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History of Radio-frequency Identification: from Birth to Advanced Applications

Whether we are aware of it or not, RFID (radio-frequency identification) technology is an integral part of our everyday life. The RFID concept was anticipated a century ago, and nowadays it continues to advance as technology progresses and rapidly evolves to have more impact on our modern societies. The objective of this chapter is to give an account of the development of RFID from its birth to the present day.

1.1. Early facts about the genesis of RFID

The US patent 17744036, first filled in France in 1924 [BRA 30], was certainly one of the very first, if not the first, documents that described the concept of RFID technology. The patent describes the novelty as follows: "*The primary station comprises a source of oscillations and an emitting circuit; the secondary has a receiving circuit with no local energy source, and in which is inserted a manipulating or modulating device (telephonic or telegraphic apparatus)*". This is no more than the principle of the RFID technology that exploits the reflected waves in order to ensure the communication between two devices: one of them is fully passive (the tag or the transponder) as it does not embed any energy source; however, it converts part of the signal sent by the other device (the reader or the interrogator) to modulate the refection towards the reader.

Two decades before this patent publication, H. Hertz noted that electromagnetic waves were reflected by metallic objects, even if he did not apply this insight in a practical engineering sense as done by others. G. Marconi was the first to show that these waves could be used for communication and also noted that radio waves were being reflected back to the transmitter by objects in radio beacon experiments that he conducted on March 3, 1899 on Salisbury Plain. Radar applications had just been born and their evolution from then will not cease and will be one of the powerful engines of RF (radio frequency) development and wireless applications. In 1904, C. Hülsmeyer [HUE 06] gave public demonstrations in Germany and the Netherlands of the use of radio echoes to detect ships so that collisions could be avoided. Moreover, in 1915, R. Watson-Watt joined the Meteorological Office as a meteorologist at Aldershot in Hampshire; over the next few years, he studied atmospheric phenomena and developed the use of radio signals generated by lightning strikes to map out the position of thunderstorms. Later, in the 1930s, the emergence of the radar system and its very rapid adoption by the military during World War II pushed engineers to explore the high-frequency domain and to master various techniques for signal generation, propagation and detection as well as broadcast. In 1935, H. E. Hollmann wrote one of the first comprehensive books on microwaves and applications. The book was titled "Physics and Technique of Ultrashort Waves". This book was used throughout many parts of the world, which favored the development of radar technology in many countries.

1.2. Birth of RFID

Although there is no logical progression to RFID technology and often key advances are not recognized until later, developments in radar and broadcasting have evidently profited RFID. Among the variety of historical facts that paved the way for the emergence of modern RFID, two major events can be considered as the cornerstones. The first is a theoretical paper that very precisely addressed the physics behind the operating principle of RFID. This is the landmark paper published by H. Stockman, in the Proceedings of the IRE, October 1948. The paper was entitled "Communication by Means of Reflected Power". Stockman stated in his paper that "Evidently, considerable research and development work has to be done before the remaining basic problems in reflected-power communication are solved, and before the field of useful applications is explored". The second fact is more practical as it regards the design and application of a device that is probably the first tag ever realized. Such a device was developed by L. Theremin, which was used as a passive wireless microphone for spying [NIK 12]. A schematic diagram of this device, known in the literature as “The Thing”, is shown in Figure 1.1. The Thing is composed of a metallic box that acts as an electromagnetic cavity with a specific resonance frequency coupled to a monopole antenna. To transform the device into a microphone, one wall of the cavity is replaced by a metallic vibrating membrane that is sensitive to sound waves. When the device is illuminated by an electromagnetic continuous wave at the resonance frequency of the system, a reflected signal (backscatter signal) at the same frequency is generated and can be detected with a dedicated system. If there is no sound, the amplitude of the backscatter signal will be constant. However, if some sound waves reach the vibrating membrane, the backscatter signal will be modulated by the sound and therefore detectable thanks to the simple envelope detector. As we can see, the system is so simple and its principle of operation is straightforward! The operation frequency was approximately 330 MHz. The beauty of the system lies in the fact that it had really been used and had worked for several years. Indeed, the device was embedded in a carved wooden plaque of the US Great Seal, and on August 4, 1945, Soviet school children presented it to the US ambassador as a “gesture of friendship”. It hung in the ambassador’s Moscow residential office and served to spy on the conversations of the ambassador for years. The existence of the bug was accidentally discovered by a British radio operator who overheard American conversations on an open radio channel as the Russians were beaming radio waves at the ambassador’s office.

A third fact is often cited as part of the history of RFID. This is the IFF (Identify Friend or Foe) that was developed and exploited by the British during World War II [BRO 00]. The operating frequency of the system was in the range of 20–30 MHz. First, the system was passive and used wires across the wings of the airplane with open/closed operations controlled by motor relay to modulate the backscatter signal. Later, the system evolved into an active solution with amplifier and modern electronics. Nowadays, the IFF enables military and civilian air traffic control interrogation systems to identify aircraft and to determine their bearing and range from the interrogator.

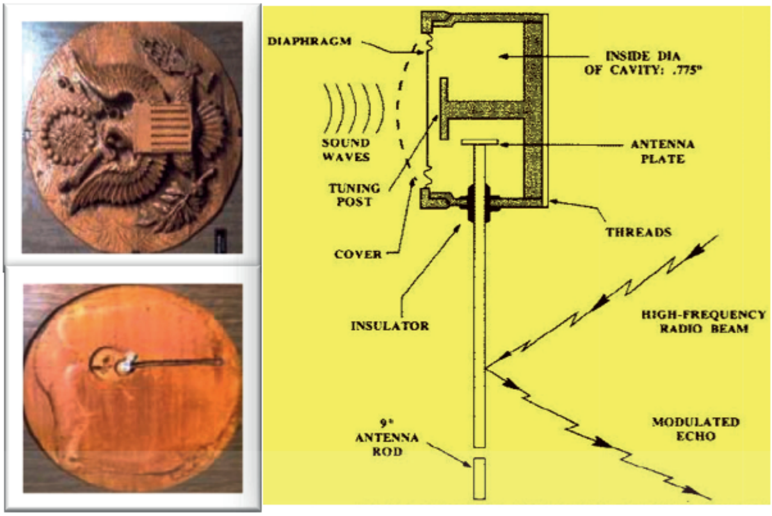

Figure 1.1. *Depiction of the device designed by L. Theremin and used as a wireless passive microphone. Left: the device as it was embedded in a carved wooden plaque of the US Great Seal. Right: the composition of "The Thing"*

Interestingly, the 1950s was the decade that explored the RFID techniques that emerged from the development of radar and broadcasting that took place in the two previous decades. Apart from the IFF, developments during the 1950s included works such as that of D.B. Harris dedicated to "Radio transmission systems with modulable passive responder" [HAR 60].

1.3. Early modern RFID

During the 1960s, thanks to the advances in electronic technology, it was possible to develop the first commercial tag, i.e. the electronic article surveillance (EAS) tag. The first tags deployed in the 1960s were hard, round and plastic. These tags are based on the resonance properties of a simple LC tank circuit. The main application of EAS is to detect the presence or absence of the LC circuit thanks to its resonance when coupled to the sweep generator used as a reader. A schematic description of the EAS system is given in Figure 1.2. The LC circuit that represents the EAS tag can be turned off if its capacitor is deactivated. Such a deactivation occurs when the reader sends an interrogation signal with a very large amplitude at the resonance frequency of the system.

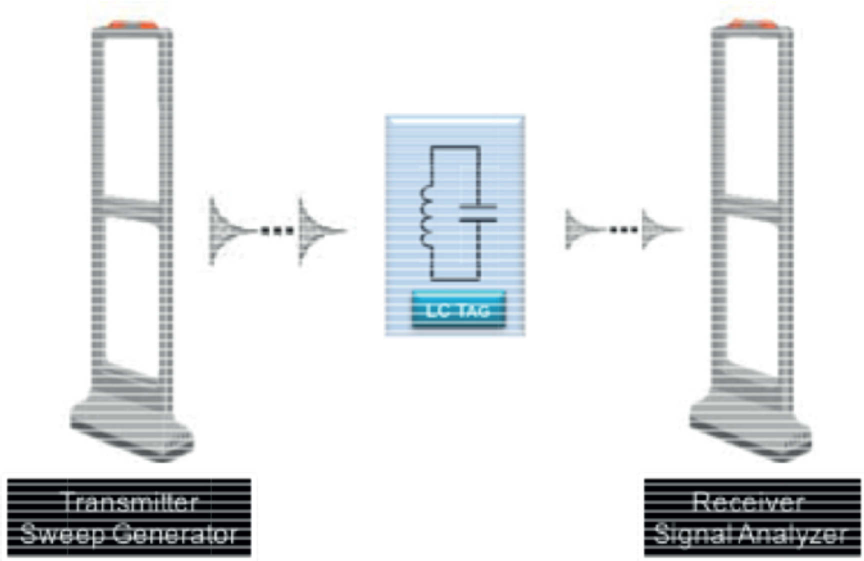

Figure 1.2. *Description of the EAS system. The tag is primarily an LC circuit whose presence is detected by a reader which is primarily a sweep generator*

Since their introduction, EAS tags have undergone remarkable evolution thanks to the huge advances in electronic and microelectronic technologies. Although EAS tags were first developed for apparel retailers to avoid thefts, they have since been applied to a wider range of goods, such as books in libraries, video and music products, etc. Companies such as Sensormatic and Checkpoint were founded in the late 1960s which, with others, developed EAS equipment to counter theft. These types of systems are often known as "1-bit" tags, because only the presence or absence of a tag could be detected. The first EAS tags introduced in the 1960s were rigid and quite big. In the 1980s, the tags became smaller and soft so that they could be attached with adhesive backs, as well as deactivated at the sale store. Later, in the 1990s, the tags could be sewn into or heat-sealed onto items of clothing at the manufacture point [DIL 15]. Therefore, EAS tags have become the most commonly used article surveillance and anti-theft technique. They are boosted by more and more cheap integration technologies, and can be made inexpensively and serve as an effective anti-theft system. Examples of EAS tags are shown in Figure 1.3.

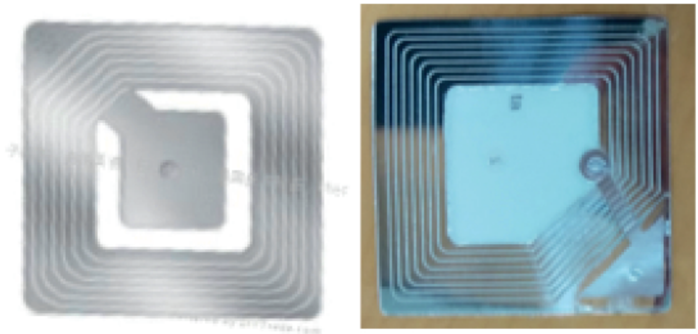

Figure 1.3. *Examples of EAS tags. We clearly see the magnetic loop connected to the chip capacitor to form the LC resonant tank circuit. Typical operation frequencies are in the range of 1.75 MHz to 9.5 MHz band. The standard frequency for retail use is 8.2 MHz*

As far as the physics behind RFID is considered, the 1960s was the prelude to several very consistent theoretical publications and practical demonstrations and inventions [LAN 05]. Among the major contributions are those of R. F. Harrington who studied the electromagnetic theory related to RFID, which was published in his papers "Field measurements using active scatterers" and "Theory of loaded scatterers" in 1963–1964. Regarding the inventions, R. Richardson developed "Remotely activated radio frequency powered devices" in 1963, O. Rittenback introduced "Communication by radar beams" in 1969, J. H. Vogelman demonstrated "Passive data transmission techniques utilizing radar beams" in 1968 and J. P. Vinding performed "Interrogator–responder identification system" in 1967. These theoretical contributions and practical advances in the developments of radar and broadcast profited the birth of modern RFID and its large and very rapid adoption.

1.4. The 1970s: the infancy age of RFID

The 1970s was probably the infancy age of RFID development. Universities, research centers and companies were very actively working on many aspects of RFID that overlapped with integration technologies, RF solutions, communications and a large diversity of application scenarios. One of the most salient advances is the work developed at the Los Alamos Scientific Laboratory dedicated to "Short-range radio-telemetry for electronic identification using modulated backscatter" that was demonstrated in 1975 by A. Koelle, S. Depp and R. Freyman. In 1971, M. Cardullo demonstrated a passive radio transponder with 16-bit memory that was presented to the New York Port Authority and patented two years later (US Patent 3,713,148 in 1973). The patent of Cardullo was applicable for RF, sounds and light. The business model could be used in numerous applications such as car ID, toll, banking, credit cards, security, access control and medical surveillance. The Port Authorities of New York and New Jersey also tested systems for transportation developed by companies such as General Electric, Westinghouse, Philips and Glenayre. Although the tests provided positive results, the first commercially successful transportation application of RFID, electronic toll collection, was not yet ready [LAN 05]. During the same period, several companies developed RFID devices such as Raytheon's "Raytag" in 1973. RCA and Fairchild were active in several developments. R. Klensch from RCA developed an "Electronic identification system" in 1975, and F. Sterzer also from RCA developed an "Electronic license plate for motor vehicles" in 1977. Furthermore, T. Meyers and A. Leigh from Fairchild developed a "Passive encoding microwave transponder" in 1978 [LAN 05].

It appears that the 1970s were characterized primarily by the exploration of several implementations of RFID in real different scenarios and applications. Most of the investigated solutions were considered in applications such as animal tracking, vehicle identification as well as factory automation. Animal tagging was the major interest in Europe. However, due to the electromagnetic characteristics of biological tissues (very high permittivity and high losses), it was possible to implement only inductive systems. Examples of tags implanted into pets are shown in Figure 1.4. During the same decade, transport applications exploited the work on microwave systems developed at Los Alamos and by the International Bridge Turnpike and Tunnel Association (IBTTA) and the United States Federal Highway Administration. In the late 1970s, new applications began to appear and the number of interested companies, individuals and institutions working on RFID began to increase very rapidly. The potential of RFID technologies and the benefit they provided in terms of application monitoring as well as return on investment became obvious.

Figure 1.4. *Examples of implanted tags for pet tracking. These tags are based on inductive systems at LF (low-frequency) and HF (high-frequency) bands to take into account the electromagnetic characteristics of biological tissues*

1.5. The 1980s and 1990s: implementation of RFID

The very practical developments initiated in the 1970s continued to progress in the 1980s and the interest in RFID technology rapidly grew in various regions of the world. While in the United States, the major interest was in the transportation systems and access control; in Europe, the major applications included short-range systems for animals, industrial and business applications. Also, toll roads in some European countries were equipped with RFID solutions. The first commercial application for collecting tolls began in Norway in 1987 and was followed quickly by the Dallas North Turnpike in the United States in 1989. So RFID became a more profitable technology and a large number of new players arrived at this very rapidly evolving market.

The 1990s was a significant decade for RFID implementation, particularly in tolls and transportation systems in many countries around the world. Some of these implementations integrate real innovations. Among the significant innovations was the one introduced in the northeastern United States, where seven regional toll agencies formed the E-Z Pass Interagency Group (IAG) in 1990 to develop a regionally compatible system for toll collection based on RFID solutions. Such a system allows the use of a single tag and single billing account per vehicle to access highways of several toll authorities. Another remarkable innovation, the toll system of the highway which was opened in Oklahoma in 1991, allows vehicles to pass collection portals at highway speeds. A combined toll collection and traffic management system was installed in the Houston area in 1992. Later on, tolling and rail applications also began to appear in many countries including China, Hong Kong, Japan, Malaysia, the Philippines, Thailand, Singapore, South Korea, Australia, South Africa and various countries in Europe.

In the automobile sector, a remarkable application was the development of the Texas Instruments (TI) TIRIS system, which was used for the control of vehicle engines. The application of the TIRIS system was further extended to dispensing fuel, gaming chips, ski passes, vehicle access and so on.

During the 1990s, several European countries were actively developing RFID technologies at both hardware and application levels. In particular, semiconductor companies were active in the development of RFID circuits. Companies such as Philips (now NXP), Electronic Marin and ST-Microelectronics proposed RFID chips for LF, HF and UHF bands. During this decade, European countries paid more attention to the implementation of innovative RFID solutions. Special interest was focused on both RF and inductive technologies, in particular, for toll collection, access control and e-commerce. Europe became very active in the RFID market with developments including Alcatel, Bosch, STMicroelectronics and Philips. A pan-European standard was necessary for tolling applications in Europe, and many of these companies were working on the CEN standard for electronic tolling. Some examples of toll tags are shown in Figure 1.5.

Figure 1.5. *Examples of tags for toll applications. Toll tags are based on RF technologies and in most cases are powered by a battery*

1.6. RFID chip age

Until the 1990s, RFID tags were composed of a PCB (printed circuit board) that contained electronic devices including a memory and antenna to ensure the wireless communication with the reader. Figure 1.6 shows some tags based on the PCB. Research and development in microelectronics and computer science did not slow down during the 1990s, and remarkable technological advances were accomplished that would benefit RFID. Indeed, for the first time, useful microwave Schottky diodes were fabricated on a regular CMOS integrated circuit. This advance in technology is a very important step because one of the major RFID circuit blocks is the rectifier that converts the RF in the interrogation signal into DC voltage to power up the RFID circuitry. Thus, it becomes possible to integrate all the functionalities of the RFID circuit in the same chip. This development allowed the construction of very compact RFID tags that contained only a single integrated circuit, a capability previously limited to inductively coupled RFID transponders. Large companies that were active in this evolution were IBM, Micron, Philips, STMicroelectronics and many other spin-offs.

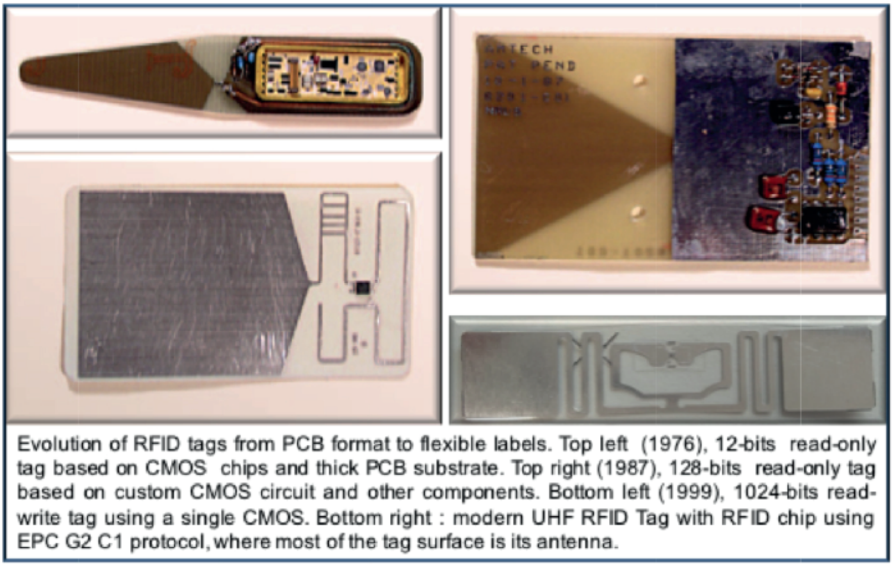

Figure 1.6. *Evolution of tags from the PCB circuit to the RFID chip. First tags used PCB and a suitable external package. Actual tags with reduced size have a label format with only two elements: RFID chip and antenna*

With the growing interest in RFID with respect to asset management and item traceability, and the opportunity for RFID to potentially positively substitute the barcode, it becomes difficult in the later part of this decade to count the number of companies who have entered the RFID market and developed many application scenarios.

1.7. Maturation of RFID

Integration technologies continued to rapidly advance at the beginning of the 21st Century, and some remarkable RFID chips were proposed by major companies. One of the most significant examples of technological process was the microchip developed by Hitachi, as shown in Figure 1.7.

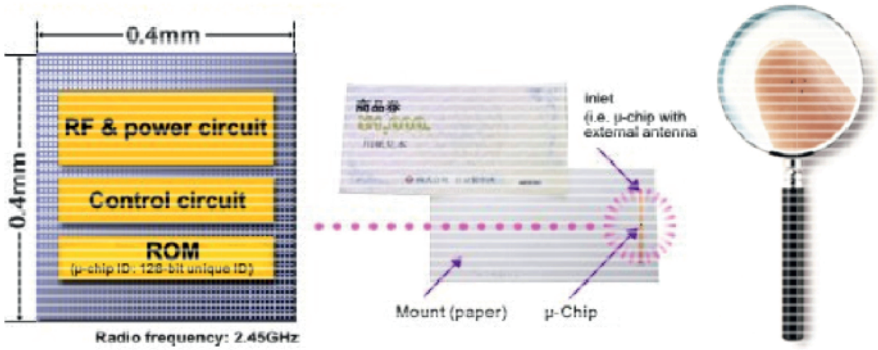

Figure 1.7. *The microchip developed by Hitachi. Known also as "Powder" or "Dust", these chips consist of 128-bit ROM (read-only memory) that can store a 32-digit number. They can be integrated into very thin substrates like paper and notes. Microchips may also have advanced applications such as "smartdust"*

This chip has a very limited size of 0.4 × 0.4 mm^2 and operates at the ISM (Industrial, Scientific and Medical) band of 2.45GHz. It exhibits 128-bit ROM. It is batteryless, decodes its microchip ID and transmits it back, and each µ-chip stores a unique 128-bit ID. The µ-chip has a read range of 25 cm with an external antenna. This evolution in terms of integration capabilities allows the building of tags with only two components: a single CMOS integrated circuit and an antenna. This development allows a reduction in the size of circuitry and the cost of tags, and an increase in functionality and reliability. Therefore, tags have become sticky labels that can be easily attached to objects to be managed somewhat similarly to the optical barcode. This similarity has pushed several research projects and partnerships between universities and companies to consider the adoption of RFID as a smart and better solution for traceability and logistics compared with the optical barcode. More recently, Hitachi has developed the world's smallest and thinnest RFID chip. Measuring only 0.15 × 0.15 millimeters in size and 7.5 micrometers thick, the wireless chip is a smaller version of the previous record. The new chip has a wide range of applications, from transportation and logistics to military and even consumer electronics.

The other salient example that remarkably illustrates the decisive advances in technology and new capabilities offered by RFID is the implanted tag introduced by VeriChip Corp, as shown in Figure 1.8.

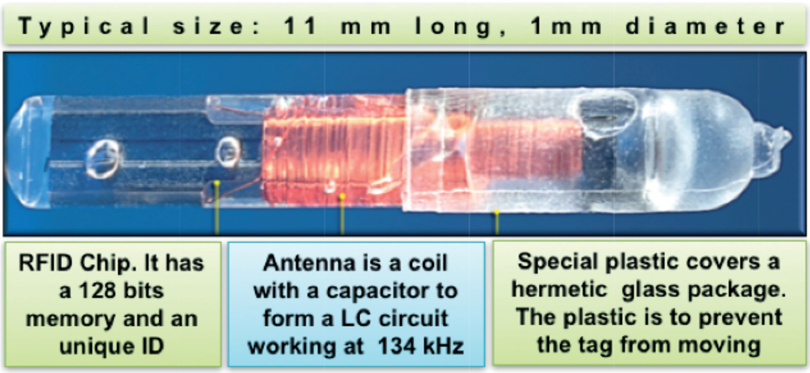

Figure 1.8. *Implanted tags developed by VeriChip Corp. The tag consists of an RFID microchip, a capacitor and a loop antenna wrapped around a ferrite core. It is enclosed in medical-compliant glass and coated in a substance called Biobond to avoid the migration of the tag within the body. The implant has the size of a grain of rice*

This is a 134.2 kHz RFID chip that can save lives and possibly limit injuries resulting from errors in medical treatments, as claimed by VeriChip [SID 17]. It received FDA (US Food and Drug Administration) approval in 2004. VeriChip suggests that the chip can be inserted in the rear part of the triceps of the right arm under the skin. According to VeriChip, the chip does not contain any medical records, but its 16-digit number could be linked to a database of patient medical information. When the tag is scanned, the number can be quickly cross-referenced to reveal specific medical data about the patient. The tags are similar to those being embedded in livestock and pets as an effective solution to tracking the mad cow health condition.

Apart from the previous remarkable examples of the technology outcome, technological development allows a reduction in the size of circuitry and the cost of tags. In addition to the RFID tag hardware, signal processing techniques and computer science allow the expansion of RFID functionalities and its widespread use in thousands of applications. Supply chain management and article tracking are the application areas of RFID that have grown rapidly. The dedicated facility Auto-ID center has been set up and organized at the Massachusetts Institute of Technology to bring together RFID manufacturers, researchers and users to develop standards, perform research and share information, in particular, for supply chain applications. EPC Global has assumed the task of standards for this application area. The International Standards Organization (ISO) also has very active standard activities for a variety of application areas. Auto-ID evolved into Auto-ID Labs in 2003, the same year in which EPC Global was established. The standard adoption is at the origin of the interoperability of products from different manufacturers, which results in increased compatibility, better performance and improved reliability of UHF RFID systems. Later, global standards, such as EPC Class 1 Gen2, encouraged major organizations, such as Walmart, Tesco, the US Department of Defense in the USA Decathlon, Inditex and Uniqlo, among other big retailers worldwide, to request their suppliers to become strictly RFID compliant with all their products. In the 2010s, major companies such as Macy's, Hudson's Bay Company, Marco Polo and a number of others turned the RFID technology into a commodity, especially in retail and industrial applications. Today, it is certain that there is no stopping RFID. It has already become an important part of our everyday life that enables many applications such as ticketing, e-papers, payments and access control.

The full potential of RFID is also being realized in other areas such as application software, development of privacy policies and other legal aspects. Besides, now that RFID has truly entered the mainstream, the development of the supporting infrastructure to design, install and maintain RFID systems is of high importance. As a matter of fact, the choice of a tag for a specific application first requires the definition of a set of parameters and criteria, and then it will introduce the infrastructure to enable the application. Figure 1.9 gives a possible classification of RFID tags using different parameters.

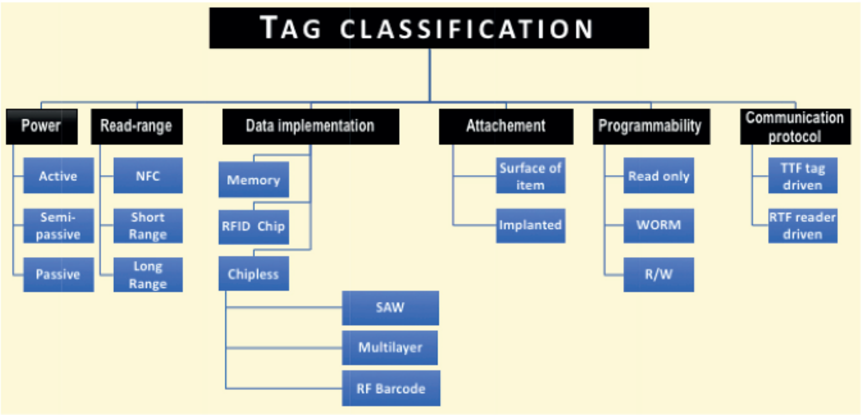

Figure 1.9. *Classification of RFID tags following different parameters. Several duties should be considered when selecting a tag category for an application. Due to their low cost, batteryless feature and long read range, passive UHF tags are very often selected*

1.8. Internet of Things: the next RFID frontier

RFID technology is a well-established technology that has been implemented in thousands of applications worldwide. One of the decisive advantages that RFID guarantees to its potential users is perhaps its standardized character which is of great importance. This standardization allows the interoperability between RFID devices from different manufacturers and geographical regions. Moreover, the passive feature of RFID tags is also very effective in terms of application reliability and the quasi-unlimited lifetime of tags. As pointed out in Figure 1.9, there are several categories of tags to fit the criteria and specific needs of certain applications. The most exploited categories of tags are reported in Table 1.1, which correspond to passive tags.

	LF 	HF 	UHF 
Frequency band	125-134 KHz	13.56 MHz	865-868, 902-928, 950-956 MHz
Example of application	Animal tattooing Car keys	Access Control Passport,	Logistics, Item Identification, Traceability, Tolls
Field zone	Near field	Near field	Near and far field
Read range	< 1 m	< 1m and NFC	up to 25 m
ISO Standard	ISO 18000-2 ISO 11784 ISO 11785 ISO 14223	ISO 18000-3 ISO 7618 ISO 14443 ISO 15693	ISO 18000-6
Data rate	up to 9.6 kbps	up to 64 kbps	up to 640 kbps (1500 tags/s)

Table 1.1. *The most exploited tag categories. These tags are passive devices that can be used for short range (less than 1 m) and long range (up to 28 m). Depending on the constraints of an application, the tags can be inserted into a suitable package before their attachment or integration to the item to be tracked*

While the frequency bands for LF and HF tags are the same worldwide, it is not the same for the UHF band. Indeed, there are three different bands: 866–868 MHz, mostly used in Europe and Africa; 902–928 MHz, mostly used in the Americas and some countries in Asia; and 950–956 MHz, mostly used in the Asia-Pacific region. Due to its long read range of several meters, several research programs and technology developments have been dedicated to RFID at the UHF band. Since the very first RFID chip with a sensitivity of -8 dBm introduced at the end of the 1990s, the pace of developments in chip sensitivity has continued to progress. Indeed, a gain of more than 10 dB has been achieved. Table 1.2 provides the progress of chip sensitivity during the last decades. It is remarkable to see that the actual read range of 28 m is quite comfortable for the majority of indoor applications.

Year	Chip sensitivity (dBm)	Read range (m)
1997	–8	5.07
1999	–10	6.38
2005	–12	8.03
2007	–13	9.01
2008	–15	11.34
2010	–18	16.02
2011	–20	20.16
2014	–22	25.38
2017	–23	28.50

Table 1.2. *Evolution of RFID chip sensitivity. Theoretical read range considering: operating frequency at 868 MHz, reader power at 2W ERP, reader antenna gain at 2 dBi, tag antenna as an ideal dipole and perfect matching between the RFID chip and the tag antenna*

Tags can now be used in a variety of applications and domains such as traceability, logistics and access control. They have become ubiquitous in industry and our daily life (ticketing, payment, passports, car keys, etc.). It is also being largely implemented in the area of health (smart hospital), personal assistance and anti-counterfeiting [DUR 18]. RFID is a standardized technology with inherent advantages of standardization, identification, wireless communication and low cost of tags, thereby providing decisive practical benefits that drive new developments in terms of concepts and applications. However, in all these applications, the major duty of the tag is to provide the ID and achieve the identification only. The perspective of RFID in terms of new paradigms for distributed ambient intelligence and the Internet of Things (IoT) is increasingly considered by many universities and industries. The future looks very promising for this technology. The full potential also requires advancements in the evolution of the RFID tag to provide more than just identification. Passive UHF tags using chips that require only –23 dBm for activation exhibit read ranges of more than 28 meters. They should allow the implementation of the last few meters of the IoT. To do so, the tags must be expanded in terms of functionalities, in particular sensing. The transformation of RFID tags into sensors is very effective in terms of wireless sensor networks. Indeed, the use of the standardized RFID communication protocol will allow the designers to exploit the normalized RFID commands to define new commands more specific to the sensing capability of the transformed tag. Moreover, like any other sensor, the calibration of the device is an important and critical issue. Such an objective can be reached by the association of some reference devices that provide correction signals to the interrogation system [MAR 10]. All these tasks will become possible if the cost of tags is low and the interrogation system is enriched and updated by additional commands to collect the sensed parameters.

There are several ways to transform an UHF RFID tag into a RFID sensor [TED 16]. They can be grouped into three categories. The first one will exploit the sensitivity of the tag antenna to the physical change that appears in its near-field region. The second category is more related to the behavior of the RFID chip and the variation of its electrical response as a function of some external parameters such as RF power and temperature. The third category consists of the integration of an external sensor to the RFID chip. It should be noted that the matching between the tag antenna and the RFID chip is the most relevant parameter that governs the performance of RFID tags, in particular the read range. Once the impedance states of the RFID chip are known, the designer should optimize the tag performance by properly choosing the antenna impedance that corresponds to a certain antenna topology on a well-defined support. Changing anything in the antenna topology, or in its immediate vicinity (near-field region), will turn into a measurable change in the performance of the tag-to-reader communication. This change can be observed in several communication parameters such as activation power of the tag, read range, frequency tuning, phase rotation and group delay. In the literature, several attempts and examples have been reported to design RFID sensors by exploiting this concept [TED 16]. The exploitation of the perturbation of the tag antenna by a metal plate to measure the inflexion of a bridge has been demonstrated. Sensing could also be achieved by adding a highly sensitive material to the antenna; that is, by adding carbon nanotubes (CNT), the gas concentration can be sensed. However, the exploitation of these RFID sensors in real applications has not been discussed much in the literature. Most of the published papers have focused on the concept of the device and restricted their study to validating the proposed structure by some experiments to demonstrate the effective variation of the backscatter signal with the sensed parameters. A real application was proposed in [SON 13]. It explained the transformation of an UHF RFID tag to detect the contamination of meat. The proposed device exploited the evolution of the permittivity of meat as a function of time. So, the measured RSSI was time dependent, corresponding to approximately 72 hours, which was considered as the optimal contamination time.

The RFID chip ensures several tasks; in particular, it scavenges wireless power from the reader and generates the DC voltage to empower the chip circuitry. Intensive work is dedicated to the optimization of chip characteristics in order to realize new functions of RFID tags. Energy harvesting for external sensors and channel diversity are among the most interesting capabilities. These two features are mainly governed by the non-linear behavior of RFID tags, which is primarily dependent on the characteristic of the scavenging section of the RFID chip. Spectral analysis and measurement of real backscatter signals demonstrated the existence of spectral components at the second and third harmonics of fundamental frequency. The exploitation of non-linear characteristics in the context of wireless communication was considered for localization applications in [HUG 09]. In RFID technology, the exploitation of such non-linear behavior opens the door to diverse new functions that can be easily integrated into the tag, especially by adapting the design of the tag antenna. This concept will be discussed in the following chapters.

1.9. Summary

In the 2010s, major companies turned RFID technology into a commodity, especially in retail and industrial applications. It has already become a part of our everyday life, and we use it without knowing that. In 2014, Smartrac, Impinj, Google and Intel joined forces to establish the RAIN alliance. The main objective of this alliance, announced in April 2014, is to boost the global adoption of UHF RFID technology, in order to promote awareness, increase education and support the universal adoption of UHF RFID technology. The members of the RAIN alliance are manufacturers, distributors, resellers and researchers who work with the EPC Gen2 UHF RFID specification, incorporated into the ISO/IEC 18000-6C standard. RAIN RFID is a wireless technology that connects billions of everyday items to the Internet, enabling businesses and consumers to identify, locate, authenticate and engage each item. On top of these advances, augmented tags are highly necessary. Exploiting the characteristics of the non-linear RFID chip is one of several ways to transform tags into augmented tags, providing the identification more surely.

At first glance, the concept of RFID and its application seems simple and straightforward. However, in reality, the opposite is true. Indeed, RFID is a solution that needs plenty of technologies, from systems engineering and software development to materials technology and mechanics. Other domains, such as microelectronics, circuit theory, antenna theory, radio propagation encryption and network engineering, are also necessary. The number of engineers involved in the development and application of RFID is increasing rapidly. This evolution will most likely continue to increase, allowing RFID to have a bright future.