Towards Autonomous Wireless Sensors: RFID and Energy Harvesting Solutions

Y. Duroc and G. Andia Vera

Abstract In this chapter, an extend vision on the sensing techniques and powering on smart and autonomous RFID tags is presented. In a society leaded by the information and networking, a link is defined between our real world and a virtual scenery for all the everyday objects. The linker is a smart wireless sensor. No better definition can be done by exploiting the real meaning of the words: This is the “Internet of the things era”. The most suitable technology for the development of smart sensors is the passive RFID technology because its battery-less operation, network interoperability and wireless capability. Several challenges are faced on the design of these smart and autonomous RFID sensors: sensing techniques, structure considerations and wireless powering are the main challenges discussed in this chapter. The power autonomy is presented under harvesting techniques with special interest on the electromagnetic energy harvesting. Design criteria of electromagnetic energy harvesters are also discussed. Some examples of applications on the most common sensed parameters including physical, biomedical, automatic product tamper detection and noninvasive monitoring are described.

1 Introduction

In the literature, the Internet of Things (IoT) concept is defined in different ways although enough similar. The definition given by the CASAGRAS consortium is maybe the most general because it refers to a Things oriented vision and an Internet oriented vision [1]: “A global network infrastructure, linking physical and virtual objects through the exploitation of data capture and communication capabilities. This infrastructure includes existing and evolving Internet and network developments. It will offer specific object-identification, sensor and connection capability as

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Y. Duroc (✉) · G. Andia Vera
University of Grenoble Alpes, LCIS, Valence 26900, France
e-mail: yvan.duroc@esisar.grenoble-inp.fr

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the basis for the development of independent cooperative services and applications. These will be characterized by a high degree of autonomous data capture, event transfer, network connectivity and interoperability.” The US National Intelligence Council provides a definition currently in use, and maybe simpler to apprehend [2]: “The IoT is the general idea of things, especially everyday objects, which are readable, recognizable, locatable, addressable, and controllable via the Internet—whether via RFID, wireless LAN, wide-area network, or other means.” Therefore the IoT include Internet-connected devices, smart connected devices, Wireless Sensor Networks (WSN), machines and devices communicating wirelessly, ubiquitous computing, ambiance intelligence, and smart matter. In this context, the association of WSN and RFID (Radio Frequency Identification) systems would enable a lot of new applications.

The RFID technology appears as a relevant technology with the convergence of sensing and identification features and presents multiple capabilities in terms of communication, identification, localization, tracking, sensing, etc.; and also it has intrinsic advantages in terms of low power and low cost solutions. The evolution of the RFID with this objective will lead to RFID sensor networks very adequate in the IoT context. In particular two interesting options are possible: passive RFID systems using tags which collect the energy from the signal transmitted by a reader for powering the chips; and chipless RFID systems which present fully passive tags.

Section 2 presents the RFID technology and its variants with the objective to develop sensing RFID systems. Section 3 introduces the energy harvesting approaches with a focus on electromagnetic power harvesting devices. Section 4 gives a conclusion and future research hints.

2 Evolution of the RFID as IoT Technology

2.1 General Presentation of the RFID

RFID technology allows data storage in small electronic transponder circuits that are particularly portable [3, 4]. Communication between an RFID tag and an interrogator is realized by radio frequency (RF) waves. In consequence, the data can be read and written without contact and often through obstructions. A typical RFID system is illustrated by Fig. 1. Three fundamental components constitute RFID systems:

- Transponder (or RFID tag), which contains the identification code, and are permanently or temporally attached to objects.
- Interrogator (or reader), which sends interrogation signals to an RFID tag in order to identify it. Its complexity and configuration depend on the functions to be fulfilled, which can vary quite significantly from one application to another. However, the main reader’s function is to provide the communication way to the RFID tags nd to facilitate the data transfer by accomplishing a specific protocol.

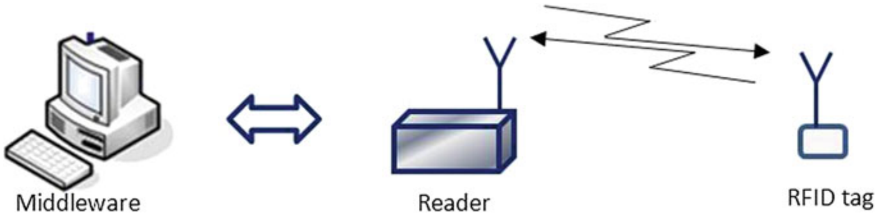


Fig. 1 Architecture of a classic RFID system

- Middleware is the software installed in a host computer that manages the interrogator or reader tasks, it is the responsible to converting tag data into meaningful information, and to ensure the integrity of the data obtained. The middleware often offers additional data processing and internet connection for a global connectivity

In a typical RFID application, RFID tags are attached or embedded into objects locking for identification or tracking. In the most frequent application such as supply chain management, the RFID tags simply serve the purpose of UPC (Universal Product Code) bar codes. However compared to bar codes, solutions based on RFID tags have much better capabilities as: non-line-of-sight communication, writing capabilities, multiple reading, durability, security; however their cost is still much higher. Moreover when combined with sensors, RFID can also help managing objects that are environmentally sensitive (e.g. food, medicine, blood) or non-sensitive (durable products and machines).

Although RFID technology is always in evolution and development, several techniques and standards exist. Table 1 summarizes the properties of the conventional RFID technologies. For each technology, used frequency range, distance range, coupling type, existing standards (mainly defined by the International Standard Organization, ISO), and traditional RFID market segments are presented.

According to the powering method, an alternative and complementary classification can be done: active, passive and semi-passive tags. Active tags embed an internal battery which continuously powers the tag. Contrary, passive tags have no internal power supply. They get their energy from the RF carrier wave continuously provided by the reader during the communication. The communication consists of a query sent by the reader, that one that the tag responses by backscattering a signal, i.e. part of RF power received from the carrier is transmitted back to the reader with an appropriative modulation and coding performed by the logical part of the RFID chip. Passive tags are the most commonly used tags. They have a shorter read range compared to active tags but they have a smaller size, are cheaper and do not require any maintenance. Semi-passive tags communicate with the readers like passive tags (using scattering principle) but they are equipped with an internal battery constantly powering their internal circuitry. Finally and more recently, a new RFID solution called chipless uses purely passive tags, which potentially means an infinite lifetime. The chipless tags do not rely in any powering to operate and present a fixed electromagnetic signature that allows its remote identification. However the development of chipless

Table 1 Summary of properties RFID techniques

	Frequency range	Distance range	Coupling	Existing standards	Applications
LF	125 kHz	~0.1 m	Magnetic	11784/85, 14223	Smart card, ticketing, access, animal tagging, laundry
HF	13.56 MHz	~1 m	Magnetic	18000-3.1, 15693, 14443A, B, C	Small item management, supply chain, anti-theft, library
UHF	900 MHz	~2–7 m	Electromagnetic	EPC C0, C1, C1G2, 18000-6	Transportation vehicle ID, access/security, supply chain, large item management
Microwave	2.4 GHz	~10 m	Electromagnetic	18000-4	Transportation vehicle ID (road toll), access/security, supply chain, large item management

solutions requires new functioning principles and adequate standard definitions to be commonly exploited [5].

Today the RFID technology is present in the industrial world with diverse applications from access control fields until logistics and automatics [6]. If the RFID is known for its current applications, it also offers promising applications for the future sensor networks and the IoT. Indeed the same mechanisms that allow the communication and identification between RFID reader and tags can also be applied to collect sensor data. The RFID-based sensor response is electromagnetically sensitive to the dielectric of its close medium and enables environmental sensing applications besides the identification, such as presence detection, gas detection, temperature detection, moisture detection or physical strain. This sensibility is analysed by processing the electromagnetic signature of the tag antenna. EPGGlobal (worldwide governing entity for RFID standards) has envisioned the architecture IoT in which devices with RFID tags dispersed through the Internet can communicate with each other, providing real-time information about their location, contents, destination and ambient conditions [7]. The potential attractiveness of RFID that enables such vision is largely based on the key advantages of RFID components relative to other technologies: small form-factor tags that afford a potentially long life, resulting from optimized low power operations and energy harvesting.

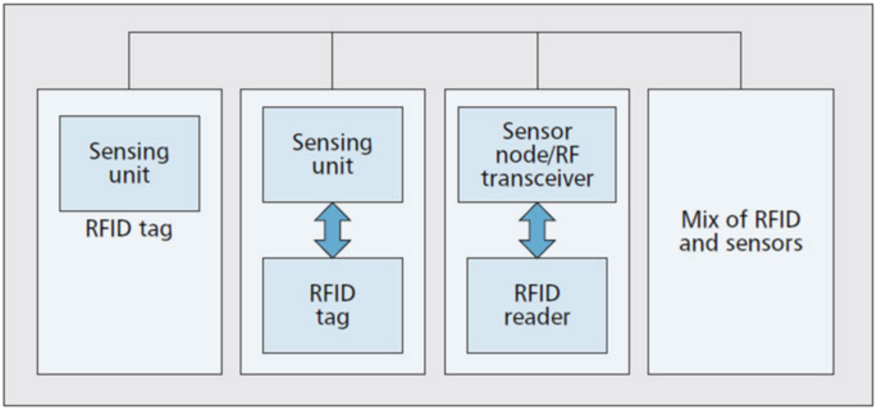


Fig. 2 Four type of integration [8]

2.2 *RFID Sensors*

RFID and WSN technologies
RFID and WSN technologies are two complementary technologies. Combining both technologies it is offered a great number of advantages. Indeed, RFID tags can replace some of the sensor nodes in WSNs and offer cheaper solutions. In addition, RFID technology provides the possibility of tracking objects. Alternatively sensors can provide various sensing capabilities to RFID tags, introducing logic into nodes to enable RFID readers and tags a certain level of intelligence, and afford the ability of operating in a multihop fashion extending potentially RFID applications. Several scenarios can be envisaged for combining RFID and WSNs (Fig. 2), such are: tag integration with sensors, tag integration with WSN nodes and wireless devices, reader integration with WSN nodes and wireless devices, and a mix of RFID and WSNs [8].

Thus, the integration of RFID and WSNs opens up a large number of applications in which it is fundamental to sense environmental conditions and to obtain additional information about the neighboring objects.

Sensing antenna
The identification information may be enhanced with physical information about local agents as well as changes in the tagged object itself. The majority of existing solutions rely on RFID UHF tags and a dedicated specialized sensor. Like RFID tags, wireless sensors can be divided into active (battery-powered devices), semi-passive sensors (battery-assisted) and fully passive sensors. Thus, RFID can be combined with a sensor to monitor different elements in their environment, including temperature, humidity, shock and vibration. However, sensor addition often increases both tag size and cost. An alternative solution for more compactness and cost-efficiency is the functional integration of the antenna and the sensor component in order to obtain

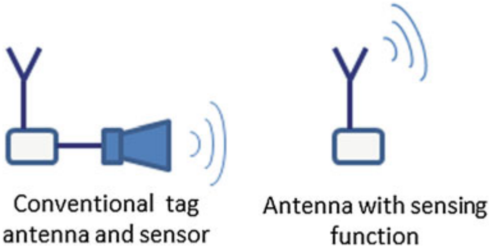


Fig. 3 Configuration of RFID tag sensing systems

a sensor tag. The challenge is then to use the RFID tag antenna directly as a sensor. The Fig. 3 illustrates these two different concepts: the conventional antenna attached to a sensor versus the antenna with sensing function.

There are three regions of interest around the antenna. The far-field region is the "simplest" case to consider since no significant coupling or perturbation will disturb the radiated field. On the contrary, the near-field region become very sensitive due to significant coupling that can exist between the antenna and any other element located in this region. Then this characteristic can be exploited in order to transform an antenna into a sensor. To do that the design should establish the relationship between the parameter to be sensed and one of the antenna parameters. Even if this seems to be challenging and difficult in term of analysis, many experimental results have demonstrated this capability. As an example, consider a RFID tag located close to a metallic surface. The proximity effect will modify the radiation pattern of the antenna and consequently the impedance of the antenna will change. This effect could be used to design a displacement sensor as demonstrated in Bhattacharya et al. [9]. The same effect, but with high permittivity dielectric, will lead to detune the tag antenna and consequently transform the tag into sensor too [10].

Examples

Several concepts for sensor tags have been proposed with different and various functionalities.

RFID-based sensors offer great promise to the perishables supply chain. The losses in perishable products are estimated around $35 billion annually [11] and it is necessary to highly increase the product visibility. One of the most relevant information is about the evolution of the temperature in the transit operations, and notably in the cold supply chain operations. In Bhattacharyya et al. [12], a temperature sensor is introduced (Fig. 4). The sensor takes into account temperature violations and changes on the tag antenna properties by using a shape memory polymer which is a temperature sensitive. The temperature actuated shape memory mechanism to preserve state changes even in the absence of transmitted power from the reader.

Other environmental information interesting to capture is the humidity. A printed UHF RFID sensor tag that indicates if the tagged object has been exposed to a certain degree of moisture (Fig. 5) in presented in Gao et al. [13]. A printed coupling loop with an embedded resistive moisture sensor is placed above the surface of a tag antenna, thus the changes on the sensor resistance cause variations on the

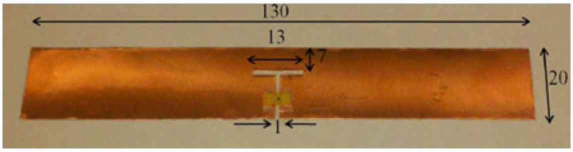


Fig. 4 Prototype of the temperature tag sensor [12]

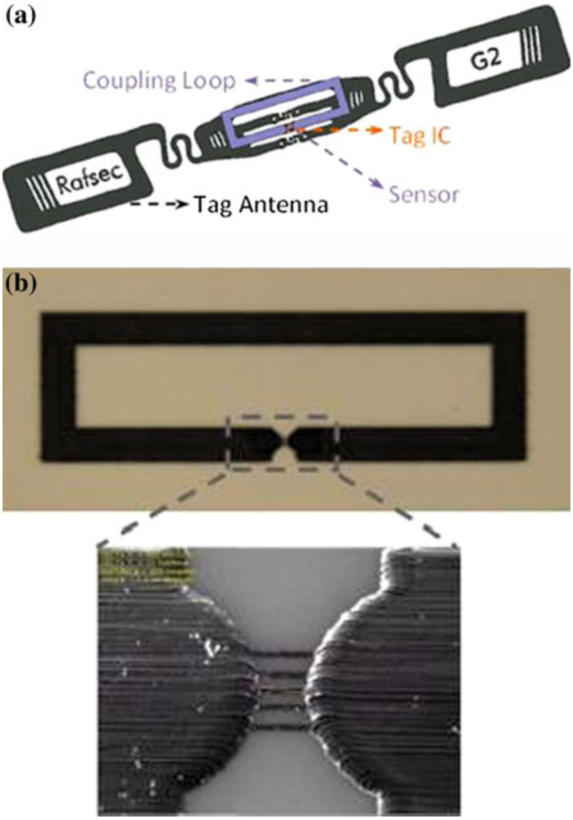


Fig. 5 **a** UHF RFID tag from Rafsec, extended with sensor functionality using electromagnetic coupling [13]. **b** Photograph of the (*upper*) printed coupling loop with the (*bottom*) write-one-read-many structure made of five parallel sensor lines enlarged [13]

tag antenna properties through electromagnetic coupling. It should be noted that the electromagnetically coupled sensor is easy to apply as a sticker or by similar manners, using commercial tags.

A patch antenna with a relative humidity sensing function is proposed in Chang et al. [14] using a modified polyimide. The proposed antenna is a passive device that physically and functionally combines an antenna with a relative humidity sensor (Fig. 6).

Another important application of wireless sensors is the remote monitoring of environments to detect the presence of hazardous gases within industrial sites (supply chain and food integrity) or do the quality control of work spaces. Otherwise, one of the most promising techniques to transform the antenna into a sensor is to

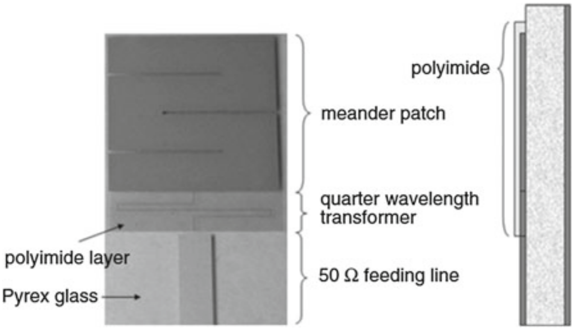


Fig. 6 Configuration of the antenna integrated with relative humidity sensor: *top view* optical photograph (*left*) and side view of structure (*left*) [14]

integrate nanomaterial to antenna. As the nanomaterials could exhibit very high sensitivity to environment parameters (such as temperature, moisture, gas, etc.) so their integration with the tag antenna will allow it to become sensitive to its environment. Some experimental works have already demonstrated this property. For example, a complete integration of carbon nanotube (CNT) film (buckypaper) into the RFID tag aiming to design a passive gas (ammonia gas, NH_3) radio sensor is presented in Occhiuzzi et al. [15]. CNT film is used as a localized and variable resistive load integrated into the tag antenna, which becomes able to transduce the presence of hazardous gas in the environment into changes of its electromagnetic features (Fig. 7).

The RFID also offers other applications capabilities. A “zero-power RFID-enabled threshold shock sensor” is proposed in Todd et al. [16]. This is a latching accelerometer which records an acceleration event above a specific threshold. The presented entire package is designed to provide low cost sensors for monitoring shock loads. The sensor is based on a mechanical bistable mechanism laser-cut from a single Delrin layer which switches between states when exposed to accelerations above a threshold (Fig. 8).

Another great field of application concerns real-time biomonitoring (temperature, blood pressure, heartbeat, glucose content, human behaviour) and location of people within hospitals or domestic environment. However the design of effective wearable tags is difficult due to the strong interaction of the antenna with the human body which is responsible of impedance detuning and efficiency degradation. Occhiuzzi et al. [17] proposes a family of wearable tags based on a particular folded geometry structure presenting a good independence to the proximity of human body. Finally in Lakafosis et al. [18], inkjet-printed flexible antennas, RF electronics and sensors fabricated on paper and other polymer substrates have been presented as system-level solutions for ultra-low-cost mass production of UHF RFID tags and RFID-enabled wireless sensor nodes or even wireless cognition applications (Fig. 9).

Otherwise, MEMS (microelectromechanical systems) technology has been also studied to be implemented in passive wireless sensors or tags. This type of wireless MEMS sensors enables very low manufacturing cost, long reading distance, high frequencies and compact size without requiring embedded electronics. One example

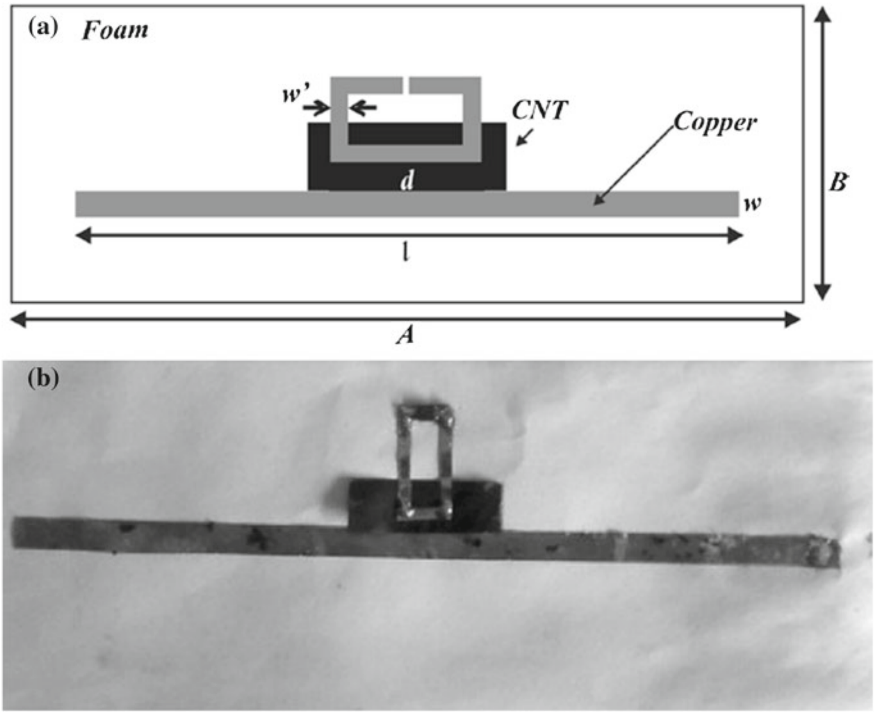


Fig. 7 **a** RFID tag inductively coupled loop with a rectangular CNT load (size in millimeters: $A = 180$, $B = 80$, $l = 160$, $w = 5$, $w' = 2$, $d = 2$) [15]. **b** Photograph of prototype [15]

of such MEMS tag sensors replying at an intermodulation frequency is presented in Viikarai and Seppa [19]. Another approach is to not include any additional sensor or sensitive material on the overall tag but rather relies on the variation that the environmental conditions have on the response of the tag. In Capdevila et al. [20], a passive multiprobe sensor using conventional UHF RFID shows the feasibility of impedance-based sensing with RFID probes. Indeed, any physical, chemical or physiological factors which are known to impact the tag antenna impedance (via the dielectric permittivity) can be used to detect changes in local neighborhood.

Finally the use of RFID technology for the automatic transmission of physical characteristics in WSN opens the way to a large class of attractive applications. However, although some RFID tags enable to transmit sensor-like information are already on the market, only a few sensors are embedded in the tag. Catarinucci et al. [21] presents a new multi-ID and cost effective RFID tag (called S-tag) for sensor data transmission. As shown in Fig. 10, the S-tag transmits the sensor value by standard RFID technology of the digital output of a generic sensor.

Fig. 8 Working shock sensor prototype, front and back view showing the inductor and RFID chip with the sensor [16]

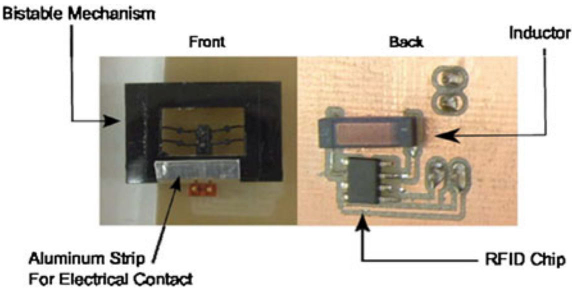
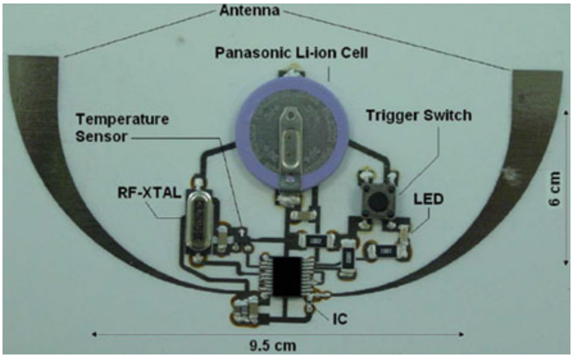


Fig. 9 Inkjet-printed wireless sensor transmitter prototype on paper substrate [18]



Alternative solution: chipless
The main cost of an RFID tag comes from the embedded chip; new solutions present new alternatives using chipless tags without silicon integrated circuit. Chipless tags encoding data can be achieved thanks to three main categories based on time domain reflectometry (TDR), spectral signature encoding and amplitude/phase backscatter modulation. Time domain reflectometry (TDR) based chipless tags are interrogated with a pulse signal and the information is given by the echoes of the pulse sent by the tag. SAW (Surface Acoustic Wave) tags, thin-film-transistor circuit, microstrip tags with discontinuities, are used. Spectral signature-based chipless tags encode data into the spectrum using (multi)resonant structures [22]. Each bit corresponds to a predetermined frequency. Amplitude/phase backscatter modulation-based chipless tags are realized by controlling the reactive loading of the tag's antenna. The Fig. 11 illustrates the layout of the proposed chipless wireless sensor node.

For example, [23] demonstrates the use of chipless tags based on periodic magneto inductive-wave delay lines in order to realize a low cost wireless sensor of temperature or humidity (Fig. 12).

However, chipless technology is in infancy recently and several challenges are facing its development in terms of technology process, coding capacity, miniaturization, sensing capabilities. The development of these chipless (and cheaper) solutions will also require new standards (the two first approaches need larger frequency bands), novel readers integrating pulse generator functions and processing signal capabilities.

Fig. 10 Simplified scheme of the designed RFID S-tag [21]

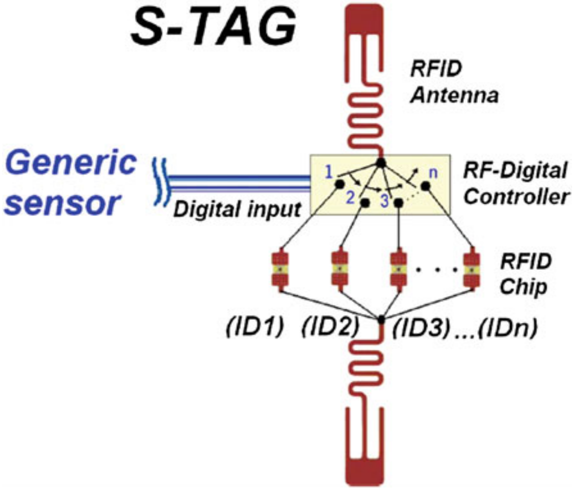


Fig. 11 Layout of chipless wireless sensor node [22]

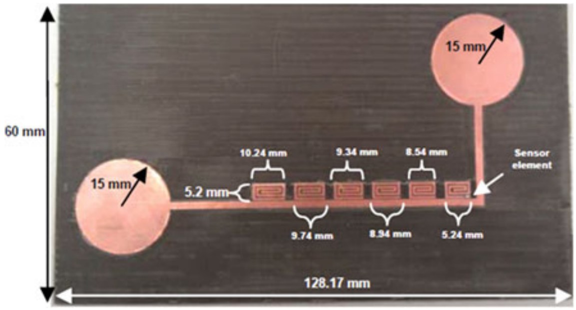
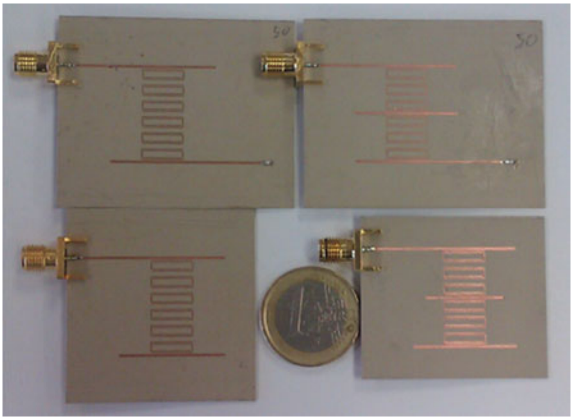


Fig. 12 Fabricated set of two-bit chipless tags [23]



2.3 Conclusion: RFID as Sensor Technology

The RFID tends to become an invisible and ubiquitous sensing technology. Using the automated monitoring capability of the RFID technology in addition to the sensing capabilities based on the near-field coupling dependence has increased the applications in which RFID is deployed. Major RFID sensing application fields include monitoring physical parameters, biomedical sensing and monitoring, automatic product tamper detection, robot direction sensing, and noninvasive monitoring. More particularly, UHF RFID is a promising approach for the development of the IoT. This technology is quite inexpensive, also naturally compatible with Internet and allows a reading range adequate for many applications. In this context, the techniques of scavenging power become one of the key points to resolve with the most possible efficient way.

Harvesting energy from environment is a very rapidly evolving topic. When combined to wireless advantages, harvesting energy could lead to all passive solutions with potentially infinite lifetime. This is why a technology like passive RFID is greatly investigated and considered in numerous domains and applications. As an example, an RFID chip needs only $-18\,\mathrm{dBm}$ power to be activated. Many existing sources of ambient energy exhibit power in the order of the milliwatt. Antenna is a well-suited tool for electromagnetic power harvesting. Indeed, an antenna loaded by a charge pump circuit obtained by connecting a diode/rectifier and a capacitance, is equivalent to DC generator. In such configuration the optimization should consider the maximum converted power, which is obtained under perfect impedance matching between the antenna and the charge pump circuit. When harvesting and backscattering are considered with the same antenna, a trade-off between the two functions must be achieved during the design.

3 Energy Harvesting Solution

Actual social tendencies are evolving toward creating smart environments where a multitude of sensors and devices are interacting to deliver an abundance of useful information. Essential to the implementation of the IoT is the design of energy efficient systems aiming toward a low-carbon–emission society. Within this context, harvesting solutions appears as an alternative to provide these sensors and devices with self-sustained operation [24].

Table 2 provides an indicative list of attainable harvested values, corresponding to solar, kinetic, thermal and electromagnetic harvesters based on existing products or published results in the literature [25]. Even if the solar power appears as the largest and most commonly available source of ambient power, a challenge of increasing its power conversion efficiency while maintaining a low cost associated with the materials and fabrication conditions is for an extended use [26]. In the case of kinetic harvesters, the major challenge is the design of multiband or frequency

Table 2 Indicative harvested power from different transducers [25]

Energy sources	Harvested power	Condition/Available power
Light/Solar	60 mW	6.3 cm × 3.8 cm flexible solar cell AM1.5 Sunlight (100 mW·cm^{-2})
Kinetic/Mechanical	8.4 mW	Piezoelectric shoe mounted
Thermal	0.52 mW	TEG ($\Delta T = 5.6\,K$)
Electromagnetic	0.0015 mW	Ambient power density 0.15 μW·cm^{-2}

tuneable harvesters. Research on the field of thermal energy harvesters consists of optimizing the related devices and circuit topologies in order to increase the conversion efficiency [27]. Electromagnetic harvesters provide the lowest harvested power. However they additionally allow a wireless power transmission (WPT): the capability to intentionally power a sensor device using a dedicate transmitter, which is the case of the passive RFID technology,

The utilization of electromagnetic energy harvesters is supported by the fact that sensors typically operate in a wireless environment, which means that they require the use of antennas and therefore the implementation of electromagnetics harvesters comes with a minimal cost.

3.1 Electromagnetic Harvesters

The concept of WPT is not new; rather it was demonstrated in 1899 by Tesla who carried out his experiments on power transmission by radio waves (Fig. 13). The main lines of historical research and development on wireless power transmission are listed below [28]:

- 1864: James C. Maxwell predicted the existence of radio waves;
- 1884: John H. Poynting defined the Poynting vector to quantify electromagnetic energy;
- 1888: Heinrich Hertz showed experimental evidence of radio waves;
- 1899: Marchese G. Marconi and Reginald Fessenden invented wireless communications via radio waves;
- 1856–1943: Nikola Tesla conducted the first wireless power transmission experiment;
- 1889: Wardenclyfee Tower was proposed by Tesla;
- World War II: Microwave Energy Converter was invented;
- 1940–50s: Photovoltaic Cell was built;
- 1958: US Solar Power Satellite (SPS) was proposed;
- 1964: William C. Brown started the first microwave power transmission;
- 1968: Peter Glaser proposed SPS System;

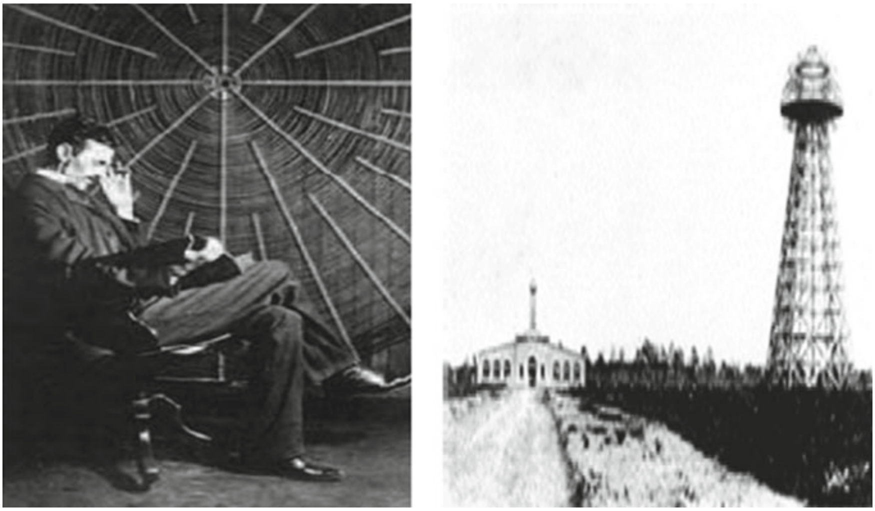


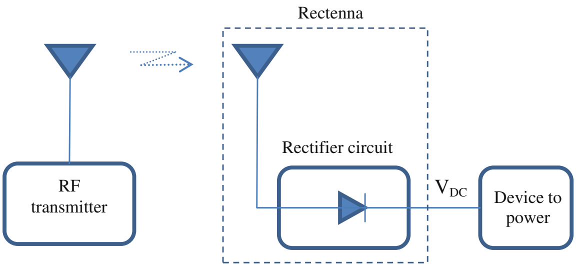
Fig. 13 Nikola Tesla proposed a gigantic coil connecting to a high mast of 200-ft with a 3 ft-diameter ball at its *top*. He fed 300 kW power to the Tesla coil resonated at 150 kHz and reached the RF potential of 100 MV at the top sphere [30]

- 1969: William C. Brown patented the device used to convert electromagnetic power to DC power, called rectenna [29] 1970s Oil Embargo turned out;
- 1978-1981: US Department of Energy Program was supported;
- 1980s: Japanese SPS System started;
- 1987: Canadian Project started;
- 1995: NASA's Fresh Look was conducted;
- 1999: NASA's SERT was supported;
- 1990s: French Grand Bassin–La Reunion was built;
- 2000: Japanese Project and 8 Joint Countries were reported;
- 2012: Chinese Project to be launched (2 national wide meetings were held and white papers were submitted);
- 2025: Low cost model demonstration will be expected.

Was in 1969 when the rectenna, device used to convert RF power to DC power was patented, then establishing the basis for the actual electromagnetic energy harvesting in the IoT era, where the device to be powered are presumed to be sensors integrating simple computing and communication capabilities into common objects of everyday use.

Figure 14 shows a simplified schematic of a WPT scenery. On one side there is a transmitting device that radiates a RF signal at a certain frequency and with certain power. On the other side there is a rectenna formed by an antenna and a rectifier circuit that collects the RF signal and convert it into DC power. One of the key parameters when designing WPT systems is the maximization of the RF to DC efficiency conversion. This will limit the performance of the final powered device.

Fig. 14 Simplified schematic of a WPT [24]



Initial applications on WPT were required for a directive and high-power transmission. One of these applications for example is the proposed solar-power satellites in 1958, where the solar energy is captured and converted to electromagnetic signals that can be potentially re-radiated to the Earth as source of power [31]. Much later on, with the interest in autonomous devices, sensors led to the concept of energy harvesting in where rectennas are used to provide DC power by converting the available RF power from existing ambient low-power electromagnetic sources not specially transmitting power to the sensor, in fact powered by electromagnetic energy harvesting.

In general, WPT can be seen as a contactless manner of transferring power to a system in order to power it. There are several classifications that can be made on wireless energy transfer systems attending to the transfer mechanism and the distance between the transmitting source and the device that needs to be powered. One of these classifications divides the WPT mechanisms in two: near field and far field. Near field mechanisms include coupling and resonant inductive coupling. Far field mechanisms include radiation of RF/microwave electromagnetic signals [24]. The electromagnetic energy harvesting or dedicated WPT for WSN and passive RFID technology belong to the far field mechanism.

3.2 WPT in Passive RFID Technology

In recent times, RFID technology is a clear example of wireless power transmission where such a tag operates using the incident radio-frequency (RF) power emitted by the transmitter. A typical far-field passive RFID sensor network consists of one (or more) RFID reader and a number of RFID sensors (called tags), where these communicate data to the reader by modulating, possibly amplifying, and transmitting back a continuous wave (CW) emitted by the reader itself through a process called backscatter modulation [32, 33]. The RF field emitted by the reader is the only source of energy that allows passive tags to activate their circuitries, while more sophisticated classes of tags, referred as semi-active and active, rely on energy storage devices (simply called batteries) charged in a previous phase (see Sect. 2.2).

The architecture of a passive RFID tag is shown in Fig. 15. The radiating antenna is typically a dipole or a patch antenna. A rectifier circuit converts the input alternating

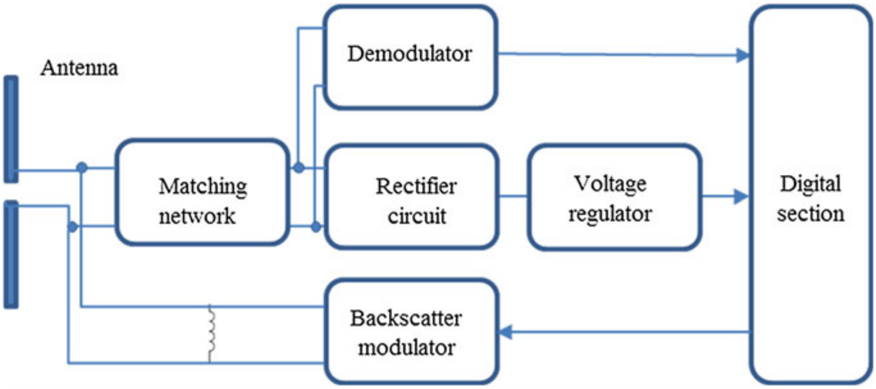


Fig. 15 Passive RFID tag architecture [35]

voltage (RF signal) into a DC voltage, which is used by a series voltage regulator to provide the regulated voltage required for the correct operation of the digital section. The rectifier is matched with the antenna in order to ensure the maximum power transfer from the tag antenna to the input of the rectifier. A backscatter modulator is used to modulate the impedance seen by the tag antenna, when transmitting [3]. The RF section is then connected to the digital section, which typically is a very simple microprocessor or a finite-state machine able to manage the communication protocol. In a general description, the conjunction of RF section (after the antenna) and digital section is known as RFID chip. To generalize, all this functions are pointed to a RFID tag but it should be understood that these RF and digital tasks are performed in fact by the RFID chip.

Smart RFID sensors

As RFID technology advances from simple passive tags to smart tags that are enhanced with sensors and computational ability, energy harvesting and power management become increasingly important. These tags may perform multiple functions, such as generating user-specific coded responses to inquiry, forming ad-hoc networks with other devices of the same class, or performing measurements of environmental parameters (e.g. temperature, pressure, or humidity). In order to facilitate these new sensing regimes, additional computing power is needed. The ability to harvest sufficient energy for long periods of operation is crucial to these applications [36]. The electromagnetic energy harvesting for smart RFID sensors in a WSN is then a critical design feature on the path to the grand vision of ubiquitous computing.

The literature defines this smart tag embodiment as the Wireless Identification and Sensing Platform (WISP) [36]. The WISP depicted in Fig. 16, is an augmented tag, powered and read by the commercial EPC Gen 2 RFID readers. Unlike conventional tags, WISPs include a fully programmable, low-power microcontroller unit (MCU) and sensors. The cornerstone of low-power operation rests on enhanced power harvesting and capacitive storage as well as envisaged future enhancements

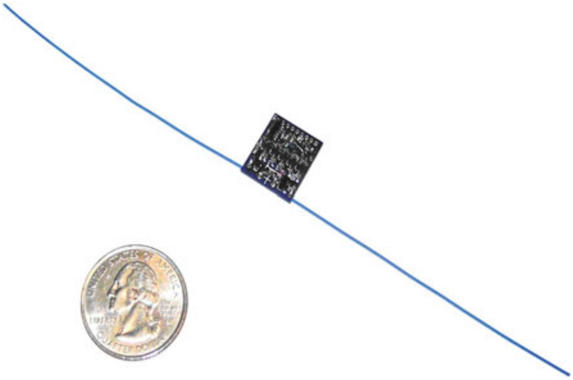


Fig. 16 WISP platform [37]

via integrated circuit and optimization of the protocol stack. In the case of the WISP, the EPC Gen 2 protocol is implemented in software on the microcontroller instead of a dedicated hardware finite state machine; this enhanced programmability is expected to be a critical component enabling future RFID system optimization [37].

The analog architecture of WISP's and RFID sensors in general slightly differs in purpose from that conventional RFID tags. Due to the relatively high power consumption of WISP, the rectifier is designed to supply more current than ordinary tags. This is why the voltage rectification is the key point on the demanding need for next generation of RFID sensors in the IoT.

3.3 Voltage Rectification

Given the recent advances in energy efficiency for the circuit components of a sensor (i.e., diodes that require less forward voltage threshold), and the low-power operation modes supported by the device itself (i.e., sleep mode consuming only millivolt), there is a visible need for revisiting energy harvesting circuit design that can successfully operate a RFID sensor node. Several works are focused on increase this efficiency conversion. Then there is still a lot of open issues when designing WPT systems, and a lot of challenges still to be achieved, especially on the receiving side [25, 33, 34].

As mentioned before, the alternating voltage induced in the tag antenna is passed through an impedance matching network and fed into the power harvester for rectification (rectifier circuit on Fig. 15). There are two important considerations to take into account in the design of voltage rectification circuits. Depending on the consumption of DC power of the digital device (a simple RFID tag or a smart tag but both on the passive classification) two models can be established:

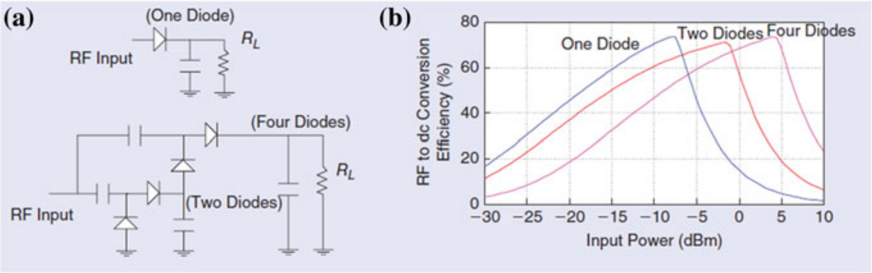


Fig. 17 RF-to-DC conversion efficiency dependency on the rectifier circuit topology. **a** Rectifier topologies. **b** RF-to-DC conversion efficiency versus RF input power [24]

- the low power model, usually used in traditional passive RFID tag without special sensing functions;
- and the duty cycle model where the RFID tag introduces some smart tasks (a microcontroller), i.e., a smart tag sensor.

Additionally and for both models and in general for all the passive RFID technology, there should be a special consideration on the non-linearity of the rectifier circuit in order to ensure the maximum transmission power from the antenna to the rectifier in the rectenna.

A low power consumption model

Figure 17 shows that for low-input power levels, topologies using a single diode lead to a better RF-to-DC conversion efficiency than topologies with more diodes. Traditionally, the optimization goal for this type of circuits with low power consumption, is to ensure that the minimum threshold voltage required by the digital logic is maintained at all times.

A schematic of different topologies of N-stage voltage multiplier conforming the rectifier are shown in Fig. 17. The power harvester is a half-wave rectifier in which current is passed to the next stage only during the positive phase of the RF signal. Traditionally, an N-stage voltage multiplier circuit (such as a Dickson multiplier) is used as rectifier, with N chosen to satisfy the minimum required voltage. Historically, Schottky diodes have been used in the multiplier circuit to utilize their very low turn on voltages, low series resistance, and low junction capacitance. The design parameters involve the number of stages of the voltage multiplier, the size of the diodes, and the coupling capacitors. The main constituent of the tag input impedance arises from the rectifier circuit (a parallel of a resistance and a capacitance [35]).

The RF-to-DC efficiency conversion depends on the topology selected for the rectifier circuit. Depending on the amount of input power at the rectifier, topologies with less number of rectifying devices may lead to better RF-to-DC conversion efficiency. This is explained because of the need of a minimum amount of input power in order to switch the rectifying devices [24].

A duty cycle model

However, in the case of RFID sensor applications when a microcontroller is used, it is not required a continuous supply of power. A duty cycling approach selected for this

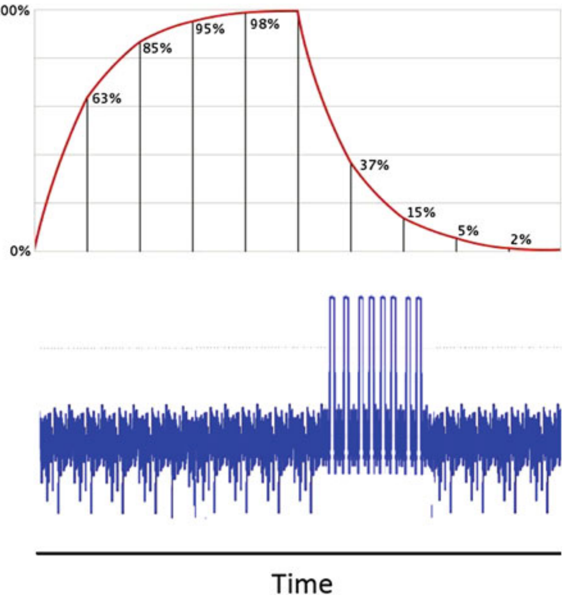


Fig. 18 WISP charge and discharge cycle of the at the *top*, microcontroller activity at the *bottom*. The duty cycle is the ratio of the time when the microcontroller is “on” to the total time of each period of charge and discharge of the WISP [37]

application allows a charge accumulation over several transmission cycles (Fig. 18). The duty cycling approach consists in reproduce a periodic sensing operation, where a duty cycle ratio is defined as the ratio of the time when the RFID sensor is “on” to the total time of each period. Once a sufficient amount of energy is harvested and the voltage threshold is met, the microcontroller can be switched “on”. In order to maintain operation of the RFID sensor enough time to let the microcontroller to accomplish its tasks, it would have to be allocated for the harvester to recharge. It means the frequency and duration of tag activity will depend on the available harvested power.

This operation mode leads to new design constraints and different optimization criteria for the rectifier stage. The optimization goals can be shifted toward producing higher voltage by sacrificing the output current since the charge can be stored over multiple read cycles. These consumption requirements are modelled by calculating the RF-to-DC conversion efficiency for different load resistances given a topology in function of the powering needs [37].

Considerations on the non-linearities in passive RFID sensors

Other important parameter that improves RF-to-DC conversion efficiency is the non-linear treatment of the rectifier circuit. In order to achieve an optimum input matching, the antenna impedance should be equal to the complex conjugate of the input impedance of the RF circuit (i.e. rectifier) to ensure the maximal power transfer. This type of matching is easily done in linear circuits where the input impedance of the circuit does not change with the input signal amplitude. However since the rectifier diodes have a non-linear behaviour, the input impedance of rectifier circuit

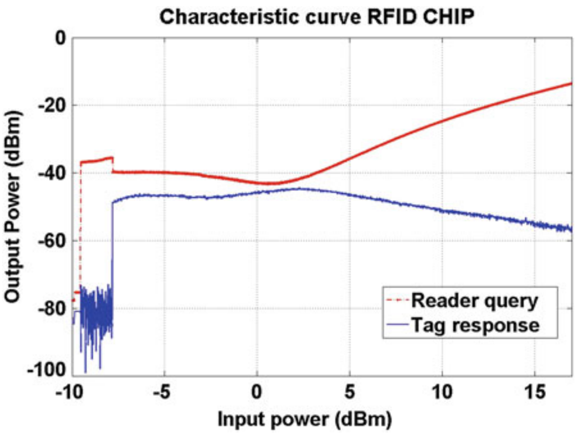


Fig. 19 Non-linear behavior of the UHF passive RFID tag. The tag response level changes in function of the input power due the impedance variations of the rectifier circuit

significantly changes with the input signal level and it is hard to get a conjugate impedance match for all values of input power. Then the rectifier circuits are typically designed for a specific value of input power level. For this reason, a behavioural model that accounts for these changes should be used on the design process. Theoretical models as the poly-harmonic distortion (PHD) [38] and simulation tools as harmonic balance (HB) [39] approximate the reactive behaviour of the circuit in order to get the proper antenna-rectifier matching.

The rectennas have similar rectifier architecture as passive RFID tags. The difference is that the harvesting rectennas achieve efficiencies of RF to DC conversion up to 77 % thanks to the treatment of the non-linearity effects with appropriate techniques of simulation as the HB, which considers the effect of the harmonics currents on the rectifier design encouraging also the effective matching with the antenna over a frequency range considering more than one impedance point minimizing the harmonic effect. In passive RFID tags contrary, the antenna design begins directly from the knowledge of one impedance value, which is the impedance of the RFID chip at the fundamental frequency described on manufacturer data sheets. Then, the design process tries to ensure the matching at the frequency of work, but there is no treatment of the harmonic currents received from the reader, which impairs the purity of the rectified DC signal, nor to those reflected in the antenna input as a result of the non-linearity of the diodes in the return link. This absence of non-linear treatment, besides that decreases the rectifier efficiency of the tag, allows the tag antenna to radiate the reflected harmonic currents generated by the rectifier that triggers in backscattered harmonics [40].

Figure 19 shows the non-linear behaviour of a UHF passive RFID tag. After the tag is activated around −8 dBm of input power (sent by the reader), its backscattered power level (output power) changes in function of the power sent by the reader. The tag response even decreases (until −60 dBm) when the input power is maximal (17 dBm). This shows the variations on the matching between antenna and chip due to the non-linear behaviour of the rectifier. The figure demonstrates how the tag has an optimal behaviour only at certain level of input power (around 2 dBm).

3.4 Conclusion: The Ubiquity of Energy

Passive sensor tags are a new area, and it is expected to appear a number of new solutions for distributed networks and sensing systems in the near future, basically powered by harvesting and not with dedicated sources of energy. The major challenges here are the need for extremely low power consumption and the limited accuracy of very low power sensors. However it is expected that new fabrication technologies, novel device structures and new processing and communication techniques will increase the power output and efficiency, while reducing the size and weight of many energy harvesters, all resumed in reduce the power consumption.

Focusing on the electromagnetic energy harvesting, its future is to add a true meaning of mobility of electrical devices by eliminating the need of centralized power sources and depending on the RF Energy existing in the air to charge these electronic devices. In this case we are not talking only about sensors or smart RFID tags, but any electrical device. This scheme imposes not only a ubiquitous computing but also the ubiquity of energy.

4 Conclusion

This chapter showed the important place that the RFID technology with its identification, communication and sensing functionalities could occupy in the IoT context. Moreover, a focus on the energy harvesting methods and in particular, the electromagnetic energy harvesting is presented while highlighting its techniques and performance.

The evolution of the RFID integrating sensing capacities, low power sensors and efficient energy harvesters will actively participate to the fast development of the IoT. It is hoped that these developments will always adopt ecological considerations and also play an important role in the development of applications that help in delivering a greener world [41]. With this vision, emerging ways of thinking must produce new ideas. For example in a tag network, each tag could benefit from the power transmitted by all the others. Preliminary works are presented in Duroc and Andia Vera [42] with an analytical development that defines some guidelines in order to choose the optimal network configuration in terms of energy efficiency.

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