reader-tag measured distance, $P_{0i,j}$ are the maximum RSSI measured (Σ-Port) after calibration at 1 meter, P_{Rm} is the instantaneous maximum RSSI measured (Σ-Port), $n_{i,j}$ are the path-loss exponents with $i=1,\ldots,N_{azimuth}$ and $j=1,\ldots,N_{elevation}$, where $N_{azimuth}$ and $N_{elevation}$ are the numbers of different calibration zones in which the room is sectorized, for azimuth and elevation plane respectively.

With the aim of validating the whole RFID system for a real indoor positioning and monitoring application, work is being done on the integration of the tag antennas in flexible textile materials, in order to dispose of fully wearable receivers.

FIG. 3 – Wearable RFID tag with antenna on denim; circuitry and components are realized on a rigid RF substrate (Rogers RO4360G2).

For this reason, the measurement campaign has been brought in a typical office scenario, using wearable tags with antennas at 2.45 GHz realized in denim flexible substrate (Fig. 3) and worn by the monitored users. For the present case, N_{el}=N_{az}=3 so that nine different sectors are used (9-zones calibration). The tri-dimensional results and percentage errors of this set of measurements are reported in Table I.

TABLE I
RESULTS OF THE 3D INDOOR LOCALIZATION MEASUREMENTS

Point	***Real Position*** **(x_0;y_o)**	***Measured Position*** **(x_m;y_m)**	***Tag Height*** ***Real*** **(z_0)**	***Tag Height*** ***Meas.*** **(z_m)**	***3D Error*** **(%)**
#1	(5.45;2.00)	(5.47;1.86)	1.25	1.25	6.00
#2	(5.45;3.00)	(5.30;3.00)	1.25	1.25	4.62
#3	(6.05;2.10)	(6.07;1.95)	1.25	1.17	6.80
#4	(4.25;3.30)	(4.46;2.86)	1.25	1.38	13.54
#5	(4.55;1.80)	(4.70;1.53)	1.25	1.20	13.21
#6	(6.95;4.20)	(6.37;3.99)	1.25	1.02	14.21
#7	(5.45;1.00)	(5.40;0.92)	0.75	0.73	7.71
#8	(6.05;3.00)	(6.34;2.82)	0.75	0.77	10.85
#9	(6.95;3.30)	(6.45;3.63)	0.75	0.97	17.24
#10	(4.55;2.70)	(4.92;2.40)	0.75	0.67	16.41

As a further experiment, a real tracking of a tagged person in the same office has been carried out: excellent agreement with actual track is achieved in real-time, in case of reader-tag Line of Sight (LoS).

The renovated aim of this RFID reader is to detect potential falls that could occur to people living alone in indoor environments.

Exploiting the elevation scanning capability of the RFID reader and its monopulse radar capabilities, it is possible to notice whenever a tag is fallen or rather positioned on the floor thanks to the MPR_{el} pattern showing its maximum in correspondence of the lower zones. Moreover, the fact that the tag is not precisely in the line-of-sight of the reader implies that the power received from the tag is way lower than expected if it was perfectly standing for a normal localization: this is the discrimination circumstance allowing to send an alert for remote falls detection.

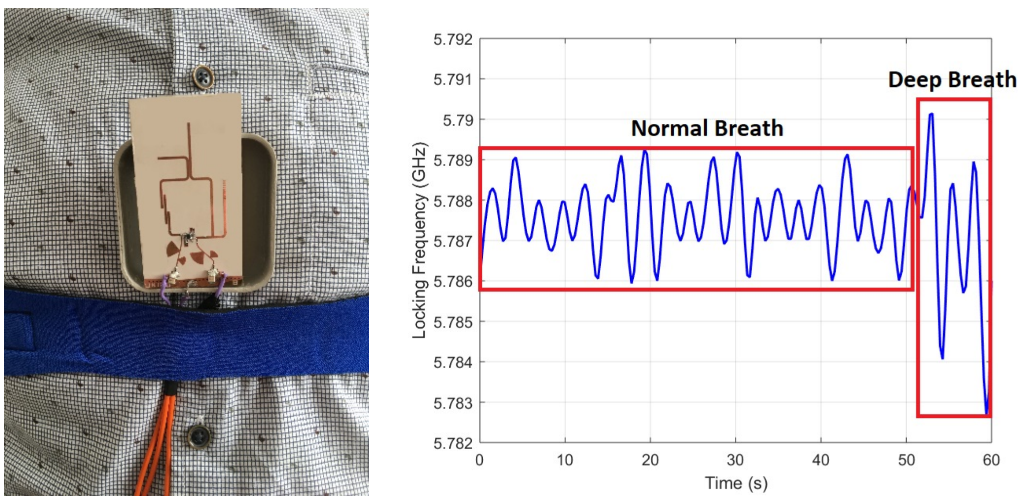
This can be particularly useful for elderly people living alone in their own houses or inside their rooms in retirement homes: in such a way, an alert can be sent to the relatives, the supporting medical team or the caregivers with a delay of maximum 15 seconds.

IV. Self-Oscillating Antenna at 5.8 GHz for Breath Monitoring

The new aim of this research concerns the breath monitoring through a wearable oscillator using the injection-locking theory. Since the radiant element and the oscillator circuit strongly interact between them, the design of the self-oscillating antenna is particularly challenging; therefore, nonlinear circuit techniques and EM analysis methods were used to realize the present configuration.

The designed SILO (Self-Injection Locked Oscillator) configuration [2] presents two ports: through the output port, the signal is sent to the subject, while, through the other one, the oscillator gets into a SIL state by receiving the signal reflected by the body and collected by the receiving instrumentation. Therefore, the oscillator must be able to manage two cross-polarized signals: the output signal horizontally polarized and the input signal vertically polarized, in the present case. The orthogonal polarizations at the two ports are achieved through non-resonating orthogonal slots etched on the ground plane. To simultaneously achieve both dual-polarized behavior and a high decoupling between input and output ports, a hole-shaped topology of the patch metallization was adopted, thus reaching good matching and good isolation. A continuous-voltage generator is connected to bias a PHEMT (Pseudomorphic High Electron Mobility Transistor) and hence to feed the oscillator: setting the drain and gate voltage at V_{DS}=3.7 V and V_{GS}=0.6 V, a stable operating point is guaranteed with an available output power of 13 dBm.

The measurements were performed asking the subjects firstly to hold their breath for few seconds in order to register the free running oscillator frequency; subsequently, they performed a normal breathing for 50 seconds, followed by 10 seconds of deep breath. Fig. 4 shows the pattern representing the typical trend of the locking frequency of the oscillator registered during the test for a subject at 1 meter. Through these measurements, the feasibility of the system has been verified: specifically, it has been noticed that the range of the locking frequency varies for each subject and depending on the distance from the receiving antenna: in particular, during inspiration/expiration, it is possible to notice an increase/decrease of the oscillator locking frequency, respectively; the biggest differences in terms of widening of the locking frequency range result in conjunction with a deep breath exercised by the subjects under test; substantial differences have also been detected for the female subject, with respect to the other three (men) [3].



(a) (b)

Fig. 4 – (a) Photograph of the SILO prototype worn by the subject under test and (b) evolution of the SILO locking frequency during a test over a period of one minute.

V. Conclusion

In this work, a portable microwave RFID reader realizing real-time movement analysis has been presented to identify the positions of people moving in an indoor environment. The effectiveness of the reader operations has been demonstrated by detecting the tags position even in harsh electromagnetic areas, with the possibility to early diagnose specific age-related diseases strictly connected to the repetition of particular movements.

Moreover, as part of the designed microwave radar eHealth platform, a wearable device exploiting the Self-Injection Locking technique able to perform a normal and deep breath monitoring has been presented and measurements have been carried out for four different subjects at three different distances from the receiving antenna. In this case, the emerged results encouraged the feasibility of wearable SIL radar for vital signals monitoring and incentive the development of this technology.

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