Multi-channel Processing of RFID Backscattering for Monitoring of Overnight Living

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Abstract

Movement detection of human body is a fertile research field in human-computer interaction, as well as in medical and entertainment applications. Moving limbs within an electromagnetic field radiated by an interrogating antenna will generate a modulation of the backscattered field detected by a receiver. The measured signals may therefore carry raw information about the human motion and behavior. Moreover, the proper placement of UHF passive Radiofrequency Identification (RFID) tags over body segments will increase the amount of collected signals.
This paper investigates the possibility to detect the quality and phenomenology of the sleep by processing the multi-channel power data coming from a set of wearable passive radio-sensors placed onto the sleeper's clothes as well as over the bed and onto the nearby carpets. The resulting ambient-intelligence system is characterized by numerical electromagnetic models as well as by extensive experimentations.

1.Introduction

Sleep is a remarkable portion of our day and is potentially exposed to disorders that could sensibly affect the quality of life, leading to daytime sleepiness, spread weariness and even moodiness. The remote observation and analysis of the sleep is considered particularly useful for weak subjects such as elderly, children and neurologic patients, for which the night could be a source of many dangerous events (falls, disorientation, nighttime wandering) that call for early detection and prompt actions. These requirements are even more pressing in case of alone-living subjects or inside hospitals and nursing houses, where many patients need to be contemporarily monitored all along the night. Typical remote monitoring platforms comprise audio/video recording systems and active sensors directly connected to first-aid remote centers. However, cost, complexity and intrusiveness have limited up to now their widespread diffusion and social acceptance by the end users. Promising solutions could come from the recent progresses of Radio Frequency Identification (RFID) passive technology. Together with its ID code widely used for logistics, an RFID tag is in fact able to carry information about the tagged object such as its physical state and its evolution along with time, without any specific embedded sensor, through low-level processing of received and backscattered electromagnetic signals [1]. This family of "transparent" and non-intrusive devices could offer great advantages in pervasive healthcare: one or more battery-less RFID sensor tags could be permanently integrated into everyday objects and clothes at the purpose to monitor the subject from different perspectives. The sampling of behavioral parameters, such as activity detection and classification, and the monitoring of human interaction with the objects and the surrounding environment are suitable applications of RFID system, very recently demonstrated in [2,3].
This paper describes a passive RFID platform, denoted as NightCare, for monitoring people during the night. Battery-less tags are integrated into clothes and dispersed in the environment. A long-range UHF RFID reader illuminates the scene and the collected tags' responses, arising from the interaction between the subject and surrounding environment, are processed in real-time. The aim is detecting the presence or the absence of the user in the bed, his jerky movements and his motion patterns, accidental falls, prolonged absence from the bed and prolonged periods of inactivity as well as the instantaneous sleeping posture (left-side, right-side, up, down). The proposed system is preliminary investigated by a three-dimensional MOM model to plan the displacement of reader and tags (shown at the Conference) and the compliance with the electromagnetic exposure limits. The accuracy and the potentiality of the signal-processing algorithm are then demonstrated throughout extensive laboratory and real-life experimentation.

2. The Sensing Electromagnetic System

The patient, lying on the bed, wears four wearable RFID tags (WT) properly sewn into his night-suit at the level of abdomen, back, left and right hip. A conventional dipole tag (Ambient tags -AT) is placed underneath the mattress, such to be completely shadowed by the body all along the night regardless the position assumed by the user. One or two other AT are positioned at each side of the bed, eventually hidden by carpets such to mitigate their visual impact. The

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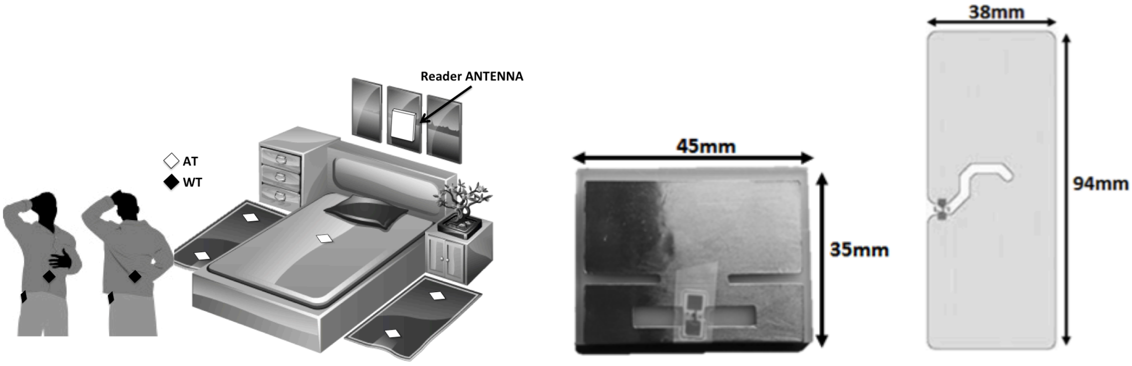
radio scanner device is placed in correspondence of the headboard, properly tilted and lifted in order to uniformly cover the entire bed and the floor surrounding it (Fig.1).



a) b) c)

Fig. 1 a) RFID system aimed to take care of the night sleep involving b) passive wearable tags (WT) and c) ambient tags (AT) placed in the surrounding environment. A long-range UHF-RFID reader, properly placed in proximity of the bed, scans the environment and interrogates the tags.

The response of the tags to the reader's query is subjected to an *ambient modulation,* in the sense that the strength of the backscattered field is modified by the proximity of the human body with the tags themselves. Moreover, in case of specific body-environment configurations, a tag may be fully shadowed by the sleeper so that it will not be able to reply the reader's interrogation. The activity of the sleeper during the night may be therefore recognized by processing the signals received from the tags. More in details, the IDs of the responding tags can be used to recognize the status of the sleeper (whether he is in the bed, he is fallen down or instead he is outside), while the processing of the strength (RSSI levels) of the electromagnetic fields that are reflected by the responding tags can be used to extract information about motion and about specific postures during the sleep.

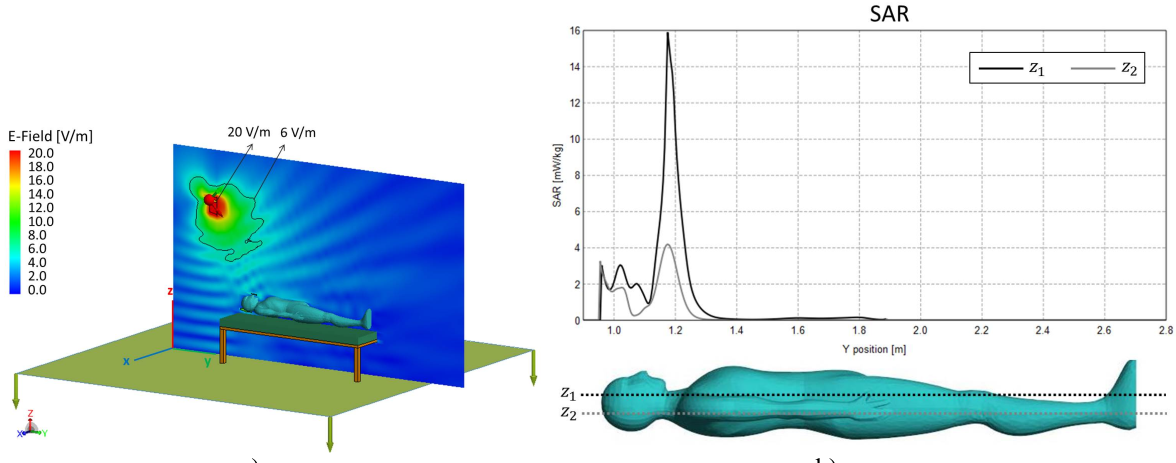
Being the tags totally battery-less, the RFID link is intrinsically weaker than that of active systems: to be activated, the tags need to receive the right amount of power from the reader and hence the antennas of the wearable and ambient tags play a key role in the overall performance of the platform. A minimum read range of three meters is estimated as mandatory for all the passive tags, in order to achieve a compliant illumination of a single bed and of the near surroundings, while preserving a safe distance between the reader antenna and the patient. The maximum read range r_{MAX} can be well approximated by the Friis equation:

$$r_{MAX} = \frac{4\pi}{\lambda}\sqrt{\frac{P_{EIRP}\eta\widehat{G_T}}{P_{chip}}}$$

where P_{EIRP} is the power emitted by the reader (fixed to the maximum value of 3.2W by the European Regulation) η is the polarization mismatch between the antennas of reader and the tag, P_{chip} is the minimum power required to activate the IC and finally $\widehat{G_T}$ is gain of the tag antenna reduced by the mismatch with the IC.

Wearable RFID tags (WT) are (35mm×45mm×2mm) folded patches (Fig.1b) with shut connection to the microchip, already proposed by the authors in [3]. Ambient tags (AT) are commercial AD-843 inlay (Fig.1c) with external size of 94mm x 38mm [4] suitable to be placed on the bed and ground. The measured free space maximum read range of both AT and WT is greater than 5m in the European 868MHz frequency. The CAEN ION reader is equipped with a broadband linear-polarized Stacked Planar Inverted-F Antenna with 5.8dB maximum gain and 3dB-beamwidth equal to 85° and 108° for the H-plane and the E-plane respectively.

The whole set-up has been preliminary modeled by Moment Method (FEKO [5]) at the purpose to estimate the electromagnetic field in the whole environment and the power absorbed by the sleeper's body (simulated by an anthropomorphic homogeneous phantom with ε_r = 41.5, σ = 0.94S/m, $\rho = 1000Kg/m^3$). Fig. **2**a shows the field produced by a reader antenna placed at *h*=180cm from the floor, *l*=40 cm from the bed, with a tilt of 45° and emitting 3.2W EIRP with a duty-cycle of 0.2, corresponding to a single interrogation per second. The resulting radiated electric field in close proximity of the sleeper is lower than 4V/m and hence fully compliant even with the more restrictive EM exposure limits [6]. Fig.2 b finally shows the estimated SAR profiles inside the body. The averaged values over the full body (SAR_b =0.6mW/Kg) and over 10g (SAR_{10} =4mW/Kg) are greatly below the exposure limits ($SAR_{b,max}$=0.08W/Kg and the SAR averaged over 10g of tissue less than $SAR_{10,max}$ =2W/Kg.) .



a) b)

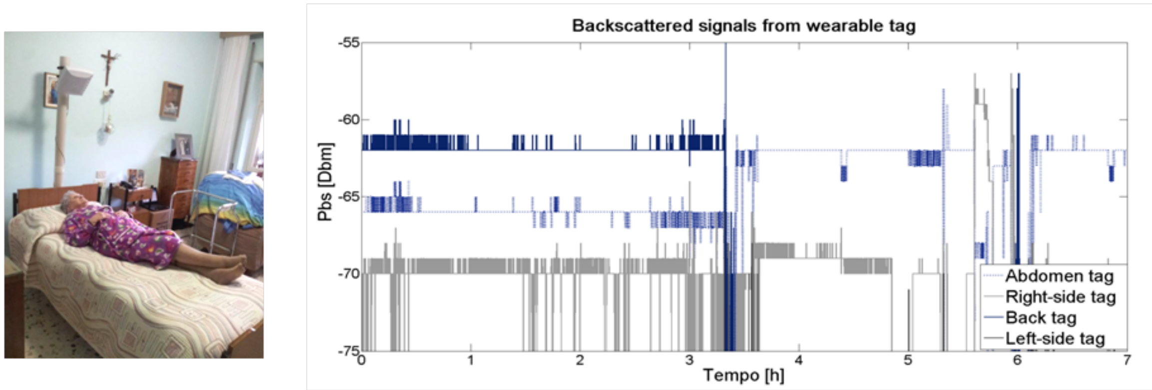
Fig. 2 a) Numerical estimation by FEKO of the field distribution in a conventional sleeping room with a reader antenna placed 1.5m far from the body, emitting 3.2W EIRP with a duty cycle d=0.20 (an interrogation per second). b) Calculated values of SAR along the sagittal plane of the body

3. Multi-channel Signal Processing of RFID data

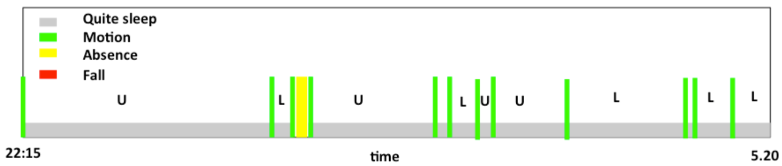
The monitoring algorithm is logically split into two parts, one for the detection of the user state, e.g. his presence/absence from the bed, and a second one for the estimation of his activity, e.g. movements, quite sleep and corresponding postures. The former relies on the analysis of the signals coming from the ambient tags $\underline{\boldsymbol{S}_A} = [s_{A1}(t), s_{A2}(t), s_{A3}(t)]$, while the latter depends on the signals from the wearable tags $\underline{\boldsymbol{S}_W} = [s_{W1}(t), s_{W2}(t), s_{W3}(t), s_{W4}(t)]$.
RFID backscattered signal is characterized by low values (~ -50dB) and high fluctuations, mainly due to the receiver internal noise, the limited stability of its components and above all on the non-stationary communication channel. Therefore, the raw data $\underline{\boldsymbol{S}_A}(t)$ and $\underline{\boldsymbol{S}_W}(t)$ need to be preprocessed before feeding the event-detection algorithm by low-pass filtering. Then, the resulting signals $\underline{\boldsymbol{S}_A}'$ undergo a 1-bit A/D conversion ($d_A(t)$), whose threshold values $\underline{s_{Th}} = [\, s_{Th1}\, , s_{Th2}, s_{Th3}\,]$ are set according to different users' categories. Finally, a *XNOR* gate is applied to the digital signals $d_A(t)$ such to retrieve the user's state. The reference *XNOR* input is a $[3{\times}4]$ matrix T_A containing the only four meaningful combinations among the 2^3 available ones, e.g. *Presence, Absence, Left-fall, Right-fall*. The *Long-Absence* state is finally appointed when the Absence condition lasts for a period longer than the physiological one set for the user.
The detection of the activity relies instead on the analysis of the filtered analog signals $\underline{\boldsymbol{S}_W}'(t)$ collected from wearable tags. The discrimination between *motion* and *quite sleep* is firstly performed by analyzing the signals' standard deviation; then if the subject is in the rest condition, his posture is retrieved by applying a simple maximum-value rule: the tag that has the maximum RSSI value is the closest to the reader antenna and, since the subject wears a tag on each side of the body, the position can be univocally retrieved.

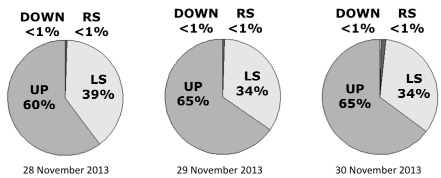
4. Experiments

A realistic experimental session has been performed during three nights by monitoring an elder subject (age 95) inside a nursing home. The subject was not fully aware of all the functionalities of the system, ensuring a natural and not-biased behavior during the three experiments. Fig.3a shows the real-life arrangement of the experiment and an example of raw RSSI response. Fig.3b gives the processed diagram referring to one of the three nights. The detected profile has been validated by the annotations about the activity kindly provided by the lady the morning after. The patient went to bed around 22.15 and slept approximately until 5.00 in the morning, with a short absence around 1.00 am, probably for going to bathroom. The sleep was peaceful, with only 12 small movements detected over the entire night and a quite constant posture: the patient rarely changes her position during the night, due to the slowness and difficulty in movement that is typical of the advanced age. Finally, the sleep appears well reproducible throughout the course of the three nights, as clearly demonstrated by the aggregated data about the body posture and the movements on Fig.3c. Each night, the lady went to bed between the 22.15 and the 22.30 and slept until 5.15-5.30 in the morning. She went to the bathroom around 1.00am and took approximately 5-10 minutes to come back to the bed.



a)





b) c)

Fig. 3. a) Left: Nightcare setup mounted in a nursing home; Right: Example of the raw signals from the wearable tags detected by the reader. b) Trace of the NIGHTCare platform as recorded November 29th 2013. For each quite sleep condition, the different body postures have been classified (U: up, L: Left-hand side). c) Aggregated statistics on the body posture and the movements

5. Conclusions

The results presented in the paper demonstrated that by combining together wearable tags and ambient tags it is possible to develop a fully passive RFID system potentially useful to the remote monitoring of the state of children, disabled and elderly people during the night. The platform is completely compliant with the EM exposure limits and hence it is suitable to be installed in both domestic and hospital environments.
By considering the advantages of RFID passive sensors, it is possible to envisage a further improvement of the platform by providing the same infrastructure also with wearable temperature sensor tags at the purpose to detect and follow fever events, as well as humidity sensor tags under the mattress to monitor incontinence and finally miniaturized tags placed over medicines and food to enrich the patients' behavioral analysis.

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