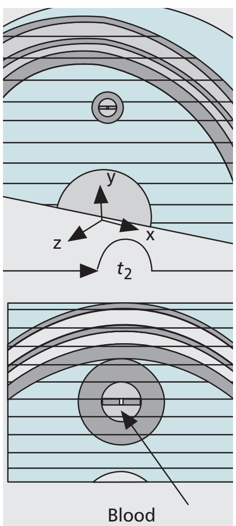
PERVASIVE ELECTROMAGNETICS: SENSING PARADIGMS BY PASSIVE RFID TECHNOLOGY

GAETANO MARROCCO, UNIVERSITY OF ROME TOR VERGATA



The author reviews the sensing of Things from an electromagnetic perspective with the purpose of showing how advanced performance may be achieved by means of low-cost batteryless devices.

ABSTRACT

Things equipped with electronic labels having both identification and sensing capability could naturally be turned into digital entities in the framework of the Internet of Things. Radio frequency identification (RFID) technology offers the natural background to achieve such functionalities, provided that the basic physics governing the sensing and electromagnetic interaction phenomena are fully exploited. The sensing of Things is here reviewed from an electromagnetic perspective with the purpose of showing how advanced performance may be achieved by means of low-cost batteryless devices. A possible classification of basic sensing modalities is introduced, and many ideas, at different stages of maturity, are then discussed with the help of examples ranging from the sensing of non-living Things up to the more challenging sensing of Humans.

INTRODUCTION

The Internet of Things can be considered as a convergence among a number of heterogeneous disciplines (wireless communication, identification, real-time localization, sensor networks, pervasive computing) that enable the Internet to get into the real world of physical objects interacting with web services. Measuring, labeling, and timing of made things and people, and their mapping into the environment is sure to stimulate new context-aware services. Pleasant user experiences will be planned in the workplace and public areas as well as in the home environment by embedding computational intelligence into the nearby environment and simplifying human interactions with everyday services.

Pervasive interconnection with Things will require the deployment of a multitude of electronic tags [1] to attach over objects, and conceiving new functions concerning habitat control, disaster relief, mobile healthcare, the monitoring of industrial processes, security surveillance, and the realization of augmented spaces in general (Fig. 1).

Radio frequency identification (RFID) is one of the key enabling technologies since it not only permits a digital code to be associated with an object in a wireless modality, but also allows its physical status to be captured. RFID tags may actually be equipped with a large variety of sensors according to very different modalities of integration, exploiting a broad range of possible functionalities and costs. Active RFID tags, which make use of independent batteries, a true microcontroller, and dedicated electronics, ensure long operating ranges and can support high data rates and the greatest versatility in sensor interconnection. The main drawbacks of this solution are high cost, limited lifetime, and large weight and size. Conversely, passive RFID tags are completely battery-free and could be permanently embedded into tagged objects for structural, medical, or product monitoring. The major limitation of this class of systems is the need for proximity to a reading device and a rather reduced set of functionalities.

The use of an antenna as part of a passive sensor is not new. In the late 1940s the Russian inventor Leon Theremin developed one of the first covert listening devices (or "bugs") using a capacitor microphone and electromagnetic induction to transmit away, through reflection, the audio signals captured in nearby environments. A modern remarkable example of a true-RFID passive sensing device is given by the Wireless Identification Sensing Platform (WISP) project [2]. The device involves two mercury switches to mechanically toggle between two commercial RFID microchips, permitting the movement of the tagged object to be monitored by modulation of the transmitted chip's identifier (ID modulation).

The unique feature of the asymmetric link of an RFID system further adds a completely new sensing possibility by taking into consideration that RFID tags are tiny computers of increasing performance with tiny low-power radios which merge together both digital (the microchip data generation) and analog (antennas and propagation phenomenology) features. Data transmitted back to the reader during the interrogation protocol are digitally encoded, but the strength of the backscattered power is governed in an analog manner by the interaction with nearby objects, the propagation modality, and even the mutual position and orientation among reader and tags. This fact poses the basis for a different sensing modality wherein the captured data can

1536-1284/10/$25.00 © 2010 IEEE

be collected by a "sensorless" tag, just by exploiting the physics of the RFID response.

The research on the basic physics of data capture together with the low-level data processing can be considered as a particular edge discipline, Pervasive Electromagnetics, which differs from the well assessed remote sensing, generally based on the raw scattering from objects, since the former seemingly addresses both the design of devices and data processing, and may profit by digital intelligence distributed in Things. Pervasive Electromagnetics merges together electrical, radio, material, signal processing, and even architectural issues and promises to stimulate, in the near future, a fan of new low-cost radio sensing devices, ready to be seamlessly embedded into objects and the environment itself.

This article describes the basic sensing mechanisms and paradigms achievable by low-cost passive RFID devices, with particular attention to showing how a simple tag can be turned into a radio sensor, and introduces the new concept of *RFID grids*, their *analog identifiers* and *fingerprints*, as well as their possible application in smart sensing. The data capture mechanisms are illustrated by some experimental and computer simulated examples concerning the sensing of Things in manufacturing logistics and quality assessment, and the sensing of Humans (e.g., the emerging radio technology for the monitoring of human motion and the progression of some internal biological processes).

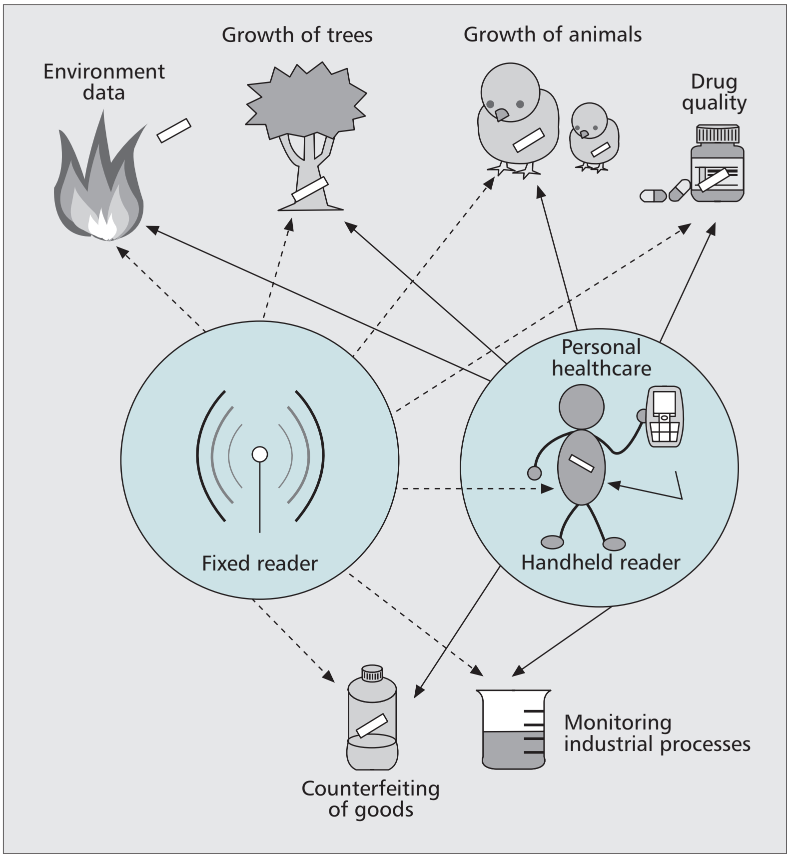


Figure 1. *Sensing of Things and humans by fixed and handheld RFID readers.*

The Way Things are Sensed

The concept of *sensing*, in the framework of the Internet of Things, deserves to be considered with the largest scope, ranging from the acquisition of an elementary status of an object (e.g., presence or absence within a given region — localization) to multidimensional description of the chemical-physical and relational parameters of a Thing with respect to the nearby environment and other Things. Here the term *Thing* is capitalized to highlight the fact that the usual tagging of an object is augmented with the physical interaction between the objects and the RFID tag itself to produce richer, more informative content. Some authors [3] refer to this concept by the more evocative term *spime* (space + time), emphasizing the idea of material objects correlated with evolving information.

The sensing modalities may fall at least into the classes of stationary and non-stationary sensing. *Stationary sensing* occurs when the measurement is performed in controlled conditions, such as when the mutual position between the reader and the Things remains unchanged during the whole phenomenon to monitor or, similarly, when a same position can be replicated exactly in successive readings. This is the case with Theremin's spy device or a card-like reader. Stationary sensing is the simplest configuration to handle since the variation of the nearby environment can easily be removed by signal processing and the tag response is unambiguously related to the physical parameter to be sensed.

Much more complex is the case of *non-stationary sensing* when interrogation is performed at different times or the Thing is moving. The eventual change of the reader-tag position and also the change in the environment can be a further unknown of the sensing problem, making data retrieval more difficult, if it is even still possible, but at the cost of more complicated data processing or more complex tag electronics. In general, additional independent data or functionalities are required to properly manage the sensing, as discussed next.

Species of Sensing RFIDs

Most passive RFID tags for sensing of Things can be grouped (Fig. 2) according whether or not they make use of integrated specific sensors to detect variation in the tagged object and the environment, and according to analog or digital modality to transmit such variation to the reader. Hence, at least four main classes of sensing RFIDs can be envisaged having different degrees of complexity. Self-sensing tags detect the change of the Thing through variation of an antenna's impedance and gain. This variation can be communicated to the reader by analog modulation of the backscattered power or, if multiple microchips are included in the tag (which becomes an RFID grid), by means of digital encoding over the microchips' IDs. True sensor tags include a specific physical receptor, which modifies the antenna's impedance and gain, and the data is transmitted to the reader by either analog modulation of the backscattering power or digital modulation if analog-to-digital functionalities are provided in the tag. It is, however,

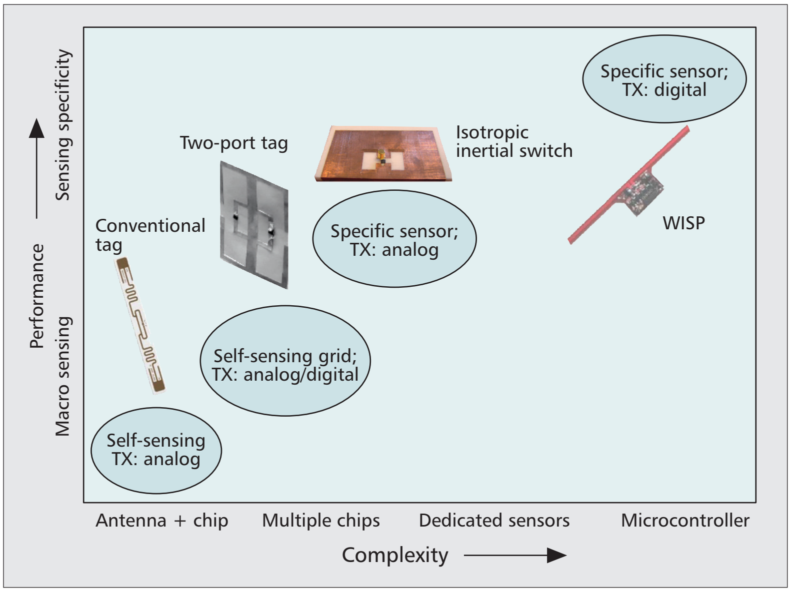


Figure 2. *Possible classification of passive sensing RFIDs according to the sensing mechanism (self-sensing or by a specific sensor) and data transmission (TX) modality (analog or digital encoding).*

reasonable to imagine that the representation of real phenomena in a virtual context will benefit from a combination of the above sensing solutions, depending on the required miniaturization and acceptable costs.

Sensorless Tag with Analog Data Communication

Any conventional RFID tag may be considered as a sensor for the effective permittivity of the object to which it is attached. Like any antenna placed onto a real medium, the electrical properties of an RFID tag, such as the input impedance and radiation gain, are strongly correlated with the physics of the nearby environment. A change of the tagged object is globally seen by the tag's antenna as a change of equivalent permittivity, which will in turn produce a change of the tag's antenna features and hence of the backscattered signals. Denoting by P_{in} the power entering the reader's antenna, the power backscattered by the tag and collected in turn by the reader itself may be written in the free space by the Friis formula as

$$P_{R\leftarrow T}(\underline{\hat{r}},d)[\Psi]=\left(\frac{\lambda_0}{4\pi d}\right)^2\frac{\sigma_T(\underline{\hat{r}})[\Psi]}{4\pi}G_R^2(\underline{\hat{r}})\eta_P^2(\underline{\hat{r}})P_{in}, \quad (1)$$

where the parameter Ψ generically indicates any physical or geometrical feature of the target that is subjected to change in the phenomenon monitored by the RFID platform, d is the reader-tag distance, G_R is the gain of the reader antenna, σ_T is the radar cross-section of the tag which depends on its radiation gain and on the impedance matching between the antenna and the microchip, η_P is the polarization efficiency of the reader-tag link, and finally, $\underline{\hat{r}}$ is the unitary vector indicating the mutual orientation between the reader and the tag. By processing $P_{R\leftarrow T}$, for instance, through the received signal strength indicator (RSSI) or another equivalent quantity collected by the reader, it is theoretically possible to detect a macroscopic change of the tagged object. So a *self-sensing*, completely sensorless, passive device [4] is obtained wherein *the sensor is the antenna* and *the antenna is the sensor*.

The tag's responses need to be unequivocally related to the variation of the Thing's status by means of *data inversion curves*, or lookup tables, produced by offline experimentation or computer simulation according to a training procedure. The antenna design effort is hence oriented to achieve monotonic inversion curves, $P_{R\leftarrow T} \leftrightarrow \Psi$, so that measurement ambiguities may be avoided. However, since no dedicated sensor is present, this sensing mechanism is rather macroscopic and non-specific; it is able to detect just an overall change of the Thing, even if such a variation is due to different causes (e.g., in case of multivariable systems). So RFID self-sensing should be applied only to Things with a single time-variant feature.

The transmitted data signal is of analog type (e.g., without any digital modulation), and hence it appears fully exposed to the interaction with the environment. The signal collected by the interrogator is indeed dependent on the particular mutual position between reader and tag since the tag's and reader's radiation gain are generally non-isotropic. The interrogation of the Thing is hence strongly undetermined in case of non-stationary sensing (e.g., when the reader-tag position is not controlled). This is, for instance, the case of an operator performing a manual sweep around a Thing by means of a handheld reader. A possible way to overcome this physical uncertainty is the processing of both direct and reverse RFID links, and in particular by also recording the *turn-on power*, the minimum power $P^{to}(\underline{\hat{r}},d)[\Psi]$ to inject into the reader's antenna to achieve the tag's microchip activation. In this case it is possible to demonstrate [5] that the following non-dimensional indicator $F[\Psi]$ is completely independent of the reader-Thing mutual position and the effect on the environment:

$$F[\Psi]=\frac{p_n}{2\sqrt{P_{R\leftarrow T}(\underline{\hat{r}},d)[\Psi]\cdot P^{to}(\underline{\hat{r}},d)[\Psi]}}=\frac{R_C}{|Z_A[\Psi]+Z_C|}, \quad (2)$$

where $Z_A = R_A + jX_A$ and $Z_C = R_C + jX_C$ are the input impedance of the tag's antenna and microchip, respectively, and p_n is the generally known power sensitivity of the tag's microchip (e.g., the minimum radiofrequency power that needs to be harvested to wake up the microchip and perform actions). The metric $F[\Psi]$ gives a unique feature of the tag and may be considered an *analog identifier*, complementary to the digital identifier; that is, a structural property invariant with the particular measurement conditions (position and orientation of reader-Thing) and nearby environment. If a scattering random object was present in the reader zone, it would affect both the direct and reverse links; the processing in Eq. 2 will remove this effect. The continuous variation of the analog identifier may unequivocally refer to the variation of the physical parameter of the Thing under test in any non-stationary interrogation. Physical parameters that could be suited to this kind of sensing are the shape deformations of the Thing, and even the change of its chemical and physical features, provided that an electrical permittivity variation of the Thing is accordingly produced. The growth of animals, plants, and living tissues could also be controlled by this sensing modality.

Sensorless Tag with Digital Data Communication

The tag works, like in the previous case, as a self-sensing device, but multiple microchips are now included to encode the occurrence of discrete events such as discrete values [4] of the changing physical parameter $\Psi \in \{\phi_1, \phi_2, \ldots, \phi_M\}$ to be transmitted through an ID modulation (two-chip tag in Fig. 2). In particular, the antenna is provided with a number of ports of input impedance $\{Z_{A,n}[\Psi]\}$, and a single microchip is attached to each port. Depending on the value of the sensed parameter, the impedance mismatch between the antenna ports and the microchips is such to enable (or not) the microchip to harvest the necessary power and respond to the reader with its own digital identification code (ID_n). Hence, several encoding schemes are possible. The simplest one requires each discrete event ϕ_n to be univocally associated to the ID_n of the nth microchip, which is the only one responding in that condition. A more general approach, reducing the number of required microchips, considers instead that more than one microchip is responding at the occurrence of the nth event ϕ_n so that such an event is unequivocally associated with a set of digital identifiers. In any case, due to digital encoding, this reading mechanism is not affected by uncertainty in the mutual reader-tag position and the interaction with the environment, and is hence well suited to non-stationary sensing.

Multichip tags may be achieved as a generally coupled multitude of RFID tags, including single-microchip tags in close proximity, as well as tags with a multiplicity of RFID microchips. This interconnected object, called an RFID grid, has recently been theoretically studied in [6] as a unique digital/analog entity having improved read-distance capabilities and other relevant properties. RFID grids could be suited to envelop a body, like a smart skin, and transmit a set of digital and analog identifiers forming the *grid fingerprint* $F[\Psi = \{F_1[\Psi], \ldots, F_M[\Psi], ID_1, \ldots ID_M\}$, a multidimensional dataset carrying information about one or more parameters to be sensed independently on the reader-tag orientation.

Tag with Specific Sensor and Analog Communication

The tag is equipped with a real sensor (motion, as in Fig. 2, temperature, pressure, chemical species [7], or other), which could be either lumped into a device, connected in some part of the tag's antenna, or distributed all over the antenna surface by chemical receptor painting. Such a sensing mechanism hence may be considered a lumped or distributed impedance loading $Z_S(\Psi)$ placed on the tag's antenna. The variation of $Z_S(\Psi)$, caused by the change of the environment, will produce a change of the tag's radar cross-section and hence a backscattered power modulation as in the case of sensor-less tags. Moreover, these kinds of devices are suited to include specific and direct sensing mechanisms, rather than macroscopic ones as in the case of self-sensing RFIDs. The sensor's equivalent impedance $Z_S(\Psi)$ should be preferably reactive (e.g., the sensing substance should work as variable inductors or capacitors) to avoid the introduction of additional electric loss, which would instead reduce the reading range capabilities of the tag. Also, in this case the RFID grid paradigm may be applied, with the additional possibility to collect data from different physical phenomena.

Tag with Specific Sensor and Digital Data Communication

This kind of tag works as a true data-logger: data collected by a specific sensor are handled by a microcontroller, and sampled and encoded into digital information that can be stored in the microchip's memory and then recovered by the reader through regular RFID interrogation.

Although these devices are typically provided with an internal battery, batteryless configurations have very recently been successfully tried. In such cases the microcontroller has very low power consumption (a few milliwatts), and the energy required to drive the data acquisition may be directly harvested from the interrogation signal, as conventional passive tags do, or generated by piezo-electric energy scavengers transforming micro-oscillations of the Thing into electrical energy. These devices are the most powerful and versatile ones since they are able to address specific sensors even if the power issues may reduce the real data rate. Moreover, since the transmitted information is digitally encoded, this sensing architecture is practically insensible to the environment interactions and may work properly for both stationary and non-stationary sensing. However, the size and cost are not currently suited to massive distribution in the environment.

Examples of this class of devices are the new version of the programmable WISP platform (Fig. 2) and low-frequency integrated temperature microchips in [8].

Sensing Non-Living Things

Some of the most interesting parameters of manufactured Things to be sensed over a large scale are definitely geometry deformation, temperature, and chemical changes. For instance, in logistics it is sometimes required to monitor the status of containers (bottles, packages, bags) to detect variation of their solid, powder, or liquid contents. The self-sensing natural capabilities of RFID tags may be exploited to handle these events in both continuous and discrete evolutions. An example of continuous sensing is the powder level control inside a plastic container,

This tag works as a true data-logger: data collected by a specific sensor are handled by a microcontroller, and sampled and encoded into digital information that can be stored in the microchip's memory and then recovered by the reader through regular RFID interrogation.

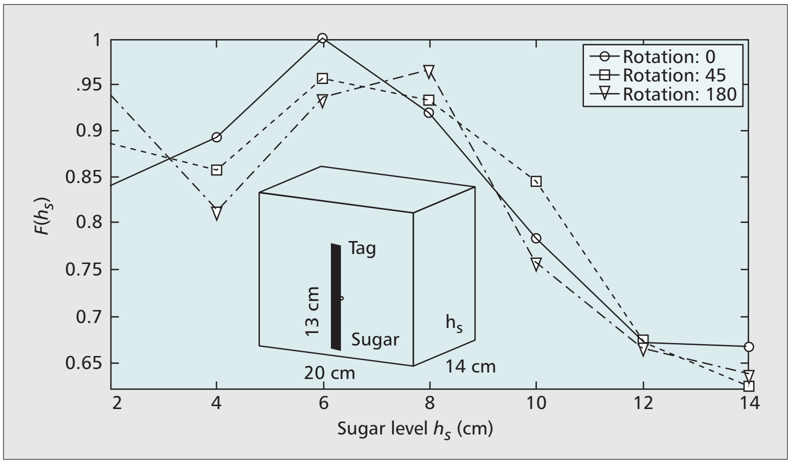


Figure 3. *Sensing the level of powder (sugar) material by analog, self-sensing modality.*

as in Fig. 3. In the reported experiment [5] (performed at 870 MHz UHF RFID frequency, as also were the next examples) the filling powder is sugar whose monitoring is a very challenging problem for RFIDs due to the low relative permittivity ((ε_r = 2.76), which is very similar to that of air ((ε_r = 1). The variation of filling level is hence expected to produce only a slight modification of the tag's radar cross-section and in turn of the sensed data. The analog identifier in Eq. 2 has been collected when the sugar level increases from 0 cm (empty container) up to 14 cm (about the full tag's length) at different angular orientation between the reader and the tag on the horizontal plane (0° rotation means that the tag and reader's antennas are facing). The analog identifier begins to sense the sugar variation when the filling level exceeds half the tag size and spans an overall dynamics of about 50 percent, up to saturation. The collected data are very little dependent on the mutual orientation between the reader and the container, even for rotation of 180° e.g., when the two antennas are completely separated by the sugar itself. This Thing may be therefore interrogated in non-stationary modalities, for instance by a robot or a human operator handling a reader and moving all around a warehouse or a factory.

A similar concept was applied very recently to the remote sensing of beverage glasses [9], while another interesting application of (stationary) analog self-sensing by regular tags aimed at the detection of geometrical displacements can be found in [10].

Temperature monitoring has so many implications in pharmaceutical (blood bags, vaccines) and food (frozen goods) supply chains, as well as in hospitals and industrial processes in general. Passive RFID tags promise to be suited to conceive a digital quality label, for example, a kind of "seal" or "fuse" [11] able to certify that the tagged item was exposed (or not) to a temperature higher than a particular threshold. For this purpose, the RFID device has to store this information over its work life in the absence of continuous interrogation. Furthermore, the over-temperature flag needs to be unchanged even if the tag temperature falls below the critical value. A possible approach to this problem is to embed in the RFID tag a shape-memory-alloy (SMA) conductor having the capability to change its shape when the local temperature exceeds a transition level. The shape's change can be engineered to permit or prevent an RFID microchip responding to the reader depending on the thermal status through the ID modulations. For example, Fig. 4 shows the time-response of a two-microchip RFID grid wherein the microchip emitting code ID.2 is conditioned by an SMA wire that forces such a microchip to be short-circuited depending on the temperature value. When the temperature is less than a threshold (around 80°C in the experiment), the reader will only receive code ID.1 of the first microchip (indicated by vertical bars in Fig. 4). This data has the sense of the code-name of the tagged object (a drug box in the figure). As the temperature exceeds the threshold, the SMA wire deforms and enables the second microchip to send back its own ID.2, which now has the meaning of "seal status."

In principle, multiple thresholds may be included in the device by using a plurality of SMAs with different thermal characteristics.

Sensing Humans

One of the most fascinating and ambitious conjugations of RFID sensing is a kind of Internet of the Body (e.g., when persons and even their internal organs are tagged). True applications are not so distant and could enable the monitoring of the proper functionalities of critical organs or detecting the progression of a disease through handheld devices, enabling the patient to become the primary hub of bio-data acquisition. Figure 5 shows some possible human-body districts and organs where sensing tags could be placed to produce bio-information.

Sensing Human Behavior

A wearable tag provided with passive accelerometers may be attached to arms to monitor human movements in entertainment, healthcare, and diagnostic applications. For instance, it was demonstrated in [12] that wearable tags with inertial switches are able to detect limb motion in some common sleep disorders like restless legs syndrome and periodic limb movements. Tags applied to the chest may be useful to detect breath. More generally, motion-detecting wireless devices may help to produce statistics to support diagnosis and discreetly monitor the activity of a patient inside a structure, and generate warnings about unusual behaviors such as when the patient falls down or stays motionless for long times. For example, one of the diagrams within Fig. 5 gives the record of clusters of arm motion collected by the RFID reader according to ID modulation. The microchip only responds with its ID when it is in steady state, while it does not respond when in motion. The motion events are indicated in the figure by black bars. The same motions have been recorded for comparison by the digital micro-electromechanical system (MEMS) accelerometers of an iPhone (used as an active sensor) attached to the arm, in close

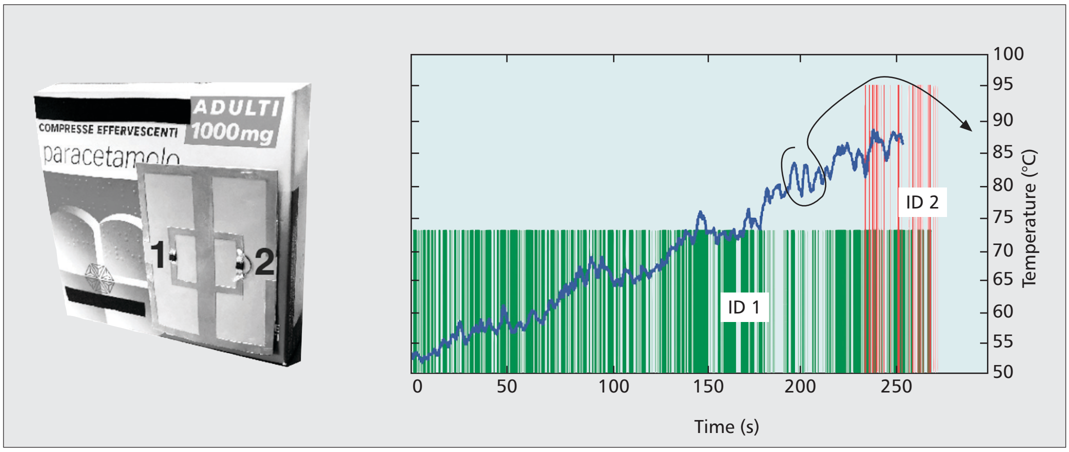


Figure 4. *Detection of thermal threshold crossing of drugs by a two-port RFID grid used in digital mode.*

One of the most fascinating and ambitious conjugations of RFID sensing is a kind of Internet of the Body, e.g., when persons and even their internal organs are tagged. True applications are not so distant and could enable the patient to become the primary hub of bio-data acquisition.

proximity to the RFID tag, which provides true acceleration. Another diagram in Fig. 5 shows the breath rhythm when the tag is attached to the chest of a volunteer. In both cases, RFID information is very poor with respect to a more specific (active) sensor, but the RFID data are naturally aggregated without any particular processing, and hence are useful to generate macro-indicators (occurrence frequency, duration) of human behavior.

Sensing from the Inside

Implanted sensing tags are much more challenging to handle due to their intrinsic obtrusive nature and the high power attenuation of the human body, which makes it difficult to establish the RFID two-way link. However, from another point of view, the high electric permittivity of human tissue helps in the miniaturization of tags' size, making body implants feasible. Implanting a bio-compatible, thin, self-sensing tag is in fact accepted during surgery. The implanted tag will scatter back toward the reader indirect information about variations in local equivalent permittivity of the tissues due to the healing process and possible complications (e.g., abnormal cell proliferations, edema, and inflammatory events).

A possible locus of implant for self-sensing RFID tags is a biological duct with the purpose of monitoring its safety condition. In this case the tag may be integrated with a stent, a

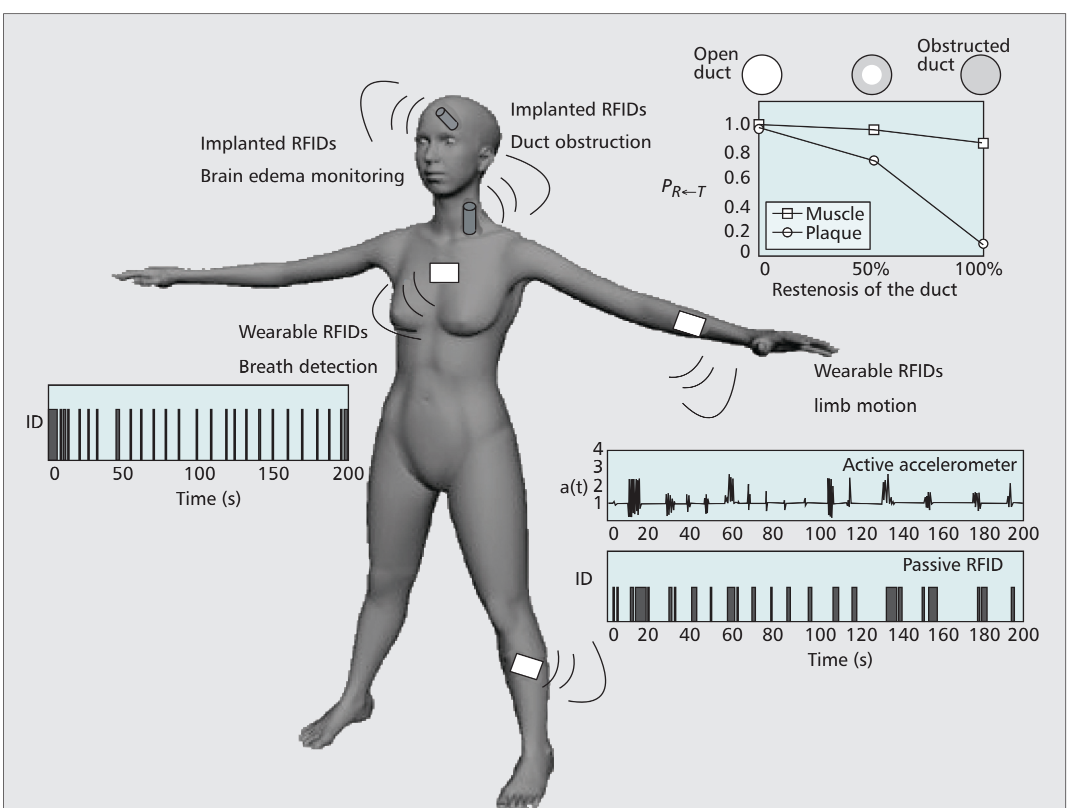


Figure 5. *Sensing humans by wearable and implanted passive RFIDs.*

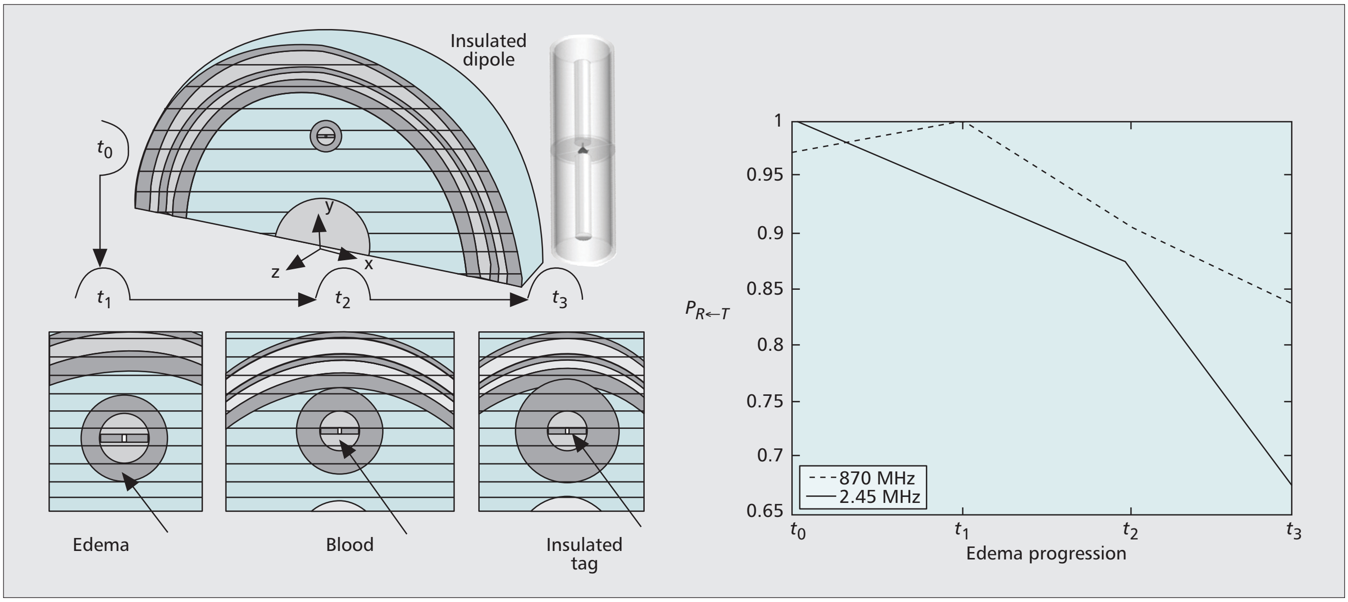


Figure 6. *Monitoring of brain edema by a self-sensing implanted tag, used in analog mode, following cancer removal surgery.*

mechanical device having the form of a cylindrical mesh of thin wires commonly implanted into a natural passage/conduit in the body (e.g., coronary arteries, urinary tract, prostate, esophagus, carotid artery, biliar ducts) to prevent or counteract localized flow constriction, called stenosis. In some cases a new reduction of the circumference of the duct's lumen may occur, indicated as restenosis, due to a new formation of cholesterol plaques against the vein walls or a new proliferation of cells in the muscle wall of the vessel. In both cases the restenosis produces a local modification of tissue (from blood to fat or from blood to muscle) and hence a variation of the effective permittivity "sensed" by the stent. So a new generation of self-sensing stents may be conceived by integrating RFID microchips into the stent geometry to turn it into a modulated backscattering antenna.

In a first feasibility study in [13] the case of the carotid artery was considered, where the tag simulating the stent has a four-turn spiral geometry. One of the diagrams in Fig. 5 shows the computer-simulated power backscattered, as in Eq. 1, by such a simplified version of a stent with respect to the in-stent restenosis evolution, from a clear duct up to a duct completely filled (in the correspondence of the stent) by fat or muscle. The curves are monotonic, and in the particular type of restenosis caused by cholesterol plaques, the data dynamic is 10:1, particularly promising for early diagnosis

Another feasibility study [13] recently discussed, by means of electromagnetic computer simulations, the possibility of monitoring brain edema evolution after surgical treatment for brain cancer. The physical rationale for RFID sensing relies on the modification of the electromagnetic characteristics of brain tissues that may be detected by the self-sensing properties of an RFID tag placed in the surgery-treated region. Figure 6 shows the computer simulated variation of the backscattered power in Eq. 1 emerging from a 1-cm-long dipole tag implanted in the head, collected by the reader, with respect to the variation of the edema size. Edema, which here roughly refers to water-imbued brain tissue, is simulated by a sphere of increasing radius embedding a blood core; the sensing tag is placed in the origin of such a sphere. The curves of power backscattered by the tag are also in this case monotonic and hence suited to data inversion, with dynamics of 15 percent (870 MHz) and 35 percent (2450 MHz) for increasing edema size.

Conclusions

The pervasive sensing of Things is still in its childhood, but it already offers an unprecedented opportunity to mix together complementary expertise and stimulate fast progress in edge disciplines. The presented examples and ideas show only that low-cost passive sensing is physically feasible, but there is a need for significant research to master the design of "sensitive antennas" and, more generally, to fully understand the many implications of the engineered use of a multiplicity of radio identification objects. When RFID microchips, augmented in their electronic and software capabilities, are fully perceived as atomic components of a more complex distributed system, just like resistors, capacitors, and diodes are in microelectronics, new devices will be conceived, working at the same time as sensors, actuators, radios, and media generators.

Acknowledgments

The ideas and results described in this article would not be feasible without the help of my present and past collaborators L. Mattioni, C. Calabrese, C. Occhiuzzi, F. Amato, S. Cippitelli, S. Caizzone, Sabina Manzari, and Giordano Contri. Moreover, I would like to thank G. Manzi of NXP for technical and equipment support.

References

[1] D. Preuveneers and Y. Berbers, "Internet of Things: A Context- Awareness Perspective," *The Internet of Things: From RFID to the Next-Generation Pervasive Networked Systems*, L. Yan *et al.*, Eds., Auerbach, 2008.

[2] M. Philipose *et al.*, "Battery-free Wireless Identification and Sensing," *IEEE Pervasive Computing*, vol. 4, no. 1, 2005, pp. 37–45.

[3] B. Sterling, *Shaping Things*, MIT Press, 2006.

[4] G. Marrocco, L. Mattioni, and C. Calabrese, "Multiport Sensor RFIDs for Wireless Passive Sensing Of Objects — Basis Theory and Early Results," *IEEE Trans. Antennas Propagation*, vol. 56, no. 8, Aug. 2008, pp. 2691–702.

[5] F. Amato and G. Marrocco, "Self-Sensing Passive RFID: from Theory to Tag Design an Experimentation," *Euro. Microwave Conf.*, Roma, Italy, 2009.

[6] G. Marrocco, "RFID Grid: Part I — Electromagnetic Theory," to appear, *IEEE Trans Antennas Propagation*.

[7] R.A. Potyrailo *et al.*, "Selective Quantitation of Vapors and Their Mixtures Using Individual Passive Multivariable RFID Sensors," *IEEE Int'l. Conf. RFID 2010*, Apr. 2010, pp. 22–28.

[8] K. Opasjumruskit *et al.*, "Self-Powered Wireless Temperature Sensors Exploit RFID Technology," *IEEE Pervasive Computing*, vol. 5, no. 1, Jan.–Mar. 2006, pp. 54–61.

[9] R. Bhattacharyya, C. Floerkemeier, and S. Sarma, "RFID Tag Antenna Based Sensing: Does Your Beverage Glass Need a Refill?," *IEEE Int'l. Conf. RFID 2010*, Apr. 2010, pp. 126–33.

[10] S.E, Sarma, C. Floerkemeier, and R. Bhattacharyya, "Towards Tag Antenna Based Sensing — An RFID Displacement Sensor," *IEEE Int'l. Conf. RFID 2009*, Orlando, FL, 1999, pp. 95-102.

[11] S. Caizzone, C. Occhiuzzi, and G. Marrocco, "RFID Radio-Sensor Integrating Shape-Memory Alloys," *IEEE Antennas and Propagation Soc. Symp.*, Toronto, Canada, 2010.

[12] C. Occhiuzzi and G. Marrocco, "The RFID Technology for Neuroscience: Feasibility of Limbs' Monitoring in Sleep Diseases," *IEEE Trans. Info. Tech. in Biomedicine*, vol. 14, no. 1, Jan. 2010, pp. 37–43.

[13] C. Occhiuzzi and G. Marrocco, "Pervasive Body Sensing: Implanted RFID Tags for Vascular Monitoring," *IEEE Antennas and Propagation Soc. Symp.*, Toronto, Canada, 2010.

[14] C. Occhiuzzi and G. Marrocco, "Sensing the Human Body by Implanted RFID Tags," *Euro. Conf. Antennas and Propagation*, Barcelona, Spain, 2010.

Biography

Gaetano Marrocco (marrocco@disp.uniroma2.it) received his Laurea degree in electronic engineering and Ph.D. degree in applied electromagnetics from the University of L'Aquila, Italy, in 1994 and 1998, respectively. Since 1997 he has been a researcher at the University of Rome Tor Vergata, Italy, where he currently teaches antenna design and bioelectromagnetics, manages the Antenna Laboratory, and is an advisor in the Geo-Information Ph.D. program. His research is mainly directed to the modeling and design of broadband and ultra-wideband antennas and arrays as well as of sensor-oriented miniaturized antennas for Biomedicine, Aeronautics and RFID. He holds two patents in broadband naval antennas and structural arrays, and three patents in sensor RFID systems. He was General Chairman of the first Italian multidisciplinary scientific workshop on RFID: RFIDays-2008: Emerging Technology for Radiofrequency Identification. In 2010 he was co-chair of the RFIDays-2010 International Workshop in Finland. Currently he serves as Associate Editor of *IEEE Antennas and Wireless Propagation Letters*.