Radio-Frequency Identification Systems and Advances in Tag Design

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Abstract

Radio-frequency identification (RFID) is one of the most enabling technologies that continues to be considered in numerous applications. It is basically a wireless system exploiting the principle of communication by reflected waves. This paper reviews the principle of RFID systems, and discusses the main characteristics. Since the tag is the most constrained device in RFID – since it is usually does not have a battery, and is quite versatile and low cost – the paper reviews different tag designs, as well as some advanced results and proposals.

1. Introduction

The history of radio-frequency identification's (RFID's) birth and development has been described in numerous publications [1-4, 13]. It is generally said that the principle of RFID communication was presented by H. Stockman in 1948 [5], and the first application was the identify friend or foe (IFF) system [4] introduced and developed by Watson-Watt. The IFF system consisted of a transmitter embedded on each aircraft. When it received signals from ground radar stations, it began broadcasting a signal back that identified the aircraft. This signal was due to the reflection of the plane, and depended on its size and shape. RFID works on the same principle. A signal is sent to a transponder, which wakes up and either reflects back a signal (passive system), or broadcasts a specific identification signal (active system).

Advances in RF communication systems and radar continued through the 1950s and 1960s. Researchers and engineers worldwide presented many papers explaining how RF energy could be used to remotely identify objects. R. F. Harrington developed the electromagnetic theory related to the RFID application [6, 7]. Commercial activities exploiting RFID also began during the 1960s. Electronic article surveillance (EAS) was really the first commercial application. This was a "one-bit" tag, since only the presence or the absence of a tag could be detected [1]. In the 1970s, and under the impulse of microelectronic technology, companies, universities, and government laboratories were actively engaged in the development of practical applications of RFID. Thousands of applications can be found in the literature [8], among them animal tracking, toll roads, vehicle identification, factory automation, access control, identity papers, and logistics. Even if the interest was different between Europe and the US, the 1980s was the decade for mass deployment of RFID technology. The interest in the US was mainly for transportation and access control. In Europe, the greatest interests were for animal tagging, industrial applications, and toll roads. Since the 1990s, many technological developments have dramatically expanded the functionality of RFID. Advances in microelectronics, embedded software, and RF/ microwave-circuit integration are opening the doors to new RFID applications.

UHF RFID got a boost with the founding of the Auto-ID Center at the Massachusetts Institute of Technology [3]. Professors at MIT developed research on the possibility of low-cost RFID tags that could be attached to all items, in order to track them through the supply chain [9]. The idea is to use a single serial number, stored on the microchip, for each tagged item. Data associated with the serial number on the tag would be stored in a database, which would usually be accessible over the Internet. These developments turned RFID into a networking technology, by linking objects to the Internet via the tag. This was a huge evolution of RFID technology, and a significant enlargement in terms of possible applications. The Internet of Things (IOF) is an interesting example of these new applications [10].

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This is one of the invited *Reviews of Radio Science* from Commission D.

Standards are very critical for many applications in order to ensure the interoperability of RFID systems, such as payment systems, ID documents, and tracking items in an open supply chain. During the last decade, many international standards have been defined under the supervision of the International Organization for Standardization (ISO). For example, they include ISO11784 (how data is structured on the tag) and ISO11785 (air interface protocol). The ISO has created a standard for the air-interface protocol for RFID tags used in payment systems, contact-less smart cards (ISO14443), and in vicinity cards (ISO15693); standards for testing the conformity of RFID tags and readers (ISO18047); and for testing the performance of RFID tags and readers (ISO18046) [11, 12, 13].

Due to its large domain of application – especially in everyday life – privacy and data security are topics of great impact, both for the technological side and societal interrogation. The security of RFID communications appeared very early with the aircraft IFF application: security breaches resulted in allied planes being shot down [40]. Basically, RFID is a wireless communication. Anyone can easily get unauthorized access to RFID data because they do not need line-of-sight, and communications must usually obey a given standard. Nowadays, many techniques have been developed in order to improve data security and ensure privacy. These include software and hardware protection, such as on-tag cryptography; communication techniques; denial of service; and physical protection [40].

2. RFID System Architecture

Any RFID system is composed of three main elements, as depicted in Figure 1. The most important element is the tag or transponder, which contains the information, or at least a part of it. The second element is the reader or the interrogator and its antenna. The latter can be integrated into the reader, or can be separated from the reader. The RFID reader emits a radio signal at a fixed frequency, which is used to power up the tag, and communicates with it using the backscattering technique. The third element is usually the database for the application, which can be of varying sizes and sophistication, depending on the processed data and security constraints. In some specific applications, the database is integrated into the reader. Due to RF signal properties, the reader is able to communicate through a large variety of material and obstacles, including conductors, but under restricted configurations in term of positioning. This reading ability over a wide range of propagation conditions differentiates RFID from optical barcode, and thus explains the huge interest for many applications.

RFID is fundamentally wireless communication, using radio waves of the electromagnetic spectrum. It operates in the unlicensed part of the spectrum known as ISM (industrial, scientific, and medical). The frequency, power limitations, communication protocols, and standards can vary for different regions in the world. This is particularly true for RFID in the UHF band. The operating frequencies are grouped in different bands. The data rates and reading ranges are quite different from one band to another. Table 1 summarizes the RFID bands and some of their practical characteristics.

RFID is a very specific technology that obeys a number of standards and regulations. There are many other wireless technologies, such as ZigBee, Bluetooh, Wi-Fi, and, more recently, UWB. These technologies are designed for very different uses and therefore have different functionalities; however, there is shared ground among all. Applications based on "mixing" these technologies are being developed in many labs. Among them, the real-time locating systems (RTLS) [14] and the Internet of Things (IOF) [10] are exploiting RFID properties.

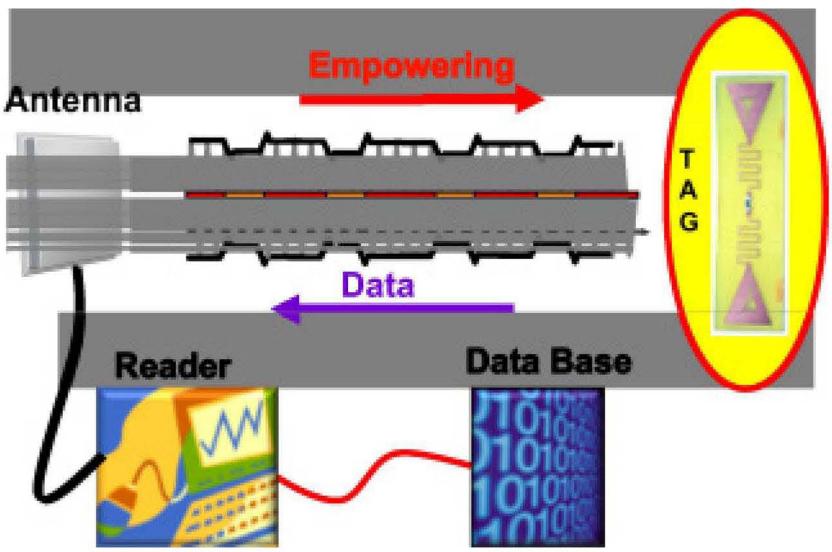

Figure 1. The elements of RFID systems

	LF	HF	UHF	Microwave
Band	125 kHz, 134 kHz	13.56 MHz	433 MHz, 865 MHz, 956 MHz	2.45 GHz, 5.8 GHz
Typical reading range	30 cm	1 m	<10 m passive tags, up to 100 m active tags	Up to 10 m
Typical data rate	<1 kbps	Tens of kbps	10 - 100 kbps	100 kbps
Main characteristics	Short range, low data, penetrates metal	Good range, good rate, penetrates water	Very good range, high rate, can't penetrate water or metal	Very good range, high rate, can't penetrate water or metal
Applications	Animal ID, car	Smart label, contactless card, access control, security	Tracking, logistics, automation	Moving objects

Table 1: RFID bands and their main characteristics

3. RFID Tags

The tag is certainly the most important element in any RFID system. Even if the overall performance of the application depends on the characteristics of each component, the performance of the tag is the limiting parameter. Most of the constraints are applied to the tag. This leads to a large variety of tag architectures, with quite different physical shapes and electrical configurations. In all cases, the tag is mainly composed of two elements: the antenna, which ensures the wireless communication, and a device that memorizes the information. The latter can be an integrated circuti (IC), but certain configurations without an IC are known as chip-less tags. They roughly operate like optical barcode, but do not require line-of-sight communication, and thus can be interrogated over obstacles. The other distinctive parameter is the manufacturing technology. In order to meet the low-cost requirement, organic printed electronics, based on thin-film-transistor circuits (TFTC), are being considered. Much progress have been made, and all-printed HF tags have been recently demonstrated [16, 22]. A possible classification of the different tag families is given in Figure 2.

The most available tags are the passive HF and UHF configurations. Many manufacturers exist worldwide, and can be found elsewhere [3].

Passive, low-cost tags are of great interest in numerous applications. Considerable advances have been made in the design of these tags, but there is still very active worldwide research and development, in order to improve the performance, lower the cost, and implement new applications. We should make a distinction between LF, HF, and UHF tags. Indeed, for LF and HF tags and readers, the metallic strap that is the interface between the integrated circuit and the reader strictly speaking is not an antenna, but a coil. The physical principle of data transfer is not based on propagating electromagnetic waves, as in UHF, but on the variation of the quasistatic magnetic or electric field. The

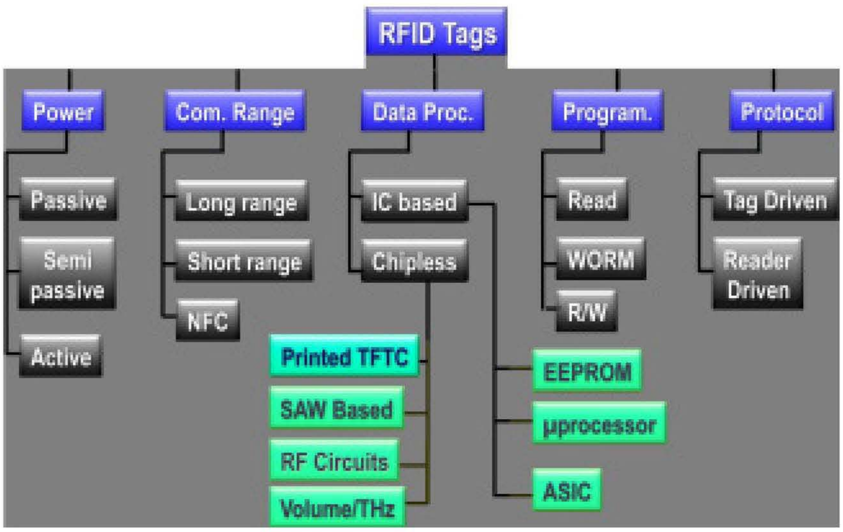

Figure 2. RFID tag classification.

objective is to maximize the coupling (inductive or capacitive) between the transponder and the reader. As inductive coupling represents the physical operation of the majority of HF tags, coils are often used as an antenna for both the transponder and the reader. The coil is modeled by an equivalent *RLC* circuit, and the electrical characteristics of the chip are supplied by the manufacturer. For coil design, the transition from geometrical to electrical parameters is obtained thanks to analytical formulas [2]. An optimization step, using an electromagnetic simulator, should complete the design phase. HF RFID is a robust technology, which greatly facilitates its full-scale deployment. It has been mature for several years: the advantages and limitations in terms of applications are actually well established.

The design of UHF tags is more complex and time consuming because there are no realistic analytical formulas linking the geometric parameters to the electric model. Moreover, one can notice that RFID UHF frequencies are not the same worldwide, which adds complexity, since interoperability is needed. The antenna design is thus the most decisive part, and may be considered the heart of a UHF RFID system. The antenna has to recover enough energy to power up the chip, and at the same time, it must backscatter enough energy towards the reader. It is thus necessary to optimize the power transferred from the antenna to the chip so that some power is re-radiated from the antenna to the reader. In practice, it should be noted that given the sensitivity of readers compared to tags, the power arriving at the tag is the important parameter. Since the reader is powered, unlike the tag, the reader will always be able to collect information if the tag receives sufficient power. The general design approach of UHF RFID antennas is entirely based on this principle. However, in some specific cases, the reader just receiving the backscattered waves from the tag is not a sufficient condition for proper operation. Indeed, the two encoding states (0 and 1 at baseband) must be distinguished by the reader. To do this in practice, the measurement of the differential radar cross section (or Delta RCS), i.e., the difference of the radar cross section for each state, should be done to get the information on the robustness of the communication [23, 24].

Considering the design phase of the transponder, the antenna design necessarily comes after the choice of the chip. For the RFID UHF antenna designer, the chip specifications may be summarized in two parameters: the impedance (Z_{IC}), and the minimum operating power of the chip (P_{ICmin}). We must also take into account the size of the chip, as well as the assembly process. Indeed, parasitic elements – which can be modeled by capacitance, C_{as}, and resistance, R_{as} – are associated with each assembly/packaging process. The chip impedance has to be modified to include the parasitic elements. Additional losses of around 1 dB could affect the minimum operating power. It can be seen that the problem is actually more complex than it seems to be. Indeed, the data transfer is based on the change of either the amplitude or phase of the re-radiated signal. This depends on whether the real or reactive part of the impedance changes. It results in the existence of two chip impedances, given as Z_{IC0} and Z_{IC1}. These impedances are functions not only of the frequency, but also of the power supply to the chip.

Unlike the frequency dependence of Z_{IC0}, chip suppliers do not provide information on Z_{IC1}. Indeed, the integrated circuit front-end impedance is depicted as a serial equivalent circuit, with a capacity (C_{IC}) and a resistance (R_{IC}). It is important to note that not having any information on the second state of the chip, Z_{IC1}, will limit the design. The tag's performance is characterized by two parameters: P_{min} and ΔRCS. However, only the optimization of the activation power, P_{ICmin} can be obtained by simulation. Very little information is available regarding the power-dependent impedance. The impedance values are therefore given for a specific power: generally, the minimum operating power. Furthermore, all these parameters are relatively difficult to measure, and generally vary according to the communications protocol, i.e., the type of query sent to the chip (writing, reading mode).

Besides chip specifications, materials used in the realization of the antenna are also vital inputs for designing an antenna. In most applications, the choice is governed by the cost of the material. In the case of passive tags, standard manufacturing processes are used, and very-low-cost dielectrics are preferred (essentially, very thin plastic material of polyethylene terephthalate (PET)). For the same reason, aluminum is often preferred over copper. Obviously, this choice is based on cost, and not on the electromagnetic characteristics that affect the performance of the tag. Moreover, the field of RFID applications is wide, and it is clear that tags can be applied to many kinds of object, with different shapes and materials. For cost reasons, the label antenna should thus mostly be used in the largest possible number of environments: different objects to track, different tag densities, tags made to work on plane or slightly curved media, etc. [17, 18].

Operating Frequency	Minimum Operating Power Supply (P_{ICmin})	Input Impedance (Z)	Input Parallel Capacitance (C_{IC})/ Resistance (R_{IC})	Parallel Assembly Capacitance (C_{as})
840-960 MHz	-15 dBm up to -18 dBm	$24 - j195$	890 fF/1.7 kΩ	~ 100 fF

Table 2: Typical input parameters for antenna design

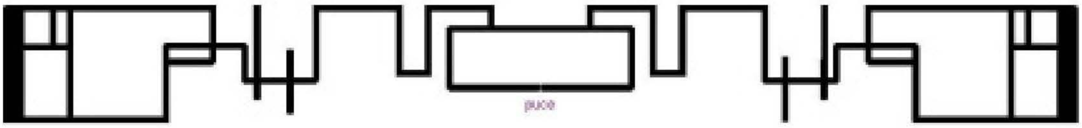

Figure 3. An example of automatic tag design using a genetic algorithm. One can notice the generation of a loop connected to the RFID chip for matching purposes.

There are several tag dimensions that are more or less "standard" (9×1 cm^2 , 9×3 cm^2 , 7×7 cm^2). However, compared to the UHF wavelength (31 cm at 960 MHz), these dimensions are quite small, and designers of RFID antennas must implement efficient miniaturization techniques [19]. RFID UHF antennas are mainly planar dipole antennas, in order to have omnidirectional space coverage. The most popular method of miniaturization is to simply to fold the arms of the dipole in order to get the desired template, as well as good EM features. As the material of the item to which the tag will be applied is not known, traditional antenna-design approaches cannot be directly applied. Indeed, designers are supposed to realize an antenna without knowing the direct environment of the tag. Moreover, these different materials directly impact the performance of the label. The solution is to try to design tags that are robust to their environment, as much as possible. However, most of the time these "universal" tags are optimized in open space (taking into account the dielectric slab), with the idea of maximizing the operating bandwidth of the transponder. Afterwards, the effects of substrates can be investigated by applying tags to various dielectrics. The impact of the direct environment on the label can be evaluated by using a set of reference materials. This design-approach principle is based on the fact that the presence of a dielectric in the vicinity of an antenna tends to shift down the operating frequency. Thus, the more the frequency range is in free space, the better will be the tag's performance in the practically disturbed environments.

All the constraints mentioned above are very important compared to the degree of freedom, so compromises are to be made. We can notice that miniaturization constraints imply a reduction in the antenna's bandwidth, and therefore limit the scope of the tags. This is why the antenna design is one of the most critical aspects in passive UHF systems. We are not arguing that this exercise is impractical. However, it can be said that this fact contributes to the lack of reliability of the UHF technology, and is sometimes observed in practice. This also explains why the design of UHF RFID antennas remains largely empirical, and requires much expertise.

Typical parameters for antenna design are given Table 2. These parameters are the operating frequency; the minimum operating power of the chip, P_{ICmin}; the IC's input impedance and its equivalent-circuit parameter values (C_{IC} , R_{IC}); and the IC's parallel parasitic capacitance. P_{ICmin} can be sued to evaluate the performance of the tags. The goal is to design an antenna able to power the chip over the largest frequency range. EM simulators must therefore be used. The structures under consideration are mostly planar, so commercial two-and-one-half-dimensional EM simulators are often used. The next question concerns the design approach that should be adopted to achieve the antenna's specifications. To start with, the design approach is rather based on the knowledge and experience of the designer. Such an approach can be described in two distinct steps. The first step is to resize a loop around the IC to compensate for its capacitive part. The system loop and chip will resonate around the desired UHF frequency, the same as for the HF tag design. The other advantage of the loop is that it will facilitate near-field communication. Indeed, in practice, readers that are used to write the tags are most of the time positioned in the near field of the antenna. This method presents the greater advantage of preventing cross-reading. The second step consists of adding metal strips, such as dipoles, to the loop. The radiating element could be either physically connected to the loop, or positioned near the loop, in order to achieve EM coupling. The coupling between the loop and the radiating element is crucial. Indeed, the space between the two arms (conducted coupling) and the space between the radiating element and the loop (inductive coupling) are key parameters that have a direct

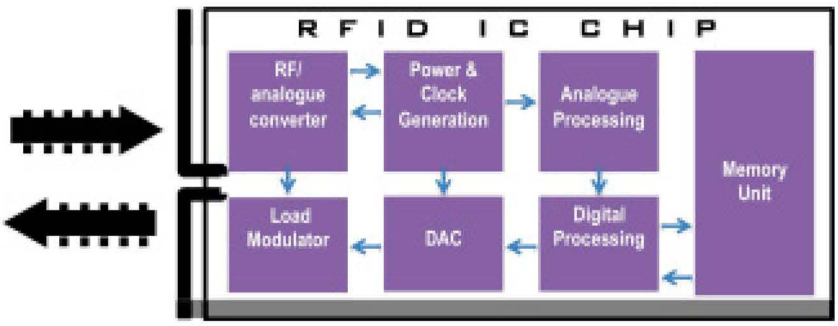

Figure4. An example block diagram of an RFID chip.

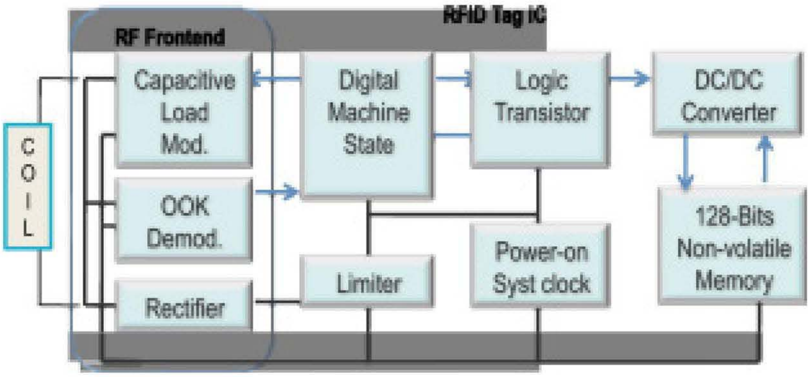

Figure 5. A block diagram of the fully integrated tag on-chip integrated antenna (OCA)

impact on the performance of the label. While the total length of the radiating element has an impact on the resonant frequency, this specific spacing can affect the bandwidth of the label's antenna. To reduce the tag's dimensions, the metallic strips can be folded back in a serpentine manner, resulting in meander lines or original shapes. To improve the bandwidth, rounded shapes rather than right angles are preferred. Finally, the antenna topology obtained is validated and optimized.

An innovative design approach, taking into account a complex environment during the design phase, has been developed. Original topologies of antennas are generated automatically, and selected according to the imposed constraints. Our approach is thus based on the advantages of combining the EM software and optimization processes. We use an optimization process based on the concept of genetic algorithms (GAs) to satisfy the constraints set during the design process. The optimization consists of an iterative process that first generates the antenna's shape, then simulates it, and finally evaluates its performance according to the imposed constraints. The antenna's shape thus changes during iteration based on an evolutionary principle. This is repeated until an antenna design that satisfies the project's specification (as well as possible) is obtained [18]. An example of a design is given in Figure 3.

4. RFID Chip

RFID tags are composed of an IC chip that memorizes the information. For passive tags, the IC chip has no battery, and it generates the needed power for biasing from the interrogation signal sent by the reader. This ability to harvest "ambient energy" is very specific to RFID. The IC chip thus has many functions, all integrated into the same circuit. A typical block diagram of the RFID chip is given in Figure 4.

Any RFID chip has an RF front end that has the function of receiving and transmitting (in fact, reflecting) the power emitted by the reader. In the receiving mode, the IC circuit must be matched to the antenna in order to collect enough power. To the contrary, in the transmitting mode, the load-modulation technique is used in order to generate two different levels of reflection, corresponding to the two signal states, for digital communication. The digital section is composed of a processing unit (state machine) and a memory unit. The memory can be electrically erasable and programmable read-only memory (EEPROM), static random-access memory (SRAM), or ferroelectric random-access memory (FRAM). The EEPROM is used in numerous applications, due to its low cost of manufacturing and large number of reprogramming cycles. Typical programmable memory sizes are from 96 to 2048 bits. Compared to EERPROM, FRAM chips show low reading power consumption and lower writing times. However, their manufacturing is more difficult [15]. More-complex tags are composed of a microprocessor-based chip. They are able to process more-sophisticated functions, such as authentication, as is necessary in smart-card applications. On the other hand, it is expected that transponders with sensors (temperature, vibration, pressure) and processing capabilities will be developed in the near future [20].

In order to lower the cost of IC-based tags, there are developments aimed to integrate the antenna and the chip, and to develop a technology that is able to realize the IC chip and the antenna in the same technological process. This will avoid the expensive process of a connection between the antenna and the RFID chip, as is the case for common tags. One way is to integrate the antenna on the top of the IC chip. In [21], a fully integrated tag, called OCA (on-chip integrated antenna), was presented. A passive-tag chip with 128-bit nonvolatile memory was realized using 0.13µm CMOS technology, and operating at 2.45 GHz, in the near-field regime. A block diagram of the IC section is shown Figure 5. The antenna was fabricated on the top of the chip using post-processing technology. It was a coil, fabricated on a thick, undoped silicon-glass (USG) layer, and connected with the underlying circuits through vias etched in the undoped silicon-glass layer. The integrated tag was smaller than $0.5\ mm^2$, with a thickness of 0.1 mm. With the reader generating an output power of 0.5 W, the RFID system was able to perform RF read/write 100-kbps bi-directional communication at a distance of 0.5 mm.

Another way to meet the challenge of cost reduction is to use one of the most-promising alternatives to silicon, i.e., printed organic electronics. Many advances have been

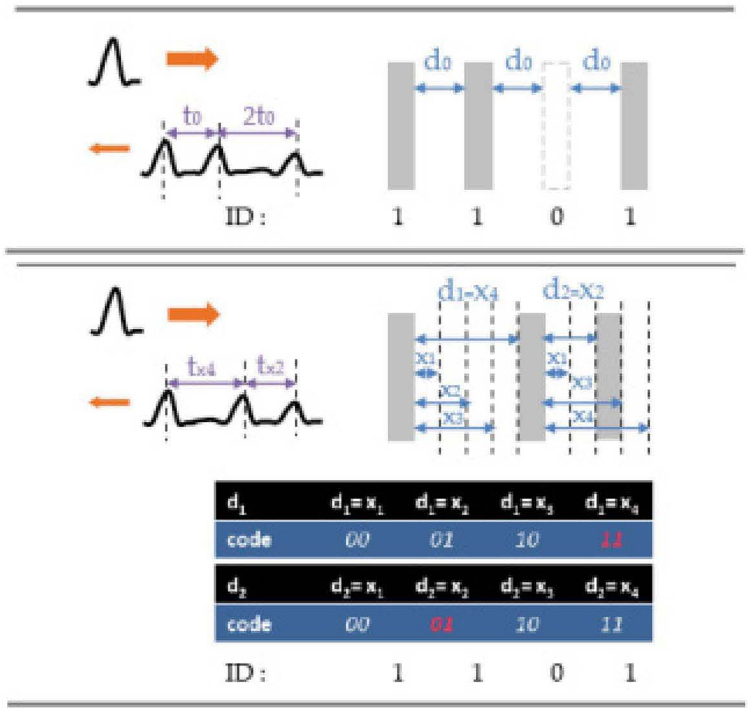

Figure 6. The interrogation pulse and reflected waves. An example of different ways to encode data using: (a) the presence or absence of a specific reflector, (b) the position between reflectors. In both cases, the data encoded correspond to the same ID: 1101.

accomplished over the past few years, and key electronic components have been developed, such as transistors and diodes. In [16], a multi-bit RFID transponder, based on polymer electronics, was presented. A four-bit organic CMOS chip was demonstrated, as well communication with the reader. In [22], there was another demonstration of an all-printed 13.56 MHz one-bit RFID tag. These recent developments are seen as important steps towards achieving truly low-cost RFID tags that are manufactured by the "kilometer." The final objective is to set up a manufacturing technology using only a gravure and ink-jet printer. This will allow completely roll-to-roll manufactured tags.

5. Chip-Less Tags

Many designers consider "chipless" as a very serious competitor to optical barcode, and many research and development projects have been dedicated to the development of this form of tag [15, 25]. The chipless tags, also called "RF barcode," are usually devices manufactured with low-cost components, and generally electromagnetic reflective or absorptive materials. Compared to passive tags, chipless tags generally have the following characteristics:

- low cost, at least in volume;
- contactless, short ranges of less than one meter;
- better reliability: thermal and mechanical behaviors much better than the tags integrating a chip.

However, these advantages should be balanced with the limited storage capacity (a few tens of bits) and the non-rewriteable characteristic (read-only tags) of these devices. Another drawback is the cost of the reader, which could be higher compared to chip-based readers.

Chipless tags are composed of different families, based on the various approaches among them:

- The acousto-optical properties of materials, more precisely, surface acoustic wave (SAW) devices [26]. This approach, already commercialized, is by far the most mature chipless RFID technology.
- Printed organic transistors. This prospective approach is mainly based on the same principle of passive RFID, and is gaining in interest due to recent developments [27].
- The electromagnetic properties of RF waves in passive microwave integrated circuits. Numerous approaches can be found in the literature [28-35]. This approach is in the developing stage.
- Electromagnetic signature of reflective surfaces. This approach is the most similar to optical barcode. It is based on implementing a specific geometry to a reflecting surface in order to generate a unique electromagnetic signature, as in radar. This approach is also under development [36].

The principle of information encoding, which consists of encoding the identification number of the tag, is based on the generation of a specific temporal or frequency footprint. This temporal footprint can be obtained by the generation of echoes due to the reflection of an incident impulse, as illustrated in Figure 6. In the frequency domain, one can

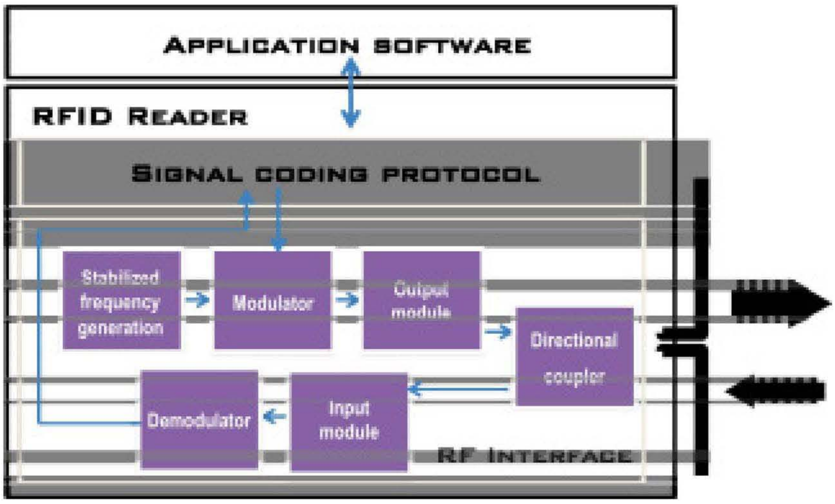

Figure 7. A typical block diagram of the reader. Some readers integrate the antenna and the database.

characterize the spectrum of the tag's backscattering. There are several ways to encode binary data.

Two easy-to-implement approaches for information encoding consist of the following:

- Locating the presence or absence of a specific signal that is known to occur at a given time or frequency (this is like using on-off keying modulation (OOK)).
- Measuring the gap (in time or in frequency) between two characteristic signals (this is like using a pulse-position modulation (PPM)).

The signals are generally electromagnetic waves; one can use the amplitude or the phase to encode the information.

In the temporal domain, the design of devices rests on the concept of reflecting signals due to discontinuities. These discontinuities can typically be due to a rough variation of the geometries of the transition line (microwave approach) or of the medium (optical approach). A simple technique is to place a number of discontinuities at different distances, in order to obtain a specific signal where the information is encoded by the temporal gap between the impulses. These discontinuities can be easily realized with localized [28] or distributed [29] capacitances, placed on a transmission line.

In the frequency domain, it is possible to encode the information by taking into account the amplitude variations in the frequency of the backscattering wave. Such work has been done by placing resonating elements near a transmission line [30, 31], or by exploiting the resonance frequency of a network of dipoles [32, 33]. Some studies have shown that it is particularly interesting to encode information using the wave's phase variations [34, 35].

The introduction of two-dimensional (i.e., volume and surface coding) structures could tackle some of the limitations of chipless structures. We also think that these different principles presented above can be transferred to higher frequencies, in order to offer miniaturized tag solutions with higher capacities. Recently, devices based on holographic principles [37] have been investigated. Such a solution requires imaging to read the information. In [38], we proposed a considerably simpler approach. The device rests on a specific spectral-signature recognition, which can be measured by a single detector. This specific spectral signature could be obtained thanks to multilayer structures.

On the other hand, mitigation of the clutter effect must be considered in RFID applications, and especially when using chipless configurations. In fact, passive UHF RFID systems are known to have reading distances of some meters, and can be very sensitive to the environment and to multi-user interference. Most of these limitations are due to the standard RFID CW-oriented communication. Using ultra-wideband (UWB) communication could avoid most of the previous effects. Indeed, UWB technology, characterized by the transmission of sub-nanosecond pulses, is very robust to multipath and to a large number of devices operating in a small area [50]. The use of a UWB signal is thus very attractive and enabling for chipless RFID.

6. Reader

An RFID reader/writer is a device used to interrogate an RFID transponder. The main function of an RFID reader is to collect the data stored in the tag. This information can be the EPC code (electronic product code) [42], information on the state of operation, or any other data contained in the internal memory of the tag. The second main function of the reader is to write information into the tag. In addition to this ability to code and decode the information received or sent from the tag, the reader ensures the link to middleware that is specific to the application and its physical environment. The middleware is the "embedded intelligence" of the reader: it notably allows filtering incoming tag data that has to be sent to the operating software. A typical block diagram of reader is given Figure 7.

In the case of passive UHF tags, the communication between the reader and the label antenna can be described as follows. The reader transmits a continuous wave (CW) that encodes no information to RFID tag to supply the tags. Indeed, the tag converts the received CW to dc power, and thus generates the biasing signals. Only the tags receiving enough energy – i.e., the tags near the reader – will be able to communicate. In addition, the CW is also used as a carrier signal. In this way, the reader sends a query to interrogate the transponder. The reader listens to the answers and drives the communications, for example, in order to eliminate or reduce tag collision. Finally, it sends only pertinent information upstream to the host.

If we set aside the tag's performance, the maximum reading range of the system is mainly determined by the emitted power and the gain of the antenna. Depending on the dimensions of the reader, the fact that it is portable or not, mainly two types of readers thus exist: proximity readers (having a range of a few tens of centimeters, often used for mobile applications), and short-distance readers (from 1 to 10 m). For a long-distance reader (up to a hundred meters), the use of active tags is required. Besides the reading range, the reading rate (which is the number of times that the reader can read a single tag per second) has to be considered. This parameter depends strongly on the embedded functionalities of the reader. Moreover, RFID devices have to meet the RF emissions limitations and power restrictions (3.3 W or 4 W EIRP, depending on the region of the world). If the application requires more power to properly operate, a solution can be to shield all of the system. For this, tunnel readers have been designed, in order to increase the reading rates in some specific RFID applications.

There is a wide variety of reader antennas, mainly depending on the application [39]. Indeed, antennas are selected based on the type of reading to be achieved, the reading conditions, the type of antenna labels, and the environment of the reader. The reader's antenna can be internal or external. Given the dimension restrictions, internal antennas generally present lower radiation gain. Antennas can be linearly or circularly polarized. In the case of UHF, tags are linear polarized most of the time, and applied with any orientation: thus, circularly polarized antennas are more popular. Depending on the application, different approaches are used to increase the reading rates. For instance, several antennas with a single reader can be a good solution to improve the coverage of a large area. A multiplexing approach is used to manage these different antennas. Finally, an RFID reader can have more or fewer functionalities, such as anti-collision technology, duplicate elimination, and output-power control. Self-adaptation to the environment to operate under optimal conditions can also be implemented for the most-sophisticated products.

As we can notice in Figure 7, the reader requires a device that separates the transmitted and the received signals. The performance of the reader will strongly depend on the isolation between the transmission and reception paths. Two main techniques exist. The first technique uses different transmitting and receiving antennas, located suitably apart from each other (known as bistatic). The second technique utilizes a single antenna and a device that separates transmitted and received signals (monostatic). This device can be a directional coupler or a circulator. In both cases, the isolation must be as high as possible, usually more than 20 dB, especially when the tags are moving. Perfect isolation is not achievable with any of those approaches. A leaking carrier is thus present at the receiver, and its reduction is needed. Several approaches have been studied [40]; some of them are used in radar applications [41].

7. Applications

The use of RFID as an enabling technology has been considered in a large variety of applications: thousands of study examples are in the literature [8]. Nowadays, no one really knows in what domain RFID will be applied in the future and the advantages it will offer, but the potentials for development and innovation remain very attractive.

Logistics is one of the domains in which the application of RFID is very desired, and major companies are developing pilots. Such pilots are usually based on the use of passive UHF tags, due to their quite good maturity. However, deployment of this technology in high volumes is still being held back by the relatively high cost of these tags, as well as some technical problems due to the characteristics of UHF signals. The environment (the object on which the tag is placed, as well as the nearby environment) in which the tags are used considerably affects their characteristics. In particular, when the tag is placed in an environment different from that for which it was specifically designed, the performance of the system can deteriorate rapidly, thereby limiting the potential for the technology. This explains why the design of UHF tags is still a challenging issue. Despite that, RFID and the EPC (electronic product code) [42] are gaining interest for the logistics pipeline. There they are expected to have a major impact on the efficiency of the whole chain, which also includes new business opportunities and strategies [43].

Battery-powered wireless sensors are the most common commercial wireless sensors used today. However, limited battery life and higher costs limit their deployment in some sensing applications. The use of passive RFID tags as an environmental sensor is a very attractive approach. RFID-tag-based sensors have several advantages, including low cost, capacity for ubiquitous deployment, and theoretically infinite lifetime, all of which are highly desirable properties. There are many examples where passive tags are used as sensors. In [44], it the wireless monitoring of the filling level of plastic containers with both low-dielectric-contrast (sugar powder) and high-dielectric-contrast (water) substances was demonstrated. In these cases, the sensed quantity was the effective permittivity of the box container linked to the filling level. In [45], it was demonstrated that it is possible to wirelessly monitor low-voltage equipment in electrical distribution boards by using passive HF tags implemented in specific positions in the switchboards. Only standard tags were used to achieve a low-cost and robust solution, which fits existing switchboards very well. In [46], an RFID-tag antenna based on a displacement sensor was described. A metal plate was fixed to the bottom of a simply supported beam at a certain distance from an RFID tag. As the midpoint of the beam displaced under loading, the metal plate came closer to the RFID tag, modifying the tag antenna's impedance, and changing the tag's power properties. A dynamic range of about 2.5 cm and an accuracy of about 2 mm were reported. In [47], an UHF tag was used as a moisture sensor. The tag was embedded in layers of absorbent material, such as blotting paper. When the blotting paper absorbed the moisture, it detuned the tag's antenna. As the amount of moisture absorbed increased, the detuning increased, changing the tag's response. The tag could thus be used as a moisture sensor. In addition to the embedded tag, a second tag, located in free space, could be used to obtain a calibrated response.

The sensors described in the previous examples were constructed utilizing low-cost standard tags, and no additional costs were incurred for custom silicon manufacturing. In the four cases, the sensing capabilities were mainly due to the electromagnetic behavior of the tag's antenna. It was evident that specific a antenna design could be realized in such a manner that the sensitivity to a given environmental parameter was investigated and optimized. On the other hand, such sensor relied completely on the reader-transmitted power for tag operations and, in this sense, had a theoretically infinite lifetime. This directly addresses the concern about sensor life in infrastructure monitoring. Moreover, tag-reader and reader communication protocols could conform to existing standards, such as the EPCGen 2 Protocol [42], which provides the additional benefit of interoperability.

Moreover, the idea of sensor-oriented design has been extended to the concept of multi-port tags, i.e., tags integrating several antennas or several chips. Such a concept is very powerful: indeed, it adds calibrating and correction capabilities to the sensor, as was shown in [44].

Last but not least, one of the future applications of RFID is what is known as the Internet of Things (IOT). Basically, this is a network of Internet-enabled objects, together with Web services that interact with these objects. Underlying the Internet of Things there are wireless technologies and, in particular, RFID. The Internet refrigerator is probably the most descriptive and fun example of the capabilities offered by the Internet of Things. This is a device that monitors its contents, and notifies you of any of the alerts you decide (availability of products, limited date of use). It also could notify Web sites and establish shopping lists. Indeed, it could also helps you to take care of your physical condition and health, since it knows which foods are good for you, and it is connected to your doctor. Even if we are away from this level of sophistication, this concept could lead to very useful applications. Leading large companies are offering a range of RFID sensors and technology solutions to built Internet of Things applications [48].

8. Conclusion

Nowadays, RFID is a well-established technology, accepted and applied in a large variety of domains and applications. Technically, it has two main advantages: wireless communication and battery-less transponders. From the economic point of view, the tag, which is the most important device in any RFID system, is potentially low in cost. This cost continues to decrease, thanks to technological advances, and tends towards the optical barcode cost. The previous advantages are very attractive in many practical environments. This is the reason why RFID is considered in thousands of studies evaluating its implementation and benefits. However, different applications and environments require different tag functionalities and performance. Such needs explain why research and development programs are not only still intense, but continue to progress in order to overcome some technical limitations, and also to develop new high-performance tags for specific applications. All-printed tags are very attractive for high-volume scenarios, because of their potential low cost. On the other hand, chipless tags are gaining in interest, thanks to their robustness and very-low-cost characteristics. Moreover, the use of passive tags as sensors has been demonstrated by several authors. This ability to exploit the electromagnetic properties of tags gives birth to a new sensing paradigm. It opens the door to what is known as the Internet of Things, and very powerful and sophisticated applications. However, the technology is still in its infancy, and whether it will revolutionize everyday life remains to be seen.

Privacy and data security, as well as societal issues, were not discussed in this paper. However, today they are topics of great interest, as RFID applications are rapidly expanding from supply-chain management and inventory towards ID papers, payment, health care, safety, and medical applications. On the other hand, international RFID standards and interoperability requirements can cause serious security and privacy risks. Many security solutions have been designed using cryptographic hash functions or private-key encryption algorithms that require less hardware and power resources than public-key algorithms [49]. However, they cannot satisfy all the desired properties for general RFID systems, and more research and development is needed. It is evident that the privacy issues cannot be solved by technology alone, and education and legislation must be involved, too.

9. Acknowledgments

The authors would like to thank the Conseil Général de la Drôme, the Région Rhône-Alpes, and Grenoble Institute of Technology for their help with and financial support of RFID activities at LCIS labs.

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