PART 1

Radio-Frequency Identifications

1

Introduction to RFID

1.1. General introduction to RFID

Radio frequency identification (RFID) is a major technology which, for more than a decade now, has undergone significant development in terms of applications. The traceability market includes a large number of families of tags, with each of these families fulfilling very specific needs. These tags include a label composed of an antenna and a medium for information (generally using a silicon chip); some contain a battery (active tag) and some do not (passive tag) [FIN 10, PAR 09, TED 09]. The operating principle is that of a classic wireless communication device. The reader is used to establish an interface between the identifier (ID) contained in the tag on the one side, and, on the other side, a database is used to access other information on the tag. The reader transmits a frame according to a standardized protocol, and the signal is then modulated. In the case of ultra high frequency (UHF) RFID, the tag receives part of this radio-frequency (RF) wave. The tag's antenna then collects the signal and transmits it to the RFID chip (Figure 1.1). For passive RFID tags, the power transmitted by the wave generated by the reader enables the tag to be fed, and thus to function. In addition, the reader transmits the carrier wave continuously, while the frame is sent periodically. In this case, the tag's antenna performs a type of double function: (1) ensuring the tag's power supply and (2) enabling the transmission of the "useful" signal to the chip to be processed.

We will look next at the tags that are most often found on the RFID market, specifically passive tags. Similarly, we will focus mainly on tags that function on UHF frequencies and therefore operate in remote field zones, and can enable communication over distances as small as 10 m. This family of tags is widely deployed, although this deployment has been slowed down mainly by current significant limitations in RFID technology, which will be discussed below. Throughout this book, we will also explore the importance of the tag antenna in an RFID system.

Figure 1.1. *Operation schema of an RFID system. The reader, most often linked to a database, questions the tag, located here on a packing box. In this way, the reader can recover the tag's ID, contained in the RFID chip located in the center of the tag*

Antenna design is at the heart of many of the issues currently being confronted by UHF RFID. This is all the more true, because the design of antennas for UHF RFID tags is different in many ways from classic RF antenna design. Before going into specific details about these differences, note the following two points: (1) the near environment, i.e. the object on which the tag is positioned for its use and which is unknown to the designer, although the tag must be able to function for the largest possible number of applications, for reasons of cost-effectiveness and (2) the antenna is connected to a chip which, when in operation, varies its input impedance between two values.

Based on this, a question arises for which antenna impedance value must be taken into account in order to optimize communication between the reader and the tag. We will see that the answer is not so obvious, and it becomes even less clear when we consider that the two impedance states of the chip are dependent on the frequency and the power received. The answer to this question depends largely on the intended application. Likewise, and this is the most interesting aspect, work on this point is still in progress. Indeed, numerous studies worldwide are focused on the development of this technology, which remains highly promising, that is with extremely high development potential.

If we return to the “antenna” aspect, we can see that the design of antennas compatible with the expected applications in the domain of traceability arouses a great deal of interest in the academic and industrial sectors. Miniature, low-cost, relatively broadband tag antennas currently represent a significant challenge in the field of UHF RFID systems. In practice, UHF RFID tags must function no matter what the usage environment is. As we have already noted, for economic reasons, a single tag must be able to be used no matter what item is needed to be tracked, and no matter where it is located. These parameters are highly variable, and are theoretically unknown during the tag design phase; moreover, they have an extremely important impact on performance, and must therefore be taken into account in one way or another during the design of RFID tag antennas. Indeed, the high pressure currently weighing on RFID has had a direct impact on the antenna design methods used up to now. As we will see, design approaches must make it possible to obtain tags that will be resistant to various environments. Finally, practical and economic constraints make both small dimensions and a wide operating frequency band necessary. Research in this area is extensive, aimed most often at developing a “universal” tag, which remains more illusion than reality at this point. To do this, as we will see in detail later on, the development of automated design approaches taking as many stresses as possible into consideration seems to be a vital element in the eventual success of this research. In the meantime, let us return to the different RFID technologies.

As noted above, RFID is a major technology in the field of identification. Its field of action is in a perpetual state of evolution. The first article describing the operating principle of RFID was written by Stockman in 1947 [STO 48]. The first practical application was the Identification Friend or Foe (IFF) system used during World War II to recognize Allied planes. Commercially speaking, the Electronic Article Surveillance (EAS) system was the first one developed in the 1960s and subsequently put on the market [FIN 10]. However, a fairly significant period of time was required after the appearance of the first RFID article for the technology to reach the applicative sector, that is, for it to reach a level of development sufficient for large-scale deployment.

The main advantage of RFID is its ability to automate ID capture procedures. This reduces human interaction so as to limit input errors, and increases the speed of information capture. RFID is used in thousands of applications; today, these are mainly used in the sectors of security (access control), traceability and identification, and it will soon be used in low-cost wireless sensors and short-range localization systems. From this, it is clear that each application includes its own constraints, which RFID must take into consideration. These constraints can be extremely diverse, concerning tag dimensions, costs, reliability, security, etc.; and they may even be contradictory from one application to the next. Taking the example of reading distance, it is clear that for security applications (access badges), a short distance is preferable, while for large retailers longer reading distances are needed to conduct inventories. Thus, all of these applications generate a considerable number of constraints, which have resulted in the application of not one RFID technology, but a large number of them. This is why, if we look more closely at RFID tags (Figure 1.2), we can see how widely they differ from each other. Consequently, we speak of families of RFID tags, which are necessarily composed of subfamilies, and so forth.

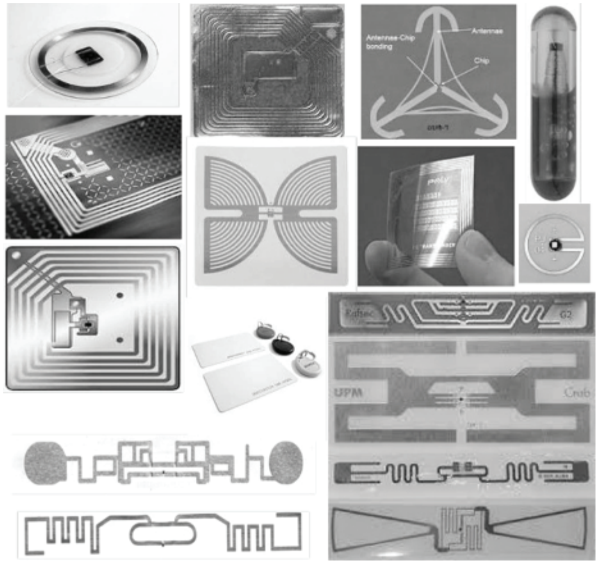

Figure 1.2. *Different types of RFID tags for various applications. Tags are not all shown on the same scale*

All the specifications introduced by applications have led designers to use several frequency bands. The use of the electromagnetic (EM) spectrum is widely restricted by governments, in terms of both frequency and power; therefore, RFID is confined to different frequency bands, sometimes very narrow ones, which do not require a license to be used. Figure 1.3 shows these different frequency bands (central frequency and associated wavelength). We can also see in this figure that an important distinction in terms of communication must be made. Two major families of RFID tags are clearly evident; the simplest way to introduce these is to go back to the applicative level. Here, we are seeking to identify the objects surrounding us, that is, mainly objects with dimensions ranging from a few centimeters to several meters. For practical reasons, tags must almost always be as small as possible, with dimensions comparable to the smallest objects being tagged. Based on this, certain standards are observed with sizes more or less comparable to that of a credit card. If we look at the wavelengths associated with the frequencies used in RFID (Figure 1.3), we can see a very wide range, from 5 cm to 2.4 km.

Consequently, we note that if we look generally at a single size for all antennas (or in any case, the same approximate size, more or less the dimensions of a credit card), these must also function in different operating systems. As Figure 1.4 shows, we have a first family of tags operating in near fields, and a second family of tags operating in far fields. In EM and applicative terms, the difference is extremely important. It enables us to obtain different reading distances: in contact or over very short distances in the first case, and over several meters in the second case. Since physical communication is completely different, we can also obtain different reading characteristics. Near-field communication is often carried out via magnetic coupling, and thus involves the use of loops by both the reader and the tag (see Figure 1.4). By using the magnetic field, reading is less disrupted in comparison to the external environment, which is most often composed of dielectric objects. To improve the extent of the reading zone, a uniform and substantial magnetic field must be transmitted throughout the zone. For far-field communication, the tag is no longer composed of a loop, but rather of an antenna (see Figure 1.4) able to receive and transmit an EM wave. Note that, to ensure far-field communications, if we place ourselves at around 900 MHz, using antennas with classic dimensions of $\lambda/2$, a minimum distance between the reader and the tag on the order of 20–30 cm is required. In practice, identification in this close-field zone (0–20 to 30 cm) must still be able to do this. For example, at the end of a tag assembly line, a manufacturer must encode its tags with a unique ID and verify that they are working properly. For practical reasons, this operation must take place with virtual contact occurring between the tag and the encoder. This is part of the reason why the vast majority of passive UHF tags include a loop around the chip, to facilitate this operation, that is, to guarantee close-field communication (see Figure 1.2).

Through these few examples, we can see how there is not a single RFID technology, rather multiple technologies that can be very different from each other. This makes RFID, from all dimensions, a subject for which an exhaustive discussion is a highly ambitious undertaking. However, this is not the objective of this book. For further details, we refer the readers to various books [BOL 10,

DOB 07, FIN 10, LAH 14, LEH 12, PAR 09]. It is also important to delineate our field of study clearly. Figure 1.5 shows one classification of families of RFID tags.

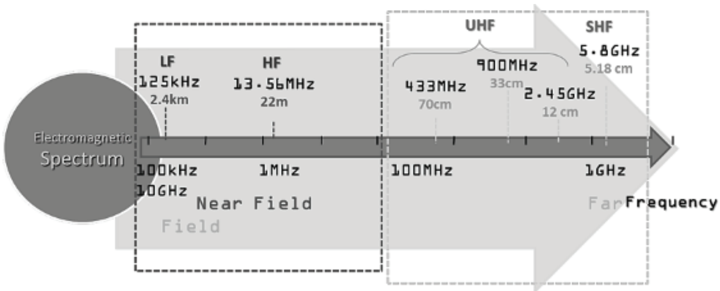

Figure 1.3. *Principal frequency bands used by RFID*

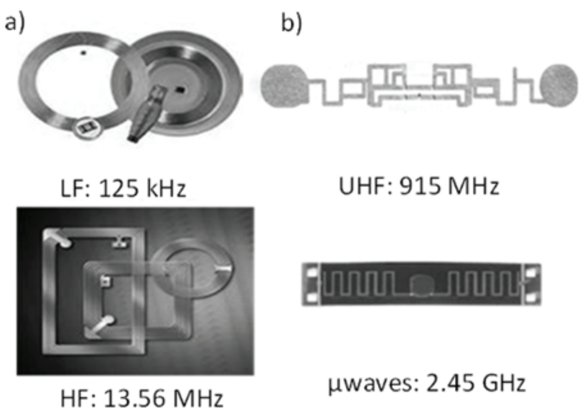

Figure 1.4. *Different types of RFID tags. a) Tags with loop "antenna" functioning in near field via magnetic coupling. b) Tags with "antenna", functioning in far field, that is, able to receive and transmit an EM wave. Tags are not all shown on the same scale*

We can define six main categories, characterized by chip feed, read range, information support, functionalities offered and programming used. We will, henceforth, focus mainly on the hardware considerations, in other words, on the first four fields. Thus, our subject of study will involve mainly passive tags (which have no battery, and in which the power supply comes from the reader only), which are able to communicate from several meters away from the reader, with or without a chip. We will also pinpoint the keys used to divert the primary function of an RFID tag – identification – in order to add functions of authentication, localization or sensor.

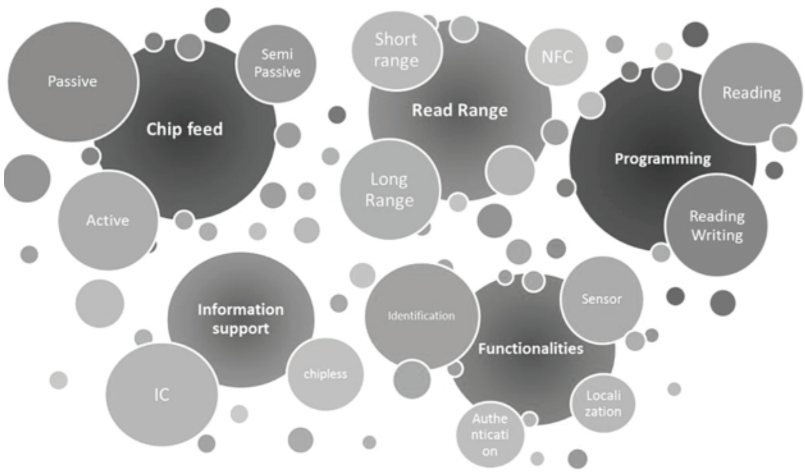

Figure 1.5. *Classification of RFID tags*

1.2. The RFID market

If we examine the RFID market, numerous studies have shown that RFID identification will experience a significant economic boom in the years to come. The economic potential of RFID is considerable, with billions of euros and tens of billions of tags sold each year [IDT 14]. Additionally, as shown by numerous prospective studies, the field of passive RFID has experienced double-figure annual advancement for several years, and this progression will continue during the current decade. Thus, it is already a considerable and fast-growing market, and it is expected that the use of RFID tags in many areas of daily life will become both widespread and common in the future. One concrete example of this generalization is the tagging of cardboard and paper packaging materials. It is estimated that 320 billion cardboard/paper packaging units are sold annually in Europe, a figure that represents only 20% of the overall total packaging materials of every type (cardboard, paper, glass and plastic). It is clear that the number of tags may rise into the hundreds of billions annually. Likewise, for many applications we are moving toward the use of tags as simple disposable consumables.

Numerous prospective studies are available on this subject [IDT 14], which generally predict the 10-year evolution of the RFID market. These predictions clearly indicate that quasi-exponential growth is expected, from a market estimated at 9 billion dollars in 2014 (or 7 billion tags sold) to more than 30 billion dollars in 2024. We would point out that even though these figures are very large in terms of numbers of tags, they are nothing in comparison to the number of barcodes used each year, which is estimated to be between 5 and 6 thousand billion. In 2012, the number of UHF tags sold per year (mostly passive tags) exceeded the number of high frequency (HF) tags. However, value-wise the UHF RFID market remains weak (on the order of 10%) compared to the HF RFID market.

Some studies also make it possible to separate the distribution between chipless tags and classic-chipped tags. The market proportion of chipless tags is currently negligible (0.1% in 2012), but this trend is expected to progress steeply [IDT 14]; the 2019 proportion of chipless tags on the market is expected to reach 31%. If we consider the number of tags sold per year, the figures are even more evocative; in fact, chipless tags – which represented 0.5% of tags in 2012 – should reach 80% in 2019. It is believed that the chipless boom will be driven principally by the development of printed electronics. In managing traceability issues, the cost of the solution, and particularly that of tags, is of primary importance, and this pressure is even greater since the objects to be tracked have little unitary value but exist in large numbers. Expectations for these applications, situated at the opposite end of the spectrum from the luxury products sector, continue to rise. It is clear, then, that cost constraints are a fundamental given in RFID. This is why the development of low-cost tags is eagerly awaited. Likewise, the possibility of being able to manufacture new families of tags using standard paper-industry techniques is a definite advantage, and the very reason for the recent development of chipless RFID. The cost of a UHF tag can be divided roughly equally between the price of the materials (conductive parts composing the antenna; dielectric parts for the medium); the price of the chip; and the price of the chip's report on the antenna. Therefore, eliminating the chip reduces the price of a tag by at least two-thirds. We will see in Part Two of this book, dedicated to chipless RFID, that this technology is compatible with mass-production processes currently used in the paper-industry. It has been shown that it is possible to produce tags of this type for a unit cost on the order of 0.4 euro cents, that is, for the same approximate price as that of barcodes, or around 20 times less than a passive UHF RFID tag. We might suggest that the desired objective is 1 American cent in 2018 for several hundred billion tags sold across all categories (chipped, chipless, passive, active, etc.). If we examine this figure in detail, we can see that the average price of chipped tags is estimated at 4 American cents, while that of chipless tags is 0.4 cents. Always with the goal of reducing the cost of tags, one solution might consist of printing the tag directly on the product or packaging material to be identified. In this case, the tag cost could quickly drop by a factor of 10.

1.3. Issues in RFID

As we have seen, RFID is an extremely vast domain with a large number of applications, each of which generates its own constraints. In this section, we will look back over the principal limitations of passive UHF RFID and examine the research that has been conducted to rectify them. This research will be discussed in more detail in later chapters.

1.3.1. *Robustness of reading*

1.3.1.1. *Description of problem*

The use of passive UHF RFID tags is becoming increasingly common. The intensive development of UHF RFID has been slowed down, however, for several reasons. The main technical reason for this is the unreliability of tags, particularly when they are in an environment other than the one for which they were specifically designed [UKK 06]. In reality, the context within which UHF RFID tags are used has a significant effect on their performances. No universal-use tag currently exists, that is a tag that is guaranteed to function in any environment. In terms of the use of a tag, the directly disruptive element is nothing but the object on which this tag is placed [RAO 05]. For this technology to be economically viable, it is important that a tag is able to be used with the largest possible number of objects.

The problem of robustness of reading is undoubtedly the most important technical difficulty encountered by UHF RFID, and the field of application of this technology is truly limited as a result of it. By “robustness of reading”, we mean the system’s capacity to recover a tag’s ID independently of the environment in which the tag and the reader are located. We can characterize this concept more precisely through the reading rate of tags in a given environment. This point is critical, as it is directly related to the use of RF waves for communication; this is in addition to the extremely strict limitations imposed by industry. The benchmark reference in the matter is none other than the barcode, which yields a very high reading rate, one that RFID must at least equal. In the world of logistics, 99% reading rates are most often inadequate. One reading failure in 1,000 is a more desirable value. However, these reading rates are difficult to achieve, and impossible for passive UHF RFID, which explains why UHF RFID is rare if ever used in the large retail sector. This is why the use of other technologies, such as HF RFID, which operates by the inductive coupling principle, is more suitable in this case.

If we consider passive HF RFID tags, we can see that they are relatively similar to UHF tags in terms of manufacturing and materials used to make them. They are also composed of a chip and metal strips ensuring communication with the reader. In the end, the costs of both are similar, although HF RFID tags are generally more costly because they require the use of an intermediary to link the two ends of the loop to the chip. The area of use is different, in that HF tags work for short-distance applications, with a maximum reading distance of a few dozen centimeters. Despite this limitation in distance, HF tags are currently most frequently used in a considerable number of sectors, particularly mass-market retailing. The reason for this is not an economic one, but rather a technical one. In real situations of use, HF tags are more robust than UHF tags. This can be explained theoretically: in near-field zones we note that, unlike the electric field, which is highly sensitive to dielectric materials and metals, the magnetic field is much less sensitive to these materials, which mostly make up objects used in everyday life. In this case, communication is accomplished via inductive coupling, in which the antennas best suited for this type of transmission are simply loops. In applicative terms, this mode of communication has an extremely significant impact for the user. A single HF tag can be used without previous testing to tag a large number of objects of various types. For example, HF RFID system operations will hardly be disrupted whether the object being tracked contains metallic inks, which are used in some packaging materials, or not. In UHF, the tag's external environment (both the object in contact that is being tagged and the near surrounding environment) may negatively affect system performance rapidly, thus limiting the field of application of this technology. These simple observations show clearly to what extent a reading rate on the order of 99% represents a real challenge. It should be noted, however, that HF RFID, though more favorable in this sense, has experienced numerous failures in the large retail distribution field.

1.3.1.2. *Solution contributed*

We will start, then, from the observation that objects being tagged have EM properties and geometric dimensions that are potentially different. We may add to this point that, in applicative terms, it is increasingly desirable to be able to integrate the tag directly into an object to be traced. It is of particular interest to be able to track the object throughout the phases of its production, and then all along the distribution chain until it reaches the final customer, for example. For all these reasons, specific work focused on the development of a new design methodology for RFID tags has been conducted with the aim of promoting the mass deployment of passive UHF RFID technology [CHA 09, CHA 10a, CHA 11a, CHA 11b]. Chapter 2 describes the development of software capable of automatically designing the tag based directly on technical specifications [PER 10]. Indications entered by the user may be limited to the geometric dimensions of the final tag and the electrical properties of the RFID chip used. If the user so desires, he or she can also provide information about the environment in which the tag will be used (range of variation of the permittivity of various tag supports; presence of metal or lack thereof, etc.). The application then sends back the tag antenna form that is compliant with the limitations imposed. This approach is radically different from the classic antenna design solutions for UHF RFID tags, which are based on a purely empirical design approach based above all on the principles of folding wire antennas and current loops (particularly for near-field aspects). This new design approach makes it possible to take usage requirements into consideration, and these constraints play a role in determining the shape of the antenna. Thus an antenna's topology is not imposed theoretically, as is the case in classically used methods. In this, the approach developed does not simply consist of optimizing a topology that has already been chosen, but rather of designing the antenna from start to finish on the basis of the constraints required for it. To do this, EM simulation software (CST, Ansoft Designer, etc.) and calculation software (e.g. Matlab) have been used in combination [CHA 10a, CHA 10b, CHA 11a]. In order to comply with the constraints imposed during the design of an antenna for a UHF RFID tag, an optimization process is used based on the concept of genetic algorithms (GAs). The principle of optimization is based on an iterative process that consists of generating an antenna form, simulating it and evaluating it in relation to the constraints imposed. The generation of forms from one iteration to another is done on the basis of an evolutionist principle. This is repeated until an antenna design is obtained that best satisfies the specifications. This approach is highly flexible, and makes it possible to take various constraints into account throughout the entire design phase, particularly in terms of the tag's external environment.

1.3.2. *Tag prices*

The question of cost is omnipresent in RFID. Like technologies meant to be used by the general public, this dimension is particularly present in RFID, where tags are often intended to be disposable. Here again, the barcode is the benchmark reference in the matter. The lower the cost of a tag, the more it can be used on low-value objects, and thus in greater numbers. This cost constraint is also present for readers, where the price cannot exceed a few hundred euros per unit.

In RFID, cost determines the production techniques and materials used in manufacturing tags. As an example, the most commonly used substrate is polyethylene terephthalate (PET), which is a very common plastic material. In order to reduce the cost of tags and thus to move toward the projections discussed above, a simple solution consists of producing chipless tags. In order to better understand the motivations behind the development of this approach, it is of interest to compare it to the barcode. Note that RFID is still a relatively complex identification technology compared to barcodes; the latter are extremely simple to apply and use. They are also completely standardized and universal in their operating principle. In addition, barcodes are extremely low-cost, both for tags and readers. For example, anyone can, using free software, generate the barcode corresponding to his or her own ID and print it using a standard office printer. This code can be read using a webcam or a smartphone. However, the main disadvantage of this technology is the way in which it captures information, which requires human intervention. If we evaluate RFID in the same way, we can see that the advantages of one of these technologies will appear as the disadvantages of the other. In fact, communication through radio waves is the principal benefit of RFID, enabling as it does the automated capture of an ID. This flexibility of reading is accompanied by the ability to execute multiple readings, and it is also possible to read over substantial distances. However, the RFID solution is not simple, and it requires the use of an electronic chip and a communication protocol that adds significant cost for tags and readers and can cause mechanical and reading robustness difficulties. Also, this solution is not universal, insofar as it uses frequency bands that may differ from one region to another, and this has an effect on the intrinsic performances of RFID systems in the end. All of these observations explain why more and more research is aimed at developing new traceability systems. Of these, chipless RFID, still referred to as an “RF barcode”, seems highly promising [PER 11, PRE 10, TED 09, TED 10a, TED 10b]. As we will see, it falls in applicative terms somewhere between classic

RFID and barcodes, that is, where the guiding objective needs to combine the advantages of RFID with those of barcodes.

With regard to the issue of reader-side cost, the current trend is toward readers with “agile” antennas, that is, with significant gains as well as the ability to turn off the beam [LEE 13]. In fact, by increasing antenna gain, it is possible to reduce significantly the price of reader amplification stages.

1.3.3. *From identification toward sensor function*

One of RFID’s strengths lies in the fact that this technology is widespread and is regulated by clearly established norms. Based on this, the temptation is great to try to reuse this technology by simply adding functionalities to it without modifying it in depth. RFID can be seen as a communication system, and the objective is to add other functions to its basic identification function. Indeed, rather than seeking to make tags more environment-resistant within the context of classic RFID applications, it is possible to try to make it sensitive to a physical value so as to be able to measure it. Any phenomenon that will modify the adaptation of the chip to the antenna, and thus the modulation of the backscattered signal, can therefore be used.

As an example, it has been demonstrated that it is possible to measure the level of a liquid in a container, or to localize it. Here, we can see the full interest of this approach, in that no major modification of the RFID system is required. In simple terms, the idea is to take a reader and commercial tags and to process the information recovered by the reader in such a way as to go back to the physical value being measured. In this way, we obtain a sensor function associated with a unique ID, all relying on a communication system that is already widespread. To optimize the sensitivity of the tag, it is possible to design a specific tag antenna for the application geared to a given chip. These ideas will be discussed in Chapter 3. It is true that the “reuse” of UHF RFID as a sensor represents a major challenge for this technology, and has excited a great deal of enthusiasm in the scientific community.

1.4. Conclusion

In this introductory chapter, we have described the principal issues that this book will address. The observations thus evoked have made it possible to introduce chipless RFID, which will play an important role later in the book. First, though, we will examine in detail the question of the design of a passive UHF RFID tag antenna. The next chapter is devoted entirely to this subject. We will see how it is possible to approach this issue from a new angle, and thus lead into an automated antenna design methodology for RFID tags.

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