RFID Technology for IoT-Based Personal Healthcare in Smart Spaces

Sara Amendola, Rossella Lodato, Sabina Manzari, Cecilia Occhiuzzi, and Gaetano Marrocco

Abstract—**The current evolution of the traditional medical model toward the *participatory medicine* can be boosted by the Internet of Things (IoT) paradigm involving sensors (environmental, wearable, and implanted) spread inside domestic environments with the purpose to monitor the user's health and activate remote assistance. RF identification (RFID) technology is now mature to provide part of the IoT physical layer for the personal healthcare in smart environments through low-cost, energy-autonomous, and disposable sensors. It is here presented a survey on the state-of-the-art of RFID for application to bodycentric systems and for gathering information (temperature, humidity, and other gases) about the user's living environment. Many available options are described up to the application level with some examples of RFID systems able to collect and process multichannel data about the human behavior in compliance with the power exposure and sanitary regulations. Open challenges and possible new research trends are finally discussed.**

Index Terms—**Internet of Things (IoT), RF identification (RFID), sensors, wearable sensors.**

I. Introduction

THE RISE in life expectancy and the consequent progressive aging of the population, with a prevalence of chronic diseases, trigger a careful thinking on the role and modes of providing care to people in order to ensure a decent quality of life, without imposing traumatic changes of habits and domestic environment. The remote monitoring and support thus become strategic tools to implement social policies over the long term. In this sense, the ability to pervasively, discreetly, and generally uncooperatively quantify the health conditions and the human interactions with the environment is the first step to provide all the information required to adapt already established healthcare protocols to new needs. The emerging paradigm of Internet of Things (IoT) and a wide variety of increasingly cheap sensors (wearable, implanted, and environmental) have the potential to put in place personal Smart-Health systems hosting new interconnections between the natural habitat of the person, his body, and the Internet at the purpose to produce and manage "participatory" medical knowledge [1]. By displacing wireless sensors inside the home, on clothes and personal items, it becomes possible to monitor, in a way that preserves the privacy, the macroscopic behavior of the person as well as to compile statistics, to identify precursors of dangerous behavioral anomalies, and finally to activate alarms or prompt for remote actions by appropriate assistance procedures. Among the various technologies that potentially converge to this scenario, RF identification (RFID) systems may represent a strategic enabling component thanks to the energy autonomy of battery-less tags. Furthermore, their low cost is compatible with a widespread distribution and disposable applications.

A passive RFID system is composed of a digital device called tag, embedding an antenna and an IC-chip with unique identification code (ID), and a radio scanner device, called reader. Despite the RFID technology is currently mostly applied to logistics of goods, the very recent research is exploring other paths with the common goal of extracting physical information about tagged objects and nearby environment through low-level processing of electromagnetic signals received and backscattered by the tags. RFID systems could, therefore, permit to implement, in a simple and efficient way, the *last few meters of the IoT* concerning the pervasive quantification of the person's interaction with the environment.

This paper is aimed at drawing a landscape of the current research on RFID sensing from the perspective of IoT for personal healthcare. The survey will cover passive (i.e., battery-less) devices in the UHF band (860–960 MHz) which are capable to provide services and enough read ranges to implement a network of sensors for tracking the human wellness and monitoring the quality of the local environment. The discussion will cover both the physical issues and the signal processing, up to the application level.

With reference to Fig. 1, a RFID-powered environment supporting new pervasive healthcare services could be a Smart-House equipped with a distributed network of readers, enforcing a uniform and robust coverage [2] in the most relevant spaces, and an heterogeneous set of battery-less tags with sensing capability. Readers may interact, for instance, through WiFi or Bluetooth links, with a concentrator node enabling the interconnection with external services that take care of data processing and of assistance procedures' activation.

Ambient sensors (Section II), able to detect physical parameters of the environment, such as the temperature, humidity, and the presence of toxic agents, could permit to quantify the wellness of the environment itself and to analyze its correlation with the person's health state. Wearable and implantable tags (Section III) could instead permit to provide indirect information about the presence of a person inside a room, his motion, the interaction among people and in more futuristic body-centric

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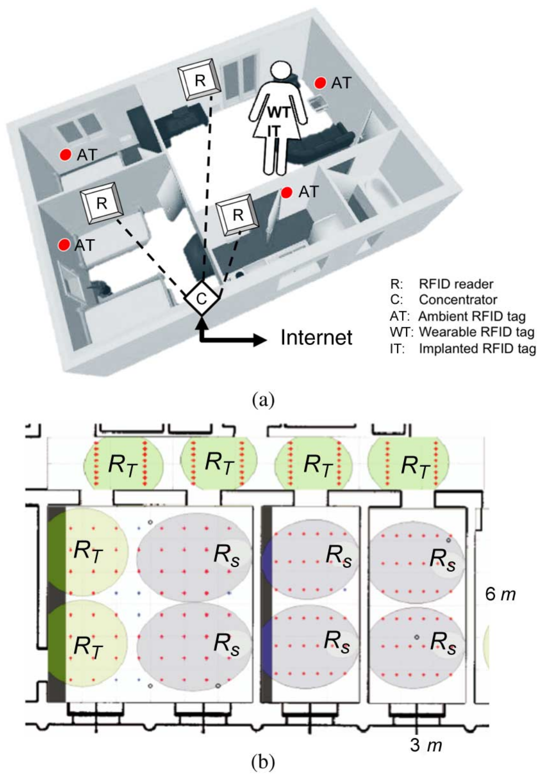


Fig. 1. (a) Sketch of an RFID-powered habitat with ambient tags (AT) attached over the walls and objects, wearable tags (WT), and implanted tags (IT) placed over and inside the human body, one or more RFID readers (R) scanning the rooms and a wireless concentrator (C) capable to pack the collected data for in-house processing and/or for internet streaming. (b) Example of RFID coverage [2] of a home-portion by a multiplicity of readers' antennas placed at the walls' side (R_S) and over the top ceiling (R_T).

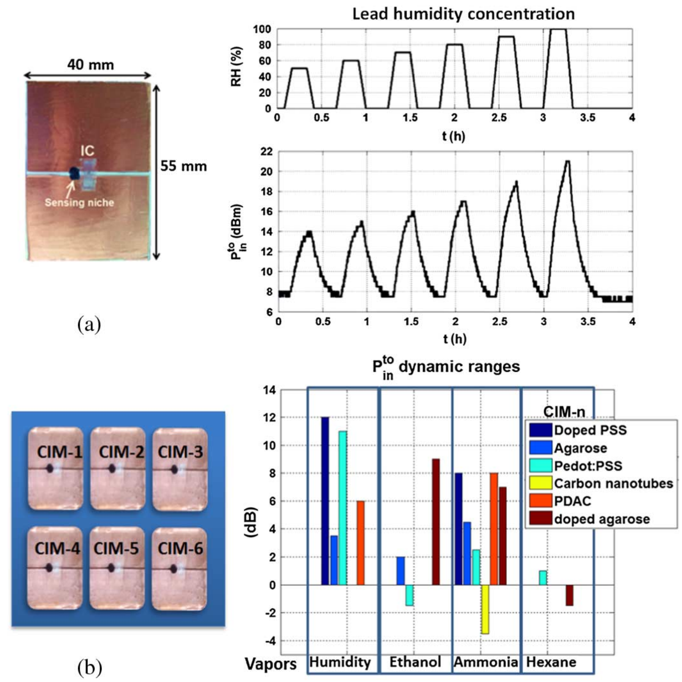


Fig. 2. RFID passive chemical sensors. (a) Moisture sensor integrating Pedot: PSS exposed to humidity cyclic variations [5]. (b) Array of six RFID chemical sensors exposed to different vapors [10].

applications, to produce data about the health state of prosthesis or artificial organs.

Data gathered from the RFID environment, e.g., generated by ambient tags or by the interaction of the user with the house, could be finally processed by means of data-mining algorithms to analyze the movements and trajectories of the user, classify its gestures in daily and sleep conditions, recognize critical events and emit alarms (Section IV). Finally, the whole technologic infrastructure has to be compliant (Section V) with the electromagnetic safety standard concerning the power absorption in the human body and the emitted field strength in living environments. Anyways, many critical issues are presented so that there is a wide margin for new challenges and new research trends (Section VI).

II. Environmental Passive Sensors

People's wellness and healthcare assessment in living and medical environments may benefit from a continuous and reliable monitoring of critical parameters such as the temperature, the presence/level of humidity, and some other gases. Sensing volatile compounds through a noninvasive and direct way may, moreover, support clinical diagnosis by means of breath analysis in order to recognize marker gases for discrimination between healthy and sick people. Air monitoring is also useful in common spaces with the purpose to avoid the inhalation of anesthetic gases by the personnel or the contamination of the patient under surgery. Even the temperature is a key parameter in several medical environments to assess the integrity of drugs and also to localize the arise of an epidemic source producing fever rush.

A passive RFID tag becomes capable to detect changes of the chemical/physical parameters of the environment, when it is functionalized with special chemical compounds or interconnected to the microchips integrating sensing features.

A. Volatile Compound Sensors

Volatile compounds can be sensed by properly shaped tag's antenna hosting specialized chemically interactive materials (CIMs) capable to selectively change their electromagnetic properties and, accordingly, the tag response during gas exposure. Changes in turn-on power[1] or backscattered power can be, hence, monitored and decoded by the reader, obtaining information about the presence and the concentration of specific gases.

Several CIM species have been experimented for applications to RFID sensors, mostly aimed at detecting humidity and ammonia by using carbon nano structures (CNTs), [3] conducting or insulating polymers [4]–[6] and even a simple blotting paper [7].

Remarkable performance has been in particular obtained by loading a folded patch tag with "PEDOT:PSS" [*poly (3, 4-ethylenedioxythiophene):poly (styrenesulfonic acid)*] that is a chemical compound capable to absorb water molecules and accordingly increases its permittivity and conductivity. A single drop of this CIM turned out to be enough to achieve a 0.5 dB/RH[2] sensitivity to the humidity Fig. 2(a). Thanks to the presence of a

[1]The minimum power emitted by the reader to remotely activate the tag.

[2]$\mathrm{RH} = \mathrm{Relative\ Humidity}$. A change of 1% in the RH produces a 0.5 dB change in the backscattered power received by the reader.

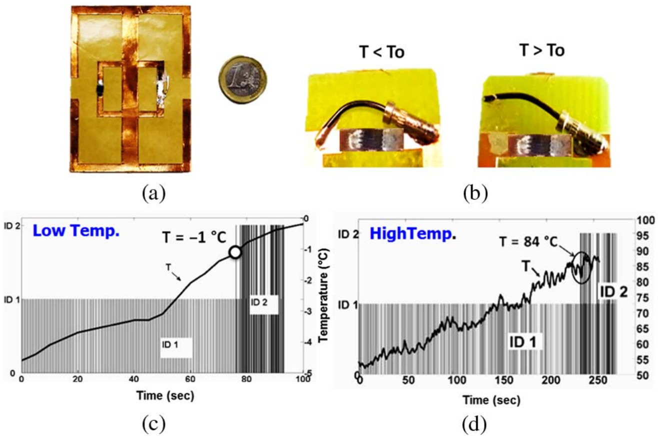


Fig. 3. (a) Two-chip (with ID1 and ID2) temperature threshold sensor integrating a Nitinol switch [13]. (b) Switch closed (chip is inactive, only ID1 is transmitted) and open (chip is active depending on the temperature, ID2 is transmitted in addition to ID1). (c) Chips' responses versus temperature for 0 °C-threshold Nitinol. (d) Chips' responses versus temperature for 80 °C-threshold Nitinol.

ground plane, the tag is suited to application over walls as well as over foods or drugs [4].

Several kinds of CIMs can be also combined into a *wireless nose*, e.g., a matrix of doped tags capable to respond in a selective way to the presence of different vapors [8]–[10]. Fig. 2(b) shows a 3×2 sensing array including layers of doped PSS, Pedot:PSS, single-walled Carbon-Nanotubes, agarose, doped agarose, and dimethyldiallylammonium chloride polymer (PDAC) exposed to saturated vapors of water, ethanol, ammonia, and hexane. The response bars show a clear selectivity of the set of CIMs which suggests the feasibility of compounds classification.

B. Temperature Tags

Three classes of passive UHF RFID temperature sensors have been experimented in the last few years, and in some cases even commercialized, ranging from threshold sensors, continuous sensors up to better performing digital data-logger.

1) Threshold Temperature Sensors: An RFID "thermal switch" or *fuse* is based on a threshold physical phenomenon, such that the material changes its state when the external temperature overcomes a given threshold, and the event is permanently written into a physical memory. For instance, the thermal-controlled event could be the melting of ice region (low-temperature threshold) loading the tag's antenna [11], the melting of a paraffin substrate (high-temperature threshold) of a planar antenna [12] or the geometric changes of shape memory alloys such as the Nitinol [13] (both low and high temperature). In these cases, the temperature change induces an abrupt variation of the antenna response so that the microchip is activated or not depending on the temperature violation of a pre-defined level. For instance, Fig. 3 shows a two-chip threshold sensor integrating a temperature-controlled Nitinol switch [13]. The normal condition corresponds to the transmission of the only ID1 (label of the product) while an occurred overheating is revealed through and additional ID2 code (thermal event). These devices could have application to the assessment of food and drugs integrity as well as to the detection of fire and over-heating of domestic devices.

2) Continuous Temperature Sensors: An instantaneous RFID sensor of temperature involves instead a CIM capable to continuously react to the change of temperature. An example in [14] considers (distilled) water region incased close to the tag whose conductivity and permittivity change with the temperature and accordingly modify the tag's resonant frequency detectable by the reader.

3) Digital Data Loggers: The real revolution in the autonomous RFID temperature sensing will be probably boosted by a new family of RFID microchips equipped with an integrated temperature sensor and with a local Analog to Digital Converter. Accordingly, the temperature information is read from the tag straight away in a digital form. These chips [15], [16] can be used in both passive and battery-assisted mode, and in the latter case the tag may trigger a temperature measurement and store the data inside the microchip's user memory. The price to pay for this very special capability is a higher cost of the chip (1–3 $ versus a few cents for conventional RFID chips) and a rather poor power sensitivity when used in fully passive mode (10 dB less than conventional chips), and therefore the read distance is currently limited to a couple of meters.

III. Body-Centric RFID Tags

Autonomous RFID tags suited to be put in contact with the body or in its close proximity are the key enabling devices to develop body-centric healthcare systems which are fully transparent to the user. Wearable, and even more, implantable passive UHF tags have been a technical taboo for a long time because of the huge power attenuation caused by the human tissues. The body-centric networks investigated so far are mostly based on active devices [17]. In the last five years, instead, the availability of commercial off the shelves (COTS) low-power RFID microchips has completely changed the games and many prototypes of passive body-centric tags have been successfully developed and experimented with read distances compatible with a true remote monitoring.

A. Wearable RFID Tags

The human body is characterized by high electromagnetic losses and, therefore, the energy scavenging efficiency of a wearable antenna is really poor [18] as well as, in case of passive systems, the expected read distances. The antenna-body electromagnetic interaction can be, however, minimized by using multilayer tags, for instance, involving dipoles with dielectric insulators [19], or more effectively folded patches [20]–[22], which are also suited to be embedded into plasters Fig. 4(a). Embroidery techniques have also been successfully experimented to fully integrate RFID tags inside clothes [23], [24].

According to the current microchip sensitivity, the maximum read distance achievable nowadays with an RFID transmitter compliant with the regional constraints over power emission, may reach 5–6 m, and it is going to continuously improve over the years thanks to the progress in the microchip transponder technology (3 dB reduction in the chip sensitivity each 1–2 years). Current link performances are, however, already enough to track inside a regular room a person provided with

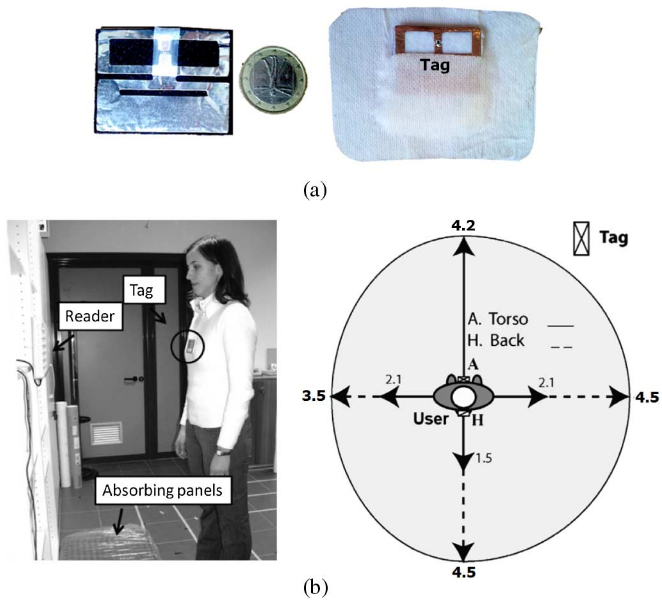


Fig. 4. (a) Example of wearable flexible tag suitable to be integrated with clothes and plasters [22]. (b) Horizontal read regions in [m] [21] by using two tags over front and rear torso.

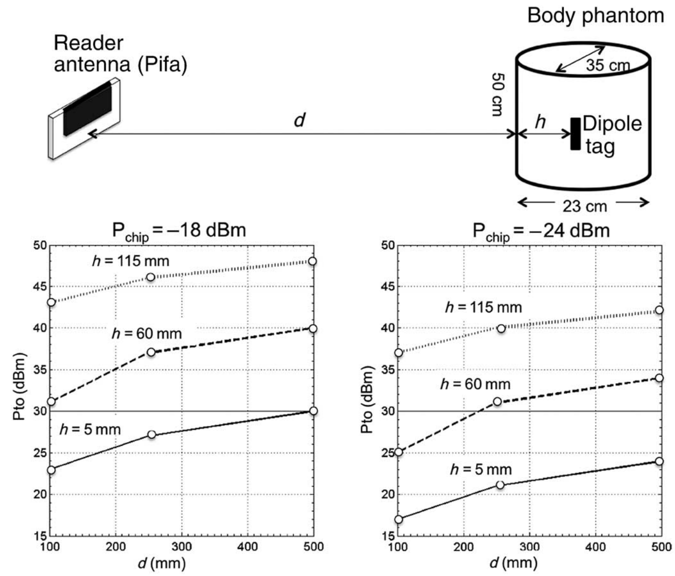


Fig. 5. Estimated turn-on power of a dipole tag ($\text{length} = 3.3$ cm) implanted into a muscle-equivalent cylindrical phantom ($\epsilon' = 43$, $\sigma = 0.7$ S/m at 870 MHz) as function of depth h of implant. The tag is assumed to be connected to microchips of sensitivity $p_{\text{chip}} = \{-18\ \text{dBm}, -24\ \text{dBm}\}$ and is interrogated by a 5-dB PIFA antenna placed in front of the dipole.

two tags placed over the front and rear torso, or over the arms Fig. 4(b).

B. Implantable RFID Tags

RFID technology has been demonstrated to be potentially useful to take care of the human health-state *from the inside* by labeling body prosthesis, sutures, stents or orthopedic fixing. Each item could be monitored in real time or on demand by the IoT infrastructure for the ambitious goal of monitoring biophysical process in evolution, such as tissue regrowth and prosthesis displacement. In this case, tags will be embedded into prosthesis, turning them into multi-functional devices capable to generate data beside providing the original medical functionality. The major challenge in the design of implantable tags is to establish a convenient communication link by using a reader power that is compliant with local emission regulation. Fig. 5 shows the minimum power (estimated by numerical simulations[3]) that is requested to the UHF RFID reader to activate (turn-on) a small dipole tag implanted, in different positions, into an homogeneous (muscle-like) phantom resembling the human body, interrogated by a 5-dB gain PIFA antenna. Diagrams consider both a well assessed RFID IC (power sensitivity, -18 dBmW) and a better performing chip family (power sensitivity -24 dBmW) that, reasonably, should be available within a couple of years. In the graphs, the 30-dBm straight line indicates the maximum available power for typical commercial readers. The diagrams show that establishing an RFID link with subcutaneous implants ($h < 5$ mm) up to 0.1–0.5 m from the reader (up to 1 m in the near future) is nowadays a feasible target with promising applications to the monitoring of some particular body areas and vascular prosthesis. A link range of about half a meter could be enough to have a reader-equipped door to automatically scan the

[3]Electromagnetic simulations by FEKO.

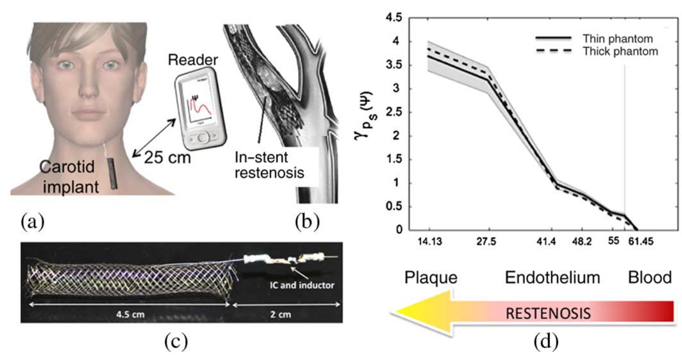


Fig. 6. (a) Application of UHF RFID technology to monitor. (b) The in-stent restenosis inside a carotid stent. (c) A first prototype of a STENTag. (d) Measured backscattered power (averaged over frequency) with respect to the variation of the restenosis grade (right to left).

health-state of a user's prosthesis without his direct involvement. Deeper implants such as inside the stomach ($h > 70$ mm) will remain instead still challenging for passive RFID systems within current power regulations, even over a long term.

An example of near sub-cutaneous prosthesis suitable to RFID integration is a vascular stent inserted into a vessel aimed at recovering normal blood flow after angioplastic Fig. 6(a). In [25], the RFID tag functionalities have been strongly integrated within the stent geometry itself to work as a self-sensor by exploiting the dependence of the tag's input impedance and back-radiation on the dielectric properties of the tissues in the close surrounding of the so obtained *STENTag* Fig. 6(c). In this way it is feasible to detect possible *in-stent-restenosis* process (ISR), e.g., a diffuse proliferation of neointima early after the implant, or a new atherosclerotic plaque in the long period, both capable to produce new occlusion of the vessel Fig. 6(b). Measurements Fig. 6(d) over a neck phantom say that the grade

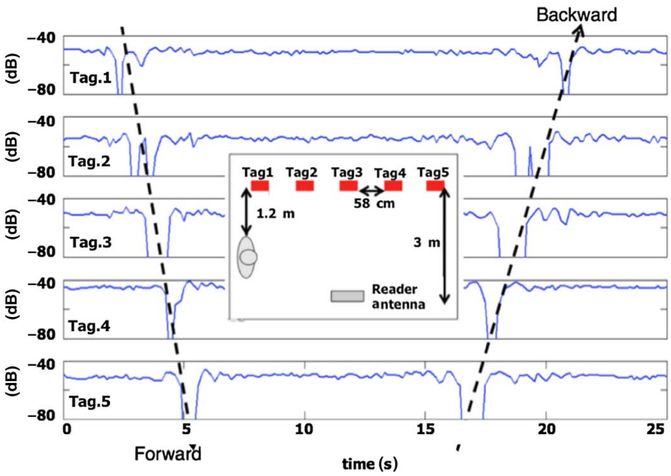


Fig. 7. Backscattered power variation from a linear cluster of tags attached on the wall during the walk of a subject into a corridor. The sequence of the nulls carries information about the direction of motion (delays among nulls) and velocity (slope of the enveloping line through the nulls)

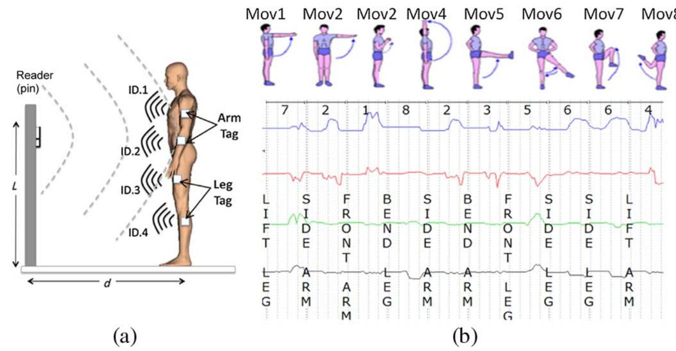


Fig. 8. (a) Set-up as in [31] for the classification of arms and leg gestures by passive RFID ($d = 1.2$ m; $L = 0.9$ m). (b) Examples of RFID backscattered patterns to be classified by the SVM algorithm performing data mining.

of the restenosis could be detected up to a distance of 25 cm even for thick necks.

IV. Data Processing and Human Behavior Analysis

The interactions between people and their habitat bring precious information on behavioral parameters concerning the activity rate during the different phases of the day and of the night. The environment itself may have the role of continuous "sampling" the state of an user by means of specific and nonspecific devices [26] at the purpose to support diagnostics and even to activate remote alarms in case of precursors of anomalous events. By processing physical data, mostly backscattered signals, from previously reviewed sensor-oriented RFID devices, the specific patterns of daily actions may be recognized, e.g., cooking, eating, bathing, taking medicine and sleeping, without altering the everyday life-style of the person. Three examples of in-house human behavior detection and classification are given below, involving only ambient tags, only wearable tags and a combination of both the kinds.

A. Tracking Human Motion Inside Rooms

Assuming a dispersion of un-expensive passive UHF RFID tags inside the environment, e.g., on the walls or on the furnitures, the communication link established with fixed readers may be disturbed by the scattering and the shadowing effects caused by the human body when it moves in close proximity of the tags [27]. Those measurable changes of signals received by the readers may therefore carry information about human activity. Fig. 7 shows for example the measured power backscattered by five passive tags aligned on the wall of a corridor, that are interrogated by a fixed reader placed on the opposite side, when a man walks forward and backward at two different speeds. By processing the variation of the backscattered power (more precisely the occurrence of deep nulls) by means of algorithms borrowed from Ground Penetrating Radar imaging [28], it is possible to infer the presence of the person in the corridor, through the envelope of the nulls, and the direction and velocity of his trajectory. The system can be further improved by collecting also data coming from the wearable tags hosted by the subject, such to identify the person and to monitor more subjects at the same time. Possible applications could be the early detection of worsening cardiovascular pathologies that produce a progressive slowing of the walk capabilities.

B. Gesture Recognition

RFID wearable tags can be used to set up a motion detection and classification system having a high degree of portability and that is suitable to be integrated inside a domestic environment, and inside the IoT infrastructure in general. For instance, the feasibility of wireless monitoring of compulsory limb movements in some common sleep disorders by means of passive tags equipped with inertial switches have been conceived and theoretically investigated in [20] and [29]. More in general, fluctuations of backscattered power from sensor-less passive tags placed over the body could provide a coarse information about the subject's state [21], permitting to distinguish if he's standing or moving and eventually to estimate the frequency of periodic movements. This experimental evidence has been engineered in [30] for the kinematics' recognition of body segments/joints during walking, while gesture classification has demonstrated to be feasible in [31] through the application of state-of-the-art classification techniques borrowed from Machine Learning and Brain Computer Interface background. Fig. 8 shows the experimental setup for RFID classification by using four tags on the arms and legs, and a typical backscattered pattern to be processed by support vector machine (SVM) algorithm [32] for data mining with possible applications to self-assisted rehabilitation of impaired people in their domestic environment.

C. Remote Monitoring and Control of Overnight Living Environment

By combining together wearable tags and ambient tags it is possible to develop a fully passive RFID system to monitoring the *state* of children, disabled and elderly people in domestic and hospital environment during the night: an Ambient Intelligence platform, capable to estimate the sleep parameters, to classify the human activity and to identify abnormal events that require immediate assistance.

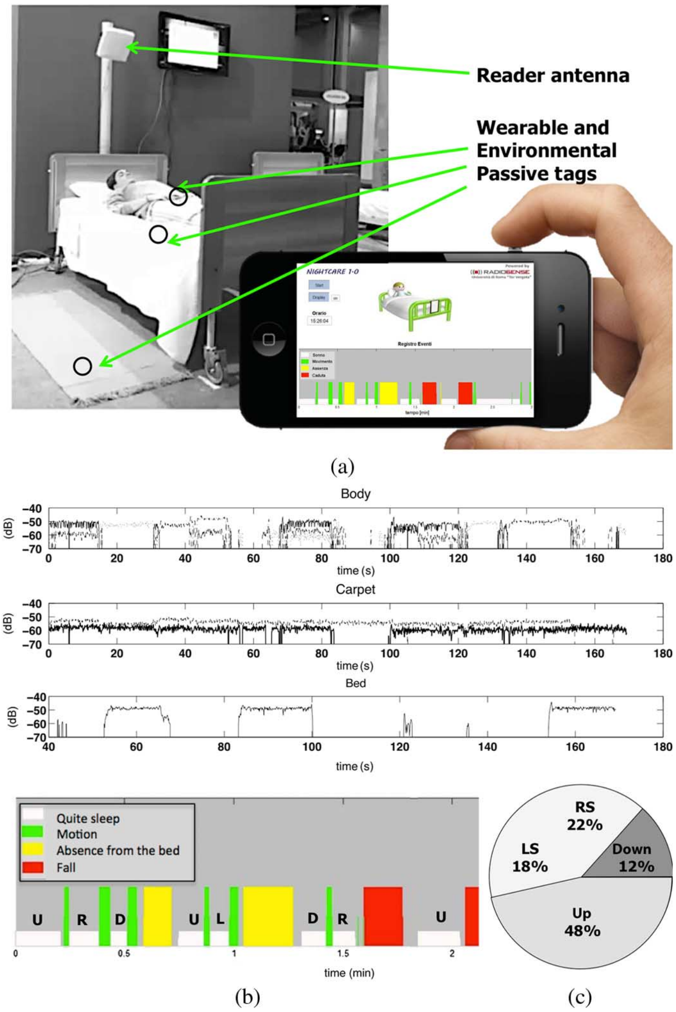


Fig. 9. (a) Ambient intelligence system aimed to take care of the night sleep involving RFID tags placed over the body and in the surrounding environment. (b) Example of a trace recording the sleep activity (raw and processed signals) and producing warning in case of falls and anomalous absence. For each quiet sleep condition, the different body postures have been classified as $\mathrm{U} = \mathrm{up}$, $\mathrm{R} = \text{right-side}$, $\mathrm{L} = \text{left-side}$, and $\mathrm{D} = \mathrm{down}$. (c) Example of aggregated statistics.

A first prototype (NightCare system[4]) has been very recently developed by the authors Fig. 9(a). Flexible miniaturized wearable tags, like in Fig. 4, are properly integrated in clothes, while conventional dipole tags are placed into the bed and underneath the nearby carpets. A UHF RFID reader illuminates the bed. A real-time software engine, based on a finite-state model of the human motion over the bed, processes multi-channel power signals coming from the scene and, finally, a web-based graphical processor and warning module permits to visualize the status of the user from everywhere by any fixed or portable device. The system is capable to detect and report 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, prolonged periods of inactivity (caused for example by fainting, unconsciousness or even death) and interactions with nearby objects (glass, urinal, medicine, etc). In case temperature or humidity RFID sensors (as in Section II) were used, even fever evolution and urine loss could be taken under control. Finally, in addition to the generation of automatic alarms at the side of operators, families, or first-aid remote centers, the system is suitable to provide reports and aggregated statistics, useful for the formulation of diagnosis, for the follow-up of therapies and not least for behavioral and clinical studies.

Fig. 9(b) shows a typical trace of the night sleep (raw and processed signals) when the user alternated periods of quiet sleep, short absence, physiological movements and fall events. Each condition is classified according to its duration and intensity: a short absence from the bed could be considered physiological, while a prolonged one (second yellow area) could foresee a problem (e.g., a fainting in the bathroom) and thus an automatic alarm must be generated.

The quiet sleep conditions and the motion events can be further disaggregated into additional information about the sleep quality, such as the postures (up, down, right-side, and left-side) of the user and his motion patterns Fig. 9(c). This feature can be particularly relevant for users suffering from disorder worsened by the position in the bed, such as snoring, sleep apnea, bedsores, and restless legs syndrome.

V. Safety Compliance Issues

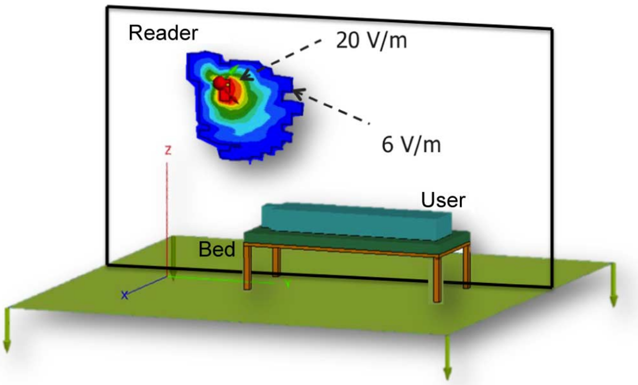
The social and sanitary acceptance of personal RFID healthcare systems, and their positioning in the emerging IoT paradigms cannot skip the concerns about the compliance of radio emission from RFID readers with the human safety.

The wearable and environmental tags have to be reached within a typical room under the constrain that the electric field emitted into the environment and the power absorbed by the human body specific absorption rate (SAR), both averaged over 6 min, are lower than countries-specific safety limits.[5] These requirements may therefore potentially induce constraints to the safety distance between the RFID reader and the human body and put in question the true feasibility of some applications. This issue has been investigated in [21], [29], and [35] with soothing results. For example, Fig. 10(a) shows the map of simulated[6] rms electric field for the NightCare system emitting 3.2 W EIRP at a duty cycle of 20% (one interrogation per second). Even the most restrictive limits of 6 V/m are fully respected in the surrounding of the bed. Fig. 10(b) shows instead a numeric simulation [36] using a realistic voxel-based human body model [37] exposed to an electromagnetic field simulating the reader's radiation (3.2 W EIRP in the very worst case of unitary duty cycle), for increasing reader-body distance. The estimated SAR is compliant even with the most restrictive European constraint for a distance roughly longer than $d_{min} = 10 - 15\ \mathrm{cm}$ from the reader which is fully compatible with the concept of remote monitoring.

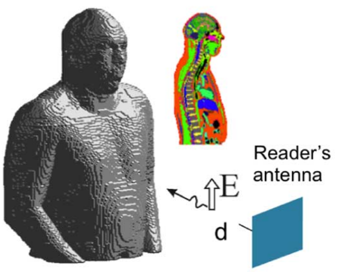
[4]More information available at: http://www.radio6ense.com/Products-Services/night-care.

[5]European Recommendations [33] impose the following rms limit to electric field emission in the UHF range: $E_0 = 1.375\sqrt{f} = 41.3\ \mathrm{V/m}$. Even more restrictive constraints may be found in some countries, as in Italy, where $E_0 = 6\ \mathrm{V/m}$. The maximum body-averaged SAR is 0.08 W/kg, while for localized exposure of head and trunk is 2 W/Kg, according to [34].

[6]Electromagnetic simulations by FEKO.



(a)



d (m)	Localized SAR in the head (mW/kg)	Localized SAR in the trunk (mW/kg)
0.1	331	197
0.2	84	49
0.5	13	8
1.0	3	2
2.0	1	1
3.0	<1	<1
4.0	<1	<1

(b)

Fig. 10. Numerical estimation of electric field and SAR. (a) Electric field distribution in a conventional sleeping room with a reader antenna placed 1.5 m far from the body (simplified parallelepiped muscle model), emitting 3.2 W EIRP with a duty cycle of 20% (an interrogation per second). (b) Peak electromagnetic field and SAR inside the human body when exposed to radiation from a reader-like antenna emitting 3.2 W EIRP with unitary duty-cycle versus mutual distance.

VI. Open Challenges and Future Research

The above survey has drawn a possible synthesis of existing RFID research and technology for application to an IoT personal healthcare environment. Nevertheless, many issues are still open and even challenging, especially concerning the reliability of the sensors and the true autonomy of the reader's node. Moreover, many other possible research paths may be currently envisaged, based on the fruitful synergy between the Material Science, the Neuroscience, and the Sociology with potentiality to develop, in the next years, new devices and new knowledge.

A. Stability, Accuracy, and Reproducibility of Environmental Sensors

Chemical sensors still require to be mastered to gain a full reproducibility of deposition, stability of performance and resistance over time. So far, only a few CIMs have been characterized within the UHF band and hence a dedicated research activity, involving a strong interactions with chemical engineers, is required to setup a more standardized procedure to characterize CIMs at radiofrequency, in order to provide a more extensive database of useful chemical receptors and their sensitivity to a meaningful set of volatile compounds.

Concerning the fabrication, ink-jet printing of both the antenna and the CIM could provide a uniform and large-scale replicable manufacturing solution, even if, at time being, the price of ink-jet processes is still prohibitive.

Moreover, it is currently unknown if the CIM-based RFID sensors would provide meaningful data set in case of placement into real environments. They are exposed to dust and dirty and to random and unpredictable change of environmental parameters such as temperature and humidity as first. Further theoretical and experimental efforts are hence required to make data retrieval and processing more robust. Current data-gathering procedures involve turn-on and/or backscattered power measurements. Some nowadays available low cost readers also provide phase retrieval which generally exhibit a larger dynamic range than power measurements. New data processing algorithms are thus possible provided that both amplitude and phase measurements are exploited at the purpose of more accurate data-inversion procedures.

Finally, beside technological issues, extensive experimental campaigns should be planned over medium scale against reference dataset to compute statistics and estimate the overall accuracy and resolution of this class of sensors.

B. Autonomous RFID Nodes and Data Processing

The readers are currently a serious bottleneck in the massive adoption of RFID in IoT Healthcare since most of available models are oriented to logistics, e.g., to provide the ID of the tag rather then to produce stable power and phase signals with high resolution. Furthermore, they exhibit high cost and usually require a PC-network infrastructure to work with. A true integration of RFID technology into a IoT domestic infrastructure would instead require a full RFID node with autonomous computation power and wireless data connectivity toward the cloud. Hand-held, fully autonomous readers are already available, but they are nevertheless still overpriced. Even tethered low-cost readers are 3–4 times more expensive than a WiFi router, that should be considered as a cost target. Possible solutions could exploit the integration of low-cost embedded systems such as Arduino and Raspberry Pi, but specific research effort should be devoted to identify processing architectures and common interfaces. Finally, in spite of the EPC as a standard protocol, the proprietary software libraries for the control of readers are heavily manufacturer-dependent so that a general purpose, and possibly open-source development framework could really simplify the design and implementation of high-level applications.

C. RFID Synergy With Epidermal Electronics

Body-centric RFID systems could greatly benefit from the synergy of the RFID communication and sensing background with the emerging epidermal electronics research [38]. Thanks to the recent advantages in biomaterial engineering, a rich variety of tattoo-like thin surface electronic devices have been experimented in the last three years, with promising application to the human body. These devices are fully bio-compatible and self-dissolvable or resorbable within a specific timeline and hence they could be used as temporary wireless wearable sensors. Anyway, since they are placed in direct contact with the human skin, they will offer a significant challenge to the electromagnetic communication because of the high power losses of the body. Antenna research, therefore, has to be advanced to achieve room-compliant read distances.

D. Electromagnetic Social Interactions

As novel pervasive autonomous wireless sensors begin to be available, new classes of high-level applications will be feasible throughout the processing of heterogeneous data and the extraction of behavioral patterns. Natural ambient electromagnetic backscattering modulation, produced by the interaction of one or more users with an embedded network of RFID readers and tags (as in Section IV-A), will enable augmented perception of the local environment. The positive contaminations among researches in contiguous engineering fields, such as the Passive Radars [39] (involving sources of opportunity) and the machine learning, and completely different disciplines such as the neuroscience and sociology, are expected to produce new knowledge tools aimed at better understanding groups' dynamics and quantify human relationships. There will be margin to facilitate the social integrations of users inside classrooms, elders in rest house and improve the interchange of information and skills in working teams (see [40] for first experimentations involving more complex active devices) and to support visually impaired people.

VII. Conclusion

The reviewed RFID technology for IoT Healthcare and the personal experience of the authors tell a story of mixed opportunities and fragmentation. Worldwide university laboratories are now researching and making prototypes of RFID sensors, both passive and semi-active that can be interrogated from a distance compatible with the interaction with a network infrastructure. On the other side, only few products are commercially available for large-scale applications. A very focused effort is, therefore, needed to manage the conversion from experiments to the real use and mass production within a so potentially fast growing market. The overcoming of the slowing factors demands a coordinated activity of the IoT community to stimulate interest in potential final users and, in parallel, to boost the evolution of readers, software, and devices toward a more interconnected perspective.

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