PROGRAMA DE DOCTORADO EN TECNOLOGÍAS DE LA INFORMACIÓN Y LAS COMUNICACIONES

TESIS DOCTORAL

DESARROLLO DE UNA ETIQUETA UHF RFID PASIVA PARA LA MONITORIZACIÓN DE LA SANGRE: APLICACIÓN AL SISTEMA SANITARIO

Presentada por Mohamed El Khamlichi para optar al grado de Doctor por la Universidad Politécnica de Cartagena

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PhD THESIS

DEVELOPMENT OF PASSIVE UHF RFID TAG FOR BLOOD MONITORING: APPLICATION TO THE HEALTHCARE SYSTEM

Presented by MOHAMED EL KHAMLICHI
to the Technical University of Cartagena in fulfilment of
the thesis requirement for the award of PhD

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Abstract

Low-cost and flexible radio frequency identification (RFID) tags for automatic identification, tracking, and monitoring of blood products is in great demand by the healthcare industry. A robust performance to meet security and traceability requirements in the different blood sample collection and analysis centers is also required. In this thesis, two novel low-cost and flexible passive RFID tags are presented for blood sample collection tubes and bags. Both prototypes work at the ultra-high frequency (UHF) European and Moroccan band (865 MHz–868 MHz). The tags are designed considering the whole dielectric parameters namely, the blood, substrate, bag and tube. In this way, it operates efficiently in the presence of blood, which has high dielectric permittivity and loss. Measurement results of the proposed designs have confirmed simulation results. The measured performance of the both tags shows good behavior in terms of reading range. The potential of these tags as a sensor to monitor the amount of blood contained in clinic tubes or bags is also demonstrated. It is expected that the proposed tags can be useful and effective in future RFID systems to introduce security and traceability in different blood sample collection and analysis centers.

Resumen

Las etiquetas de identificación por radiofrecuencia (RFID), flexibles y de bajo coste, para la identificación, el seguimiento y la monitorización automática de los productos sanguíneos tienen una gran demanda en el sector sanitario. También se requiere un rendimiento robusto para cumplir con los requisitos de seguridad y trazabilidad en los diferentes centros de recogida y análisis de muestras de sangre. En esta tesis se presentan dos novedosas etiquetas RFID pasivas, flexibles y de bajo coste, para tubos y bolsas de recogida de muestras de sangre. Ambos prototipos funcionan en la banda europea y marroquí de ultra alta frecuencia (UHF) (865 MHz-868 MHz). Las etiquetas están diseñadas teniendo en cuenta todos los parámetros dieléctricos, como la sangre, el sustrato, la bolsa y el tubo. De este modo, funciona eficazmente en presencia de la sangre, que tiene una alta permitividad y pérdidas dieléctricas.. Los resultados de las mediciones de los diseños propuestos han confirmado los resultados de la simulación. El rendimiento medido de ambas etiquetas muestra un buen comportamiento en términos de rango de lectura. También se ha demostrado el potencial de estas etiquetas como sensor para controlar la cantidad de sangre contenida en los tubos o bolsas clínicas. Se espera que las etiquetas propuestas puedan ser útiles y eficaces en futuros sistemas RFID para introducir seguridad y trazabilidad en diferentes centros de recogida y análisis de muestras de sangre.

List of acronyms

Acronyms	Signification
RFID	Radio Frequency Identification
UHF	Ultra-High Frequency
SHF	Super High Frequency
LF	Low Frequency
HF	High Frequency
IOT	Internet of Things
RF	Radio Frequency
UPC	Universal Product Code
UPC	Electronic Product Code
QR	Quick Reponse
ISS	International Space Station
SAW	Surface Acoustic Wave
RTF	Reader-Talks-First
ITF	Interrogator-Talks-First
TTF	Tag-Talks-First
ISO	International Electrotechnical Commission
ASK	Amplitude-Shift Keying
PSK	Phase-Shift Keying
NFC	Near-Field Communication
PIFA	Planar Inverted-F Antenna
EIRP	Effective Isotropically Radiated Power
ERP	Effective Radiated Power
FCC	Federal Communications Commission
ETSI	European Telecommunications Standards Institute
ADC	Analog-to-Digital Conversion
RSSI	Received Signal Strength Indication
ISBT	International Society of Blood Transfusion
BB	Blood Bank
BU	Blood Unit
VNA	vector Network Analyzer
ΔRCS	Differentiel Radar Cross Section

General introduction

Motivation

In recent years, patient safety related to the blood transfusion has gained considerable attention owing to the transfusion errors which may ultimately lead to catastrophic morbidity or death. Nowadays, healthcare system suffers from many problems caused by the outbreak of the Covid-19, shortage of medical staff. Moreover every year, millions of patients around the world require blood transfusions. This situation can drastically increase errors in this vital service and particularly in the blood block chain. In general, in blood banks, errors are attributable to sample misidentification, adverse effects of medications, or incorrect blood transfusion, which are mainly caused by patient misidentification and/or human intervention errors.

Reducing errors in blood transfusions require concerted and coordinated effort by all stakeholders to add more safety across the entire supply chain, from collection to transfusion.

One way to do this, is by introducing new technologies based on automatic identification of objects using radio waves such as radio frequency identification (RFID). This technology is becoming more and more popular in everyday life. It has been extensively used in many practical applications in Internet of Things (IoT) and has become essential for a set of applications including identification, localization, tracking, sensing, inventory control, and supply chain management. Barcode technology is currently the most common technology used in blood supply chain and has been shown to reduce errors. Some potential problems in operating a bar code label system represent an obstacle to larger adaptation of this technology to blood supply chain. For example, barcode scanners require a direct line of sight to the barcode to be able to read. In some circumstances, dust covering the barcode can prevent barcode scanners from getting an accurate read. Another big problem with bar codes is that it has no read or write capabilities; once the barcode label is mounted on the blood bag or tube, the information cannot be changed. This feature becomes an issue when the barcode label is mis-attached. All these problems can be avoided by using radio frequency technology (RFID). RFID technology can track in real time blood bags or tubes, read tags from a greater distance compared to barcodes. In addition, it doesn't require line of sight with the reader, it allows simultaneous read of multiple tags, and the modification of the information stored in the tag. Another important advantage of RFID technology compared to barcodes is that RFID technology can include sensors such as temperature sensors which is important for preserving the cold chain.

Research Objective

The aim of this thesis is the monitoring of blood bags and tubes using RFID technology. The key idea of the design is to consider the presence of the blood, dielectric substrate and tubes/bags during the design of the tag. In this way, the antenna will operate in optimum conditions when it is attached to a blood tube/bag, which is the final intended operational environment. For this purpose, it is very important to characterize the electrical properties of the blood, together with a good understanding on the materials employed in the fabrication of clinic tubes/bags and the tag antenna (substrate). Once these elements are properly characterized, their presence is taken into account during the design of the tag antenna.

The designed UHF RFID tag antennas are fabricated on an adhesive, flexible, and resistant substrate of Kapton polyimide thin film (3MTM Kapton polyimide film tape 5413 amber), thus allowing it to be easily molded and attached to blood tubes and bags. These tag antennas are designed to operate optimally in a real environment with a smaller size and larger reading ranges than the available solutions for blood bag or tube traceability. To achieve these goals, the blood, PVC bag, and Kapton substrate were considered during the design process. To overcome the problem of high values of loss and permittivity of the blood, the proposed RFID tag antennas includes some capacitive parts, which form a novelty and make them innovative structures. While in many applications the use of inductive tags is preferred, since it leads to smaller sizes, this is no longer the case for blood bags and tubes tracking, where the tag must operate in the presence of blood. Due to the high real relative permittivity value of the blood, the inductive tag tends to be very small, therefore leading to low efficiencies. However, the capacitive configurations, as the ones proposed in this thesis lead to tags with higher radiation efficiencies, still exhibiting small sizes. This is due to the natural size reduction effect that occurs when the tag operates near to the blood. A second benefit of introducing capacitive parts is its high sensitivity to the real relative permittivity value of the blood. This high tag sensitivity could be used to reduce non-relevant information collected from empty bags or tubes. In a similar way, the tag could be used as a sensor to monitor the amount of blood contained in a specific bag or tube, as it will be demonstrated in this PhD work.

Thesis structure and outcome

In order to give a better view about the work done during the last five years, this section briefly discusses the structure of the thesis and the outcome and achievements of each chapter. The thesis is divided into five chapters.

Chapter 1 presents an overview about RFID technology and its advantages compared to barcode technology. In addition, the structure and standards of an RFID system is presented. We have also briefly presented the current research directions that are considered for the development of RFID and its applications.

In chapter 2, the main parameters of RFID tag antennas are introduced. Next the concept of sensing is defined along with some applications when RFID chips with sensing capability such as SL900A are introduced.

Chapter 3 is devoted to outline the problem of RFID tag antennas when mounted on liquid materials, and the most relevant contributions published in the literature so far to tackle this problem are described.

In chapter 4, a new method for the design of RFID tag antenna for blood tubes is proposed. Such method is based on introducing some capacitive parts in the design to optimize the size of the tag, and therefore achieve a good compromise between compactness and radiation efficiency. In addition, the added capacitance provide higher sensitivity in the presence of blood. Owing to this behavior, the reading range is increased when the RFID tag antenna is attached to a clinic tube full of blood, while the reading range drastically drops when the tube is empty. This property may also be an advantage for some traceability systems, in order to reduce non-relevant information relative to empty tubes. As a proof of concept, a new compact RFID tag antenna for blood tube traceability is designed, fabricated and tested. The obtained results are presented and discussed.

In chapter 5, the knowledge gained in the previous chapter is applied to the design of an RFID tag antenna for blood bag traceability. To overcome the problem of high values of loss and permittivity of the blood, the proposed RFID tag antenna includes inductive and capacitive parts with nested slots, which form an innovative structure. Good impedance matching between the NXP G2XM IC-chip and the tag antenna in the presence of the blood is achieved by tuning the inductive and capacitive parts with nested slots in a flexible way, thus improving the reading range. This new tag antenna is expected to be of interest in future blood bag traceability systems enhancing patient safety in health infrastructures.

Lastly, conclusions and future research that result from this work are outlined.

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Chapter 1

General Information on RFID Technology

1. Introduction

The first part of this chapter is dedicated to RFID technology and to the propagation phenomena related to it. We first present a brief review of the RFID technology, and the basic structure of an RFID system. We study in particular the frequencies used in RFID, an various important definitions are given. The international standards as well as the various applications encountered on the market are also presented. The second part of this chapter aims to present the RFID technology, with a particular interest in passive UHF RFID technologies.

RFID technology has been used in several areas, including identification, traceability and data analysis. To identify or track products, we can use other technologies such as barcodes, or smart cards. These technologies are competing with each other, but some basic differences give advantages to RFID over other technologies.

2. Means of identification

There are many forms of identification (ticket, chip card, magnetic card and barcode). Bar code is the most widely used identification method, mainly in the form of paper labels for product identification. Identification allows to assign a unique identifier to an object to avoid any possible confusion among multiple objects. The goal of the Internet of Things is to create a global network of interconnected and uniquely identifiable objects that communicate through standard protocols. As shown in Figure 1, the Internet of Things covers three types of communication (object-to-person, object-to-object, and machine-to-machine (M2M)) that can be established in restricted areas ("Internet of Objects"). The arrival of smart phones enabled more connected users. It is for the same reasons that the Internet of Things cannot exist without the development of smart objects.

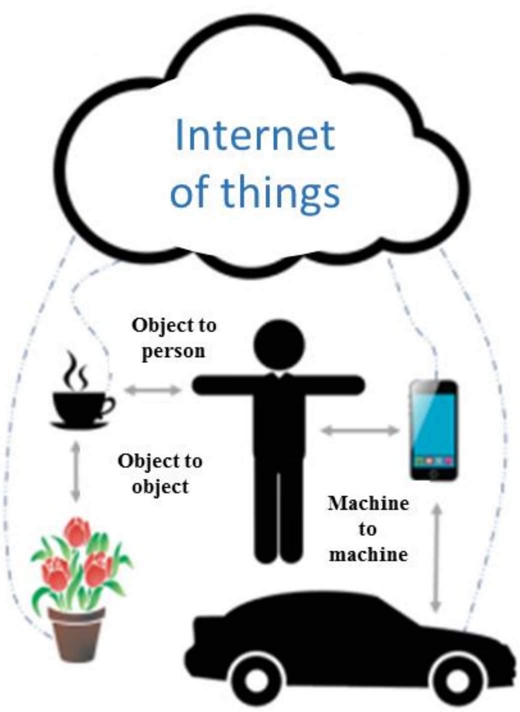


Figure 1: Illustration of the Internet of Things

In order to meet current challenges, such as ecology, an aging population and the monitoring of sensitive products (drugs, blood bags, and flammable products), the simple identification of an object is no longer enough. Adding sensor functionality and / or memory for data storage has become essential when tracking an object.

Automatic identification can be done by several types of technologies with advantages and disadvantages. A comparison between all these technologies is not in the scope of this work, but a brief comparative study is given in Table 1, covering the bar codes, the smart cards, the passive RFID and the active RFID. We will focus on bar codes and RFID technology.

	Bar codes	**smart card**	**Passive RFID tags**	**Active RFID tags**
Changes of data	Not modifiable	Modifiable	Modifiable	Modifiable
Security of data	Minimal	High	Average	High
Volume of data	Linear barcodes can contain 8-30 bytes.	Up to 8MB	Up to 64 KB	Up to 8MB

	Some 2-D barcodes can contain up to 7200 Bytes.			
Costs	Low (fraction of a cent to a few cents per item)	High (over than one dollar per item)	Medium (less than 25 cents per item)	Very high (between 10-100$ per item)
Interference potential	Light barriers, dirt or objects placed between the reader and the label.	Contact blocking	Environment or field that affects radio frequency (RF) emission	Very limited as long as the emission of the strong signal.
Reading range	In view (3-5 feet)	Contact required	No contact (up to 20 meters)	No contact (up to 100 meters)
Lifetime	Short	Long	Undefined	Battery life (3- 5 years)
Standards	Stable and approved	Non standard	Evolve to the standard	Evolve to an open standard

Table 1: Comparisons of different types of automatic identification technology

Barcodes are the most widely used of all the technologies listed in Table 1, but unfortunately they have huge shortcomings. Before discussing RFID, we briefly review the barcode technology.

2.1. Bar Code

For the past 25 years barcoding has been the primary means of automatic product identification in the supply chain, since more than 6 billion barcodes are recorded all over the world [1]. Barcodes have proven to be very effective, however, they also have limitations.

The key attributes to be considered when comparing RFID with barcodes revolve around readability, speed of reading, tag durability, amount of information, information flexibility, technology costs and standards. A migration to RFID involves a number of considerations, the most important being whether the barcode should be complementary or whether it will be permanently replaced.

Reading Method: bar code readers require direct visual verification. The reader indicates when it gets a good reading within its range, and a bad reading is immediately associated with a specific tag and item. This type of relationship is established on a one-to-one basis. RFID reading does not require line of sight to obtain the tag information. The radio frequency (RF) signal is able to travel through most materials. This is particularly advantageous in goods receiving operations in warehouses and in applications where information must be collected from items that have a heterogeneous orientation. An RFID reader is able to distinguish and interact with an individual tag even though multiple tags are within the given read range. However, tag discrimination does not provide the absolute physical location of an item that barcoding does when targeting a specific point on the packaging line. Tags that do not respond for one reason or another require a manual search and verification step, or alternatively the diversion of the entire pallet to perform a root cause analysis.

Read Speed: RFID tags can be read faster than bar code tags at theoretical rates of 1,000 per second or more. This exceeds the reading speed at the level of each unit that applied to the barcode. The speed of RFID is of great value in high-volume goods receiving and dispatching applications, where a large number of items need to be accounted for quickly. For example, when a pallet of tagged boxes is received in a warehouse, an RFID reader can potentially identify all the boxes without having to deconsolidate the pallet and scan each one individually.

Durability: For added protection, RFID tags can be inserted into hard plastic substrates or other materials. Although they are significantly more durable than paper barcode labels, both rely on adhesive to keep them intact and attached to an item. The nature of RFID tags allows them to outlast barcode labels.

Data Storage: The UPC (Universal Product Code) code identifies the classification of a generic item, but EPC allows an item to be identified individually through an assigned serial number. High-value RFID tags will contain several kilobits of memory (thousands of characters). This increase in data storage capacity creates a portable database of information, allowing a large number of products to be tracked, with data such as date of manufacture, time spent in transit, location in the distribution center or the expiration date of the item.

Information Flexibility: With respect to dynamic information, RFID tags are able to perform read and write operations, allowing real-time updating of information on an item moving along the supply chain.

Information Redundancy: RFID tags hold information in captive form, offering it only through a reader set to receive that data. The integrity of the system is non-linear (it can accept or reject what the reader transmits). Barcodes, on the other hand, usually have a human-readable format attached to them. This allows direct recovery in case the barcode fail to read. The combination of RFID tags containing barcodes and human readable characters offers the best alternative for redundancy and integrity of the information.

Security: Some RFID tags support the combination of keywords that can make them unreadable for reading systems that do not use the access keys of the EPC code.

There are 3 types of barcodes; one-dimensional or linear barcodes, stacked linear barcodes and two-dimensional barcodes, as shown in Figure 2. The main difference between them is the printable character capacity; linear barcodes can contain 8-30 bytes, and some 2D barcodes can contain up to 7200 bytes [2].

(a) (b) (c)

Figure 2: the different types of bar codes: (a) one-dimensional or linear, (b) stacked linear, (c) two-dimensional

2.2 RFID

In recent years, radio frequency identification (RFID) technology is rapidly developing and is becoming very important for monitoring and tracking applications [3–5]. Usual applications with this technology include security identification, retail item management, inventory, access control, and tracking. Thus, RFID technology can be used in the healthcare sector and, more specially, within medical centers for the management of blood products [6,7]. It may have some benefits with regards to optical technologies, such as quick response codes (QR) and barcodes [8], since it is possible to increase the automation level of stock, identification, tracking and monitoring tasks and, therefore, reduce possible human intervention errors. Passive tags working at the ultra-high frequency (UHF) European band (865 MHz–868 MHz) can be used for this type of applications.

2.3 The fields of application of RFID technology

In recent years we have witnessed the insertion of RFID tags in different areas of our lives: from the toll payment system (teletag), to when we examine new garments, books, in lockers, cards for opening doors, or when paying with the credit card. . Furthermore, there are still many more applications that may be unknown to the layman, such as vehicle fleet control, tire control, product authenticity, product and / or livestock tracking, item classification and storage, access control, immobilization of vehicles, handling of shipments, identification and follow-up of patients and a long… [3].

Despite their presence in the daily lives of millions of people, the bulk of the systems currently in place are solutions for industry. Below, we list various applications that, today, have a greater presence in the market [9]:

2.3.1 Supply chain

Automation in the receipt of goods is one of the most popular and successful application, providing visibility in real time and in the control of time of delivery, reduction of errors and a greater punctuality of movement of material, reducing stock-outs and improving work efficiency. The use of RFID systems optimizes warehouse operations, improves inventory availability, and promotes the development of the shopping experience (see Fig.3).

Figure 3: Example of inventory in a warehouse using RFID technology

2.3.2 Transport and logistics [10]

RFID systems are now widely used in the transport and location of goods within the supply chain (Figure 4). However, there is a much wider variety in the use of technology to facilitate the maintenance of moving goods and informed operations with accurate, automated and error-free address. RFID systems are currently in place for vehicle and train fleet tracking, baggage tracking, aircraft critical parts monitoring, tool and equipment tracking, etc.

Figure 4: Tracking moving items using RFID

2.3.3 Hospitality

The hotel sector today faces the challenge of protecting its assets from theft. Valuable assets valued in thousands of euros, such as paintings, furniture and electronic equipment, can be labelled with RFID technology instead of being monitored 24 hours a day. In addition, the use of RFID systems provides the services of inventory tracking, asset management, access control through smart locks, tracking uniforms and bedding, and much more (see Fig.5).

Figure 5: RFID technology in hospitality

2.3.4 Food and beverages

Supermarkets use RFID systems to increase their performance both at the level of productive management, as well as logistics and stock management, in addition to quality management. These systems allow to automate price changes to be made quickly and virtually without errors. In addition, they make it possible to identify products in a uniform manner and to optimise the management of information on the receipt, classification, storage and dispatch of goods [11].

2.3.5 Healthcare

RFID technology is having a big impact on this industry due to various factors. Firstly, it reduces costs by speeding up asset tracking (Figure 6), and eliminates loss or theft of material. Second, it improves supply management through automatic inventory, helping to reduce out-of-stock situations and the amount of consumables used. In addition, the ability to correctly identify a patient and know where he is at all times results in improved safety and bed allocation.

Figure 6: Instruments and tools used in hospitals that require monitoring and inventory

2.3.6 Industrial manufacturing

The use of RFID technology in the industry provides accurate real-time visibility of inventory, equipment and finished products (Figure 7). RFID applications in the industry reduce costs, increase quality control, streamline automated processes and increase overall efficiency.

Figure 7: Production Chain.

2.3.7 Refineries and gas plants [12]

The use of RFID technology can help reduce costs and manage the inherent risks of these facilities (Figure 8) by tracking assets in hostile environments, tools, vehicles, people and contractors, evacuation management, as well as develop preventive and predictive maintenance management using sensors.

Figure 8: Gas plant.

2.3.8 Space

NASA has improved inventory time by 30% using RFID systems. The items on the space station are small, unique and irreplaceable with a launch cost of thirty dollars per gram. In addition, with an on-board RFID reader (see Figure 9), astronauts maximize the use of space in the ISS (International Space Station) [13].

Figure 9: Inventory process in the ISS.

3. RFID System Operation

RFID (Radio Frequency Identification, or called identification by radio frequency, or more simply radio identification) uses, as its name implies, radio frequency waves for the identification of goods or persons. It should be noted that the term wave normally refers to electromagnetic waves propagating in free space. But here the term wave is used more generally taking into account the waves that propagate but also the waves (fields) that oscillate around the antenna.

Generally, an RFID system consists of a transmitter and a receiver. The role of the transmitter is to provide the receiver with both radio frequency (RF) energy and information and/or commands. The receiver, which contains the information necessary to identify the asset to which it is attached, receives the energy and the command transmitted, and then sends its "information" (i.e., its identifier). In the universe of RFID, the transmitter is called the base station or more frequently reader (whose functionality is not only to read but also to emit, as noted above), and the receiver is generally called tag, or RFID transponder.

Figure 10 gives a schematic representation of the principle of operation described also showing the two radio links: RFID reader to receiver means uplink, and to RFID reader means downlink.

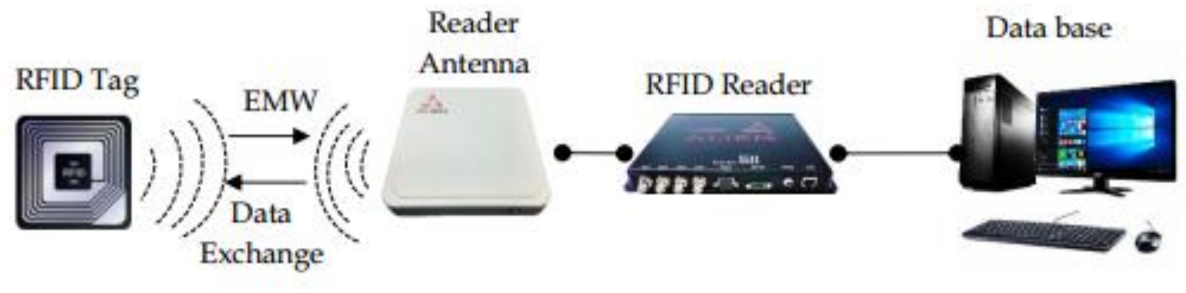


Figure 10: Schematic representation of an RFID system

The Communication between the RFID reader and the RFID tags is via radio frequency waves. RFID tags may include other components depending on the type of application. The contactless smart card is an example of an RFID tag specific to secure applications. So, RFID system is based on a reader or interrogator and a tag or transponder, and middleware. An RFID tag is a passive/Active device, which can be attached to or introduced within a product. It uses inductive coupling (near-field) or electromagnetic radiation (far-field) to communicate with the reader [14], this is what we will discuss in the following paragraphs.

3.1 RFID Operation Frequency

The frequency under which the reader sends energy and commands to the tag is defined as the operating frequency or frequency of the RFID system. The operating frequency is one of the main parameters to consider when classifying an RFID system. Indeed, the entire system is configured according to the operating frequency: antenna(s) of the reader and antenna of the tag, and chip of the tag. The frequency of operation indirectly also defines the data capacity that can be exchanged between reader and tag. The communication between the tag and its reader takes place in different frequency ranges and is determined according to three important parameters: the distance between the reader and the tag, international standards and the place of use (hospitals, factories, nuclear power plants, etc.). In the upper part of Figure 11, the general representation of the different frequency bands, including the frequency bands used or available in RFID are shown.

The frequencies or frequency bands most frequently encountered are: 125/134 kHz, in low frequencies (LF), 13.56 MHz, in high frequencies (HF), 860-960 MHz and 2.4-2.45 GHz, in ultra-high frequencies (UHF). These frequencies are shown at the bottom of Figure 11 and listed in Table 2. The main difference, besides the frequency range, is in the type of coupling used for communication and powering the tags.

	Operating frequency	Coupling type	Types of labels
LF	125/134 kHz	Inductive	Passive
HF	13,56 MHz	Inductive	Passive or active
UHF	860-960 MHz	Radiative	Passive or active
	2,4-2,45 GHz	Radiative	Active

Table 2: Summary table of RFID tag ranges

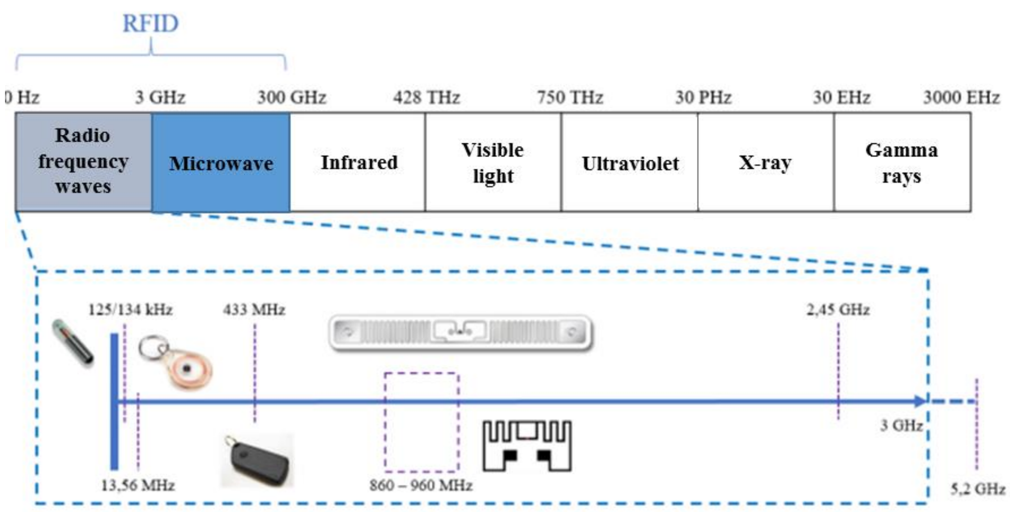


Figure 11: Electromagnetic spectrum of radio frequencies

3.2 RFID Tag Type

Several criteria can be used to classify or characterize an RFID tag. In this section the main ones are recalled.
RFID tags can be differentiated according to the type of power supply they use for their operation. Three categories are possible:

3.2.1 Passive Tags

This type of tag uses only the energy provided by the reader to power the electronic circuit of the RFID chip and to transmit data to the reader. Therefore, no internal power source is required by a passive tag which greatly reduces the cost of manufacture and simplicity of the design. The architecture of the chip is relatively simple: it does not have a chain of own emission; to send the stored information, the tag modulates its load impedance and thus re-radiates the received signal by inserting the information by retro-modulation (or load modulation). Since there is no onboard energy source, the passive tag is the cheapest and its price can reach around fifty euro cents in large volume.
These are very suitable for electronic surveillance of supermarket items. If someone tries to come out with a product that has not been paid for, a reader at the exit recognizes the status of the transpose as high or low. They can also transmit more data such as a string of up to 256 bits with an EPC memory that sends an ID to the reader. However, this data cannot be modified. This type of passive label systems have low costs and a useful life of more than 20 years with respect to active RFID tags, these have the disadvantage of a limited field of operation, which is between 10 cm and 20 m without considering propagation losses.

3.2.2 Semi-Passive Tags

Tags are supported by an internal on-board power source, battery (Figure 12). The purpose of this power source is to provide sufficient supply voltage to the chip. The transmission of data to the reader is achieved by retro-modulation or load modulation as for passive tags. The presence of the on-board source then increases the reading range up to a distance of 30 m, and also offers the advantage of allowing the integration of sensors to the RFID chip and thus collect environmental data. Storage memory is also more important than in passive tags. They have a reliability comparable to that of active tags in addition to usually exhibiting a superior life cycle. Like active tags, some semi-passive tags have built-in temperature, motion, etc. sensors to provide greater functionality. The advantages they present with respect to passive tags are the response speed and the reading range.

Figure 12: UHF RFID Semi Passive Tag

3.2.3 Active Tags

This type of tags does not exploit the energy sent by the reader and therefore their operation is independent of it because the incident electromagnetic field is no longer necessary to power the chip or to perform the modulation [3]. The architecture of an active tag (Figure 13), therefore, integrates a transmission chain that allows it to generate its own information-carrying signal. Active tags have a much larger reading range (up to 100 m) than passive tags, and have a larger storage capacity (128 KB).

It is important to highlight their ability to store information, as they normally have a greater capacity to store data than other types of tags, beyond the simple unique code, such as content, origin, destination, processes carried out, etc. They can also carry additional sensors to the memory itself, such as temperature, speed, movement, pressure sensors, etc., which allow vital data to be stored or controlled in some applications. Other relevant characteristics are the battery life can last several years of good operation in an environment close to water or metal, a high level of reliability and wide signal diffusion coverage, that is, greater range. These tags are the most expensive on the market, but have demonstrated a return on investment in many applications.

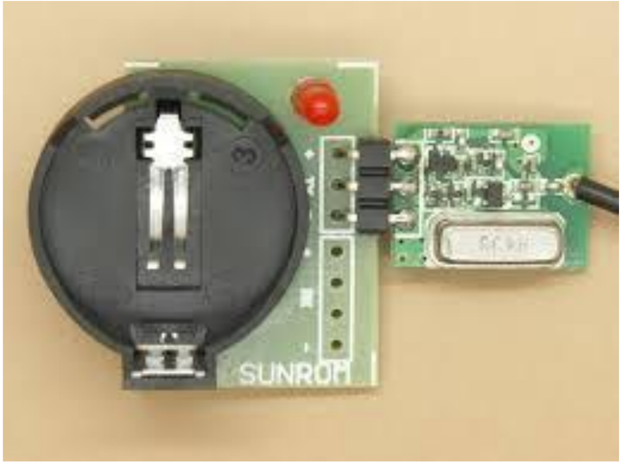


Figure 13: UHF RFID Active Tag

3.2.4 Chipless Tags

Another criterion for classifying RFID tags is whether or not the RF chip is used. Tags without chips (or chipless tags) (Figure 14) are a very low-cost alternative for RFID systems that could replace the traditional bar code system. The principle of operation of tags without chip is based on the electromagnetic signature of the antenna of the tag which then bears directly the identification information. The antenna is usually designed from planar resonators that resonate at specific frequencies thus including a spectral signature. In the presence of the signal sent by the reader, in this case consisting of multiple frequencies or impulsional type, the tag reflects more or less the frequencies of the received signal allowing the reader to decode the information sent by the tag from these changes [15]. Alternatives exist that exploit phase information jointly. Other types of technologies are also used for the design of chipless tags such as surface acoustic wave tags or SAW (Surface Acoustic Wave) tags [16]. The chipless tag technology also represents an approach for the design of low-cost wireless sensor networks as illustrated in the example of applications presented in [17] and intended for fluid detection.

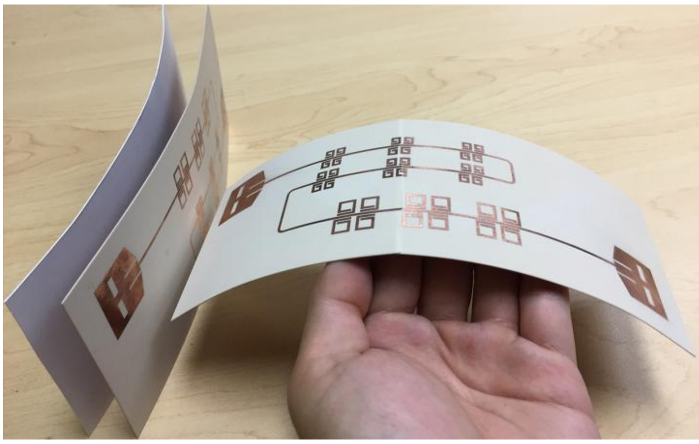


Figure 14: Chipless Tags

3.3 Classification by operating frequency

RFID tags can also be classified according to the operating frequency LF, HF, UHF or SHF, for which chip and antenna are configured. This parameter plays a very important role on the main characteristics of the tag such as the dimension (related to the wavelength), the rate of reading of data and indirectly on the type of coupling with the antenna of the tag. The loop-type antenna is the most used for LF and HF tags while the inductive dipole-type antenna is preferred for UHF frequencies. Figure 15 shows some peculiarities of passive tags in the three most commonly used RFID frequency bands, LF, HF and UHF.

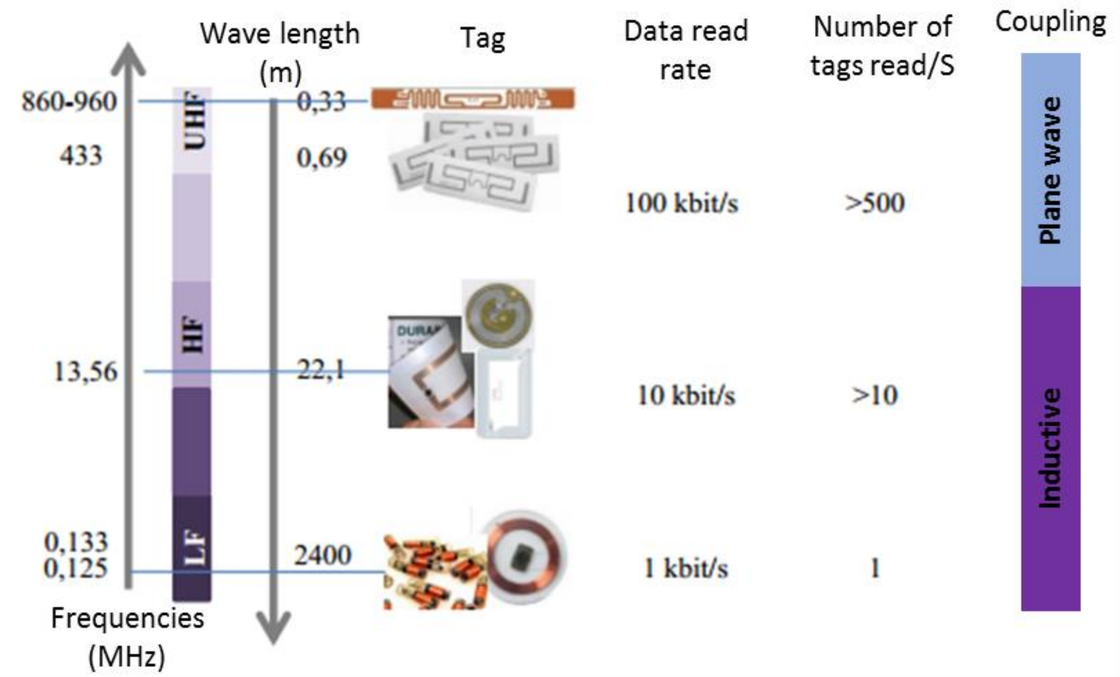


Figure 15: The main characteristics of passive RFID tags in the three most used frequency bands

RFID tags are generally designed to operate in a single frequency band. But it can also have tags configured to work in two frequency bands simultaneously. These types of tags have an electronic chip whose architecture allows activation under the presence of an LF signal while the return signal, carrying the tag data, is sent on an HF frequency [18]. This solution allows the transmission of data between tag and high speed reader (once the connection is established in the higher frequency) in environments hostile to penetration of electromagnetic waves. In [19], the authors show the feasibility of using a single RFID chip for the design of a dual band HF and UHF antenna. Another possible configuration is the use of two separate frequency chips assembled under the same substrate. Each chip then has an antenna adapted to its operating frequency [20].

3.4 RFID Communication Norms

In passive UHF RFID technology, there are two families of communication protocols "Reader-Talks-First" and "Tag-Talks-First" [21].

- **RTF** (Reader-Talks-First) or **ITF** (Interrogator-Talks-First): the reader broadcasts a power signal, but the tags present in its field remain inactive, until the reader sends them an identification request. The concerned tag responds to the reader if it is within range of the reader. The reader is able to find tags with specific identifiers by querying all tags whose identifiers start with 0 or 1. If several tags answer, it asks those whose identifier starts with 01 to answer and so on. This search is a walk through the binary tree representing the tags. It is known as the singularization (anticollision) algorithm. The UHF Class 1 Gen 2 protocol for example is part of this family.

- **TTF** (Tag-Talks-First): an RFID tag, when it immediately enters the reader's field, signals its presence by reflecting the received signal and sending its identifier. The reader responds with a brief modulation of the power signal and the data transfer can begin [22]. This technique is very useful to know all the tags that pass near the reader, especially in the vicinity of the reader, such as objects transported by a conveyor belt in a warehouse or airport.

RFID standards are guidelines or specifications for all RFID products. These standards provide guidelines for how RFID systems work, at what frequencies they operate, how data is transferred, and how communication between the reader and the tag works. They also help ensure that RFID products are interoperable, regardless of vendor or user. They also provide guidelines by which companies can develop complementary products, such as different types of cards, readers, software and accessories. In addition, standards help to expand markets and increase competition in the industry, which lowers the cost of RFID products. RFID standards also help increase widespread confidence in the technology.

The two main bodies in charge of drafting RFID standards are [23]:

- ISO/IEC- International Standards Organization / International Electrotechnical Commission.
- Auto-ID center o EPC global - Electronic Product Code Global Incorporated.

Although these two organizations provide the main RFID standards, there are also a large number of different standards that apply to RFID areas.

3.4.1 ISO Standards

The ISO standards for the communication protocols of the different frequency bands are [24]:

- ISO 18000-1: defines the reference architecture and the parameters to be standardized.
- ISO 18000-2: communication parameters for frequencies below 135 KHz.
- ISO 18000-3: defines the communication parameters for the 13.56 MHz frequency.
- ISO 18000-4: concerns the 2.45 GHz frequency.
- ISO 18000-5: concerns the 5.8 GHz frequency.
- ISO 18000-6: for frequencies between 860 and 930 MHz.
- ISO 18000-7: for 433 MHz operation.

3.4.2 EPC Global Standard

EPC global Inc. is a non-profit organization born following an agreement in July 2003, between the Auto-ID Center of MIT (Massachusetts Institute of Technology) and GS16 (also known as EAN 7 in Europe and Uniform Code Council for GS1 US). The mission of this organization is the development and deployment of the EPC (Electronic Product Code) and EPC Network standards, as well as the promotion of RFID technology throughout the world.

3.4.2.1 Electronic Product Code (EPC)

The EPC code is the new means of identifying objects after barcodes. It allows the identification of an object throughout the world in a unique way. Its structure is defined by global EPC in such a way that it can be used to determine several attributes of the object bearing the code in question. The size of such a code can be 64 or 96 bits (which are the most common) or 128 or 256 bits. The attributes of a 96-bit EPC code (which theoretically allows the identification of 2 96 objects) are represented in Figure 16.

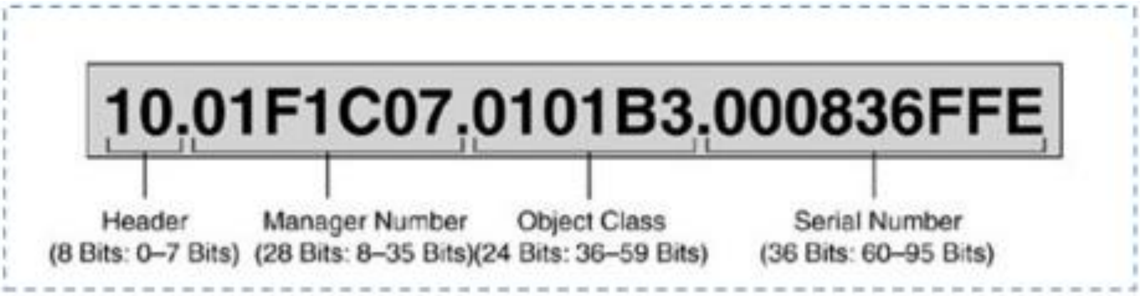


Figure 16: 96-bit EPC code format

Header: consists of the 8 most significant bits (bit 0 to bit 7) and allows to define the length, the type of identification key, the structure and the version of the EPC code.

EPC Manager Number: (28 bits) identifies the domain or company (product manufacturer code) that is responsible for assigning the data in the "object class" and "serial number" fields.

Object Class: (24 bits) identifies the class or type of objects (product type).

Serial Number: (36 bits) identifies the object (the product) within the same product type in a unique way.

3.4.2.2 EPC tag classification

With the EPC standard, RFID tags are classified into four types [25]:

EPC Class 0 and Class 1: these classes concern passive tags that can store EPC data but also user data (optional). Class 0 tags are read-only while Class 1 EPC tags are "Write Once / Read Many". The UHF class 1 GEN 2 protocol allows to increase the communication performances (several hundreds of readings simultaneously) but also to improve the data security through to blocking functionalities (data access restriction by password) and tag deactivation with the "KILL" function.

EPC Class 2: this class concerns passive tags with a rewritable memory (read/write memory) that can store the EPC code as well as user data.

EPC Class 3: it concerns semi-passive tags, it includes the characteristics of class 2, with the possibility of including sensors (temperature, humidity...) and the data log.

EPC Class 4: concerns active tags. In addition to the characteristics of class 3, it adds the possibility to communicate between tags.

4. Architecture of a Passive UHF RFID System

The passive UHF (Ultra High Frequency) RFID is a technological breakthrough that revolutionizes the methods of identification and traceability that are among the major concerns of the industrial world, especially since the establishment of the EPC (Electronic Product Code) (see Figure 17). This standard with its different classes consists in assigning a unique identifier to the RFID tag. This identifier is expressed on 64, 96 or 125 bits and allows the traceability of objects using the 860-960 MHz spectrum worldwide. Class 2 as we mentioned before is reserved for passive tags; these consist of an electronic chip and an antenna. Unlike conventional communication systems, they are remotely powered and have no own source of radio frequency emission. Passive tags consist of an electronic chip and an antenna, and works by retro-modulation principle, it’s one of the most efficient and low-cost technologies. It allows a lower cost of manufacturing RFID tags. Higher order classes are for active tags. The 2.45 GHz and 5.8 GHz bands are reserved for medical applications such as heart rate and temperature sensors.

For this family (UHF RFID system), the data transfer is performed by wave propagation between reader and tag antennas. On the reader side, the antenna often takes the form of patches with circular polarizations to ensure a better reading rate compared to unknown orientations of the tags. The tag antenna is most often based on the shape of a λ/2 dipole, which allows to have a quasi-omnidirectional radiation diagram. Miniaturization techniques reduce the size of tags to match the dimensions of targets. The most common size is less than 10 cm in length, well below λ/2.

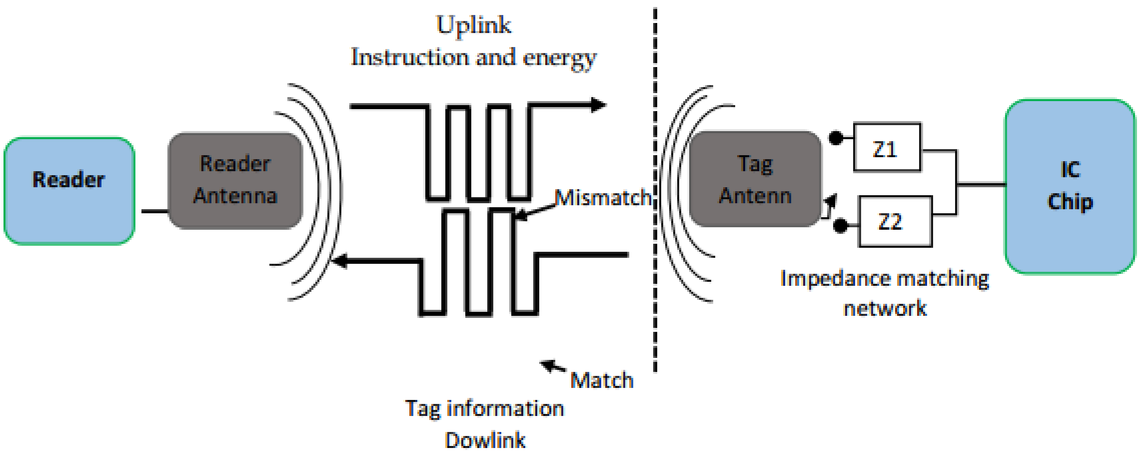


Figure 17: Architecture of UHF RFID system

4.1 UHF Passive Tag

A classic RFID tag is «simply» composed of an antenna and an RF chip. The type of antennas used for tag depends mainly on the frequency band at which the system operates, as well as the environmental conditions in which the tag is inserted. The electrically small, loop antenna is the most common type of antenna used in the LF and HF frequency bands. The term "electrically small" refers to the size of the antenna compared to the wavelength, λ, of the operating frequency. Due to the size of the antenna, the current flowing through the loop generates an almost stationary magnetic field which facilitates inductive electromagnetic coupling.

In the UHF band dipole antennas are preferred because the electromagnetic coupling between the base station and the tag is often achieved by the radiative electric field of plane waves. Some UHF RFID applications operate at a very short distance, and then the coupling is performed by magnetic and/or reactive electric field lines.

The second main element of an RFID tag is the microchip it embeds, which is an integrated circuit. The RFID chip is an essential element of a conventional RFID system because it contains the unique identifier that gives meaning to an RFID application. The performance of

the tag in terms of reading distance will depend mainly on the sensitivity of the chip. The architecture of an RFID chip is shown in Figure 18 [26]. It is divided into three distinct main blocks: the analog signal control block, digital processing and, non-volatile memory.
The operation of the RFID chip can be divided into three detailed steps below:

- Energy recovery step:

The RFID chip recovers energy through the tag antenna. Impedance antenna input is matched to the conjugated complex impedance of chip in order to establish a maximum power transfer to a given frequency or frequency band. The RF energy is rectified by the rectifier circuit to provide continuous voltage, to the analog and digital modules of the chip. For the chip to be activated, a minimum level of power is required, which now reaches about -22 dBm for the most powerful chips.
-Step of recovery and processing of data sent by the reader:

After the tag is powered on, the commands or information sent by the reader are processed by the analog module. The signal is first demodulated: the information is extracted from the carrier wave and converted into a digital signal. This signal is interpreted by a digital module, which, after verifying the accuracy of the control, performs read/write functions or deletes data on the chip's non-volatile memory. Figure 19 illustrates the steps of energy recovery (step 1) and information detection (step 2) of passive RFID tags [16].

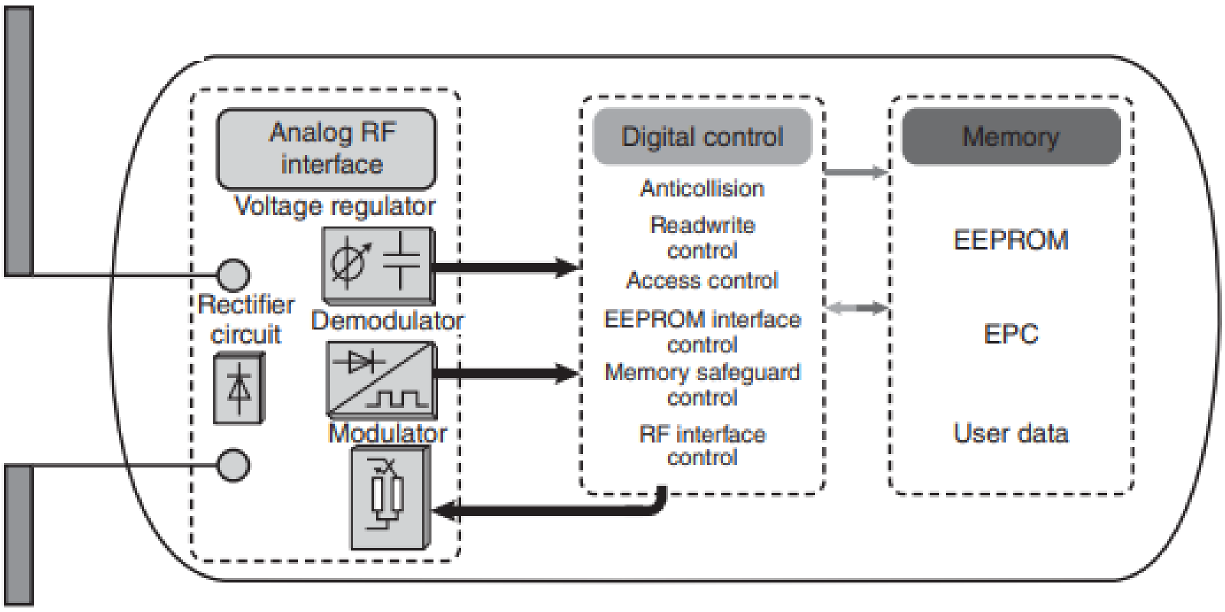


Figure 18: IC-RFID UHF Chip Architecture

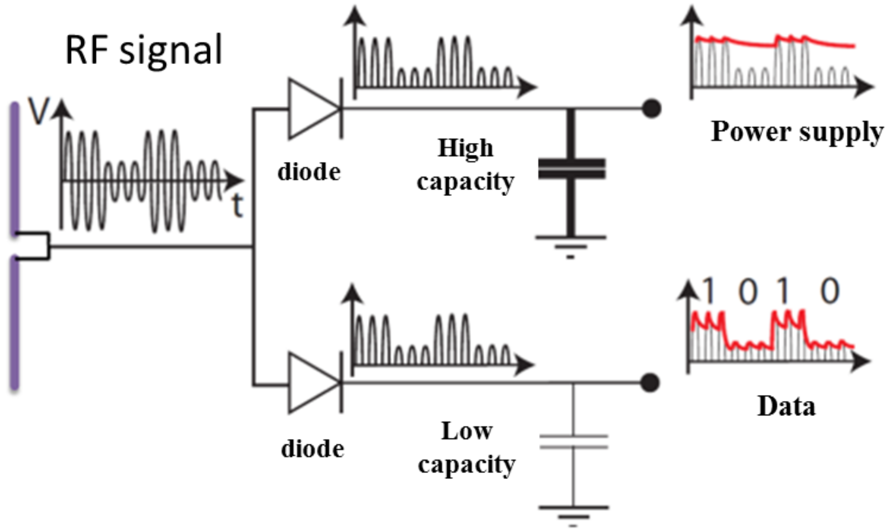


Figure 19: Diagram of energy recovery and data detection by a passive RFID tag

- Data transmission step:

The information stored in the chip is transmitted to the reader through the retro-modulation technique which consists in modifying the load impedance of the tag antenna between the reflection state and the power absorption state respectively, and this at the rate of the data rate to be sent to the reader. The absorption state corresponds to the energy recovery step as described above. The reflection state corresponds to the state for which a maximum of power is reflected by the antenna. In this case, the antenna input impedance is connected to a short or open circuit. During the retro-modulation, the reflection coefficient of the tag antenna, Γ, can be varied in amplitude or phase, in order to obtain respectively a ASK or PSK modulation. The reflection coefficient represents the quality of the matching condition of the antenna to the complex impedance of the chip. Figure 20 illustrates the retro-modulation technique and how the reflected signal is re-radiated by the tag. It should be noted that the adaptation between the antenna and the chip is never perfect. As a result, a small amount of energy is always reflected by the tag during the absorption state.

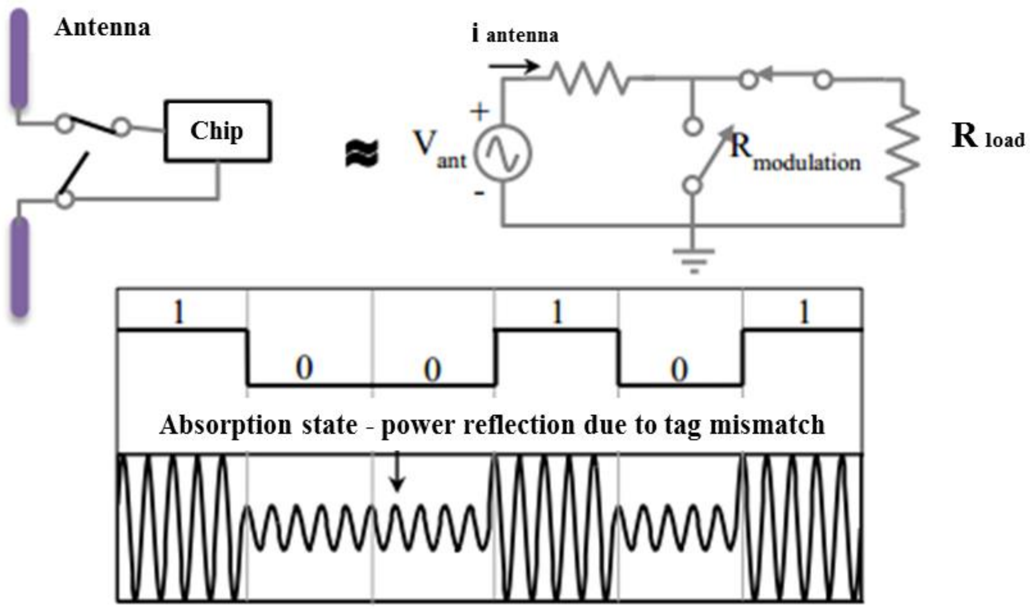


Figure 20: Principal of the Retro-reflector

It is important to note that the energy recovery step occurs concurrently with step 2. In fact, the tag is a passive element that strongly depends on the power available at the antenna terminals, and the energy recovery must remain constant during all steps. Due to the presence of nonlinear circuits such as rectifier circuits and voltage regulators, the performance of the chip depends not only on the input power available at the tag antenna terminals, but also on the frequency.

4.2 Reader

The reader is the component that coordinates RFID communication and provides remote feed for tags in the case of passive RFID. It is formed by a Radio Frequency module for transmission and reception, a control unit, an antenna and also an additional interface to transmit data to a terminal (RS232, USB, Ethernet) [3,27].

The control unit sets the communication protocol and manages basic band coding and decoding operations. Then, we find the front end which is finalized by an antenna (Figure 21).

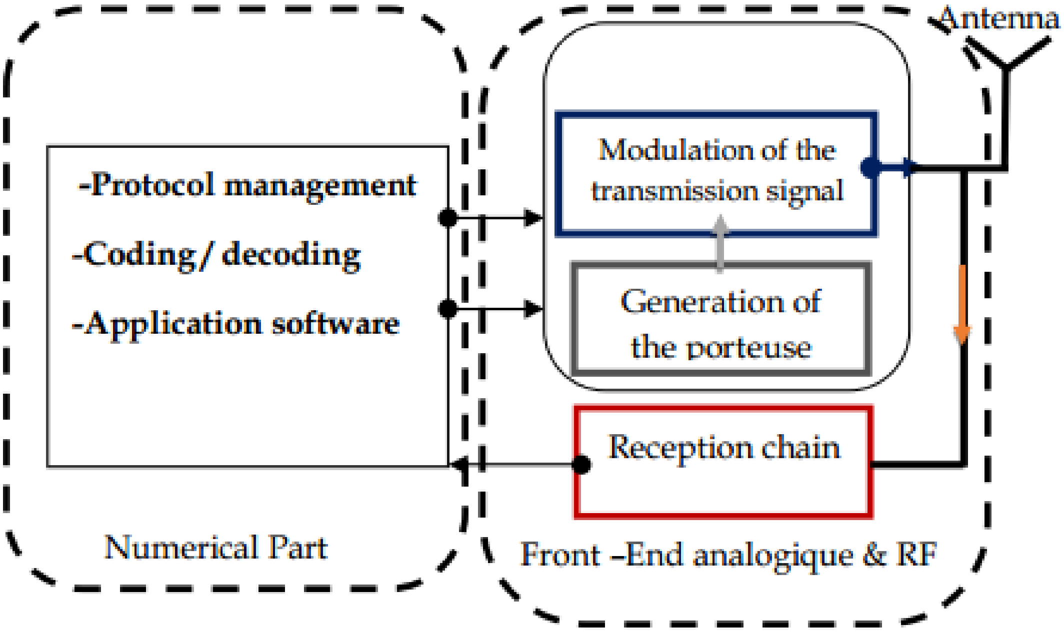
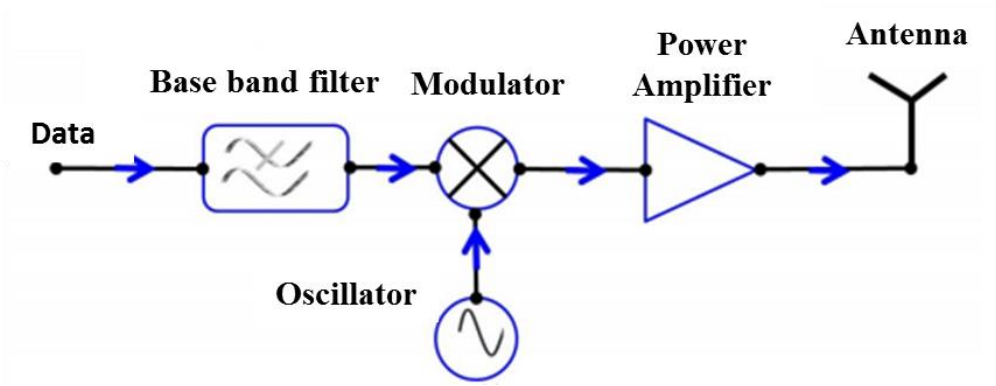
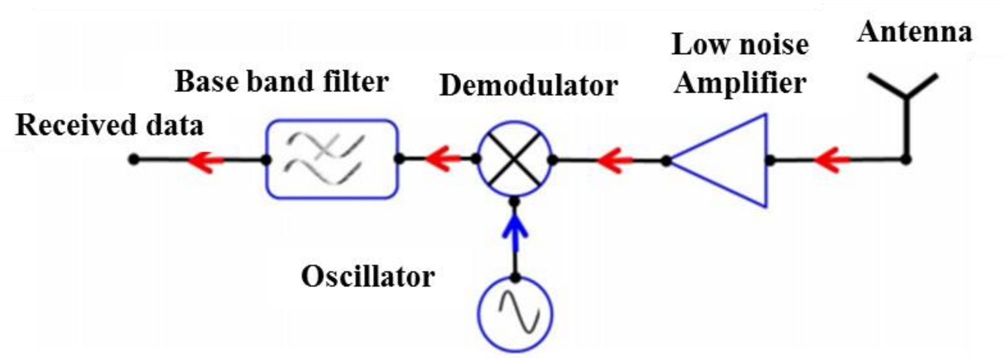


Figure 21: Schematic of a UHF RFID Reader



(a)



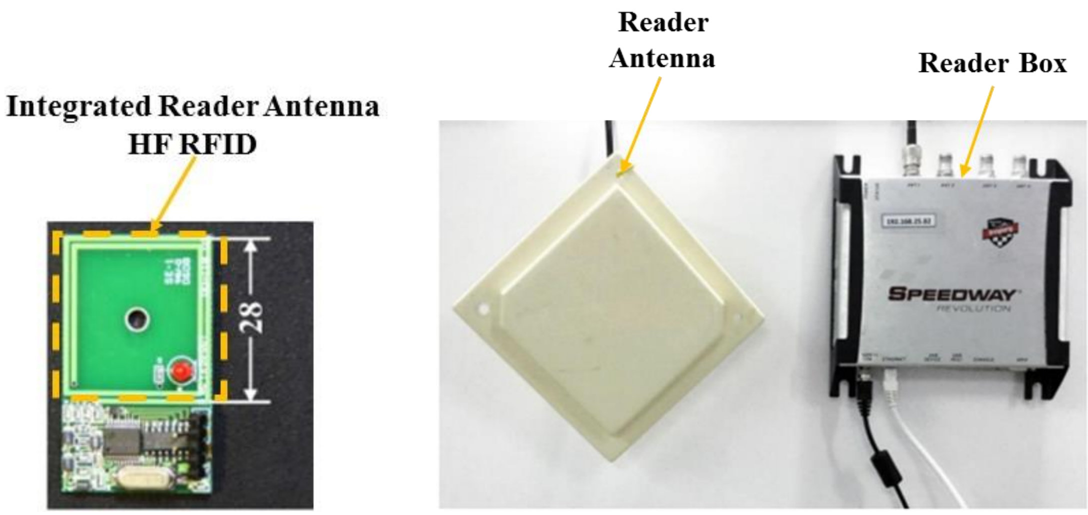
(b)

Figure 22: (a) Transmission chain of a UHF RFID reader, (b) reception chain of a UHF RFID reader

The front end has modulation/demodulation blocks synchronized to a local oscillator. It also has the filter blocks, and amplification blocks, which constitute the transmit chain (Figure 22-a) and receive chain (Figure 22-b).

The information in digital form is therefore generated in base band and then coded by an appropriate algorithm. It is then transformed into an analog signal, then modulated to the RFID communication frequency. The modulated signal is finally amplified. In the last step, the transmission of the signal is done by the antenna. The reader therefore transmits a modulated signal at the operating frequency which also contains its request. This signal will enable the RFID chip of the tag. Afterwards, the reader continues to send the query to maintain the feed of the tag. This signal is also used to create the tag response by retro-modulation. To do this, the tag will modify its input impedance (it presents successively two different values) so that the reflected signal also presents two different states. Then, the reader recovers this reflected signal, amplifies it, demodulates it and extracts the information returned by the tag. It can thus obtain the UID (Unique ID) of the tag. The speed of transmission and data processing varies according to the RFID frequency used. The flow rate is higher in the UHF band compared to the LF and HF bands.

RFID readers can have integrated antennas (Figure 23-a) for low reading ranges as in HF band [28, 29]. For traceability applications, especially for logistics and mass distribution, the antennas are separated from the reader case and one can have several antennas to widen the reading area (Figure 23-b). There are fixed readers such as access control and validation of transport tickets as well as mobile readers used for scanning articles in large areas [28]. The reader antenna design shall take into account these integration (space, application environment) and dimension constraints. It’s can therefore have reader antenna printed on the same board as the RF module as in the case of an integrated reader or have a support independent of the reader.



(a) (b)

Figure 23:(a) RFID reader with integrated antenna [28], (b) UHF RFID reader housing with the possibility to connect four antennas (separate antenna).

The reader antennas differ according to their emission and reception parameters, in particular polarization, directivity, efficiency, gain and equivalent surface area. These parameters are specific to the operating area and the intended application.

4.3 Middleware

In computer architecture, a middleware of an RFID system is a layer of software that creates an information exchange network between different computer applications as in Figure 24. The network is implemented by using the same information exchange technique in all the applications involved by means of software components. The software components of the middleware ensure the communication between the applications whatever the computers involved and whatever the hardware and software characteristics of the computer networks, the network protocols, the operating systems involved.

The role of RFID middleware:

- Filtering and validation of raw data.
- Fusion of the data emitted by the different sensors.
- System management (monitoring, service levels ...).

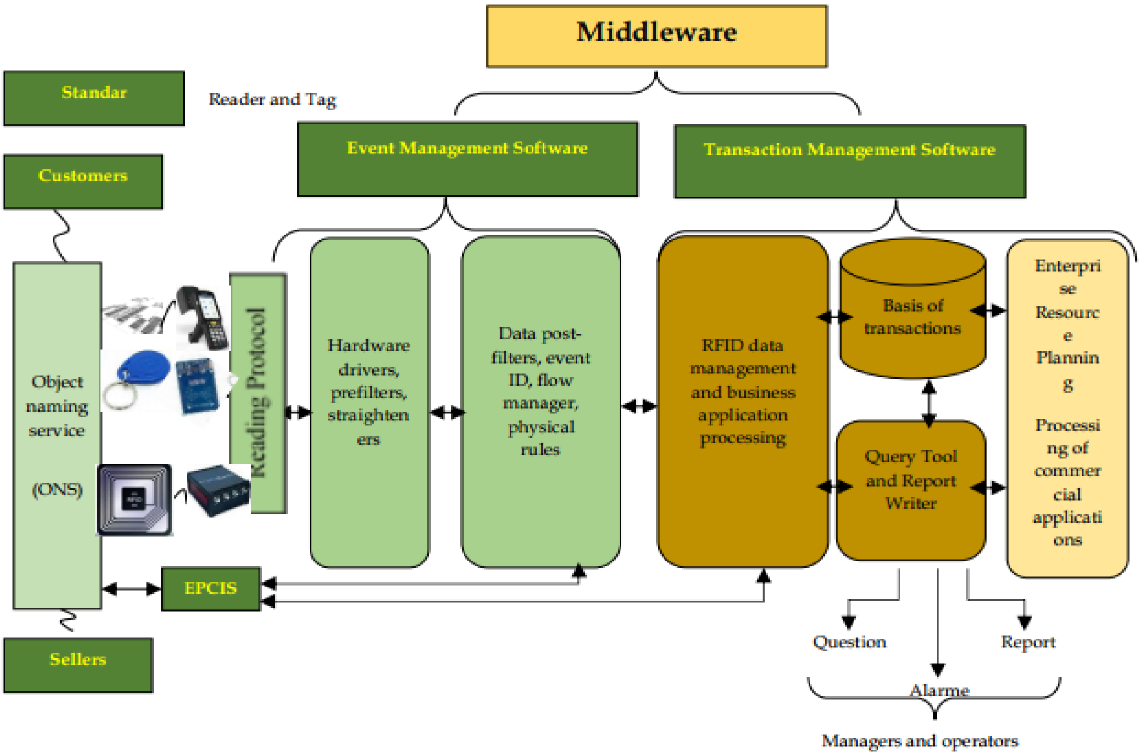


Figure 24: Middleware Architecture

5. Types of coupling

Electromagnetic waves are generated by the antenna shown in the center in Figure 25. Depending on the distance R, they behave in different ways. We speak of near-field area when the distance R is small compared to the far-field area wavelength (λ) if R becomes significant in front of λ. This distance is given in Figure 25, it depends on D the size of the transmitting antenna and λ the wavelength associated with the operating frequency by:

$$\lambda = \frac{c}{f} \quad (1)$$

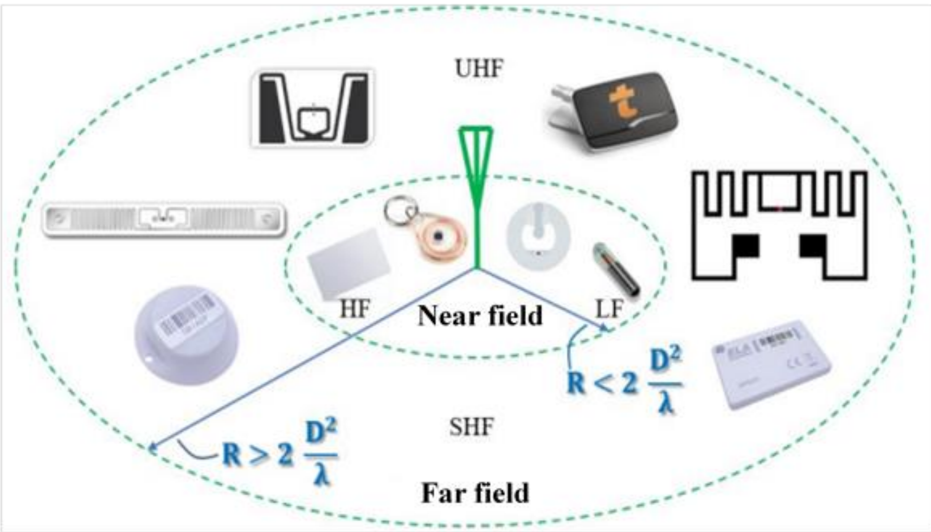
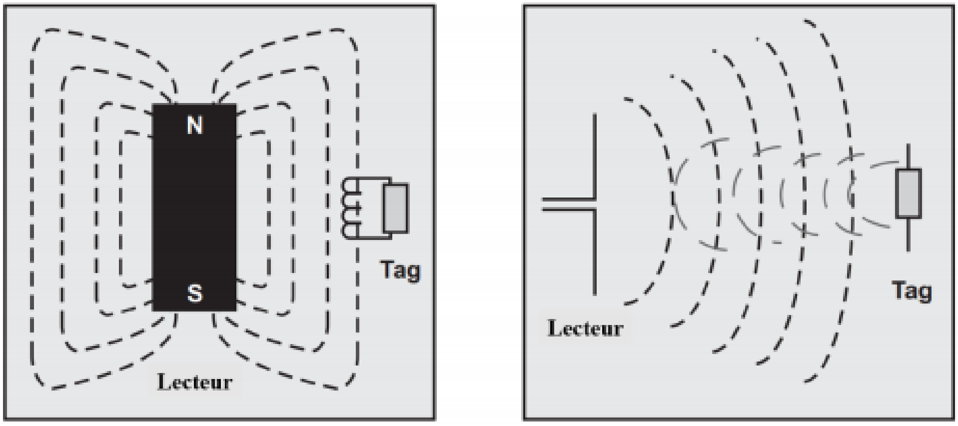


Figure 25: Classification of RFID tags according to their operating area [3].

Using the relation (1), we simply notice that if the frequency is small, the wavelength is very large, and therefore, so that the antenna radiates effectively in far field, its physical length must be close to the wavelength at the frequency considered.



(a) (b)

Figure 26: Types of RFID couplings, (a) inductive coupling (near field), LF and HF technologies, (b) radiative coupling (far field), UHF and SHF technologies [30].

The antennas of the LF and HF systems must be much larger than UHF and microwave antennas to achieve comparable signal gain, that due to the long wavelengths of low-frequency signals. This is why systems where the wavelength is much longer than the antenna are usually coupled by magnetic induction: almost all the available energy is contained in a region close to the antenna of the reader (Figure 26-a). In this region, the communication between the tag and the reader is actually instantaneous since the propagation time to the tag is low. On the other hand, when the frequency is high, the size of the antenna decreases accordingly, for example for ultras high frequencies (UHF) the size of the antenna is of the order of tens of centimeters. In this space region the coupling is performed by radiation (Figure 26-b) since the antenna is of a size comparable to the wavelength.

5.1 Inductive coupling or near field

This mode of operation is generally defined as having the same operation as a transformer (Figure 27). Generally, inductive coupling exists when a magnetic field created by an electric current induces an effect (mechanical or electric) on something else. For example: in a transformer, at the primary level, an electric current circulating through a wire wrapped around a core, creates a magnetic field that induces a current in the secondary winding. The same effect is used in radio frequency, when the antenna is well tuned to the impedance of the chip. The electromagnetic field generated by the reader, induces a current at the antenna of the tag, which allows to power the chip. Then, in order to generate a response in return suffices the chip to modulate its load so that the reader is directly impacted by these current variations and thus deduce a response Figure 26-a.

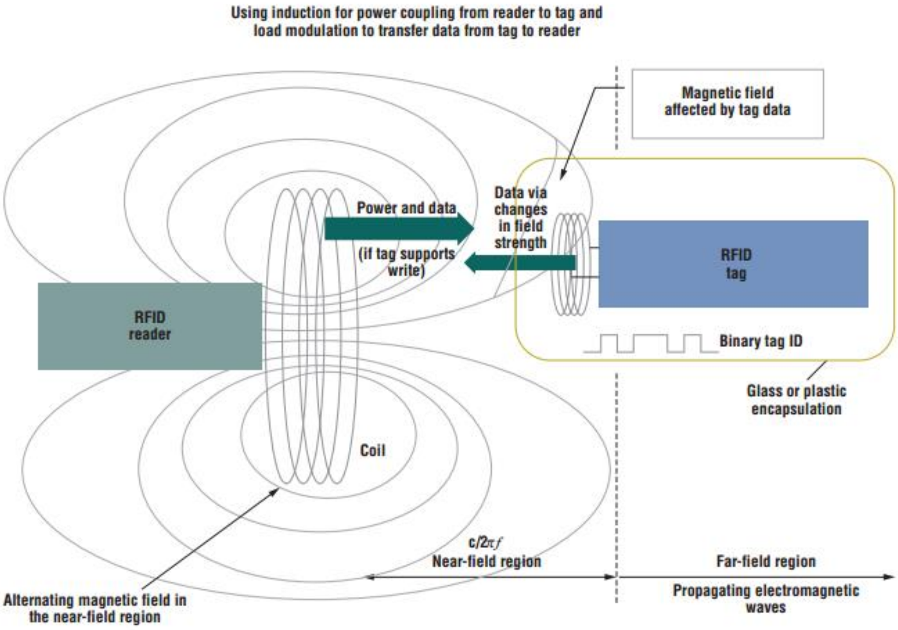


Figure 27: Communication mechanism for near field RFID tag [31]

The antenna used in inductive coupling is in the form of a loop (Figure 28). LF and HF bands are primarily used for animal identification, access control, transit passes and contactless payment. In NFC, antennas have very similar shapes to each other. They are composed of loops of conductors forming several windings in order to obtain an inductance value of a few µH, and easily integrated into objects such as paper tickets, tokens or credit cards.

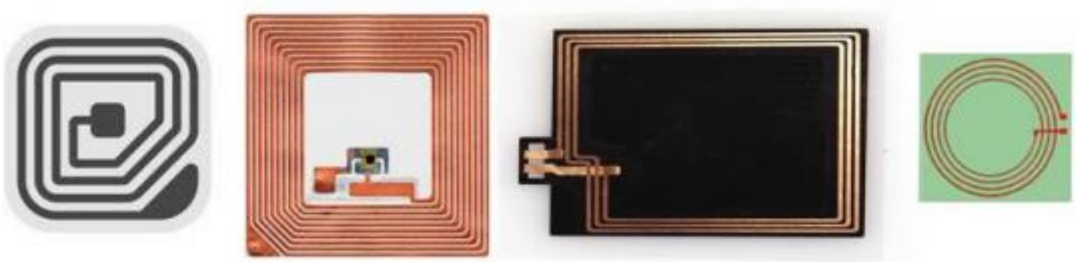


Figure 28: Different form of HF RFID (NFC) tag

5.2 Radiative coupling or far field

In UHF or SHF band, data exchange is based on electromagnetic (EM) wave propagation

(Figure 26-b). When a high frequency signal is applied to the antenna of the reader, an EM wave is generated (Figure 29). Reciprocally, if the antenna of the tag is placed in the EM field generated by the reader, an electric voltage appears at its terminals. This voltage is used to power the tag chip.

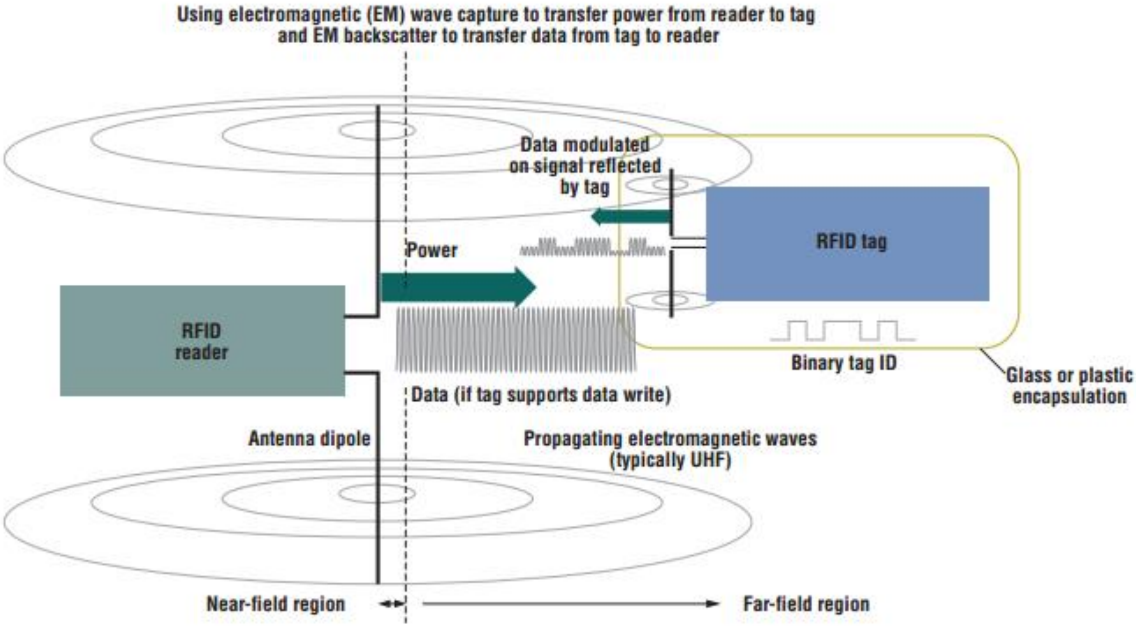


Figure 29: Communication mechanism for far field RFID tag [31]

The antennas of passive UHF RFID tags in radiative coupling are available according to a multitude of different geometries (Figure 30). The choice of an RFID antenna is largely defined by the application. The first constraint is the price of the antenna, which includes the substrate, the means of fixing the chip and the material that makes up the antenna (copper, conductive ink, etc.). The second constraint is the size of the antenna, since it determines the final size of the tag. The latter depends heavily on the application.

This type of RFID is very widespread in the world for applications of management of production lines, traceability of manufactured products, localization, etc. The reading ranges of several meters allow to identify objects without requiring the reader to be close, this allows a great freedom of deployment of the RFID system at the expense of security.

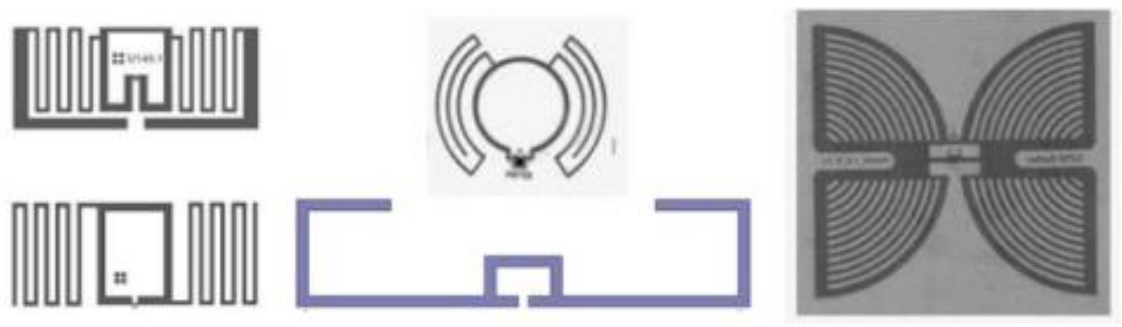


Figure 30: Different form of UHF RFID tag

We can also mention: the polarization of the antenna (defined as the preferred direction of the wave emitted/received by the antenna) which modifies its shape, the adaptation between the antenna and the RFID chip, allowing a good transfer of power supply. And also the radiation efficiency of the antenna allowing to have correct communication regardless of the dielectric or conductive properties of the objects on which it is affixed (paper, plastic, metal, etc.).

6. Conclusion

In this chapter, we have presented an overview of RFID technology and its benefits. In addition, we have presented the structure and standards of an RFID system. From this presentation we can better identify the characteristics and characteristics and properties of each component. We have also briefly presented the current research directions that are considered for the development of RFID and its applications. It is within the framework of this evolution that our own work is going to be situated, which is the subject of the third chapters. More specifically, we are aiming at the development of sensor tags, able to give information when it's mounted on the blood tubs.

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Chapter 2

State of the Art of UHF RFID

1. Introduction

Wireless communication by modulating backscattered signals from a transponder (RF tag) is fundamentally different from conventional radio communication because it involves two distinct links: the trigger link, to feed the passive RF tags, and the backscatter link in which the tag sends information to the reader. Because of the severe constraints to which the RF tag is subjected, detailed knowledge of the backscatter channel is essential to maximize the backscatter of the power intercepted by the tag antenna.

In the first part of this chapter, we will present some fundamental notions of tag antennas, Afterwards, the second part is dedicated to discuss all types of sensors under RFID technology.

2. Fundamental concepts

Passive RFID tags, as described before, are simply composed of an antenna and an RFID chip. The antenna allows the reception of electromagnetic (EM) waves from the RFID reader, thus providing the necessary energy to the chip considered then as a load. Moreover, the same antenna transmits to the RFID reader the information contained in the chip (EPC code...) by using the principle of retro modulation. As a reminder, this communication principle is based on a charge modulation connected to the antenna. This shows the importance of the antenna/chip couple, to ensure a communication between the RFID tag and the reader.

2.1 Impedance of the tag

The impedance matching step is essential to ensure maximum power from the antenna to the RFID chip and thus optimize the tag performance. For this, the impedance of the antenna of the RFID tag must be directly matched to the chip impedance, which is usually a complex impedance.

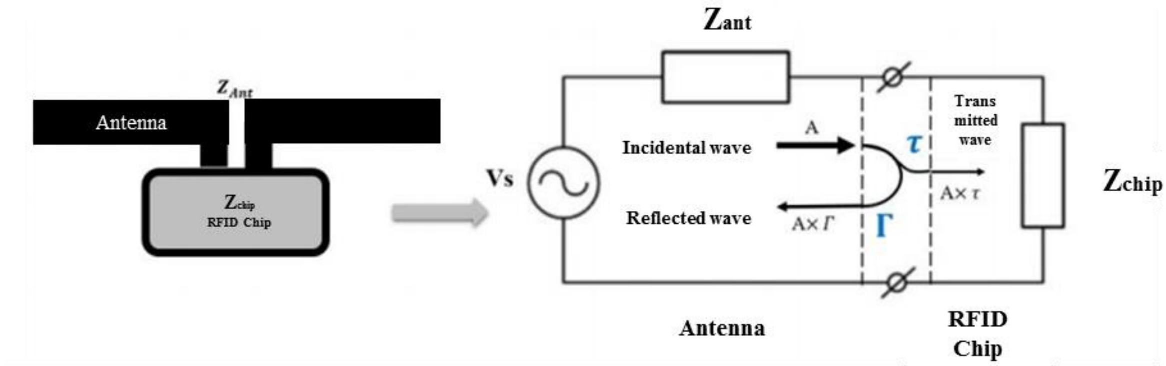


Figure 31: Equivalent electrical circuit of a passive UHF RFID tag

The equivalent circuit of the antenna load is given in Figure 31. With, V_s which represents the

AC voltage across the antenna, induced by the electromagnetic (EM) wave coming from the reader. Z_{ant} (equation 1) represents the complex impedance of the antenna. With: $R_{ant} = R_{\text{radiation}} + R_{\text{losses}}$, The load resistance R_{losses} is used to represent the conduction and dielectric losses associated with the antenna structure, while $R_{\text{radiation}}$ called the radiation resistance, is used to represent the radiation properties of the antenna [1]. Z_{chip} (Equation 2) represents the complex impedance of the RFID chip.

$$\mathrm{Z_{ant}} = R_{\text{ant}} + \mathrm{jX_{ant}} \tag{1}$$

$$\mathrm{Z_{chip}} = R_{\text{chip}} + \mathrm{jX_{chip}} \tag{2}$$

The impedance of the RFID chip is specific to the design of the integrated circuit, it depends on the frequency, and is provided by the manufacturers [2]. In order to guarantee a maximum power transfer from the antenna to the load (chip), the input impedance of the antenna must be equal to the conjugate complex impedance of the integrated circuit in the operating frequency of the tag [1].

$$R_{\text{ant}} = R_{\text{chip}} \quad \text{et} \quad \mathrm{X_{ant}} = -\mathrm{X_{chip}} \tag{3}$$

Impedance matching can be achieved using localized or distributed components in the form of dedicated matching circuits. Most antennas used for passive UHF RFID tags are based on dipole geometries etched or printed on thin dielectric substrates. The various geometries that can be observed meet the constraints of size, manufacturing cost and guaranteed operation for a particular environment. Alternatives exist, some devices use patch antennas, and others use PIFA (Planar Inverted-F Antenna). Impedance matching techniques for dipole antennas have also multiplied with, among others, the use of "T-match", "T-slot", "loop", "meander" and "Tip-loading" [3]. As an RFID chip is a nonlinear element in power, the adaptation must be designed for a given input power level.

2.2 Notion of Reflection and Transmission coefficient

The Reflection coefficient Γ (Equation 4), shown in Figure 1, is the amplitude ratio between the reflected EM wave at the antenna input and the incident EM wave. It depends on the input impedance of the antenna Z_{ant} and the characteristic impedance of the RFID chip Z_{chip}.

$$\Gamma = \frac{Z_{ant} - Z_{chip}^{*}}{Z_{ant} + Z_{chip}} \tag{4}$$

If the matching is not ensured, part of the power is sent back to the source (re-radiated by the antenna), called "mismatch loss" [4].

The Transmission coefficient τ (see Figure 31), also widely used in RFID, represents the fraction of power transmitted from the tag antenna to the chip, or conversely from the chip to the antenna for re-radiation of the wave, during tag response. This coefficient also depends on the impedances of the antenna and the chip, and is expressed according to the equation [4]:

$$\tau = (1 - |\Gamma^*|^2) = \frac{4R_{Chip}.R_{ant}}{|Z_{ant} + Z_{chip}|^2} \quad (5)$$

Γ^* is called the reflection-conjugate adaptation coefficient, the coefficient $|\Gamma^*|$, reflects the adaptation state of the system.

2.3 Notions of gain and directivity of a dipole antenna

In general, the directivity of an antenna is defined as the ratio of the maximum radiated power density in a given direction divided by the radiated power density of an isotropic antenna [5], see the illustration in Figure 32. The realized gain of an antenna that takes into account all loss elements is defined by equation (6). This gain is based on the directivity D (θ, φ), transmission coefficient τ and radiation efficiency e of the antenna. It also depends on the antenna aperture angle θ and the polarization angle φ between the transmitting and receiving antenna.
In the lossless case, the ratio of the antenna efficiency multiplied by the transmission coefficient is equal to 1, and thus the gain is equal to the directivity.

$$G(\theta, \varphi) = D(\theta, \varphi).e.\tau \quad (6)$$

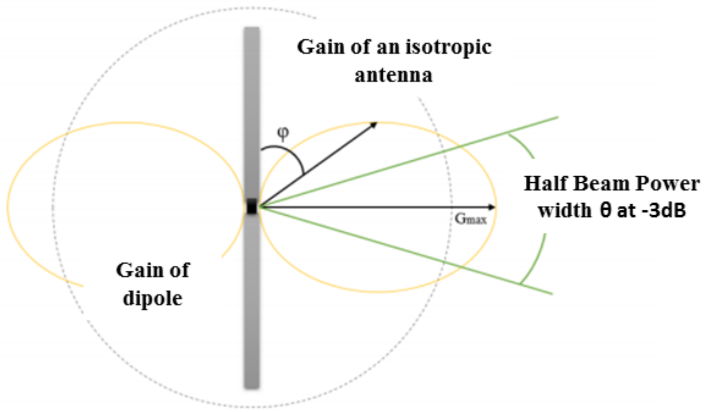


Figure 32: Radiation diagram of a dipole compared to that of an isotropic dipole [5]

The polarization of an electromagnetic wave is determined by the orientation of the electric field of the wave. There are several types of polarization including linear polarization and circular polarization. In linear polarization, if the electric field lines are parallel to the Earth surface the polarization is horizontal, and if the electric field lines are perpendicular to the Earth surface, the polarization is vertical. Thus, as illustrated in Figure 33 (a) and (b), the dipole antenna is a linearly polarized antenna in which the electric field lines are parallel to the dipole axis. The energy transmission between two linearly polarized antennas is optimal if both antennas have the same polarization direction. On the other hand, the power transmission is at its lowest point when the polarization directions of the transmitting and receiving antennas are arranged exactly 90° or 270° to each other (e.g. a horizontal and a vertical antenna).

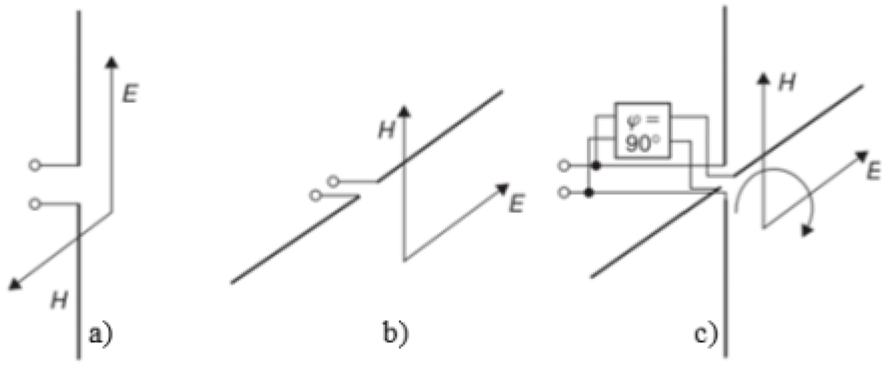


Figure 33: Polarization of an electromagnetic wave, a) vertical polarization, b) horizontal polarization and c) circular polarization

In circular polarization, the antenna emits an EM field whose norm does not vary when the antenna is rotated. In order to generate a circularly polarized wave, as shown in Figure 33 (c), it is sufficient to arrange two perpendicular dipoles, and to feed one of the two dipoles via a 90° delay line. The polarization direction of the resulting electromagnetic field rotates 360° each time the wave front advances by one wavelength [6].

In RFID systems, using mainly linearly polarized dipole antennas, there is usually no fixed relationship between the position of the tag antenna and the reader. Especially for logistics applications, this can lead to fluctuations in the reading range that are both high and unpredictable.

2.4 The theoretical reading distance

The read distance (Figure 34) is a widely used parameter in passive UHF RFID, as it combines several essential parameters of tag and reader performance into a single formula. It is taken from the Friis equation (7) and is often put in the form of equation (8).

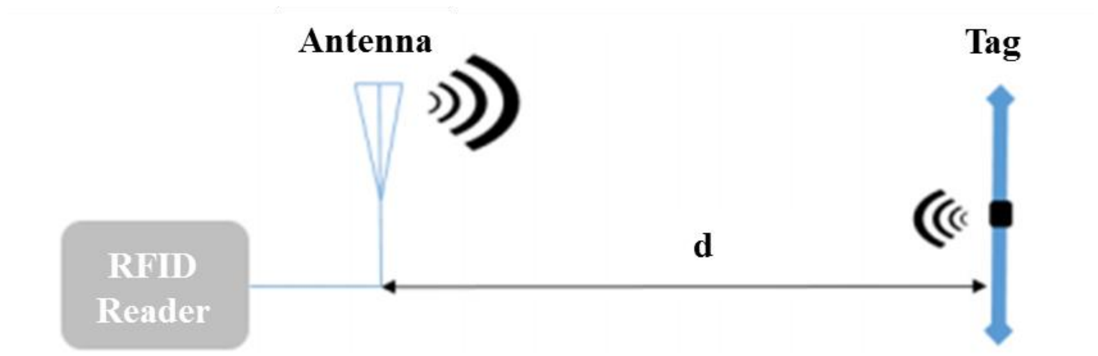


Figure 34: Illustration of the reading distance between an RFID reader and a tag

$$\frac{P_r}{P_t} = (\frac{\lambda}{4\pi d})^2 G_t G_r \tau \rho \tag{7}$$

P_t (W) the power delivered to the transmitting antenna (reader antenna)
P_r (W) the power collected on the receiving antenna (related to the sensitivity of the RFID chip used)
G_t is the gain of the transmit antenna (reader antenna)
G_r is the gain of the receiving antenna (tag antenna)
d (m) the theoretical reading range
λ (m) wavelength
τ Transmission coefficient
ρ Polarization losses

$$d = \frac{\lambda}{4\pi}\sqrt{\frac{G_t G_r (1 - |\Gamma^*|^2) P_t}{P_r}} \tag{8}$$

These equations are given as a function of several parameters, some of which will be fixed and known such as the wavelength λ, the reader antenna gain G_t, the RFID chip sensitivity P_r.
On the other hand, the polarization losses ρ are variable and depend on the orientation of the tag at the time of the measurement. The maximum power P_t at the output of the RFID reader must comply with the limits imposed by the authorities of each country on the radiated power at the output of the antenna. According to the standards we will use:
The effective isotropically radiated power (EIRP) defined by equation (9). This quantity is the product of the power injected into the antenna and the gain of the antenna (when power and gain are linear). In the case of a hypothetical perfectly isotropic antenna (gain of 1) the PIR power is equal to the power injected into this antenna. The FCC committee imposes in North America a limit of 4W EIRP in the UHF RFID band.

$$P_{EIRP} = G \, . \, P_t \tag{9}$$

The effective radiated power (ERP) has a definition close to the EIRP power, but in this case the quantity expressed corresponds to a power injected into an ideal half wave dipole antenna (gain of 1.64). This quantity is defined by equation (10). In Europe, the ETSI committee imposes a limit of 2W ERP (or 3.28W EIRP) in the UHF RFID band.

$$PERP = \frac{Gt. Pt}{1.64} \tag{10}$$

The relationship between ERP and EIRP power is given by equation (11).

$$P_{EIRP} = 1.64 \, . \, P_{ERP} \tag{11}$$

In the case of a RFID sensor, the environment impacts several parameters of the tag antenna, including the gain and the transmission coefficient. This is even truer for RFID sensors with functionalization of the antenna. This functionalization is done by deposing a sensitive material, whose relative permittivity varies according to the parameter to be detected. In the remainder of this section, we will study the different types of sensors also, the impact of these permittivity variations on the performance of the RFID sensor antenna

3. Status of RFID sensor technology

Over the last decade, the great interest in RFID systems and the Internet of Things (IoT) has stimulated industry and scientific research and has resulted in numerous publications, proofs of concept, prototypes or products. The RFID devices have improved considerably and new applications have been studied. These improvements concern both the RFID chip, the tag and the RFID reader. Passive RFID tags have been successfully developed in industry as a replacement or complement to barcodes [7]. The RFID technology has several advantages over barcodes: the reading of several products in parallel, inventory tracking, less handling, etc... For some applications, cost is an important concept. So for RFID to completly replace barcodes, it is clear that the electronics must be printed in the same manner as the barcode is today. However, there are still significant challenges to overcome before fully printed RFID tags can be commercialized [8].

Today, one of the main areas of interest in RFID is the addition of sensors to the basic RFID automatic identification capabilities [9]. Indeed, traceability is no longer enough, there is a real need in some applications to obtain sensor information. The sensor is generally defined as a device that receives and responds to an external signal or stimulus. The stimulus is the physical parameter to be detected (also called target parameter). Generally, a wireless sensor is a device that combines the capabilities of a sensor and an RF or wireless device and is therefore able to detect, process data, transmit and/or communicate to other wireless devices.

The goal of RFID-sensors is therefore to create a system that can not only track, but also monitor (condition). Passive RFID technology, as a low cost and long life technology, offers great potential for sensor data transmission combined with EPC. This is especially true for tags operating in UHF band, the data transmission can be done over relatively large distances (~ten meters) for the vast majority of applications. In the following, we will focus our study on the passive UHF RFID technology.

To add detection functionality to passive RFID tags operating in the UHF band, there are several approaches, which we have divided into two main families shown in Figure 35. The first family (named digital communication RFID-sensors) depends on the chosen RFID chip, indeed some RFID chips accept external sensors via a dedicated input, or directly integrate a sensor internally. The second family concerns RFID-sensors based on the antenna mismatch principle (named analog communication RFID-sensors).

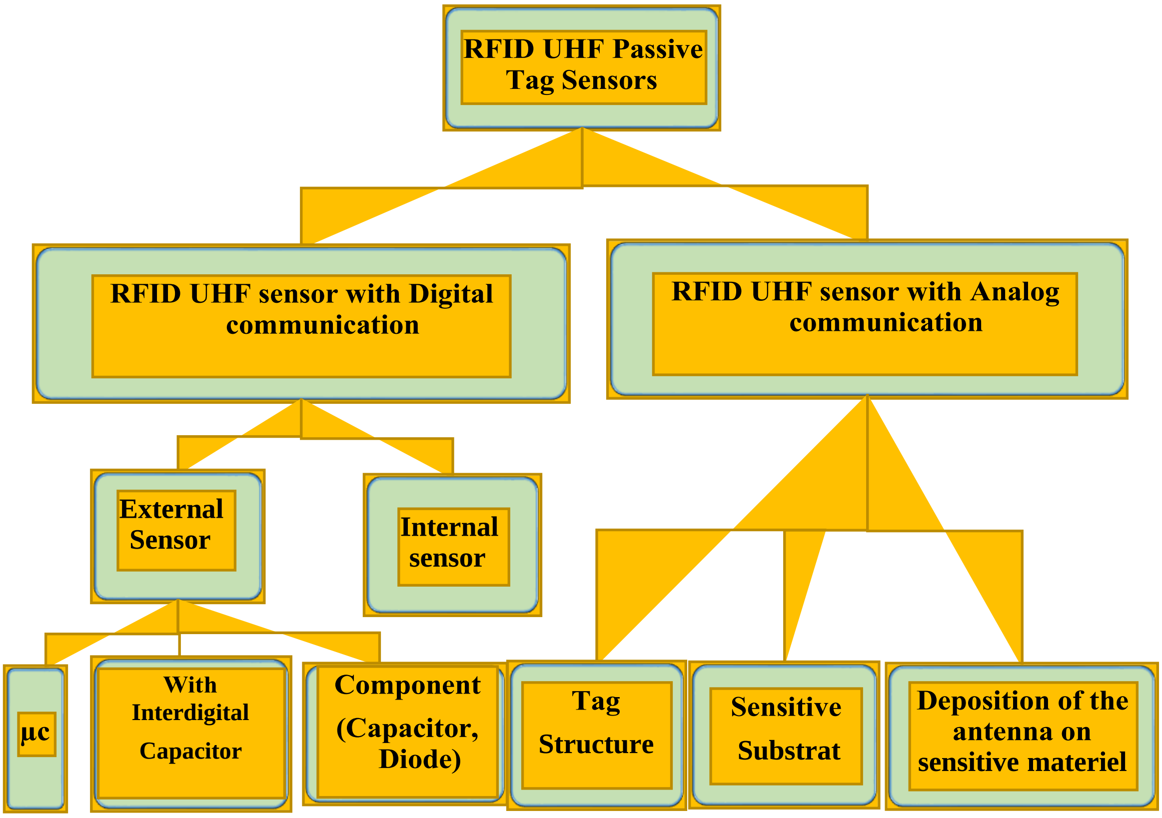


Figure 35: Distribution of the different types of passive UHF RFID sensors

Figure 35 summarized all types of RFID UHF tag sensor, which will allow us to develop the way this sensor made and its working principle. In this regard, we focus on the methods of manufacturing RFID antennas, and combine them with the work of non-invasive sensors, based on the matching of RFID tags with sensitive materials, focusing on specific applications. This was done in the blood tubes article, which we will discuss in chapter four.

3.1 RFID sensor with digital communication

The first family, presented in Figure 36, concerns the RFID sensors with digital communication, so named because the sensor information is sent back to the reader in digital form (reading a register). The sensors are arranged either internally, in the case of some chips, or externally, for example by using a commercial sensor [10], or a microcontroller [11]. There are also studies in the literature of sensor-RFID with components directly printed on the substrate, to accommodate a sensitive deposit. For example [12], a photodiode in order to detect brightness. The family of RFID sensors with digital communication can be very expensive, because the chips used are the most expensive, they embed several electronic devices (an ADC for example). By adding external devices (a commercial sensor), powered by the chip, the power consumption can very quickly degrade the sensitivity of the sensor. This is why studies have been conducted on efficient energy recovery and storage. This makes it possible to have so-called semi-passive RFID devices guaranteeing a greater detection range and making the recovery of the sensor data more reliable.

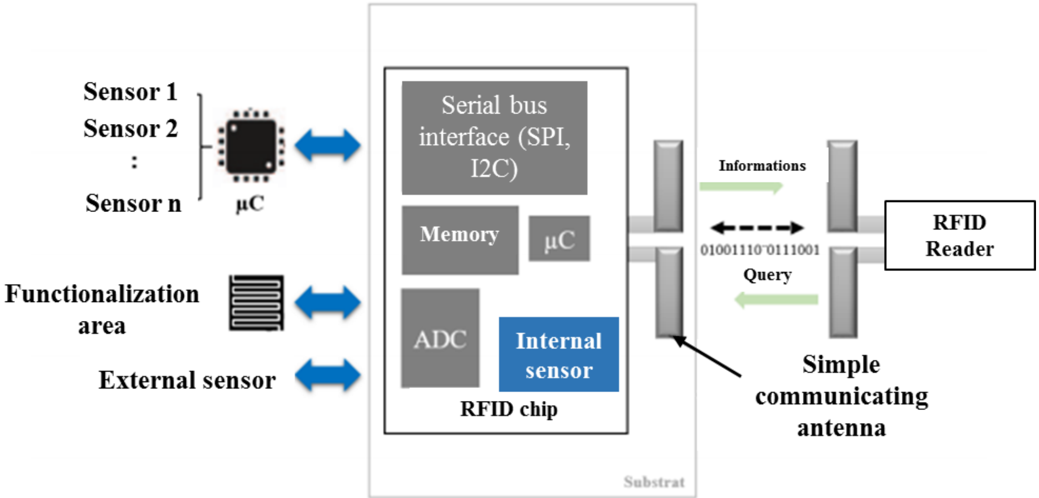


Figure 36: Family of RFID sensors with digital communication

It is the choice of the chip that determines the type of sensor, we have divided these chips into two subfamilies: RFID chips with internal sensor (Table 3) and RFID chips with external sensor (Table 4). The SL900A chip [13], which is present in both subfamilies because it has a temperature sensor and two inputs allowing the addition of external sensors.

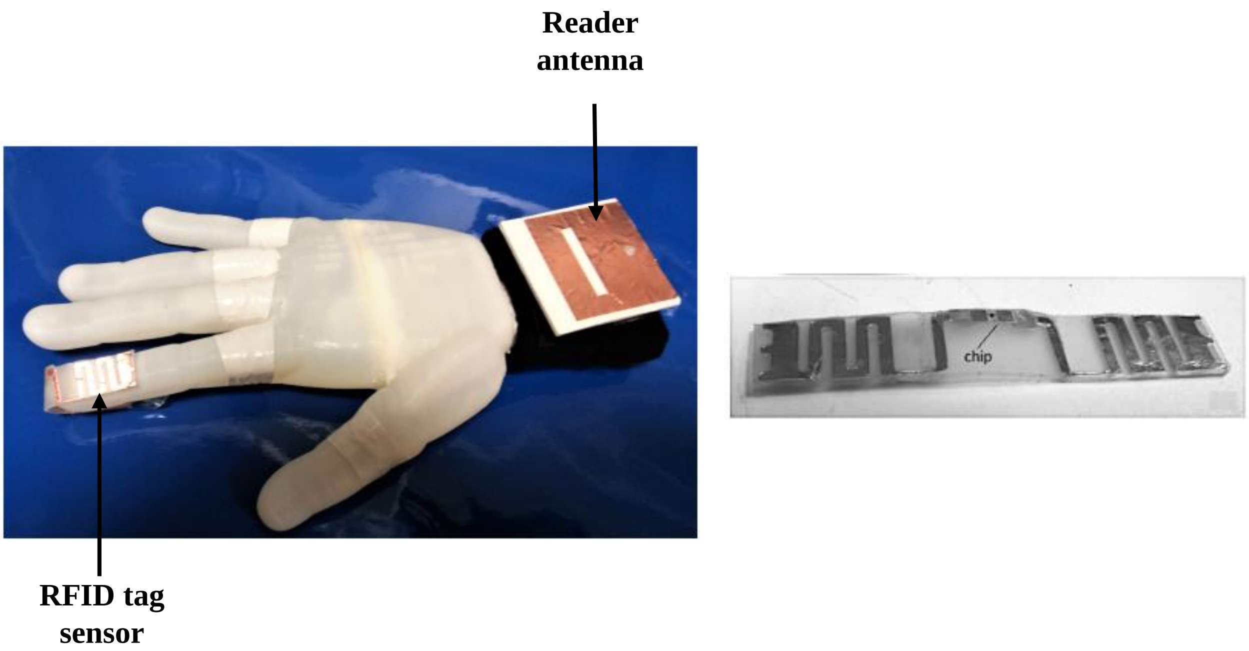
3.1.1 Internal RFID-sensor

Not many RFID chip manufacturers integrate a sensor directly into their product. We have listed, in Table 3, the RFID chips that embed an internal temperature sensor.

Referance	Manufacturer	Activation power	Detection range	Sensor Resolution
SL900A [13]	AMS	-7 dBm	-29°c to 58°c	± 0.5 °c
EM4325 [14]	EM Microelectronic	-8.3 dBm	-40°c to 65 °c	……..
Magmus83 [15]	RFMicron	-16 dBm	-40 °c to 85 °c	± 1 °c
PE3001 [16]	Productivity Engineering	0 dBm	-20°C to 50 °c	± 1°c

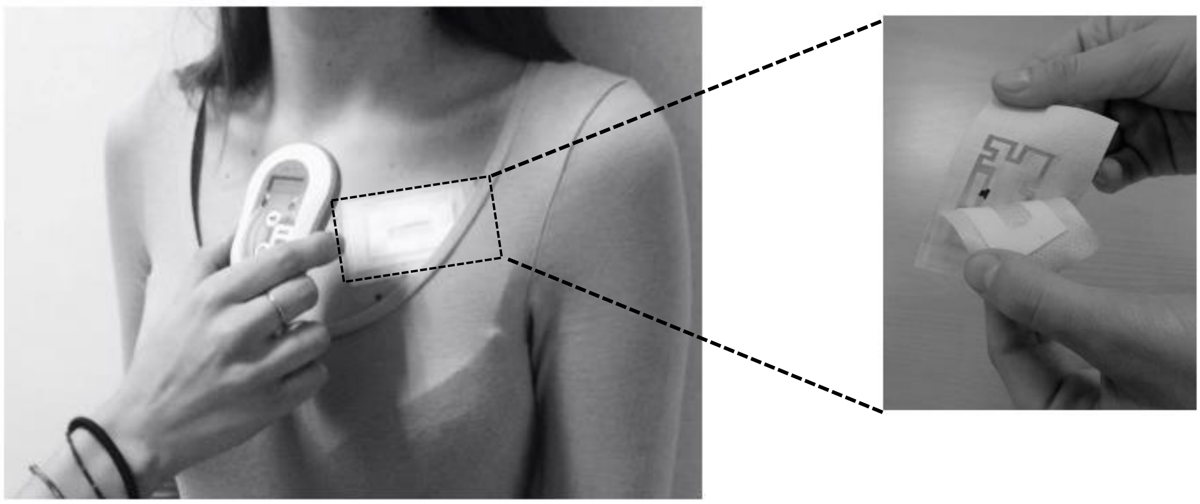
Table 3: Existing RFID chips with internal temperature sensor

An example of application [17] concerns a system that aims to provide people suffering from a lack of thermal sensation with a real time measurement of the temperature detected at the fingertips. The "RadioFingertip" system, comprising a reader antenna placed on the wrist and an RFID tag placed on the fingertip, is illustrated in Figure 37-a).

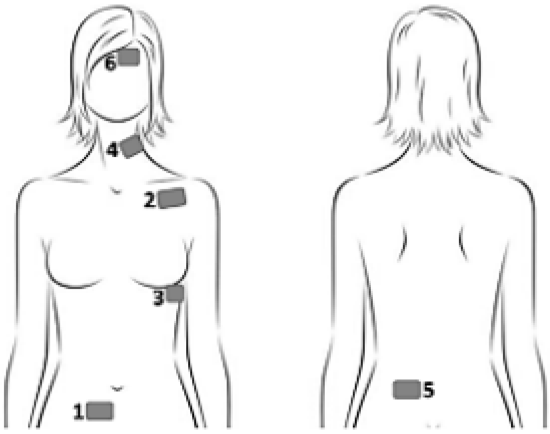


(a) (b)

Figure 37: a) Radio Fingertip thermal detection system, b) internal sensor tag [17].

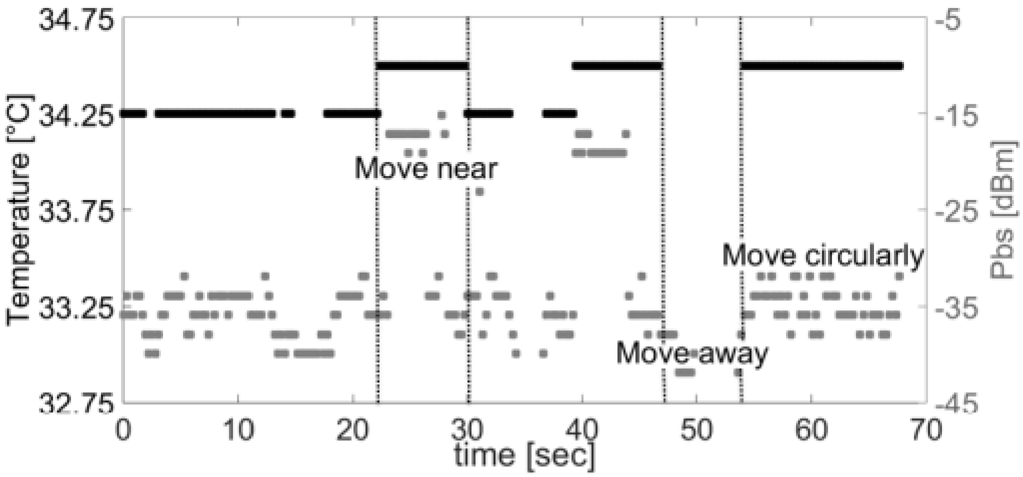


(a)



Body location	d_{max}[cm]
1	3-3.5
2	2.5-3
3	2.5-3
4	2-2.5
5	3.5-4
6	4-4.5

(b)



(c)

Figure 38: a) The epidermal RFID temperature sensor on a flexible substrate mounted on human body wirelessly read by an handheld reader, b) maximum reading range of the proposed tag placed in several positions over the body, (c) Temperature (black line) and backscattered (PBS) signals (gray line) recorded during reader's random motion [18]

Figure 37-b shows the sensor-RFID tag, which uses the temperature sensor of the EM4325 chip. The challenge of this study, in which the two antennas are put in direct contact with the human body with losses, is to establish a robust RFID communication link so the power supplied by the RFID reader positioned on the wrist to the RFID tag positioned on the finger is sufficient for its and to send back the collected temperature information.

Another study [18] has also developed a temperature sensor (using the EM4325 chip), for medical applications, such as: wound infection after surgery, evolution of epidemics, as well as the monitoring of sports activities (Figure 38). This sensor can be read up to 4.5 cm (Figure 38, b), in different places in human body. Figure 38,c shows the temperature signal recorded from a tag placed on a low back as the reader moves away from the tag, close to the tag, and then cyclically moved at a fixed distance. The same graph also shows the backscattered power (PBS), which is derived from the reflection of the interrogation power from the reader by the tag.

In order not to influence the temperature measurement, the substrate was chosen to be biocompatible and impermeable.

3.1.2 External RFID-sensor

It is also possible to connect a sensor externally to an RFID chip in three ways:

- The first method consists in connecting a digital sensor or a microcontroller with a serial access communication bus (SPI or I2C). The solution using a microcontroller allows to increase the chip's capacities by adding memories and sensors. This method has the disadvantage of considerably increasing the consumption and to strongly reduce the performances of the tag.

-The second solution is based on the use of an analog-to-digital conversion (ADC) interface. For example, the AMS SL900A chip has two analog inputs to which it is possible to connect capacitive, resistive or optical sensors (diodes).

Reference	Manufacturer	Input external sensor	Possibility to connect with µcontroller
SL900A	AMS	2 input dedicated to external resistive, capacitive or optical type sensors (diode)	SPI Protocol
EM4325	EM Microelectronic	No sensor input but possibility of extraction detection	SPI Protocol
PE3001	Productivity Engineering	x	SPI Protocol
WM72016-6	Cypress		
ANDY100	Farsens		
ROCKY100			

MONZA X 2K Dura	Impinj	x	I2C Protocol
MONZA X 8K Dura			
UCODE I2C	NXP		
EM4324	EM Microelectronic	No sensor input but possibility of extraction detection	x
UCODEG2iM, G2iM+	NXP		

Table 4: Comparison of commercially available RFID chips with external sensor inputs and/or with protocol communication protocol

In Table 4, are presented the different RFID chips for which it is possible to connect one or more sensors externally and which have the possibility to connect a microcontroller, using their serial communication buses. The AMS SL900A chip has the most complete functionality.

3.1.3 RFID-Sensor by adding a microcontroller

One of the major challenges of adding a microcontroller to an RFID tag is its power supply. In Figure 39 are illustrated the three methods of powering a tag with a microcontroller. In the literature, studies are mainly focused on RFID tags with energy recovery circuits, with for example the recovery of body heat [19], or solar energy [20]. However, these systems still need to be improved, as they are bulky, battery-powered [21], and therefore require maintenance.

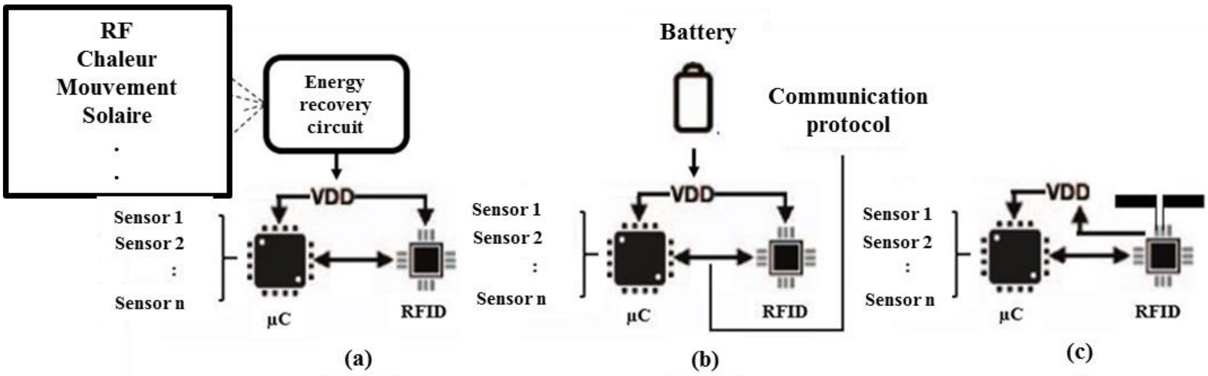


Figure 39: Different methods of powering a tag composed of: a microcontroller, one or more sensors and an RFID chip, using: a) an energy recovery circuit, b) a battery, or c) energy harvested by the RFID chip from the reader.

On the other hand, RFID tags without batteries, shown in Figure 39-c, have an unlimited lifetime and are less bulky. These types of sensors are the subject of intense research [22], [23], but manufacturers are already offering many products as shown in Table 5. However, their costs are still high, ranging from 40 € 753 € per tag.

Reference	Embedded Sensor	Detection range and activation power (P-A)	Chip used	Price
Farsens Atlas-Q2000L	Pressure (4 Sensors)	0kg à 900kg (±1kg) P-A : -2 dBm	Andy100	753,06 € /10 units
Farsens Cyclon-30BA	Pressure (4 Sensors) & temperature	0bar à 30bar (±300mbar) -30°C à 85°C (±1°C)P-A : -2 dBm	Andy100	90 € /10 units
Farsens Electra-CT	Temperature	-30°C à 85°C (±0.5°C) P-A : -2 dBm	Andy100	53 € /10 units
Farsens EVAL01-Fenix-Vartex-RM	Pressure & temperature	260 mbar à 1260 mbar (±0.2 mbar) -30°C à 85°C (±2°C)	Rocky100	40 € / units

Table 5: Commercial passive UHF RFID tag with integrated microcontroller and without battery

3.1.4 RFID-Sensor by adding an external component

This method to achieve an RFID-sensor is one of the simplest to implement, because it is enough to connect a commercial sensor externally on a RFID chip having an ADC, allowing to convert the analog information into digital before transmitting it to the RFID reader. In Table 4, we notice that only the AMS SL900A RFID chip has two dedicated external inputs for sensors. It is thus with the help of this RFID chip that in the literature is exposed: a luminosity sensor in [23], RFID sensors for medical applications. For example, the study referenced [24] focuses on a flexible finger movement sensor for monitoring rehabilitation after a stroke. Another study [25] concerns a pressure sensor for monitoring the adhesion between the bone and a knee prosthesis. Finally, in [10], a research work concerns the monitoring of food products, which combines: a pressure sensor to detect product drops, and an opening sensor (Figure 40). In this study the addition of an external sensor and the cardboard substrate (lossy) strongly degrades the detection performance of the RFID sensor with an activation power of -2dBm.

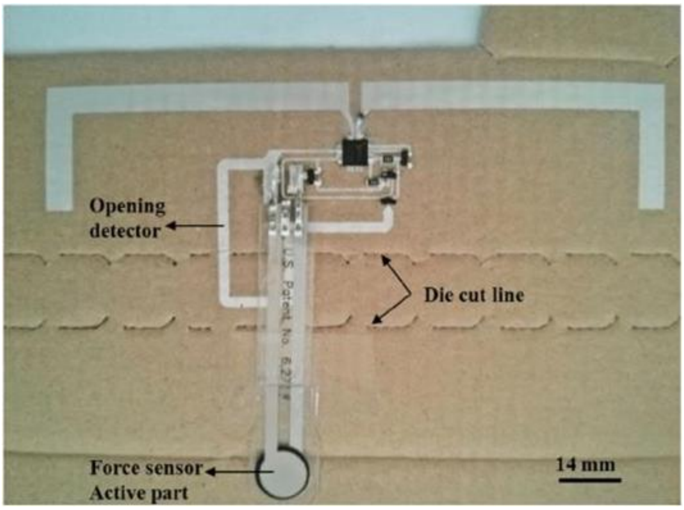


Figure 40: RFID tag with external force sensor for food product tracking [10].

3.1.5 RFID sensor by adding a deposit of sensitive material on an external dedicated area

A representative example of this type of sensor is reported in [26]. It is an RFID-sensor based on a functionalized area using the deposition of a sensitive material. In this study, the characterization of the device as a moisture sensor is based on the variation of the resistance of the graphene oxide (GO). This variation is due to the adsorption and desorption of water vapor on the surface of the OG (Figure 41-a). In order to measure these resistance variations, the sensor was exposed to increasing cyclic concentrations of moisture. The measurement protocol consisted of circulating dry air through the system for 1 hour to establish a baseline value for the system, then circulating a dry/wet air mixture at different concentrations. Calibration was performed using a reference humidity sensor.

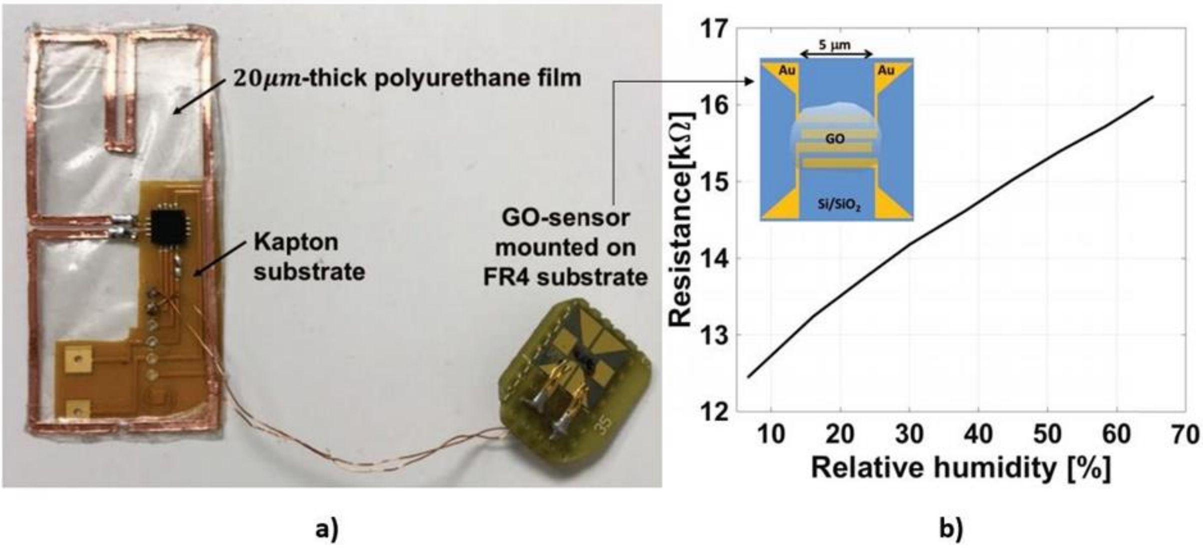


Figure 41: (a) RFID-sensor using an external functionalized Graphene oxide area and b) results of resistance changes versus relative humidity change [26]

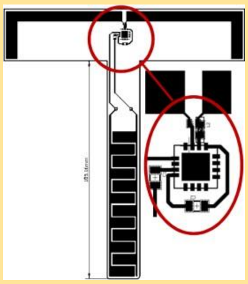
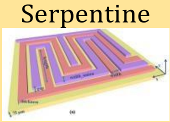
Figure 41-b shows the results of the resistance variations with respect to the variation of the relative humidity. The profile appears almost linear with respect to increasing humidity levels and it is therefore possible to extract the sensitivity of the sensor:

$$[R] = 60\Omega/\%HR.$$

We have listed in Table 6, other RFID sensors from the literature showing devices based on an external sensor in the form of a functionalized zone. All these sensors use the SL900A RFID chip. In terms of performance, the reading distance does not exceed two meters and depends on the sensitive element used and more specifically on the sensitive area on which the deposit is made. For example, in the work of José F. Salmerón et al [43], two moisture sensor devices, based on the variations of permittivity of the polyimide substrate as a function of relative humidity, were studied. The formula is given by the substrate supplier:

$$\varepsilon r = 3.05 + 0.008\, X\, RH\, (\%) \text{ à } 1\, Khz, 23\, °C$$

The first RFID-sensor has a serpentinel-shaped area and the second one has an interdigitated capacitance shape. Both sensors have good reading performance related to the operating range. The serpentine-shaped area is preferred for low humidities (37% RH - 70% RH) while the interdigitated capacitor-shaped area is preferred for high humidities (60% RH - 90% RH).

Reference	**Type of functionalize d zone**	**Reading distance (m)**	**Sensor sensitivity RFID**	**Device**	**Sensitive element**
S. Tedjini and al. [42] 	Interdigitated capacity	1.1	6.95 LSB/% Of water content	FR4 Substrate, copper antenna	Soil moisture
José F. Salmerón and al.[43]	Serpentine 		750 measureme nt points in the range 37%HR - 70%HR	Polyimide substrate	Ambient

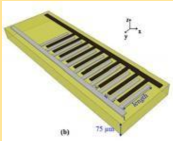
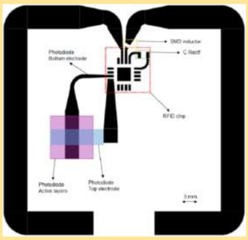
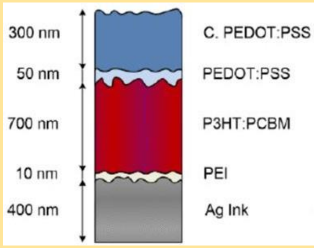
	Interdigitated capacity 	1.6	370 measurement points in the range 60%HR - 90%HR	(Kapton HN Dupont^{TM}) 75µm of thikness, silver conductive ink antenna	humidity using the sensitive substrate
Falco and al. [27] 	Printed photodiode	1.2	---	Luminosity sensor  Photodiode deposition layer	

Table 6: RFID-sensor, taken from the literature, augmented by the addition of an external component in the form of a functionalized area.

3.2 RFID sensor with analog communication (with functionalization)

The second family is undoubtedly the most studied, as it provides low-cost technological solutions for specific technological solutions for specific applications. This part concerns the RFID-sensors with analog communication, named like this, because the sensor information is contained in the analogical parameters of the EM wave received by the reader. In this type of sensor, the physical parameter to be measured acts on the antenna impedance which has the effect of varying the power re-radiated to the reader. As shown in Figure 42, four parameter sensitive elements can be used to mismatch the antenna impedance:

-Substrate
-Structure of the antenna
-Deposit on the antenna
-External element used as a 'second' substrate

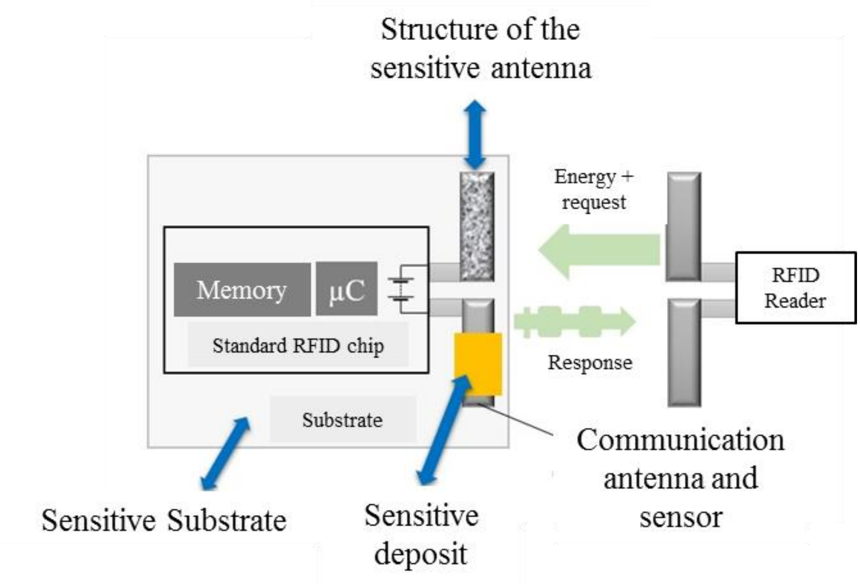


Figure 42: RFID Sensors with Analog Communication

Generally, this second family is the most complex to implement, due to its operating principle. Seen from the reader, the sensor information is available by following the variations of the transmission power necessary to activate the tag or in the power reflected by the tag RSSI (Received Signal Strength Indication). It is therefore necessary to be certain that these variations come only from the physical parameter to be measured and not from the measurement environment.

Functionalized RFID sensors are of interest to the research and industrial communities in the sector, mainly because of their very low manufacturing cost compared to the solutions described above. Today, there are several types of RFID sensors that differ according to the type of functionalization. We have classified this type of RFID sensor according to four principles that depend on the position of the sensitive element impacting the impedance adaptation:

- The first principle is simply based on the effect of the close environment on the tag antenna. In this case a simple unmodified RFID tag is sufficient. For example, the physical masking of an RFID tag allows to detect a passage [27]. The soil moisture content can be measured with a simple buried tag [28].

- The second principle requires making the substrate on which the antenna is placed sensitive to a physical parameter. For example, a paper substrate sees its dielectric constant evolve as a function of the absorbed humidity [29].

- Then, the sensitive element can be the antenna itself. The structural modification of the conductive deposit realizing the antenna can allow the detection of humidity [30].

- Finally, transforming a tag into an RFID sensor can be done by depositing a sensitive element on the antenna [31].

In this section, we have reviewed the state of the art of RFID sensors for each of the four principles mentioned above.

3.2.1 Sensor functionality based on the use of a simple RFID tag

In the literature, detection applications using a simple tag are mainly focused on localization [32] using more or less complex algorithms [33], [34]. This has allowed the realization of indoor robots moving autonomously [35], [36] and manipulating objects [37], [38]. Then, there are motion detection applications [39] or presence detection applications [27] for which the detection is done by modifying the signal retro-modulated by the tag (RSSI level) when the tag moves or when a person passes near the tag. Many have exploited this technique to realize other types of sensors such as the detection of soil moisture [28] or the level of a liquid [40]. The principle is always the same, the modification of the retro-modulated signal of the tag by interaction with its close environment can be assimilated to a material whose effective dielectric constant varies.

In the objective of the Internet of Things, there are detection systems in the literature, which can be related to home automation, allowing to automate the house according to the manipulated objects. In this study [41], a simple RFID tag is used to detect three different situations:

- The detection of a simple touch of the tag's antenna (brief mismatch).
- The masking of the object (long maladjustment).
- The detection of the movement of an object (fluctuating mismatch).

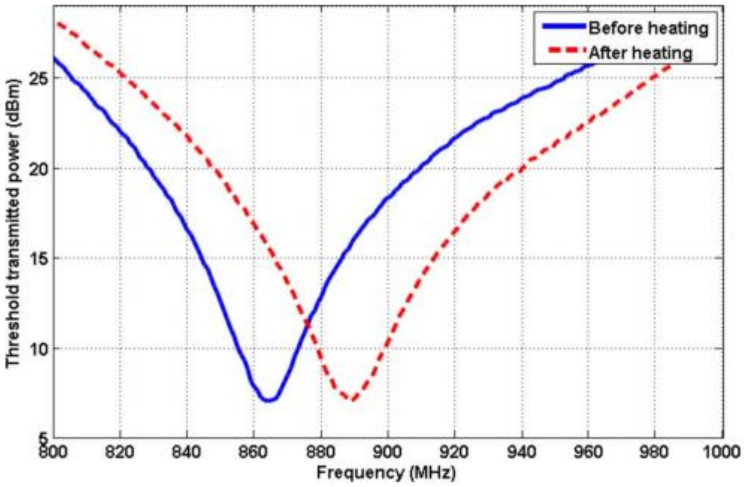
This home automation system allows, for example, to turn on the light, without having to get up, by simply touching a book. The disadvantage is that you need one RFID reader per room.

Other studies [42], have been conducted on the possibility of positioning the monitoring device directly on the wrist of the person (for example, for medical monitoring of the elderly), in order to analyze the proximity with an object, to make a daily follow-up. The monitoring of sleep quality with a similar device is another application studied in [43] showing all the potential of this type of simplistic sensor-RFID approach.

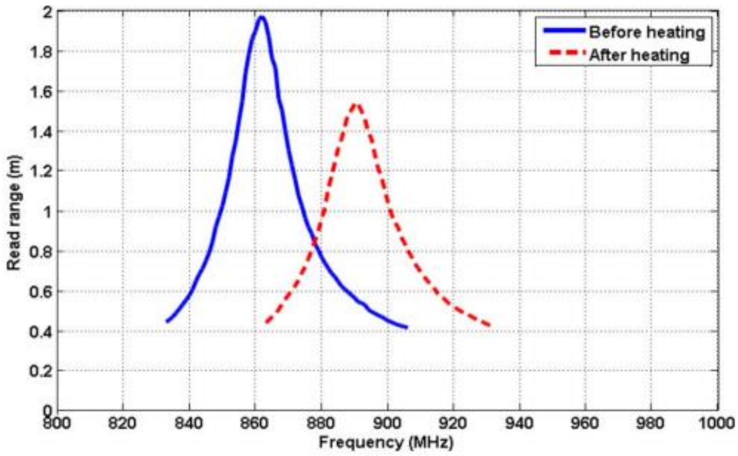
3.2.2 Sensor functionality based on the use of a sensitive substrate

In the literature, there are several sensor-RFIDs using the substrate as the sensitive element. For example, the design of a biosensor [44] using kerosene wax as a temperature sensitive material as the tag substrate (Figure 43-a). The main idea of this type of temperature sensor is based on affecting the overall performance of the RFID tag. Exposing this substrate to high temperatures changes the physical and chemical properties of the kerosene wax and induces a frequency shift. This frequency offset reduces the performance of the RFID sensor tag at a given frequency, as shown in the results presented in Figure 43-b for a frequency of 870 MHz, We can see this shift as well in the measured reading range as presented in Figure 43-c, when the temperature change the maximum reading range shift from the desired band to other frequency. This sensor is called a temperature threshold sensor, because, the change in the properties of the kerosene wax after exposure to heat is irreversible. This type of sensor can be used, for example, to handle heat-sensitive products.

(a)



(b)



(c)

Figure 43: Passive UHF RFID Tag for Heat Sensing Applications

3.2.3 Sensor functionality based on the sensitivity of the antenna material

There are new types of RFID sensors, allowing to measure an environmental variable using the material composing the antenna itself. It is thus by interaction between the antenna and the medium in which it is immersed, that sensor information is recovered. The internal properties of the antenna are influenced by the medium, for example Figure 44 the conductivity of Graphene as a function of relative humidity [30] or toxic gases [45].

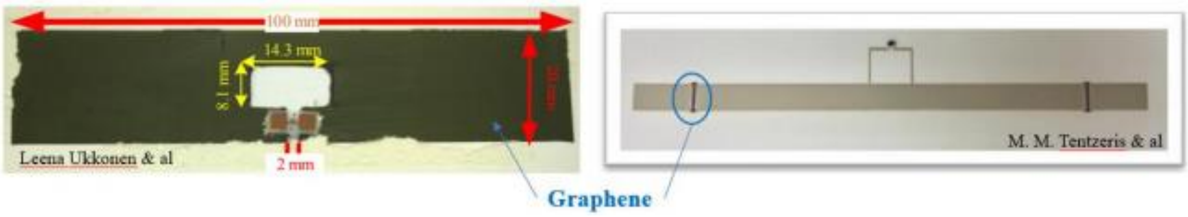


Figure 44: Example from the literature of a RFID-sensor with sensitive antenna left: antenna completely made of Graphene [30], right: antenna composed of thin Graphene parts [45].

3.2.4 Sensor functionality based on the deposition of a sensitive material on the antenna

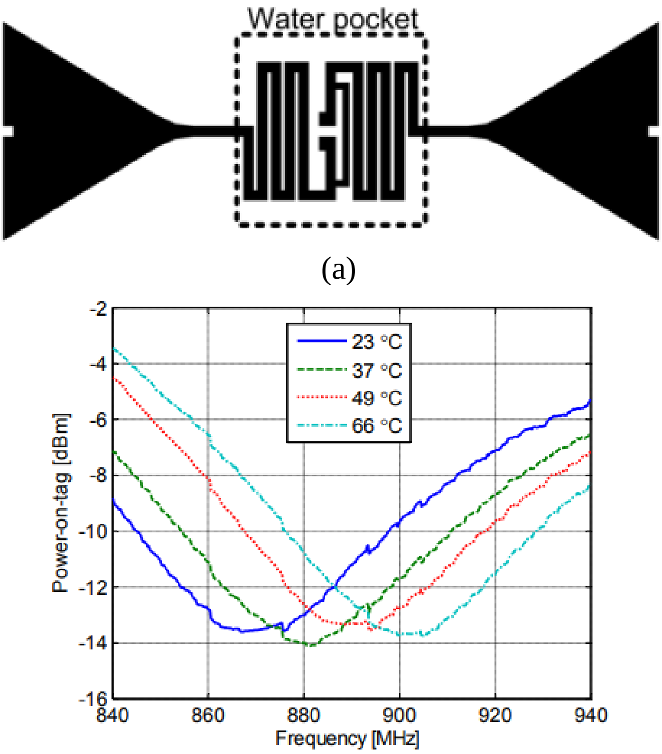
The last method used in the literature to realize an RFID sensor is the method of antenna functionalization by deposition. It consists in depositing a sensitive material on the RFID tag antenna. Several sensitive elements are used:

- PTFE, SnBiIn for temperature.
- Polyimide, PEDOT: PSS for relative humidity detection.

The study [46] uses a commercial dipole antenna using a meander T-match (Figure 45), on which polyimide is deposited in order to realize an RFID moisture sensor. Using another layer of absorbent paper on top (allowing to concentrate the humidity on the antenna) the dielectric properties of the sensitive layer vary and thus influence the RFID tag antenna.

Figure 45: a commercial tag antenna with polyimide humidity sensing material

Still using the same principle, another study [47] made it possible to realize an RFID sensor by using water as a sensitive element Figure 46-a. The dielectric properties of water vary strongly with temperature.



(a)

(b)

Figure 46: (a) passive UHF RFID temperature tag sensor, (b) measured power-on-tag at different air temperatures.

The dielectric properties of water vary strongly with temperature, as shown in the curves presented in Figure 46-b, making it an ideal candidate for thermal sensing.

4. Conclusion

We have introduced in this chapter the most important parameters of the antennas. Then, we have made a technological progress of the existing RFID-sensors, from a commercial and academic point of view. This study allowed us to draw a framework to follow to achieve the objective of this thesis. The central point is to realize a functionalized RFID antenna optimized for well defined performance criteria. In the following chapter we will detail the operation of the antenna simulated (under the EM CST modeling software) and realized. We will discuss in detail the area on which the deposition of the sensitive material will be done. For this we have set up two measurement benches: the first allows us to validate the operation of the antenna in the antenna in initial condition, the second allows us to validate the operation of the RFID sensor in a controlled environment.

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Chapter 3

UHF RFID Tag Antennas for Liquids Materials: Overview and State of the Art

1. Introduction

Over the past decade, UHF RFID has been growing and increasingly deployed worldwide to meet logistics and management needs in healthcare sector. Many types of liquids products to be identified can be found in various fields such as blood, IV solution, vaccines, drug anti-counterfeiting, tracking and supply chain management of medical things. There is therefore a strong need for traceability of this type of object. Unfortunately, the performance of conventional UHF passive tags is strongly degraded when the said tags are attached directly to these objects. This is particularly the case for dipole type tags which then present very limited or even zero reading ranges [1] because of the proximity with the loss materials which strongly mismatches the impedance of the antenna, degrading its radiation and the impedance matching of the chip.

Specific tags for liquids materials are then used, but these tags are often more expensive and cumbersome than their conventional counterparts. In order to provide an efficient tagging of liquids, a lot of work has been done in the literature on the design of the tag antenna itself, so the latest achievements in robust tags in the literature are reviewed in this section. Based on the application and the structure of the design, the works are divided into two groups. In the first part, the tags applicable on liquid bottles are reviewed. The second, the most important tags for blood bags and tubes monitoring are discussed.

2. Tags for liquid materials

Liquid bottles are one of the most difficult objects for RFID tags. There are a variety of bottles of different materials on the market for filling different liquids, which requires the use of RFID technology. Liquid-filled bottles and containers are the most challenging objects and severely affect the performance of the label type labels attached to them. The high dielectric constant and electrical conductivity of water are the main reasons for this effect [1], [2].

There are a lot of works in the literature for solving the problems of tags mounted on liquids materials. There are discussed in this part.

One of these solutions for liquids bottle in the literature is to fold the tip of the dipole, as proposed in [2]. By folding the dipole arms, the length of the dipole becomes longer. This improves the radiation efficiency of the antenna, which is vital to the bottle. According to [2], by bending the folded dipole shown in Figure 47, around the bottle filled with water, the zero point in the radiation pattern of the dipole E plane can be eliminated, and the label can be read from different angles. The high dielectric constant of water is the main reason for this phenomenon. In this case, the entire bottle becomes part of the antenna and changes the radiation pattern. As shown in Figure 48, after placing the antenna on a bottle filled with water, the zero point in the directivity of the antenna representing the radiation pattern disappears.

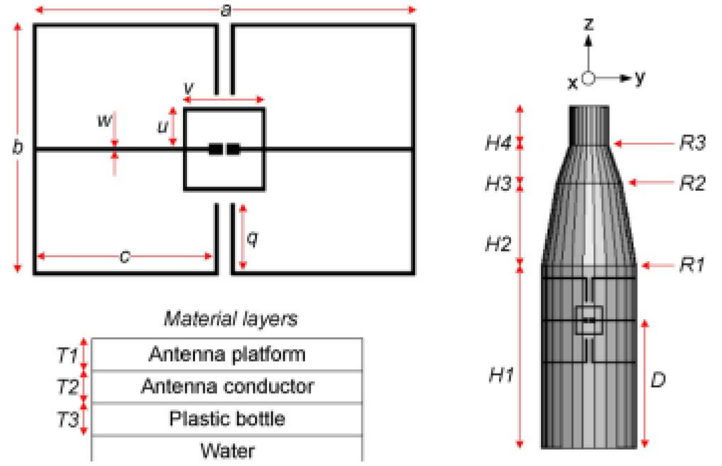


Figure 47: Conformal tag antenna for integration with bottle water [2].

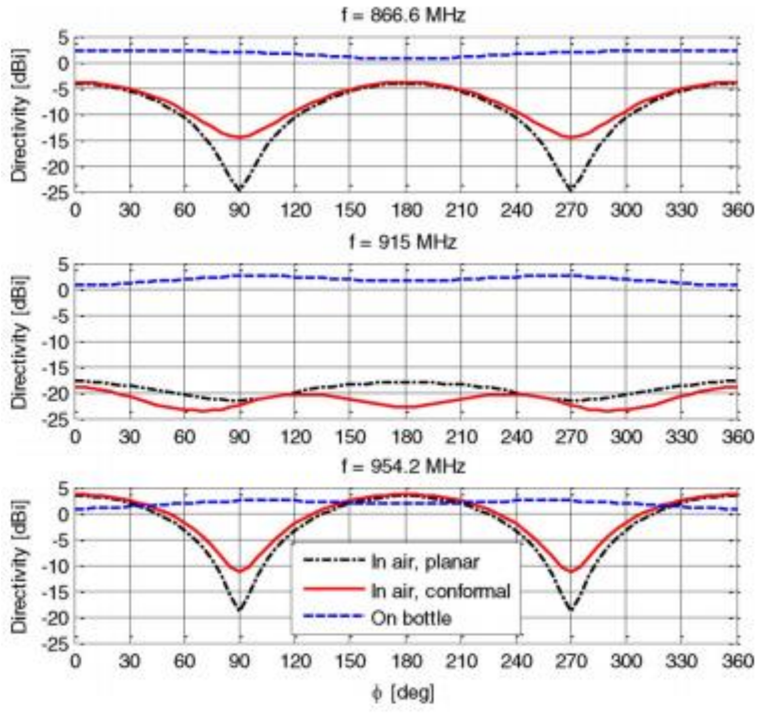
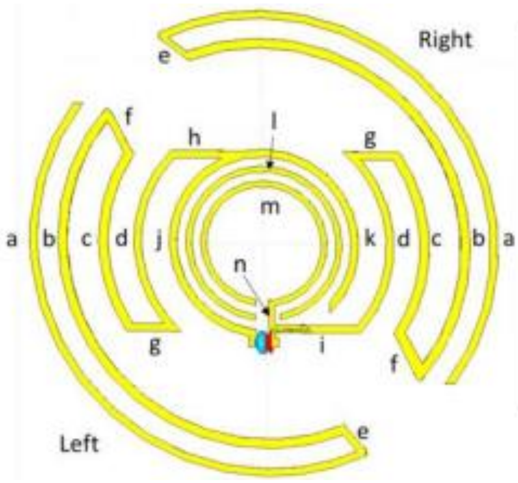


Figure 48: Directivity of the tag in xy-plane at different frequencies [2].

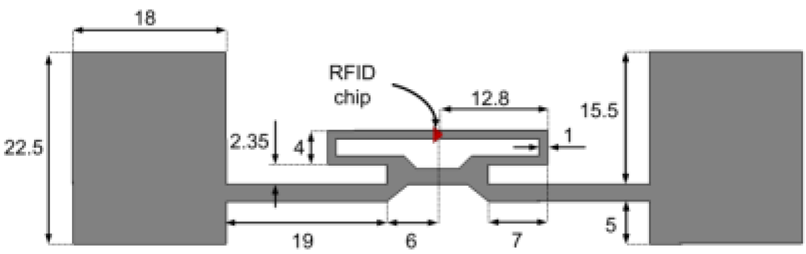
Another solution is proposed in [3], is capacitive tag that uses the concept of shunt scaling, to achieve good matching for range of different liquids. The tag is intended for flat surface (Figure 49), especially petri dishes. Is an inexpensive, low-complexity and unobtrusive design useful for real-time monitoring and in situ evaluation of liquid solutions such as chemical research and healthcare, this tag achieve good reading rang up to 7 meters when it’s placed on filled water bottle.



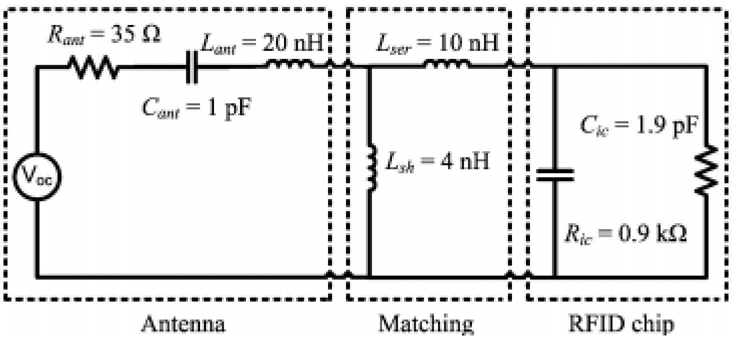
	Length (mm)		Length (mm)
a	36	h	5
b	33	i	6
c	12	j	13
d	12.5	k	13.5
e	3.3	l	23
f	3.7	m	20
g	3.5	n	2

Figure 49: Liquid sensing UHF RFID half wave dipole antenna design [3].

The effect of liquid on the performance of a tag is presented in this example [4] by translate the physical structure of the tag to the equivalent circuit. In this work [4], the idea starts by analysis of a commercial tag of Alien ALN-9768 (Figure 50) which is known as “Wonder Dog”.



(a)



(b)

Figure 50: Commercial tag of Alien ALN-9768. (a) Physical structure with dimension details, all values are in millimeters. (b) Equivalent circuit, the values are for the tag working in free space [4].

It is found that the function of the liquid bottle is to reduce the radiation resistance and increase the loss resistance. This destructive effect was compensated by adding two arms to the dipole without increasing the size of the tag (Figure 51), and then a new design with improved read range and bandwidth was proposed.

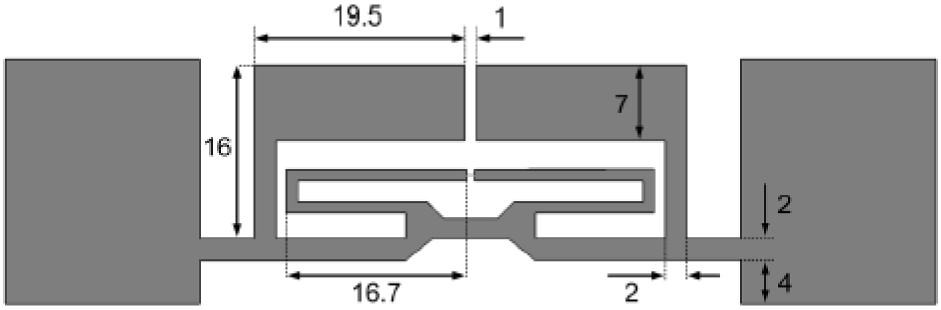


Figure 51: Proposed modified structure of the tag for compensating the effect of liquid on the frequency response. All values are in millimeters [4].

The final prototype proposed tag by adding arms to compose the water effect is fabricated, and reading range measured in an anechoic chamber. Table 7 present the maximum reading range of the proposed design compared with wonder dog design of Alien on different bottles.

Material	Wonder Dog	Proposed design
Free space	150	220
Paper bottle	45	79
Glass bottle	22	31
Plastic bottle	23	54

Table 7: Reading range of tags on centimeters.

As we know the high permittivity of water has negative effect on the tag by decrease the gain of antenna that leads to decrease on reading range of tag. In this example [5] we can see one of some techniques that help to reduce some of these losses by adding reflector on back of the bottle of liquid (Figure 52).

Due to the existence of liquid, most of the energy is absorbed by it, so the radiation efficiency of the antenna is extremely low and it is almost unusable. Since we added a reflective surface behind the bottle and redefined the antenna size to obtain the pretended resonant frequency, the antenna in this example proposes a possible solution to overcome the liquid problem while maintaining a reasonable reading range this is the most important consideration in an RFID system.

(a) (b)

Figure 52: The proposed RFID tag antenna in the bottle. (a) RFID tag, (b) added reflector on back of bottle [5].

As results on reading range of the tag without the reflector back of a bottle is poor 0.7 m, but after placing the reflector on the back the reading range increase to achieve 1.4 m. This technique can be considered a solution can increase the directivity of the antenna and slightly reduce the energy absorbed by the liquid in the bottle, which can be clearly seen from the increased communication range of the tag, but it may be more expensive, and it may distort the shape of the bottle.

Another solution in the literature for liquids bottles is to place the RFID tag in the neck of the bottle (Figure 53) [6], to avoid the energy loss caused by the liquid inside the bottle.

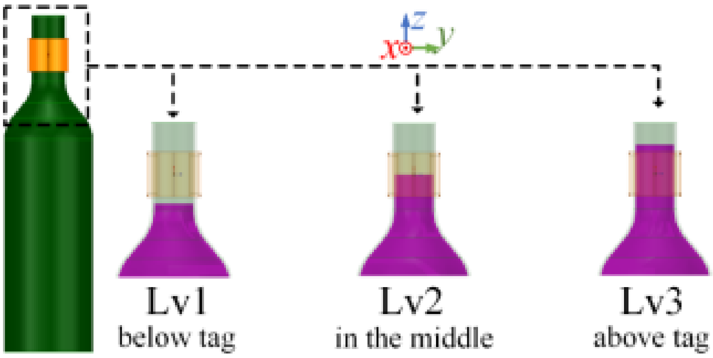


Figure 53: The proposed RFID Tag attached on the bottle neck with three different levels [6].

The label configuration is shown in Figure 54. The tag substrate is flexible and it's made by silicone rubber with a thickness of 3 mm. The Impinj Monza 4 RFID chip is placed in the middle of the gap on the top layer of the loop. The compact size of tag is 70 mm × 30 mm × 3 mm this is allows it to be convenient installed on the neck or body of the glass bottle. At the same time, the use of appropriate support structure design, such as belt buckles or buckles, can easily install or uninstall tags. This tag can be replaced and reused, further reducing the cost of the proposed bottle labeling solution.

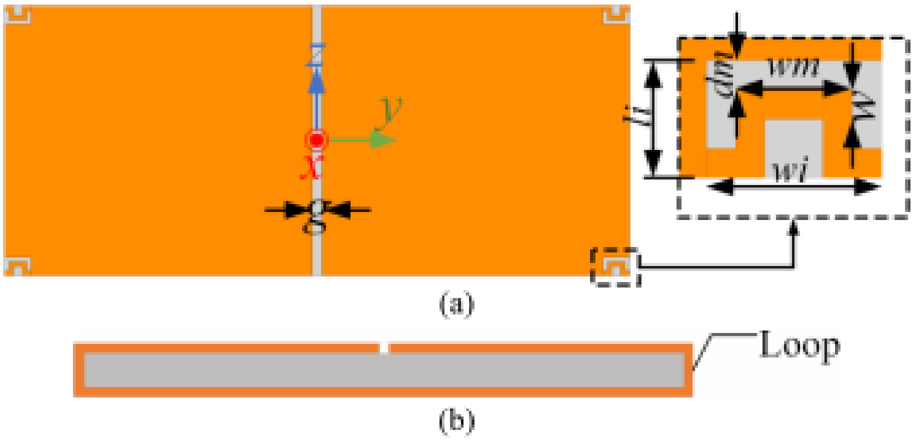


Figure 54: The proposed RFID Tag. (a) Top view and (b) Side view [6].

The proposed tag is fabricated and, reading range measured for different liquids, the Figure 55 show the proposed tag under test of six liquids products. As we can see in the picture, the RFID tag is positioned in the neck of the bottle to avoid the negative impact of liquids.

Figure 55: Photograph of liquids products under test [6].

This table summarizes reading range of the proposed tag attached on different liquids bottle.

Liquid	Read Range (m)
Sake	2
Wine	1.9
Vinegar	1.9
Orange	1.8
Sauce	1.6
Oil	2.5

Table 8: The measured read range of the proposed tag antenna on different solutions.

3. Tags for blood solution

Healthcare items are one of the most important applications of traceability, because these items must often be handled in emergency situations, and the effects of errors can even be fatal. Among them, the traceability of blood bags and tubes are the most concerned because blood bags and tubes are prepared, stored and used in different locations, sometimes in different buildings, or even handled by different organizations. The current leading traceability technology is bar code, but its limitations are well known. Bar codes require physical contact between the bar code and the reader, or at least a small distance, and good alignment between the two. In addition, each barcode can be scanned individually at most. Therefore, the operator is required to perform a large number of operations on the item or the reader, which significantly slows down the operation of a large inventory of items. In addition, barcodes are affected by mechanical stress and external factors, so they are easily damaged. In addition, blood bags and blood vessels must be supplemented with a large amount of additional information, such as blood type or collection date, which cannot handle barcodes because they can store a limited amount of information. For these reasons, RFID technology [7] is becoming a leading alternative because it offers many significant advantages [7-10]; however, in order to be fully functional, this technology needs to reorganize the process [11]. For example, using a portal reader can significantly reduce reading time. However, the blood movement and electromagnetic environment must be considered to select its location. In addition, these advantages can only be effectively used if the electromagnetic (EM) field of the RFID reader does not cause any adverse effects on the blood.

Currently, the International Society of Blood Transfusion (ISBT) has recommended HF RFID (with a frequency of 13.56 MHz) as an international standard for blood bag traceability. ISBT also issued guidelines for the use of RFID technology in blood transfusion medicine [12]. They gave some technical suggestions (such as operation frequency and storage capacity), and demonstrated the use and benefits of RFID in the blood transfusion chain, distinguishing between blood bank processes and hospital processes. One of the reasons for using HF is to reduce the interaction between the HF electromagnetic field and the liquid. However, from the point of view of EM, the use of UHF RFID can obtain significant advantages, that is, greater Reading range, faster reading speed, multiple reading capabilities and better performance at low temperatures. However, in order to be fully functional, this technology needs Process reorganization [13] and new development of tags and tag antennas [14]. In fact, standard tag antennas are not designed to be close to lossy materials (blood), so special antennas will significantly improve the RFID circuit. On the other hand, it is well known that UHF can interact with blood more significantly.

In the previous section, based on the examples studied, we knew that liquids have a negative effect on the RFID tags when it is mounted on filled liquids bottles.

In this section we will look at the different UHF RFID solutions suitable for tracking blood bags in the literature. The implementation of a UHF RFID solution on high permittivity liquids (water, blood...) has been the subject of a lot of research, especially in order to find a solution to improve the performance of the system. Several antennas types are used such as dipole antenna or patch antenna.

This work [15], introduces a prototype system that uses UHF RFID technology to monitor and track blood units (bags) in real time as they are transmitted between the hospital blood bank (BB) and the operating room. In consultation with the local medical center BB medical officials, the blood unit (BU) storage and processing logistics were determined, and automated processes were recommended to monitor and track them. Proposed a real-time, efficient and cost-effective UHF RFID system. The tag that used in this work is a commercial tag the “ALN-9640” from The Alien Technology for tracking blood bags (Figure 56).

Figure 56: Commercial tag the “ALN-9640” from The Alien Technology [15].

This tag is placed on blood bag as we see in Figure 57, and tested, the reading range is less than 0.2 meters, because the RF signal was completely absorbed by the blood in the bag, so as mentioned on [16] The main disadvantage of general commercial RFID tags is that the antenna impedance matches the IC chip impedance without considering the characteristics of the tagged product. In the case of blood, the product to be marked is a liquid, which exhibits a high dielectric constant and loss. Therefore, this means that the typical reading range of commercial tags will be significantly reduced to less than 0.5 m.

Figure 57: Commercial tag the "ALN-9640" placed on blood bag [15].

In [17], the new implementation of the pseudo-location principle is used to locate blood bags equipped with dedicated passive tags, which are designed to be resilient for blood access and small size. The detector antenna is placed at the bottom of the drawer and uses additional passive tags to identify each position in each drawer (Figure 58). The transceiver unit is made of an off-the-shelf commercial electronic board and is controlled wirelessly by software running on a PC. The whole system is small in size, easy to transport, battery powered, and low cost.

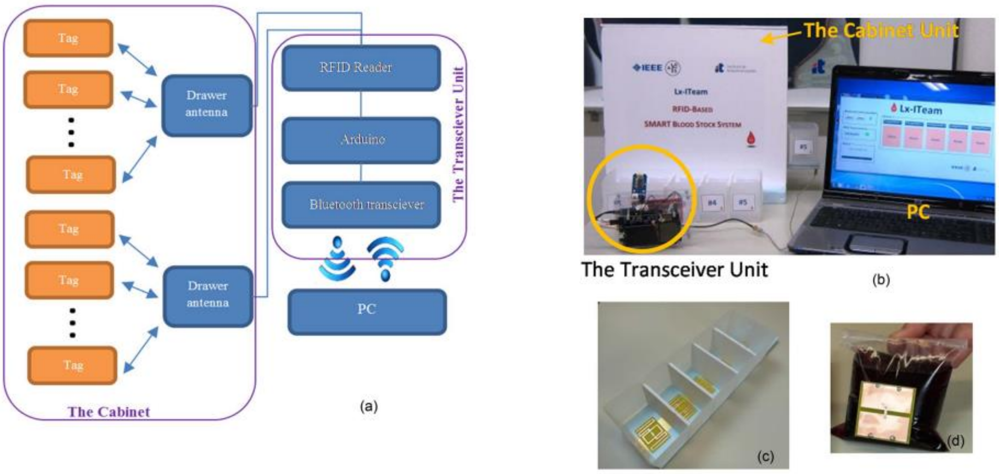


Figure 58: Schematic and (b) photo of the RFID-based Smart Blood Stock System. Drawer with C-Tags in (c) compartments and (d) blood bag with B-Tag [17].

The purpose of B-Tags is shown in Figure 58 (d), used to identify each blood bag. The B-Tag is affixed to the blood bag, so it must be able to withstand the negative liquid dielectric influence. In most cases, this resilient is achieved by adding a ground plane to the tag. The geometric shape of the designed blood bag tag is shown in Figure 59. It is a planar antenna with a single metal layer printed on the front and a ground plane. 3.6 mm FR-4 substrate thickness used. Two 46 mm x 22 mm metal patches are printed on the front, and each patch is shortened to the ground through 2 vias so that the vias are placed as close to the edge as possible. There is a 4 mm gap between the two metal patches. ALIEN Higgs-3 IC is soldered in the middle of the gap.

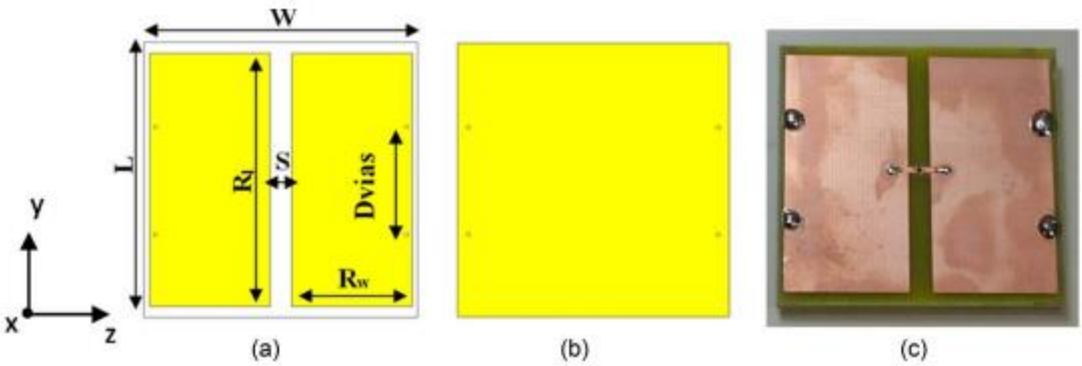


Figure 59: Geometry of the B-Tag antenna. (a) Front. (b) Back. (c) Fabricated Tag [17].

Disadvantages of this tag it is inflexible so, that not compatible with blood bag shape, in addition, the dimensions of this tag are large 50 mm x 50 x 3.6 mm, so it is considered as inappropriate choice.

Another solution for blood bags management is proposed in [18], The tag antenna consists of a modified dipole antenna with a reflector, and it is considering high permittivity of blood (εr=60) in the blood bag, Figure 60 show the proposed tag placed on blood bag.

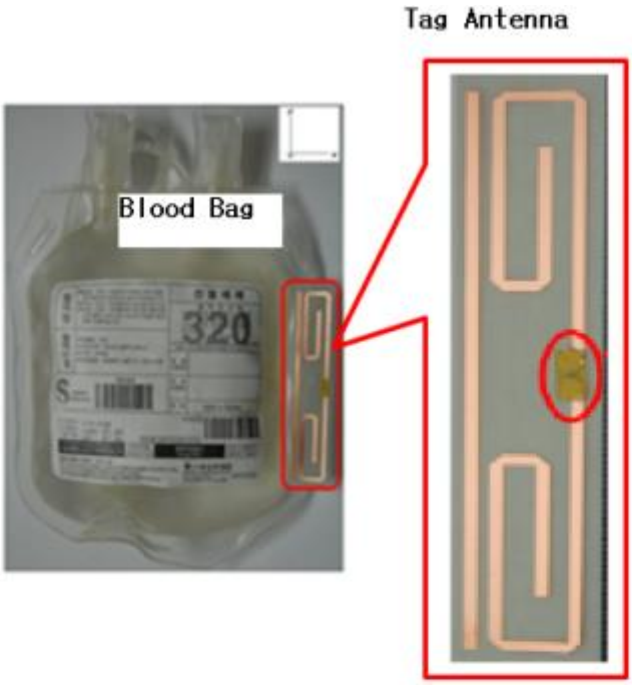
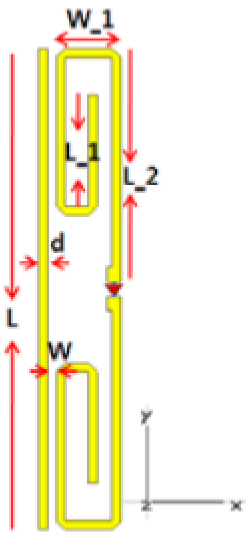


Figure 60: The geometry of a proposed tag attached on a blood bag [18].

The proposed tag antenna designed on PET film with thickness of 0.04 mm, dimensions of design parameters are presented in Figure 61, d is the width of the reflector, and W is the distance between the dipole antenna and the reflector.



Parameter	Value
L	82.4mm
L_1	19mm
L_2	39.9mm
W	1.5mm
W_1	11mm
d	1.5mm

Figure 61: Tag antenna parameters [18].

The proposed tag is fabricated and reading range pattern measured for two cases with and without reflector (Figure 62), as we see when tag placed on blood bag without reflector the maximum reading range at 0° is 86 cm, and 125 cm with reflector.

Depending on [5] and [18], we conclude that adding the reflector to the antenna can increase the reading distance.

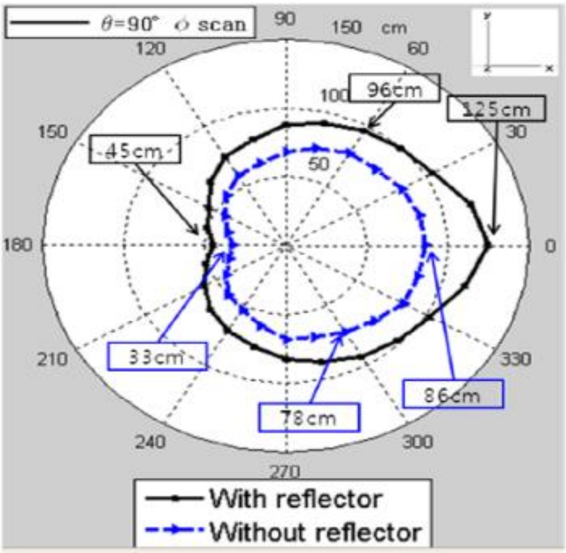


Figure 62: The measurements reading range pattern of the tag antenna with/without the reflector [18].

In [19] a commercial tag "impinj button near-field" is used for blood tubes tracking (Figure 63). This tag achieve a poor reading range about 4 cm as we mentioned before a commercial tags has low performance when it attached on loss materials like water, blood….

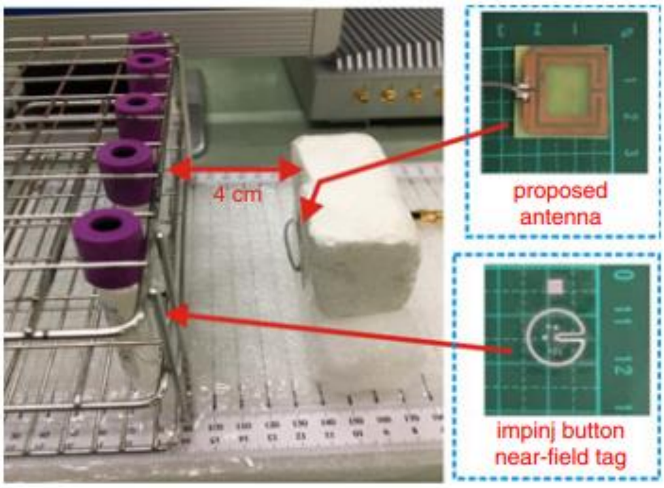


Figure 63: Impinj button near-fied tag attached on blood tube [19].

In [20] a good solution for health care applications is presented, authors proposed a versatile tag antenna that can be placed on water bottle, blood bag, IV solution bag, and human body. The proposed tag antenna is shows of Figure 64 with optimized dimensions.

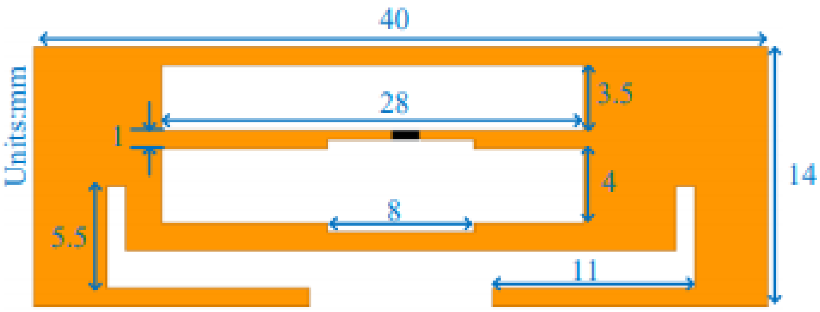


Figure 64: The proposed tag antenna [20]

Figure 65 shows the proposed tag antenna is fabricated on 50 µm paper substrate using conductive ink (15 µm Silver with σ = 12.5 x 106 S/m) by an ink-jet printer to achieve a good flexibility compatible with used bags.

Figure 65: A fabricated prototype of proposed tag [20].

The fabricated tag is placed on IV solution bag as illustrated in Figure 66 to measure reading range by using the Tagformance setup as shown in Figure 67. This tag was also mounted on blood bag and placed inside the refrigerator Figure 68.

Figure 66: The fabricated tag mounted on IV solution bag [20].

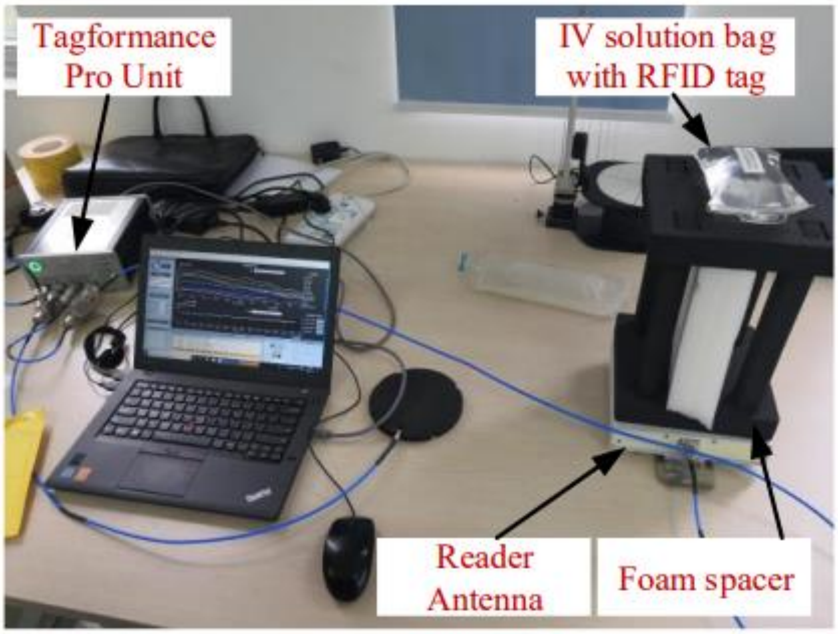


Figure 67: Read range measuring setup [20].

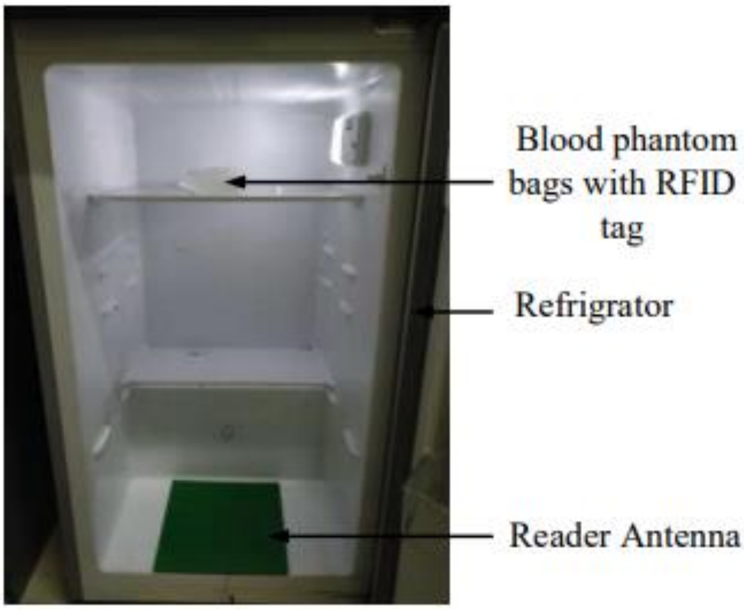


Figure 68: Read range measuring inside refrigerator [20].

As we see on Figure 69 this tag achieve a good reading range comparable with previous studies and also it’s better than commercial tags when it’s mounted on liquids.

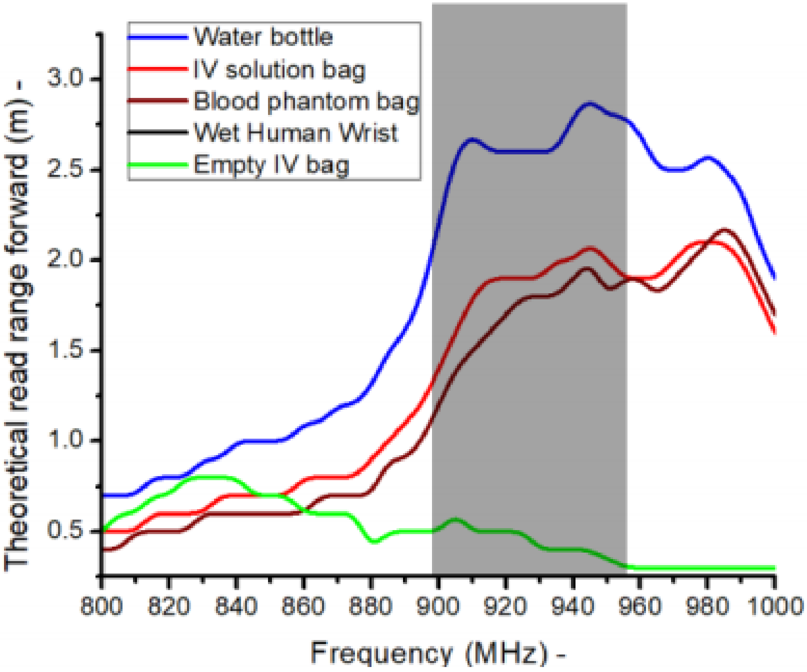


Figure 69: Theoretical measured read range of proposed tag on different material [20]

In [21] authors propose RFID tag for inventory management and IV fluid level warning system, this system consist of accurate patient identification for medication safety; infant identification in hospitals to avoid mismatching; patient identification to avoid wrong drug dosage; accurate patient identification; and tracking of drug supplies and procedures performed on each patient. In Figure 70 we see the proposed idea is the tag placed on IV bag full of injection fluid to monitor the level of this liquid.

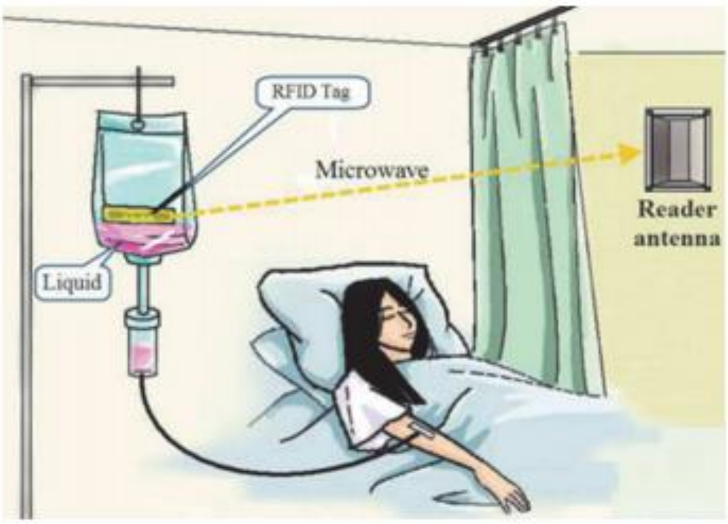


Figure 70: The proposed idea for IV liquid level monitoring [21].

Before antenna design, measure the dielectric constant of the target fluid to know the dielectric constant that's will use for simulation to optimize the antenna parameters. Figure 71 shows the dielectric measurement of fluids on the Agilent 85070E dielectric probe kit and 8753E network analyzer Test environment. Figure 72 shows the result of the comparison of the dielectric constant and conductivity with frequency between glucose and saline. The measurement results are very similar, so the antenna can be used for two fluids.

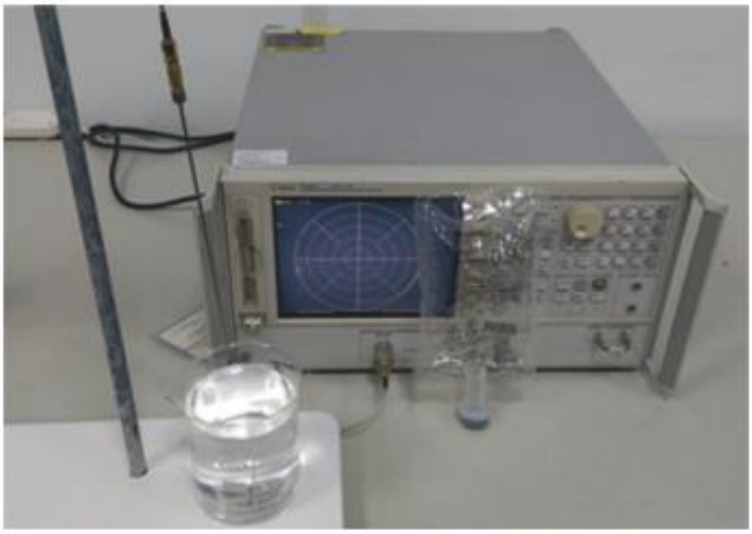


Figure 71: The characterization of IV fluid [21].

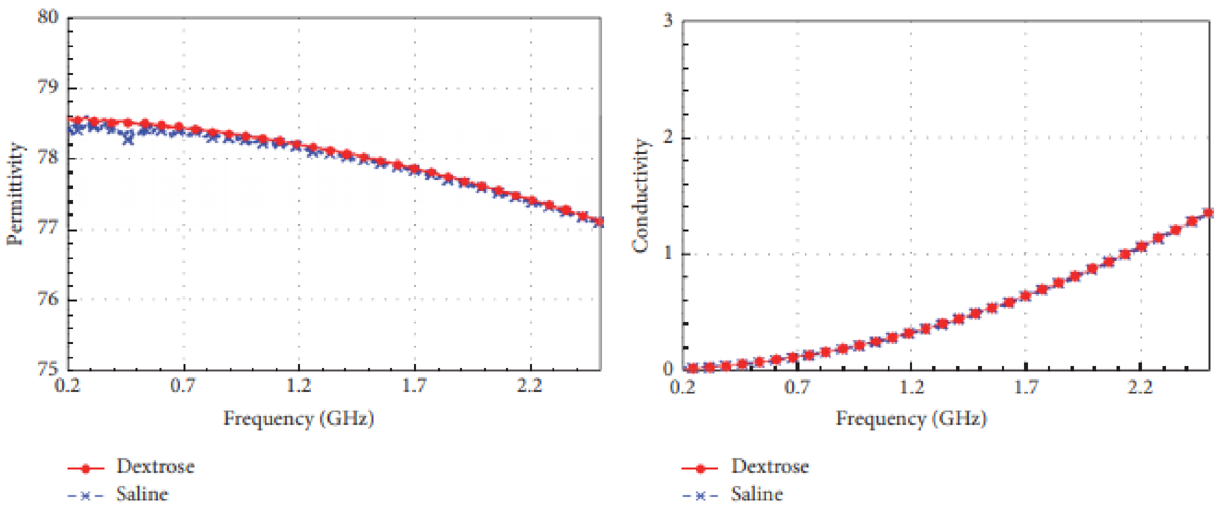


Figure 72: The permittivity and conductivity measurement result of injection fluid [21].

The proposed tag antenna is designed by using 0.8 mm thick glass-reinforced epoxy laminate FR-4 substrate, and all optimized parameters are shown on Figure 73.

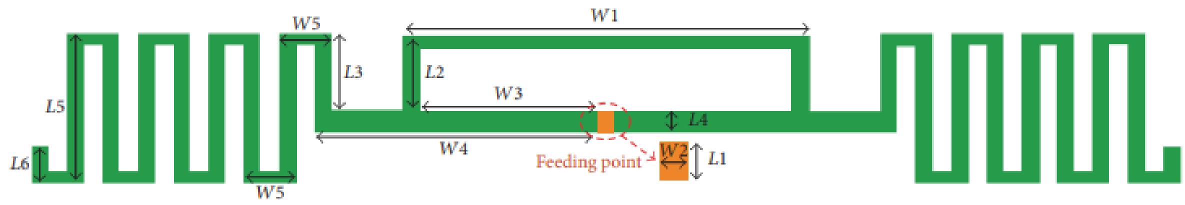


Figure 73: Antenna top view geometry: L1 = 5.8 mm, L2 = 6 mm, L3 = 6.2 mm, L4 = 1.8 mm, L5 = 12 mm, L6 = 3 mm, W1 = 23 mm, W2 = 1 mm, W3 = 7 mm, W4 = 13 mm, and W5 = 3 mm [21].

As we see on Figure 74 the proposed tag antenna fabricated and placed on full IV solution bag to measure reading range for different level of liquid.

The RFID tag antenna is attached to the bag (500 ml), and the minimum level that can cover all tag width is 20 ml, this test start from 0 ml to 500ml.

Figure 74: The proposed tag placed on full IV solution bag [21].

When the liquid exceeds 20 ml (the antenna is covered by the liquid), it will absorb most of the radiation, so the tag cannot be transmitted over long distances. When the antenna radiating arm is partially exposed to the air, the liquid is equal to or less than 20 milliliters. At this time, both the dielectric constant and the transmission distance begin to change.

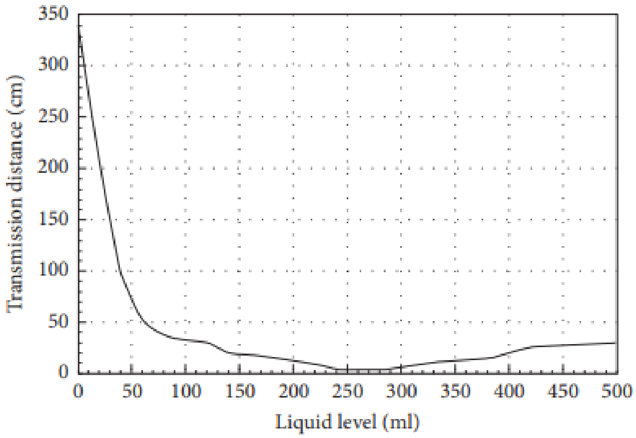


Figure 75: The results of measured reading range [21].

The test results are shown in Figure 75 the maximum distance is 340 cm when tag antenna placed on empty bag, and when level of solution increase we see the distance decrease, these results clearly demonstrated that this tag has bad properties on high permittivity solutions.

4. Conclusion

The basics of passive UHF RFID tags for liquids materials have been introduced in this chapter. Some designs in the literature for liquid bottles were reviewed. It is learned that there is a lack of study in the literature on the effect of liquid bottle on the performance of the tag antenna in terms of equivalent circuit and impedance matching. All the reviewed efforts were about increasing the directivity of the tag on the bottle or avoiding close contact between the liquid and the tag.

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Chapter 4

Flexible UHF RFID Tag for Blood Tubes Monitoring

1. Introduction

Low-cost and flexible radio frequency identification (RFID) tag for automatic identification, tracking, and monitoring of blood products is in great demand by the healthcare industry. A robust performance to meet security and traceability requirements in the different blood sample collection and analysis centers is also required.

In this chapter, a novel low-cost and flexible passive RFID tag is presented for blood sample collection tubes. The tag antenna is based on two compact symmetrical capacitive structures and works at the ultra-high frequency (UHF) European band (865 MHz–868 MHz). The tag antenna is designed considering the whole dielectric parameters such as the blood, substrate and tube. In this way, it operates efficiently in the presence of blood, which has high dielectric permittivity and loss. Measurement results of the proposed tag have confirmed simulation results. The measured performance of the tag shows good matching in the desired frequency band, leading to reading ranges up to 2.2 m, which is 4.4 times higher than typical commercial tags. The potential of this tag as a sensor to monitor the amount of blood contained in clinic tubes is also demonstrated. It is expected that the proposed tag can be useful and effective in future RFID systems to introduce security and traceability in different blood sample collection and analysis centers.

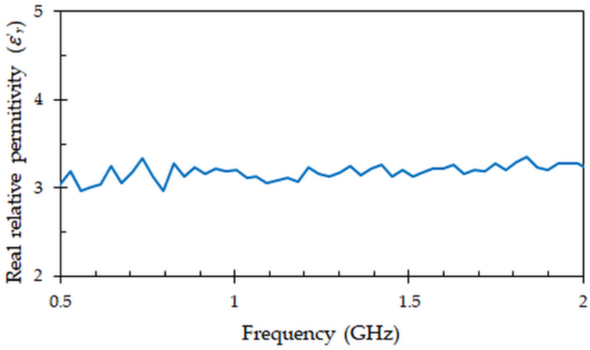
2. Electromagnetic Characterization of the Materials Involved in the Design of the Tag antenna

Following the strategy proposed in this work, the design of the UHF tag antenna will be carried out considering the presence of the flexible substrate, the clinic tube, and the blood. Therefore, it is important to extract the electrical properties (permittivity, loss tangent) of these elements, before starting with the design tasks of the tag. The main techniques to characterize dielectric materials are based on free space, transmission lines, coaxial probe, parallel plate, and resonators [1–2]. One of the most popular technique to measure the complex dielectric permittivity of solid and liquid materials is the coaxial probe method [3-4]. This electromagnetic characterization technique is non-destructive and allows to carry out fast broadband measurements of biological substances [5-6].

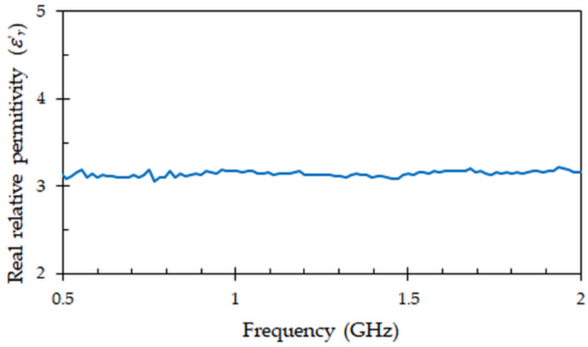
The complex permittivity of the tag antenna substrate, clinic tube and blood were measured between 0.5 GHz and 2 GHz, by employing the coaxial probe method developed in [7] and a vector network analyzer (Agilent Technologies E5070B) (Figure 76). The results were obtained at room temperature. For the tag antenna substrate, a flexible DuPontTM Kapton polyimide [8] was used, while for the blood storage container, a polyethylene terephthalate (PET) tube [9] was employed. The blood sample was prepared from animal blood powder to achieve a real relative permittivity (ε'_r) similar to human blood, which ranges from 58 to 62 in the measured frequency band.

Figure 76: Materials characterization

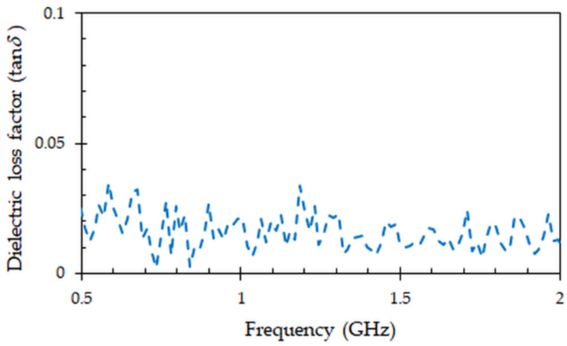
Figure 77 presents the measured results of the materials involved in the tag design. The real relative permittivity obtained for the Kapton polyimide in the frequency range from 0.5 GHz to 2 GHz is presented in Figure 77a. Results show a constant real part (ε'_r) of the relative permittivity around the value $\varepsilon'_r = 3.2$, which is in good agreement with the typical manufacturer data $\varepsilon'_r = 3.1$ [8]. The imaginary part of the relative permittivity of this material is not given, because it has a very small magnitude ($\tan\delta = 0.0015$) and the electromagnetic characterization technique using the coaxial probe does not allow to measure it accurately. This magnitude can be neglected during the design of the tag antenna, since dielectric loss and power dissipation in the polyimide substrate will be very small.



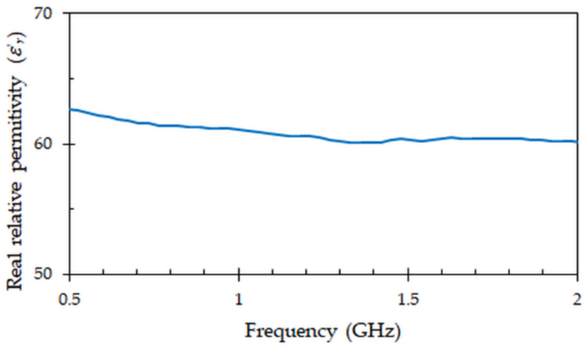
(a)



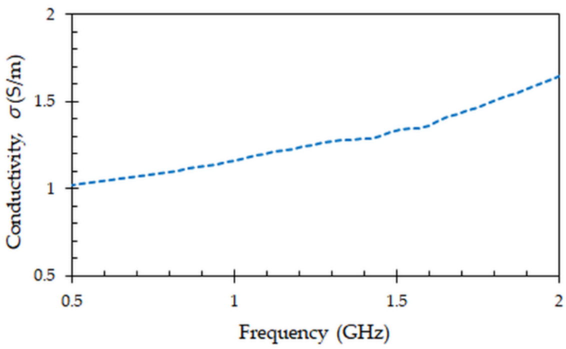
(b)



(c)



(d)



(e)

Figure 77: Measured electrical parameters of the materials involved in the tag design: (a) Real part of the relative permittivity for Kapton polyimide; (b) real part of the relative permittivity for polyethylene terephthalate (PET) tube; (c) Dielectric loss tangent for PET tube; and (d) real part of the relative permittivity for blood; (e) conductivity for blood.

Figure 77b, c represents, respectively, the real part (ε'_r) and loss factor (tanδ) of the dielectric complex permittivity for the PET material. This material is used to make blood sample collection tubes. As it can be seen in Figure 77b the real part of the complex permittivity is constant in the frequency range 0.5 GHz to 2 GHz. The measured value is $\varepsilon'_r = 3.1$. Its value is very similar to that of Kapton polyimide. However, the dielectric loss tangent (tanδ =0.016) depicted in Figure 77c is an order of magnitude higher (tanδ = 0.0015 for Kapton polyimide). Both values (ε’r = 3.1, tanδ = 0.016) match with data (ε'_r = 3.2, tanδ = 0.016 at 1 GHz) reported in [10]. Therefore, the measured values will be used during the design of the tag antenna.

Figure 77d, e shows the real relative permittivity (ε'_r) and conductivity (σ) of the blood, respectively. In the frequency range 0.5 GHz to 2 GHz, the value of the real relative permittivity (ε'_r) decreases from 62 to 60, while the conductivity (σ) value increases from 1 S/m to 1.65 S/m. This trend, and the values of permittivity (ε'_r) and conductivity (σ) are in agreement with the data obtained in a previous blood study [11]. At the center frequency f_c = 867 MHz of the UHF band, the real permittivity and conductivity values for the measured blood are, respectively, ε'_r = 61.2 and σ = 1.12 S/m. Therefore, these are the values that will be considered during the design of the tag antenna.

3. Tag Design and Analysis

In this chapter, the design of the tag antenna is presented. The structure of the proposed tag was developed from some initial design considerations. Then, an optimization of the tag dimensions attached to a tube full of blood was carried out at the center frequency f_c = 867 MHz of the UHF band. Finally, the optimized tag was simulated to obtain the generalized reflection coefficient in different scenarios, namely, tag attached to a tube full of blood, tag attached to an empty tube, tag removed from the tube but maintaining its initial curvature of the tube, tag removed from the tube and unfolded, and tag unfolded and attached to a bag full of blood.

3.1 Design considerations

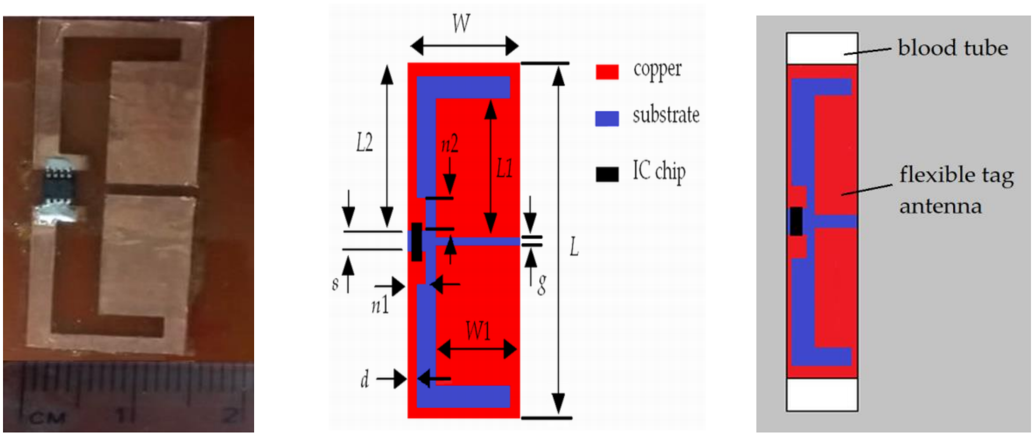
For the design of a suitable tag antenna for blood tube labeling, some initial considerations should be taken. First, the tag should be flexible and low-cost. Second, the thickness of the tag antenna substrate should be as thin as possible, and it should also be adhesive, so it can be attached easily to the blood tube. Finally, the design should be attractive, and for this, the general recommendation is that the size of the tag should be small, so as not to cover the full surface of the blood tube. In the case of the Becton Dickinson (BD) Company, three different sizes of blood tubes are available. The tube with largest volume (10 mL) has a height of 100 mm and an inner diameter of 16 mm, the medium volume tube (7 mL) has 100 mm and 13 mm, and the height and the inner diameter of the smallest volume tube (5 mL) is 75 mm and 13 mm, respectively. All blood tubes have the same PET wall thickness of 1 mm.

Taking into account these initial considerations, a compact and low-profile RFID tag antenna has been designed to operate from 865 MHz to 868 MHz. The elements and dimensions used for the tag design were: an adhesive copper sheet with a thickness of 35 μm, an adhesive Kapton polyimide substrate (3MTM Kapton polyimide film tape 5413 amber) with a thickness of 70 μm, the smallest blood tube size (75 mm x 13 mm) with a PET wall thickness of 1mm, and the NXP UCODE G2XL IC chip with a TSSOP8 package [12]. This IC chip has a power threshold sensitivity of -17 dBm, a complex impedance Zc = 16 – j156 Ω and a die size (length x width) of 0.31 mm x 0.51 mm. In this work, we have used the Kapton polyimide [13], since it is flexible and thin. In addition, as shown before, it has a real permittivity similar to the PET tube and has a low dielectric loss factor.

While most of the commercial tags are of inductive type, and are designed using the T-matched technique, we have found that such designs lead to small reading ranges and low radiation efficiencies when they operate attached to clinic tubes, in the proximity of blood. Due to the high relative permittivity value of the blood, capacitive antennas experience a good size reduction, and can be adapted to the size and curvature required by clinic tubes. Consequently, our design approach started with a basic capacitive dipole antenna, and some bending was applied to fit the tag in the curvature and space available in clinic tubes. In addition, these conforming operations were applied trying to maximize the amount of copper area in the capacitive pads. This is better from the point of view of losses, since then induced surface currents can flow across larger areas.

3.2 Structure of the tag antenna

Using these considerations, the photograph and the final structure of the tag antenna are presented in Figure 78a,b, respectively. The tag consists of two symmetrical capacitive pads with two etched meandered substrate arms. Both pads are separated at the center by means of two different gaps s and g, which are placed at the left and right sides, respectively. The IC chip (NXP UCODE G2XL) is mounted across the gap s between the two pads, while the gap g is used to introduce a capacitive behavior to the tag antenna. The structure of the dipole antenna is meandered to achieve a compact design. Due to the good flexibility of the Kapton polyimide, the tag antenna can be easily conformed to the curved shape of the blood tube as shown in Figure 78c.



(a) (b) (c)

Figure 78: Proposed flexible ultra-high frequency (UHF) radio frequency identification (RFID) tag antenna. (a) Photograph of the tag antenna attached to a flat surface (FR4 substrate). (b) Structure and dimensions. (c) Flexible tag antenna attached to a blood tube.

3.3 Optimization

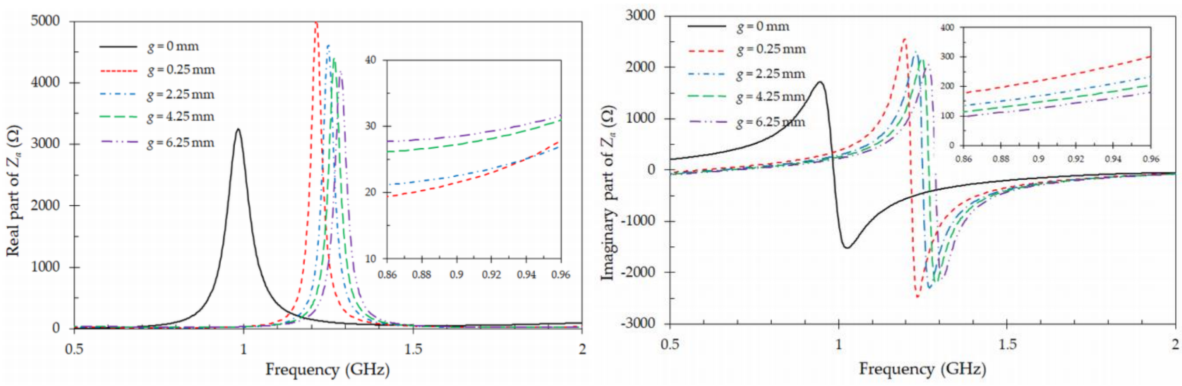
One of the important characteristics in the design of tag antennas is the input impedance. A good matching is needed between the IC chip and the tag antenna to avoid undesired reflections. This condition can be monitored by means of the generalized reflection coefficient calculated as:

$$\Gamma = \frac{Z_a - Z_c^*}{Z_a + Z_c} \tag{1}$$

Where Z^*c represents the complex conjugate of the IC chip impedance and Za is the input complex impedance of the antenna. The magnitude of the generalized reflection coefficient is monitored in real conditions with the tag attached to the smallest blood tube, as shown in Figure 3c. Therefore, all the relevant elements, namely the substrate, blood and tube with the electrical characteristics discussed in Section 2, are included during the design process. Note that in order to minimize the reflections between the tag and the IC chip, the magnitude of the generalized reflection coefficient given in (1) must be minimized during the design process.

The commercial electromagnetic simulator CST Studio Suite® was used for the optimization, analysis and design of the proposed tag. The tag attached to the smallest tube is drawn in the modeler as shown in Figure 78c, and all its element parameters (dimensions, substrate permittivity, blood permittivity, and thickness substrate), including the IC chip, are defined. The real and imaginary parts of the complex chip impedance (Zc = 16 – j156 Ω) are respectively specified by means of a discrete port and lumped RLC series element. The discrete port and the lumped RLC series element are situated across the gap s between the two pads, in the same place than the IC chip (Figure 78). Then, the simulation is started from the transient solver. Once the simulation is finished different parameters such as impedance, reflection coefficient, and gain can be analyzed.

For the design of the tag, the resonant frequency is mainly controlled with the length L1 of the meandered substrate arms. This resonant frequency is also affected by the substrate thickness and other dielectric properties of nearby objects such as the tube and the blood [14-15]. In addition, the maximum attainable gain and bandwidth have limitations, due to the size of the tag antenna and the frequency of operation [16]. Figure 79 shows the dependence of the input impedance of the tag antenna (Figure 78b) with the gap g between pads as a function of the frequency (0.5 GHz–2 GHz), while all other parameters are kept constant (Table 9). It can be observed that this gap controls the capacitive coupling of the two pads. The capacitive effect increases when the gap g decreases, and this results in a lower resonant frequency. Consequently, the adjustment of the gap g allows a fine tuning of the resonant frequency of the tag antenna. The insets inside Figure 79a,b shows details on the variation of the real and imaginary parts of the input impedance Za of the tag antenna with the gap g in the frequency band of interest (0.86 GHz–0.96 GHz). As it can be seen in the insets, the values of both real and imaginary parts of the input impedance Za can be fine adjusted to match the conjugate of the chip impedance Zc, needed to minimize the magnitude of Equation (1). This study also serves to discuss the particular case of g = 0. For this case, the two pads are in electrical contact, and the antenna turns from a capacitive behavior to an inductive behavior. For this inductive behavior, currents can flow from one pad to the other, and the resonant frequency shifts to lower values, as shown by the black line in Figure 79. Due to the high value of the relative permittivity of the blood, the resonant frequency of the antenna becomes too low, and the input impedance exhibits values which are too large for both the real and the imaginary parts at the frequency of interest. This shift in resonant frequency could be compensated by reducing the length L1 of the meandered substrate arms. However, we have verified that the size reduction has a strong negative impact on the efficiency of the resulting tag antenna.



(a) (b)

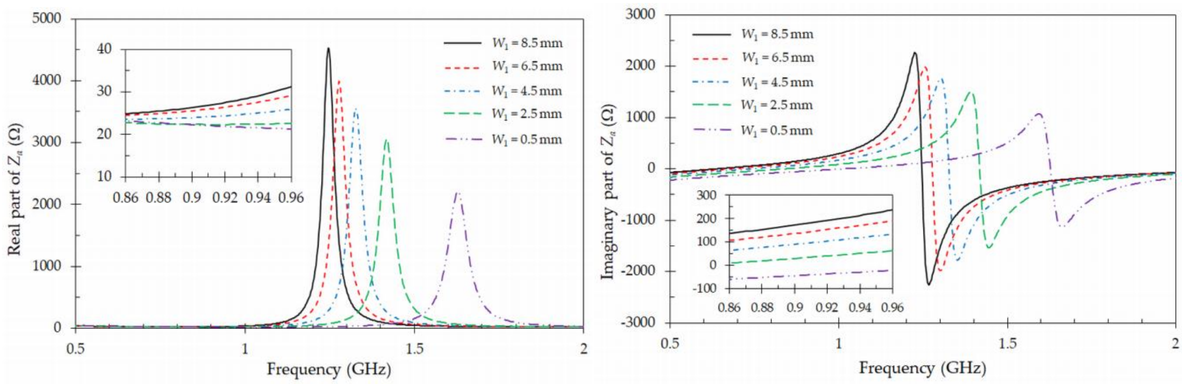
Figure 79: Simulated input impedance Za of the designed tag antenna (Figure 3b) for different gap values g. (a) Real part of Za; (b) Imaginary part of Za. The other dimensions are defined in Table 1.

Parameter	Value (mm)	Parameter	Value (mm)
L	49.5	s	5
W	15	g	2.25
L1	18.75	n1	5
W1	8.5	n2	3.5
L2	18.25	d	2

Table 9: Optimized parameters of the proposed tag antenna with the NXP UCODE G2XL C chip.

An important conclusion can be draw from this study. While in many applications the use of inductive tags is preferred, since it leads to smaller sizes, this is no longer the case for this application, where the tag must operate in the presence of blood. Due to the high real relative permittivity value of the blood, the inductive tag tends to be very small, therefore leading to low efficiencies [17]. However, the capacitive configurations, as the one proposed in Figure 78b with $g > 0$, lead to tags with higher radiation efficiencies, still exhibiting small sizes. This is due to the natural size reduction effect that occurs when the tag operates near to the blood. A second benefit of this capacitive design is its high sensitivity to the real relative permittivity value of the blood. This high tag sensitivity could be used to reduce non-relevant information collected from empty tubes. In a similar way, the tag could be used as a sensor to monitor the amount of blood contained in a specific tube, as it will be demonstrated in Section 5.

In the previous study, it has been observed that the gap g between pads can be used to control both parts (real and imaginary) of the input impedance Za of the tag antenna. However, for a practical design, it is needed to be able to adjust the real and imaginary parts independently. To achieve this, it is necessary to add a second design parameter. For the structure proposed in Figure 78b, the fine tuning of the input impedance Za of the tag antenna can be performed by means of the parameter W1. Figure 80 presents the variation of both real and imaginary parts of the input impedance Za of the tag antenna as a function of W1 and the frequency (0.5 GHz–2 GHz), when all other parameters are kept constant (Table 9). It can be observed in Figure 5 that the parameter W1 can also control the resonant frequency of the antenna. Smaller values of W1 lead to higher resonant frequencies, since the effective length of the pad is reduced. Details on the variation of the real and imaginary parts of the input impedance Za of the antenna with the parameter W1 in the frequency band of interest (0.86 GHz–0.96 GHz) are shown in the insets inside Figure 80a,b. As it can be seen in the insets, the impact of this parameter (W1) in the real part of the input impedance is much lower, as compared to the influence introduced in the imaginary part. This behavior allows to optimize the values of the real and imaginary parts of the input impedance Za of the tag antenna, with respect to those of the impedance Zc of the IC chip, by following an iterative procedure involving the gap g and the parameter W1. In the iterative process, first the real part of the input impedance Za of the tag antenna is adjusted with the gap g, but this also modifies the imaginary part. Then, the imaginary part is readjusted by controlling the value of W1. Several iterations are performed following this strategy until the input impedance Za of the tag antenna is adjusted to the IC chip (NXP UCODE G2XL) impedance (Zc = 16 – j156 Ω), in both real and imaginary parts, in order to minimize the magnitude of the generalized reflection coefficient given in Equation (1). The values of the optimized parameters obtained by means of the previous iterative procedure and the electromagnetic simulator (CST Microwave Studio) are presented in Table 9. Due to the limited accuracy prototyping technique available for fabrication-in-lab of tags, the optimization procedure was stopped when a generalized reflection coefficient value less than -10 dB was reached at the center frequency f_c = 867 MHz of the UHF band.



(a) (b)

Figure 80: Simulated input impedance Za of the designed tag antenna (Figure 3b) for different values of W1. (a) Real part of Za; (b) Imaginary part of Za. The other dimensions are defined in Table 1.

In general, the impedance variation shown in Figures 79 and 80 can be modeled with an equivalent circuit composed of a single resonator coupled on one side to the chip and on the other to free space, thus producing radiation. With a fixed unloaded quality factor of the resonator, the bandwidth will be controlled with the amount of coupling, and the center frequency with the resonant frequency of the resonator. However, it will be difficult to derive specific formulas relating the equivalent circuit parameters to the actual geometrical variables of the physical design.

Finally, a sensitivity analysis of the tag antennas regarding to its main geometrical parameters W1 (Figure 79) and g (Figure 80) has been performed to ensure the robustness of this design. In Figure 4, the resonant frequency of the tag varies by 100 MHz when the gap g varies 6 mm. This gives a sensitivity of the resonant frequency with the gap of 16.6 MHz/mm. On the contrary the sensitivity of the resonant frequency with the length W1 is higher, as it can be observed in Figure 80. In this case, the resonant frequency varies by 350 MHz when the length varies 8 mm, leading to a sensitivity of 43.7 MHz/mm.

3.4 Simulation Results

Figure 6 shows the simulated magnitudes of the generalized reflection coefficient (1) for the optimized tag antenna (Table 9) operating in five different scenarios in the range of frequency 0.5 GHz–2 GHz: (i) Tag attached to a tube full of blood, (ii) tag attached to an empty tube, (iii) tag removed from the tube but maintaining the initial curvature of the tube, (iv) tag removed from the tube and unfolded, and (v) tag unfolded and attached to a bag full of blood (dimensions length × width × thickness in mm: 160 × 130 × 30). As it can be observed, a good impedance matching is obtained in the desired band when the tag is attached to a tube full of blood, thus indicating that the design process described previously has been successful. The resonant frequency and 3 dB bandwidth are, respectively, f_0 = 867 MHz and Δf = 75 MHz (covering the range 830 MHz–905 MHz). The return loss (RL) at the resonant frequency is RL = 11.5 dB. However, the resonant frequency is shifted upwards when the tag is attached to an empty tube. In this case, a return loss of RL = 9.8 dB is obtained at f_0 = 1.2 GHz. This resonant frequency is far from the range allocated to the RFID system. This property of the proposed tag is due to the capacitive design employed, which makes the tag to be very sensitive to the high real relative permittivity value of the blood. This behavior may be of great interest for traceability of blood tubes. In fact, using the described capacitive loading effect, the tags will only be detected when the tubes are full of blood, with a drastic decrease in reading range as the blood tubes are emptied. This can reduce the amount of data collected in a specific traceability application, when the information of empty tubes is not considered relevant. When the tag is removed from the tube but keeps its initial curvature, the resonant frequency shifts to a higher value. The return loss is RL = 13.4 dB at f_0 = 1.3 GHz. This demonstrates that the PET material of the tube has also some influence on the operation of the tag. This last resonant frequency moves to an even higher value (f_0 = 1.32 GHz) when the tag is removed from the tube and unfolded (Figure 81). This confirms that a curvature radius of the tube does not have very strong effect in the resonant frequency when the tag operates in air. Finally, when the tag is unfolded and attached to a bag full of blood, the antenna cannot match the complex impedance of the chip (Zc = 16 – j 156 Ω). This is because the environment becomes too capacitive due to the presence of the blood, and the tag cannot provide enough inductive component to compensate for it.

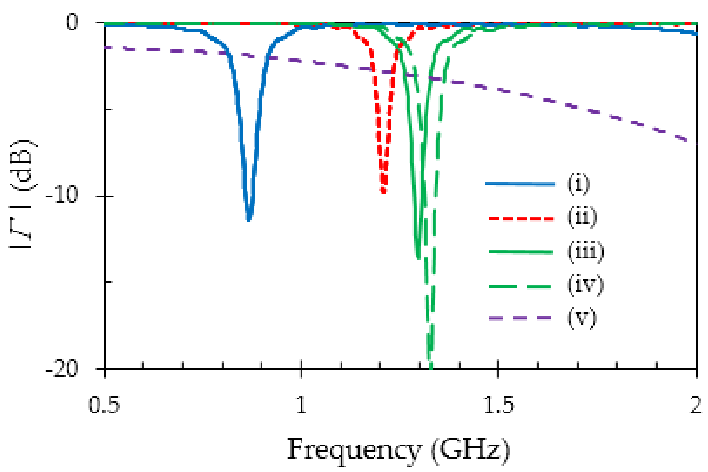


Figure 81: Simulated generalized reflection coefficients of the optimized tag antenna in five different scenarios: (i) tag attached to a tube full of blood, (ii) tag attached to an empty tube, (iii) tag removed from the tube but keeping its initial curvature, (iv) tag removed from the tube and unfolded, and (v) tag unfolded and attached to a bag full of blood.

4. Fabrication and Experimental Characterization of the Proposed Tag Antenna

The proposed UHF RFID tag antenna (Figure 78) was fabricated and experimentally characterized. In addition to the impedance measurement, other useful parameters for the characterization of the proposed tag antenna such as the realized gain, reading range, tag power sensitivity, differential radar cross section, and radiation patterns were measured wirelessly in an anechoic chamber by using the Voyantic Tagformance measurement system in two different scenarios, namely, when the clinic tube is filled of blood and when the tube is empty. Finally, the proposed tag was compared with other tag designs for blood and liquid monitoring. In this way, the operation of the designed tag in blood traceability is characterized. All measurements presented here were carried out with the proposed tag antenna attached to the smallest clinic tube. Very similar results were also obtained using different tag prototypes mounted in several blood tubes standards manufactured by the Becton Dickinson (BD) Company. However, the number of tests performed is still small to be considered relevant for a statistical analysis and, therefore, this will be carried out in future work.

4.1 Fabrication

The tag (Figure 78) with the design parameters collected in Table 9 was fabricated by using a simpler and faster prototyping technique than the traditional photolithographic method, although with less accuracy. It consists of three main steps. In a first step, an adhesive and flexible copper sheet is pasted on a FR4 substrate and inserted into a laser milling machine (LPKF protolaser S). Then, the tag is shaped and cut on the copper sheet by means of the laser milling machine. In a second step, the tag is removed from the copper sheet pasted on the FR4 substrate by using a sticky tape. Then, it is pasted again on a flexible and adhesive Kapton polyimide substrate with a thickness of 70 µm, which was characterized in Section 2. In the last step, the IC chip (NXP UCODE G2XL) is mounted across the gap s between the two pads of the tag antenna (Figure 78). Once finished, the tag antenna is ready to be attached to a blood tube as it can be seen in Figure 82. Note that in our design, the inlay is directly attached to the Kapton polyimide substrate. The use of an intermediate absorbing layer between these two elements could be considered in future designs. This could help to introduce an additional isolation effect between the tag and the blood, and reduce absorption of electromagnetic energy. This approach will require additional research, for instance to determine the optimum thickness and materials for the absorbing layer. Also, depending on these factors, viability of the design for blood tubes will have to be assessed, especially with issues related to the attachment of the tag into blood tubes (available space, curvature).

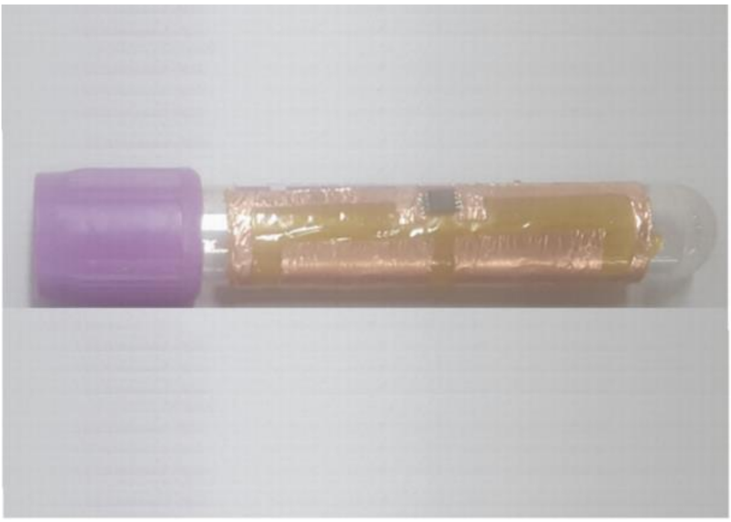


Figure 82: Photograph of the proposed flexible UHF RFID tag antenna attached to the smallest blood tube.

4.2 Impedance Measurement

The impedance of the proposed UHF RFID tag antenna was characterized by using a two-port vector network analyzer (VNA) and a port-extension technique introduced in [18]. Recall that the design of the UHF tag antenna was carried out considering the presence of the flexible substrate, the clinic tube, and the blood. Therefore, the impedance measurement of the tag must be performed with the same design conditions, using the measurement system shown in Figure 83. As it can be seen, the tag is first attached to a clinic tube full of blood. Then, in a second step, the two antenna feeding points are soldered to two inner conductors of a differential probe, which is based on two semirigid coaxial cables soldered together with an outer conductor diameter of 2.2 mm and a length of 100 mm. The other end of the differential probe is connected to the VNA by means of the SMA connectors and test cables, and the S-parameters of the resulting two-port network are measured. To remove the effects of the differential probe a previous Through, Open, Short, Match (TOSM) calibration was realized at the opposite end of the SMA connectors. Finally, the impedance of the proposed tag antenna is calculated as [18]:

$$Z_a = \frac{2Z_0(1 - S_{11}S_{22} + S_{21}S_{12} - S_{21} - S_{12})}{(1 - S_{11})(1 - S_{21}) - S_{21}S_{12}}, \qquad (2)$$

Where Z0 = 50 Ω is the characteristic impedance of the measurement system.

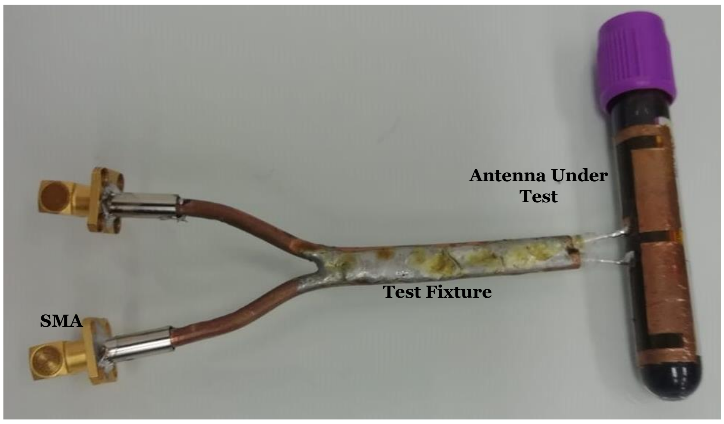


Figure 83: System for the impedance measurement of the proposed tag antenna.

The input impedance of the proposed antenna measured in an anechoic chamber by means of the above technique in the frequency range from 0.5 GHz to 2 GHz is shown in Figure 84. The simulated input impedance of the tag and the impedance of the IC chip (NXP UCODE G2XL) are also included. The insets inside Figure 84a,b shows details on the variation of the real and imaginary parts of the impedances between 0.86 GHz and 0.96 GHz. Except for a small shift in the resonant frequency, a good agreement between simulated and measured results for both real (Figure 84a) and imaginary (Figure 84b) parts of the input impedance is obtained. The measured impedance of the antenna is Za = 13 + j 130 Ω at 867 MHz. This value is close to the conjugate of the chip impedance at the same frequency Z*c = 16 + j 156 Ω, therefore leading to a small magnitude of the generalized reflection coefficient given in Equation (1). The small mismatch is due to inaccuracies for fabrication-in-lab of tags and negative mounting and soldering effects.

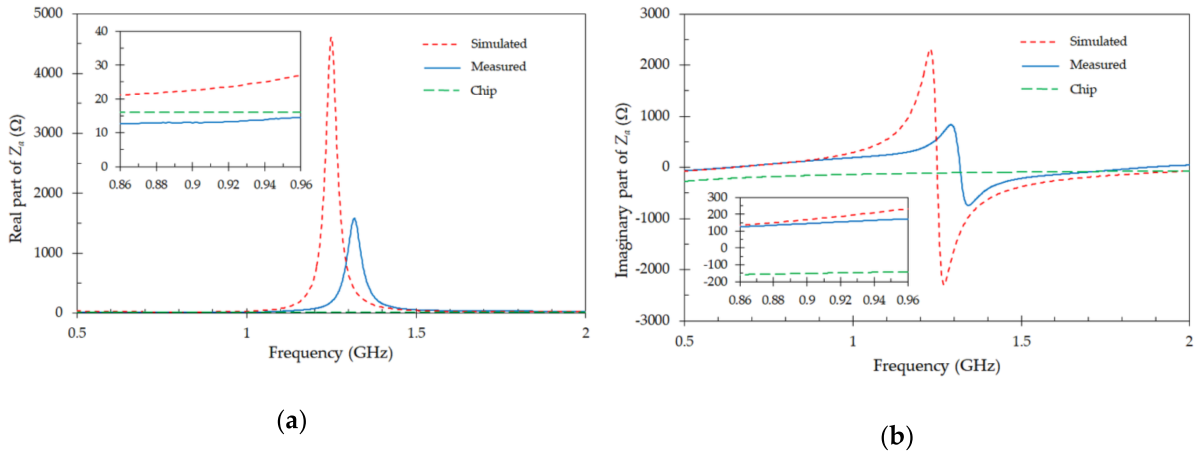


Figure 84: Simulated and measured impedance of the proposed tag antenna. (a) Real part of the impedance; (b) imaginary part of the impedance. Green dashed line denotes the impedance of the chip (NXP UCODE G2XL)

4.3 Realized Gain

A useful parameter to assess the performance of the tag is the realized gain (Gr,tag = Gtag x τ), which is defined as the tag antenna gain (Gtag) times the power transmission coefficient (τ). τ is given by τ= $(1 - |\Gamma|^2)$, where Γ is defined in (1). Figure 85 depicts a good agreement between the simulated and measured values of this parameter for the proposed tag attached to full and empty blood tubes. At the resonant frequency f_0 = 867 MHz, the realized gain of the tag is of –13.5 dBi for measurements (-12.3 dBi for simulations). In this case, it is useful to compare this value (–13.5 dBi) with data reported in [19] for a tag that operates in water, which is –9.8 dBi. Our tag exhibits quite good matching to the IC-chip as reported in Figure 81. Therefore, the lower realized gain as compared to [19], is essentially due to a higher power absorption of the blood, and a higher directivity of the tag presented in [19] due to its larger dimensions. However, when the tag is attached to an empty tube, the realized gain drops to -24.7 dBi (-23 dBi for simulations) at the same frequency of 867 MHz. In absence of blood, the transmission coefficient and the gain of the tag decrease drastically.

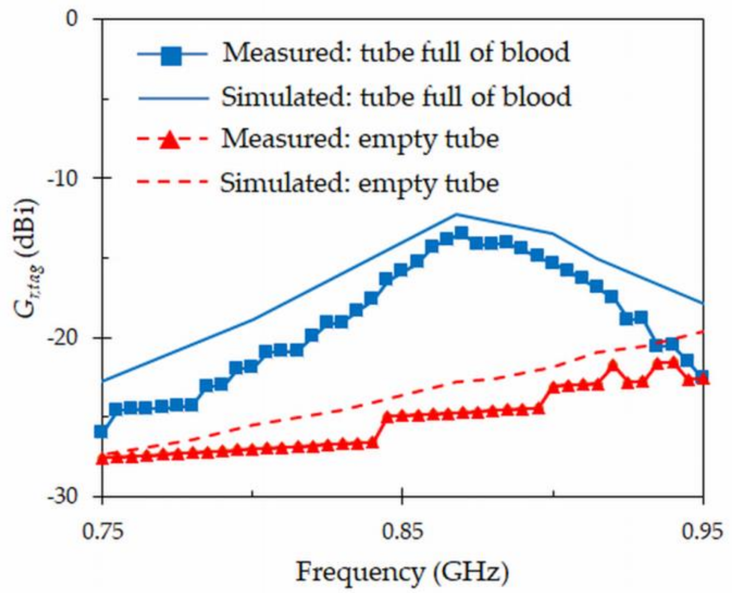


Figure 85: Simulated and measured realized gain Gr,tag for the proposed tag antenna attached to full and empty blood tubes.

4.4 Reading Range

The critical parameter that determines the performance of an RFID tag antenna is the reading range [16], which corresponds to the maximum distance at which the RFID reader can detect the modulated backscattered signal and successfully identify the tag. The reading range r can be obtained by means of the Friis free-space formula [20]:

$$r = \frac{\lambda_0}{4\pi}\sqrt{\frac{P_r\, G_r\, G_{tag}\, \tau}{P_c}} \tag{3}$$

Where λ_0 is the free space wavelength, Pr = 1 W is the power transmitted by the reader, Gr = 4.5 dBi is the gain of the reader antenna, Gtag is the gain of the tag antenna, and τ is the power transmission coefficient defined in the previous subsection. Besides, Pc = −17 dBm (NXP UCODE G2XL IC chip) is the minimum power threshold needed to provide enough power to the chip (sensitivity). The simulated and measured reading ranges obtained for the proposed tag attached to a tube in the frequency range from 0.8 GHz and 0.9 GHz are shown in Figure 86. The measurements include the results obtained for the smallest and largest tube standards manufactured by the Becton Dickinson (BD) company. It can be observed that the measurements are in good agreement with predictions. The measured reading range reaches a peak value of 2.2 m at the frequency of 867 MHz when the tag is attached to the smallest size tube full of blood, while the largest size tube has a peak value of 2.3 m at 860 MHz. At 867 MHz, the largest size tube presents a reading range of 2.25 m, which is similar to the measured value (2.2 m) for the smallest size tube. For both tube sizes, the reading ranges drastically decrease when the tubes are empty. This confirms that the proposed design can be applied to different tube standards, and that it is possible to detect the tag at reasonable distances when the tube is full of blood. In addition, in both cases the reading range drastically reduces for empty tubes. This behavior can be used to reduce the amount of information collected in the tracking system, coming from empty tubes.

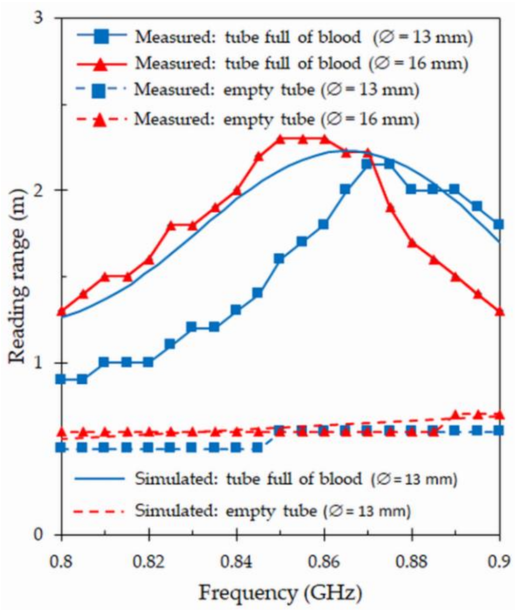


Figure 86: Simulated and measured reading ranges obtained for the proposed tag attached to two standards (∅ = 13 mm and ∅ = 16 mm) of full and empty blood tubes.

To check the performance of the proposed tag attached to a tube full of blood in a natural environment, measurements out of anechoic chambers have been realized in two different scenarios. The first scenario consists in the measurement of a single individual tag, while the second one is the measurement of the tag located behind a group of four tubes full of blood. Figure 87 depicts the reading ranges for these two scenarios. As it can be seen (Figure 87), there is no substantial change in the performance with respect to previous results (Figure 86) obtained for an individual tag by means of the Voyantic Tagformance measurement system. The reading range reaches the same peak value of 2.2 m, but shifted to a higher frequency of 875 MHz. On the other hand, the results of the second scenario confirm that a group of filled tubes located in the vicinity of the tag does not greatly affect its performance. In this test, the maximum reading range and the resonant frequency slightly decrease (with respect to the tag placed alone) to 2.1 m and 870 MHz, respectively.

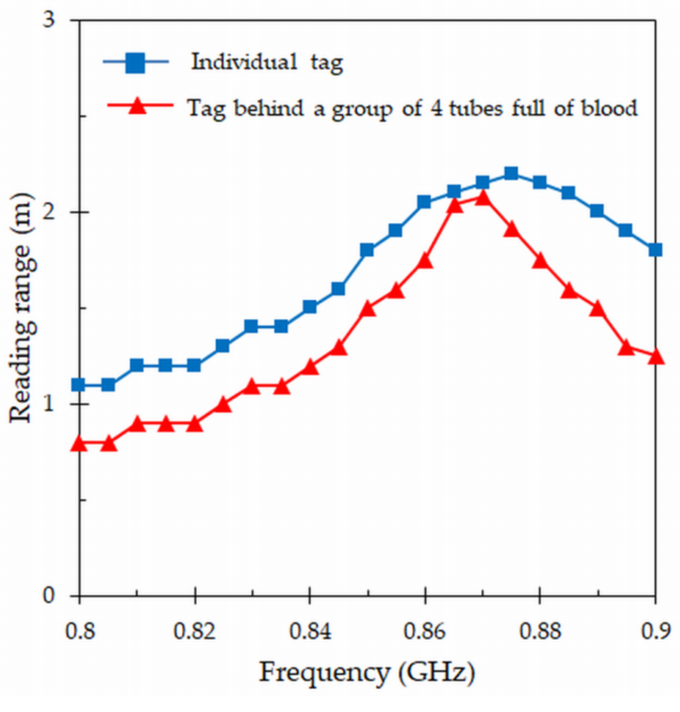


Figure 87: Measured reading ranges for the proposed tag attached to a tube full of blood in two different scenarios: Single tag placed alone, and tag located behind four filled tubes.

4.5 Tag Power Sensitivity

Figure 88 represents the tag power sensitivity, which defines the minimum power that should be received by the tag to be able to power on the IC chip. At the resonant frequency of 867 MHz, the minimum transmitted power needed to activate the tag is 14 dBm when the tube is full of blood. Moreover, there is a large difference when the tube is empty, requiring a minimum power of 27 dBm to activate the tag. This large amount of power required to activate the IC chip is due to the fact that most of the power present at the antenna terminals is not delivered to the chip, but it is in fact reflected back, as shown by the generalized reflection coefficient of Figure 81.

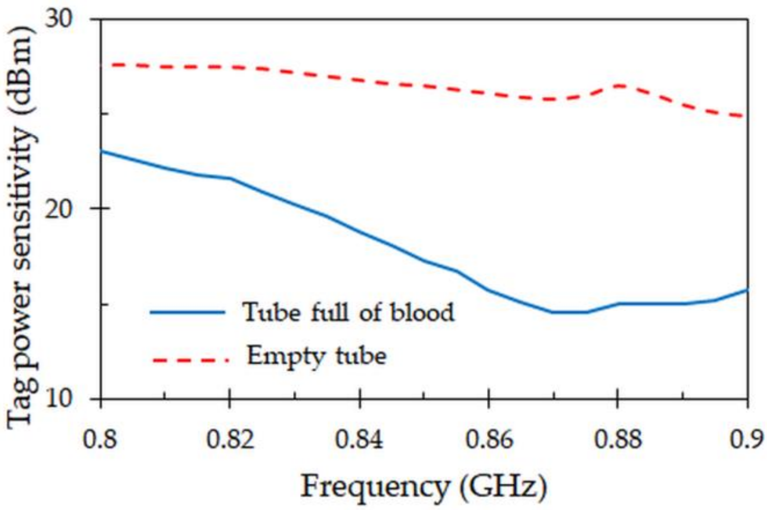


Figure 88: Measured tag power sensitivity obtained for the proposed tag attached to full and empty blood tubes.

4.6 Differential Radar Cross Section

The differential radar cross section (ΔRCS) is also an important parameter, which measures the strength of the modulated backscattered signal reradiated by the tag. It is expressed as the ratio of backscattered power of the modulated signal reflected from the tag to the incoming power received by the tag from the reader. It can be obtained from the following relationships [21]:

$$\Delta\text{RCS} = \frac{P_{tag}(4\pi)^3 d^4}{P_r\, G_r^2\, \lambda_0^2} \tag{4}$$

Where *Ptag* is the power of the modulated signal received by the reader from the tag, *d* = 0.45 m is the distance between the tag and the reader antenna. Also, *Pr*, *Gr* and λ_0 were defined in (3). The measured differential radar cross section obtained for the proposed tag attached to a full and empty tube in the frequency range from 0.8 GHz and 0.9 GHz is shown in Figure 89. The peak value is ΔRCS = −43 dBsqm at the resonant frequency of 867 MHz when the tag is attached to the tube filled with blood. Again, there is a big difference when the tag is attached to an empty tube, as the value of ΔRCS considerably decreases to about −53.8 dBsqm at the same frequency. Note that the very small values of the differential cross section are an indication that it will be difficult to detect the tag when the tube is empty, especially in real conditions with non-negligible values of RCS noise floor level. However, the strong backscattered signal at the resonant frequency 867 MHz when the tube is full of blood leads to a maximum reading range and allows the reader to detect the backscattered signal more easily. As indicated, this may be useful in blood traceability applications, where the important information to be collected comes from tubes that are full of blood.

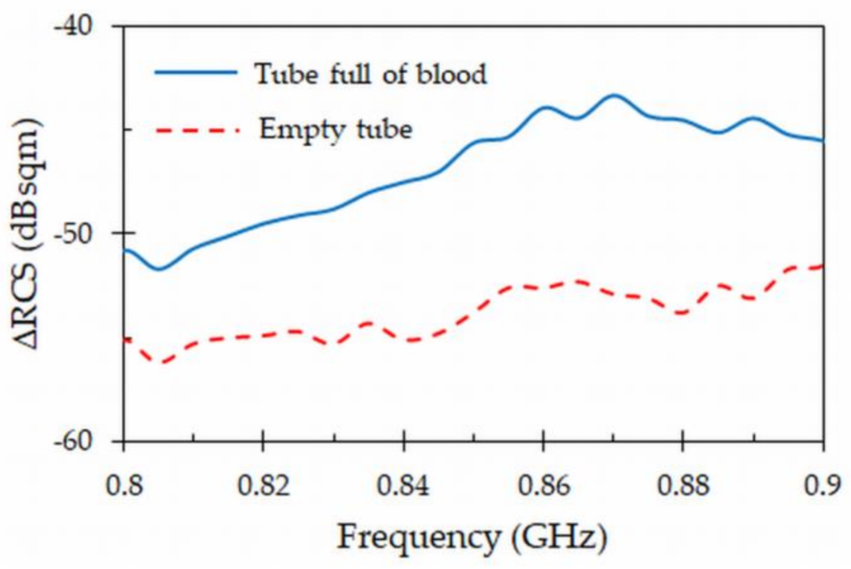
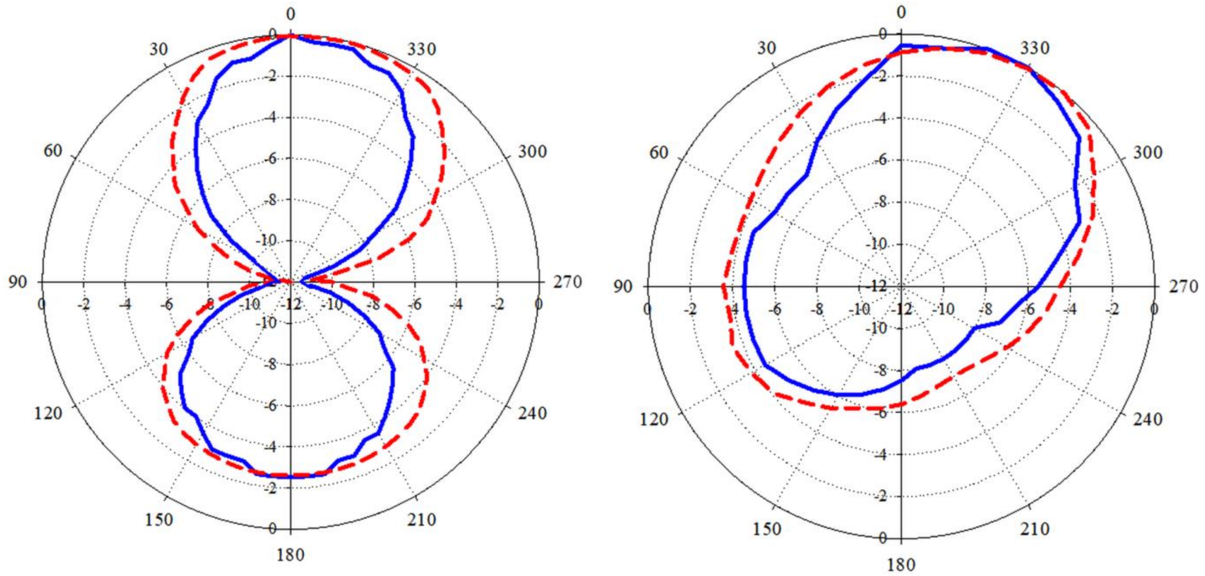


Figure 89: Measured differential radar cross section (ΔRCS) for the proposed tag attached to full and empty blood tubes.

4.7 Radiation Patterns

The last parameter measured for the characterization of the proposed tag antenna is the radiation diagram shown in Figure 90. The radiation patterns were obtained for the proposed tag antenna attached to the tube full of blood at the center frequency f_c = 867 MHz of the UHF band. By placing the tag in horizontal or vertical positions, the H-plane or the E-plane cuts of the radiation patterns can be measured. As it can be seen in Figure 90, the simulated and measured results are in good agreement for both E-plane and H-plane. The radiation patterns are essentially quasi-omnidirectional at fc = 867 MHz, and with linear polarization. The maximum radiation in the H-plane (Figure 90b) is not directed at broadside, but it appears at 330º. In addition to this tilt in the pointing angle, we observe that the H-plane radiation pattern is asymmetric. This is due to the effect of the feeding point of the antenna and to the presence of the blood tube along the back-side direction.



(a) (b)

Figure 90: Simulated (red-dash) and measured (blue-solid) radiation patterns for the proposed tag attached to a tube full of blood (scales of the graphs are given in dB). (a) E-plane; (b) H-plane.

It was observed that the simulated total efficiency (radiation efficiency × τ) of the tag when it is mounted on an empty tube reaches a peak of 81 % out of the UHF band at f_0 = 1.2 GHz. This shows that the designed tag has quite high efficiency due to low losses in the materials used for manufacturing. However, when the tag operates attached to a tube full of blood the total efficiency reduces to 3.5% at the center frequency of the UHF band (f_0 = 867 MHz). This is due to extra absorption of the electromagnetic power by the blood, and it is the major factor that limits the reading distance in our design.

4.8 Comparison with Other Designs

A comparison between the proposed RFID tag and several tag designs for blood and liquid monitoring is provided in Table 10. As it can be seen in Table 10, only one tag is applied to the monitoring of blood tubes [22], while the others are used for blood bags and different liquids. The tag for the monitoring of blood tubes is of capacitive dipole type, like the proposed tag antenna. However, it is not flexible, and it is applied to a near field RFID reader system (therefore the reading range distance is very small). Among the other tags presented in Table 10, five flexible tags can be used in far-field applications [9,23, 24,25,26]. The first four tags are of inductive dipole type [9,23,24,25] and the last one is of capacitive type [16]. The high permittivity and dielectric loss of blood and water were considered in the design of these tags, which reach reading ranges above 0.79 m. However, unlike the proposed tag, their sizes are not suitable to be attached to the smallest tube (75 mm × 13 mm). The design of last tag is circular, and it has a diameter of ∅ = 29 mm [26]. Therefore, its size could be adapted to the smallest tube. However, this tag is only tested on flat surfaces in [26], and the effects of the strong bending required by blood tubes are unknown.

Reference	Tube / Bag / Liquid	Flexible (Yes / Not)	Antenna type	Max. reading range (m)	2-D size (mm)
[27] Figure 3	Bag	Not	Inductive dipole	–	50 × 50
[22] Figure 1	Tube	Not	Capacitive dipole	0.04	25 × 25
[28] Figure 3	Bag	Not	Traveling wave	0.015	120 × 50
[9] Figure 1	Bag	Yes	Inductive dipole	2	90.37 × 61.09
[23] Figure 2	Bag	Yes	Inductive dipole	1.25	82.4 × 15
[24] Figure 4	Liquid (water)	Yes	Inductive dipole	2	87.8 × 57.9
[25] Table I	Liquid (water)	Yes	Inductive dipole	0.79	86 × 22.5
[29] Figure 6	Liquid (water)	Yes	Capacitive dipole	3.2	29
This work Figure 9	Tube	Yes	Capacitive dipole	2.2	49.5 × 15

Table 10: Comparison between the proposed RFID tag and other designs for blood and liquid traceability.

5. Application of the Proposed Tag as Volume Sensor

In this section, a study of the proposed tag as sensor to determine the blood levels in tubes is proposed. This study is a consequence of the variation of the tag power sensitivity previously measured for the proposed tag (Figure 88). In addition, how blood level affects to the reading range is also presented. The aim of this study is to test if the proposed tag exhibits good level sensing capabilities, and if the variation in the blood levels can have impact on the reading range. As for the previous section, the measurements were carried out by means of an anechoic chamber and the Tagformance Voyantic System, and for the smallest clinic blood tube.

Figure 91 represents the minimum transmitted power (tag power sensitivity) required to activate the IC chip (NXP UCODE G2XL) of the proposed tag attached to a clinic tube with different blood volumes. The results have been obtained when the volume of the blood inside the clinic tube varies from 4 mL (full tube) to 0 mL (empty tube). It can be observed that the minimum power required to activate the tag shifts to higher frequencies when the volume of the blood is decreased inside the tube. This is a consequence of the capacitive design proposed in this chapter, which increases the sensitivity of the tag to the presence of blood. In any case, by comparing the different states shown in Figure 91, it is easy to establish what are the blood levels inside a particular tube. This can simply be done by monitoring the minimum power required to activate the IC chip at the center of frequency fc = 867 MHz of the UHF RFID band.

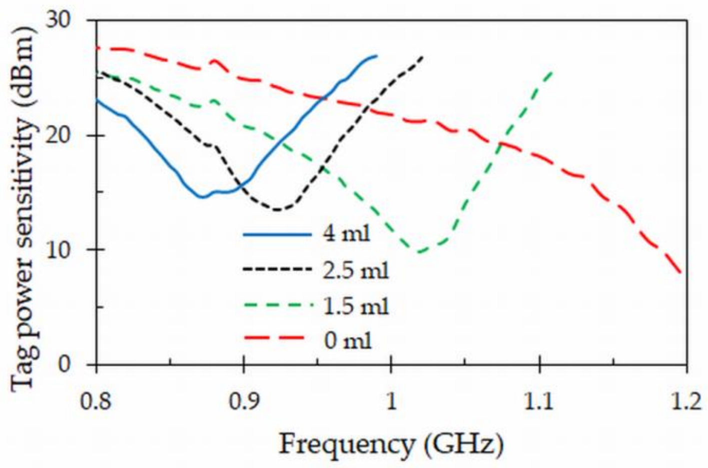


Figure 91: Tag power sensitivity obtained for the proposed tag (IC chip: NXP UCODE G2XL) attached to a clinic tube with different blood volumes.

This study is completed with the reading range. Figure 92 shows the results of this critical parameter measured with the proposed tag and with the same previous conditions. The results confirm once more that at the center of frequency f_c = 867 MHz of the band of interest, a maximum reading range is achieved when the clinic tube is full of blood (4 mL). The reading range gradually decreases at the same frequency (f_c = 867 MHz) when the volume of blood inside the tube decreases. As it can be seen in Figure 92, this is due to the shift of the resonant frequency of the tag to higher values. In addition, the peak values of the reading ranges increase when the volume of blood decreases. This is because lower quantities of blood introduce smaller absorptions in the power radiated by the tag. However, due to the shift in resonant frequency, this increase in reading range occurs at higher frequencies, out of the frequency band where the RFID UHF system operates. The results obtained in this study at the center frequency of 867 MHz are summarized in Table 11. The results collected in this table clearly indicate that the designed tag can indeed be used as a sensor to detect the blood levels inside a specific clinic tube.

A possible method would be to find a dependence equation of the different volume levels of blood inside a clinic tube with the transmitted power or the reading range by means of a linear regression method [30]. Another approach for modelling input/output relationships, would be to use an artificial neural network or a fuzzy technique instead of a linear regression [31]. In this way, it is possible the determination of the volume level of blood inside a clinic tube from only the calculated transmitted power or the reading range, without the need to use any other equipment other than the UHF RFID reader. It is important to point out that the measurements have been performed for the smallest clinic blood tube and using an anechoic chamber. Therefore, they should be confirmed in a future work in a real environment, in order to train the algorithm with more realistic data.

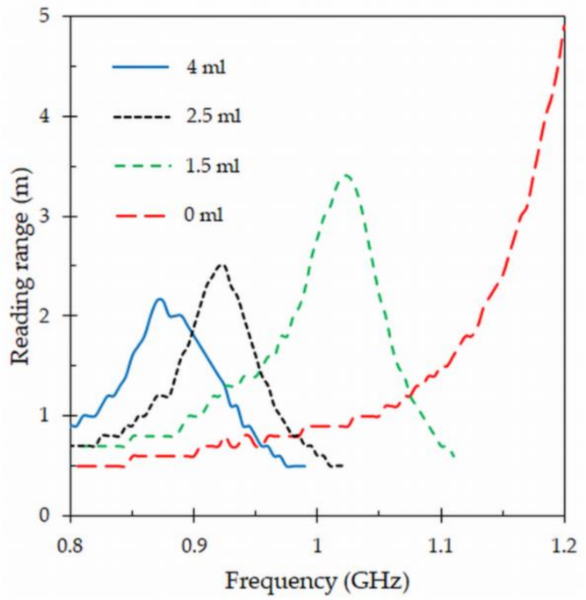


Figure 92: Reading ranges obtained for the proposed tag attached to a clinic tube with different blood volumes.

Blood level (ml)	Transmitted power (dBm)	Reading range (m)
4	15.1	2.2
2.5	20.1	1.1
1.5	22.6	0.8
0	25.9	0.6

Table 11: Minimum transmitted power required to activate the integrated circuit (IC) chip (NXP UCODE G2XL) and reading ranges of the proposed tag attached to a clinic tube with different blood volumes, measured at the center frequency fc = 867 MHz of the UHF RFID band.

The potential of this tag for the design of new traceability and level sensing systems for blood container tubes using RFID UHF technology has been demonstrated in these last two sections.

However, it is important to point out that these systems can only be used by the health industry, if they do not have negative effects on the blood contained within the clinic tube. One of the negative effects would be the overheating of the blood, which would involve discarding the sample collection tube from the system. This can occur when the blood coagulates, since there is a decrease in its electrical conductivity [32]. However, numerical studies have shown that the effects of electromagnetic fields produced by an RFID reader on blood container bags and tubes should not cause overheating during a typical UHF RFID reading cycle [33,34].

6. Conclusions

A novel compact and high-performance tag antenna for blood tube traceability applications, working at the European RFID UHF system, is proposed in this paper. The proposed tag is based on a capacitive dipole design, which consists of two coupled compact capacitive meandered pads. The design of the tag is carried out by considering the electrical properties of the elements in which it must operate. These elements are blood, the clinic tube and the substrate employed for the tag manufacturing. Thus, a characterization technique based on a coaxial probe has been used to obtain the electrical properties of these elements in the frequency band of interest. The designed tag has been manufactured on a Kapton polyimide substrate by using a low cost and fast prototyping technique. This is a flexible substrate with excellent electrical parameters, which allows the tag to conform to the curved shapes of clinic tubes. The high values of relative permittivity of the blood and the capacitive design of the proposed tag have allowed to achieve a compact structure without sacrificing radiation efficiency. Results have demonstrated that the new tag attached to a clinic tube full of blood exhibits reading ranges above 2 m. Moreover, its capacitive design has shown a strong sensitivity with the presence of the blood inside the tube. Therefore, reading ranges drastically drop when the tube is empty. This property may be interesting for many tracking applications, since it could reduce the amount of information generated from empty tubes. The same property can also be exploited to use the tag as a sensing system to detect and measure the amount of blood in clinic tubes. This novel proposed tag can be useful for the design of new blood traceability systems using RFID UHF technology.

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Chapter 5

Low Cost Flexible UHF RFID Tag Antenna for Blood Bag Monitoring

1. Introduction

A new low profile flexible RFID tag antenna operating in the ultra-high frequency (UHF) European band (865 MHz–868 MHz) is proposed for blood bag traceability. Its structure combines inductive and capacitive parts with nested slots allowing to achieve conjugate impedance matching with the IC-chip. The whole electrical parameters of the environment (substrate, bag, and blood) have been considered for the design of the tag antenna. A good agreement has been obtained between the measurements and electromagnetic simulations for the input impedance of the tag antenna in the UHF band. A reading range close to 2.5 m has been experimentally obtained. Therefore, this tag antenna could be effective and useful in future RFID systems for blood bag monitoring, thus improving patient safety in healthcare infrastructures

Automatic identification of objects using radio waves can be carried out using technologies such as radio frequency identification (RFID). This technology is becoming more and more popular in everyday life. It has been extensively used in many practical applications in Internet of Things (IoT) and has become essential for a set of applications such as identification, localization, tracking, sensing, inventory control and supply chain management [1-7].

In [8], it is reported that most of the medical errors are attributed to sample misidentification, adverse effects of medications, and incorrect blood transfusion, which are mainly caused by patient misidentification and/or human intervention errors. The use of RFID technology offers many benefits to the health system, especially with nowadays staff shortages, which can enhance patient safety. Passive RFID technology working at the ultra-high frequency (UHF) can be used in healthcare infrastructures. Possible applications include tracking of physiological parameters such as patient body temperature [9-12], blood glucose monitoring [13,14], real time monitoring and discrimination of breath anomalies [15], and monitoring of blood tubes [16,17] and bags [18-24] for the management of blood products [25-27].

The goal of this work is the monitoring of blood bags. The low cost and easy manufacturing of passive RFID tags have significant advantages in being a good candidate for this application. Other important factors to be considered are reading range and flexibility. Among the available solutions [18-24], general-purpose commercial UHF RFID tags have reading ranges below 0.5 m when they are attached to blood bags [18], while the others vary from a few centimeters to 1.5 m for blood management systems operating in near- or far-fields [19-24]. These commercial and specific RFID tags are mainly of inductive dipole type to facilitate the impedance matching with the capacitive IC-chip impedance; although there are also some of them that are based on traveling wave antenna [19] or capacitive dipole type [24]. Except three tags [19,22,23], most of them are flexible. In addition, many flexible tag antennas have been developed for purposes different from the one addressed in this paper [28-35]. Among them, those based on paper material [28,29], high-conductivity graphene assembly film (HCGAF) [30], inductive coupling loop [31], textile fabric and yarn [32,33] and PTFE and Kapton substrates [34,35], stand out. Except the tag antennas printed on PTFE and Kapton substrates, which are low cost and have ideal physical, thermal and electrical proprieties [36,37] for inexpensive practical blood bag monitoring, the other materials are not suitable for this application, since the paper and textile fabric and yarn are not resistant to mechanical and thermal stress. Moreover, HCGAF material, although strong, it requires an expensive fabrication process and an inductive coupling loop using conductor wire, that can pierce the bag.

The best option for the traceability of many blood bags in different scenarios [25-27] (donation site, shipment to laboratory, inventory, shipment to hospital, etc.) are low-cost, flexible and far-field passive RFID tag antennas. However, the design of passive RFID tag antennas operating in far-field and UHF band is limited by the high values of the loss and dielectric permittivity of the blood, which prevent a good impedance matching between the IC-Chip and the tag antenna and cause a reduction of the reading range due to the high absorption of the electromagnetic radiation produced by the blood.

In this chapter, a new passive low-cost tag antenna covering the European (865 MHz – 868 MHz) UHF band and exhibiting flexibility, reduced size and large reading range for blood bag traceability is proposed. The designed UHF RFID tag antenna is fabricated on an adhesive, flexible and resistant substrate of Kapton polyimide thin film (3MTM Kapton polyimide film tape 5413 amber) [37], thus allowing it to be easily molded and attached to blood bags. The tag antenna is designed to operate optimally in a real environment with a smaller size and larger reading ranges than the available solutions for blood bag traceability [18-24]. To achieve these goals, blood, PVC bag and Kapton substrate have been considered during its design. To overcome the problem of high values of loss and permittivity of the blood, the proposed RFID tag antenna includes inductive and capacitive parts with nested slots, which form an innovative structure. A good impedance matching between the NXP G2XM IC-chip [38] and the tag antenna in the presence of the blood is achieved by tuning the inductive and capacitive parts with nested slots, in a flexible way, thus improving the reading range. This new tag antenna is expected to be of interest in future blood bag traceability systems and enhance patient safety in health infrastructures.

2. Proposed uhf RFID tag antenna design and analysis
2.1 Antenna structure

Figure 93 displays the structure and dimensions of the UHF RFID tag antenna. It is based on an inductive and capacitive part with nested slots. The dimension of the nested slot for the inductive part is $L1 \times S1$. The capacitive part of the tag antenna is introduced through the vertical slot $g \times W2$ and the horizontal slot $(2 \times L2 + g) \times S2$. The inductive part is separated from the capacitive part by the gap $W1 \times d$. The IC-chip is mounted across the gap $W1 \times d$ between the inductive and capacitive part. The proposed tag antenna with slots provides an excellent impedance matching on high permittivity materials such as blood and a reduced size. When the antenna operates in close proximity to the blood, the high value of the relative permittivity has an effect to reduce the size of antennas, thus leading to structures with low radiation efficiency. Consequently, the basic idea was to start the design with a capacitive dipole structure (g, S2, L2). However, using only a capacitive slot leads to a configuration that is too large. This is because a capacitive antenna will need extra-length to introduce an inductive component that can compensate for the capacitive impedance of the RFID IC-chip. In this work, we have introduced another slot (d, S1, L1) that acts as an inductive part in parallel with the capacitive slot to maintain a compact design.

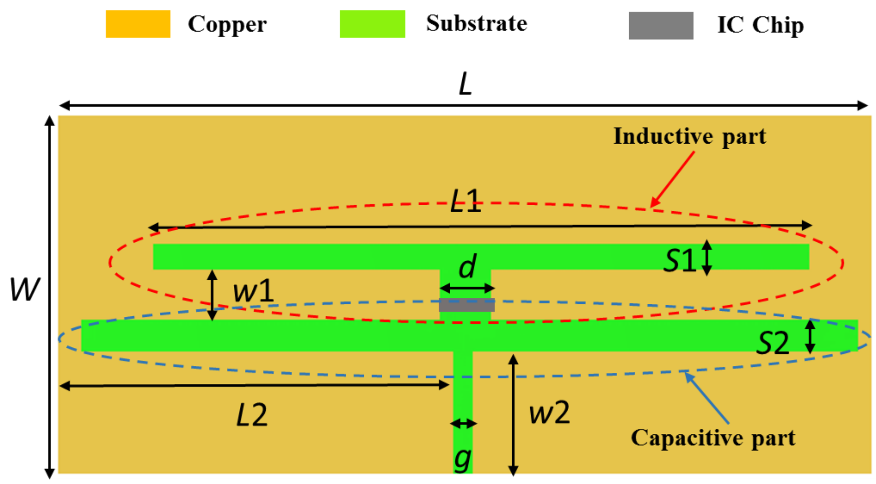


Figure 93: UHF RFID tag antenna structure for blood bag traceability

The tag antenna is realized by means of the following elements: an adhesive and flexible Kapton polyimide substrate of thickness 70 µm [37], an adhesive copper sheet (pre-cut copper tape) with a thickness of 35 µm, and a NXP G2XM IC-chip with TSSOP8 packaging [38]. The electrical characteristics of the Kapton polyimide between 865 MHz–868 MHz (UHF European band) are $\varepsilon_r = 3.1$ and tanδ = 0.0015 [17,37]. The power threshold sensitivity of the NXP G2XM IC-chip is $P_c = -17$ dBm [38].

2.2 Design and Optimization

The tag antenna design was performed simulating the scenario shown in Figure 94. The tag is placed on a bag, which is simulated by means of a PVC layer ($\varepsilon_r = 2.2$) of 160×130 mm2 with a thickness of 0.4 mm. The whole set is placed above a rectangular box simulating the blood. This box has the same dimensions as the bag, except the thickness which is 20 mm. The permittivity and conductivity ($\varepsilon_r = 61.2$ and $\sigma = 1.12$ S/m at 867 MHz) of the blood used in the simulation model were obtained from [17].

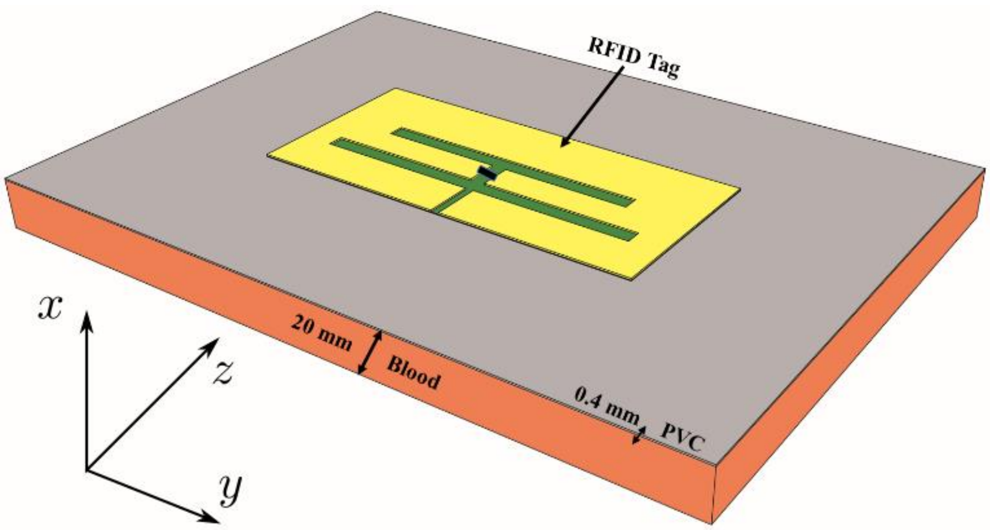


Figure 94: UHF RFID tag antenna placed on blood bag.

The commercial electromagnetic simulator CST Microwave Studio Suite® was used for the design, analysis, and optimization of the proposed tag. The tag attached to the blood bag is drawn in the modeler as shown in Figure 94, and all its element parameters (dimensions, substrate permittivity, blood permittivity, and thickness substrate), including the IC chip, are defined. The real and imaginary parts of the complex chip impedance (Zc = 28 – j 157 Ω) are respectively specified by means of a discrete port and a lumped RLC series element. The discrete port and the lumped RLC series element are situated across the gap d between the two pads, in the same place than the IC chip (Figure 93). Then, the simulation is started from the transient solver. Once the simulation is finished different parameters such as impedance, reflection coefficient, and gain can be analyzed.

The design and optimization of the antenna were carried out in three steps. In a first step, the effects of the design parameters of the tag antenna in a real environment (blood, PVC bag, Kapton substrate), where the tag should operate, were studied from several simulations. In a second step, the parameters of the proposed tag antenna were optimized in the UHF European band (865 MHz – 868 MHz). Finally, in the last step, the length of the horizontal slot L1 and the width g of the vertical slot were finely tuned to match the conjugate impedance of the RFID tag antenna with the IC-chip impedance ($Z_C = (28 - j157)\ \Omega$ at 867 MHz) to avoid undesired reflections, realize a good power transfer and obtain a large reading range. The other parameters (S1, W1, d, L2, S2, W2) are fixed during the final impedance optimization step with the IC-chip. The tuning is achieved by minimizing the power reflection coefficient:

$$\Gamma = \frac{Z_a - Z_C^*}{Z_a + Z_C} \quad (1)$$

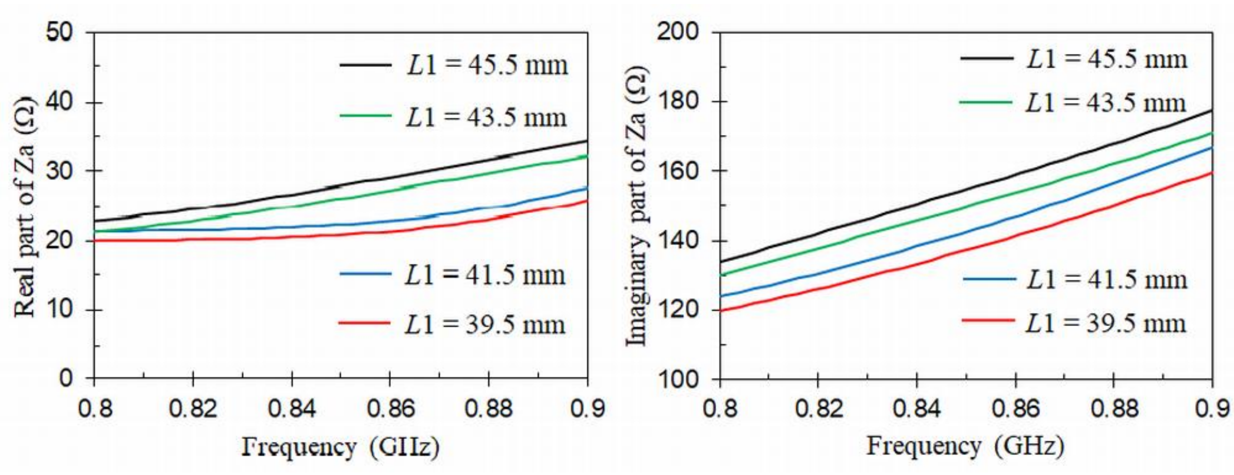
Where Z_a and Z_C correspond, respectively, to the input complex impedance of the tag antenna and the complex impedance of the IC chip. The asterisk denotes complex conjugate. Table 12 lists the optimized parameters of the tag antenna.

Table 12: Optimized parameters of the proposed tag antenna.

Parameter	Value (mm)	Parameter	Value (mm)
L	64	*d*	4
W	28	*L*2	31.5
*L*1	43.5	*S*2	2.5
*S*1	2	*W*2	9
*W*1	4	*g*	1.5

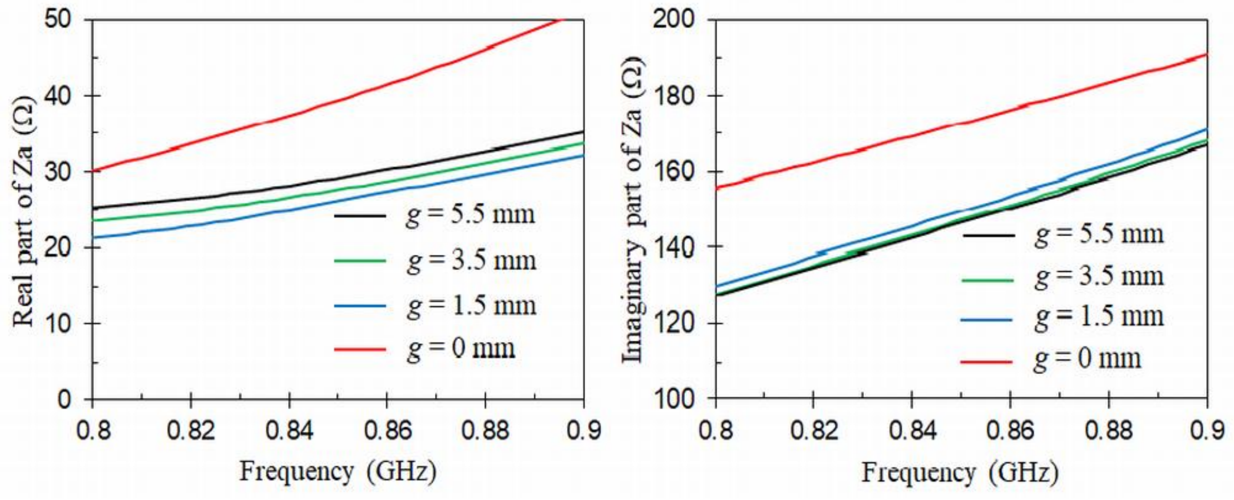
2.3. Parametric study

Figures 95 and 96 show the simulated input impedance (Z_a) of the UHF RFID tag antenna as a function of frequency (0.8 GHz – 0.9 GHz) for different values of nested slot length L1 (39.5 mm – 45.5 mm) and vertical slot width g (0 mm – 5.5 mm), respectively. It should be noted that when one parameter (L1 or g) was varied, the others were kept equal to the values indicated in Table 12. As can be seen in Figure 95, the real and imaginary parts of the input impedance increase as the length L1 goes longer from 39.5 mm to 45.5 mm, while it decreases as the width g grows from 0 to 5.5 mm in Figure 96. From these results, it can be observed in Figure 95b that the reactance of the UHF RFID tag antenna is positive (inductive type), as it is required to accomplish a good matching condition with the IC-chip. In addition, Figure 96b displays that the introduction of the vertical capacitive slot g, substantially lowers the value of the reactance. This shows that the capacitive slot is effective in the compensation for a too large inductance caused by the presence of the blood, by introducing an additional capacitive behavior. Therefore, the parameters L1 and g can be used to fine tune the UHF RFID tag antenna input impedance and provide optimum control on the matching condition with the IC-chip.



(a) (b)

Figure 95: Designed UHF RFID tag antenna (placed on a blood bag) input impedance (Za) simulations for different values of L1: (a) Real part; (b) Imaginary part.



(a) (b)

Figure 96: Designed UHF RFID tag antenna (placed on a blood bag) input impedance (Za) simulations for different values of g: (a) Real part; (b) Imaginary part.

2.4. Radiation Diagram

Figure 97 displays the simulated radiation patterns in E and H planes for the proposed tag antenna attached on a full blood bag. The simulations were carried out for the optimized tag (Table 12) at the center frequency of the UHF band: $f_c = 867$ MHz. Data were normalized to the maximum value of the 3D pattern. As can be seen in Figure 97, the radiation patterns of the antenna are quasi-omnidirectional, typical of small size planar antennas. Moreover, the tag exhibits linear polarization. As can be observed, the radiation reaches its maximum in both planes at 18°. This slight tilt with respect to the broadside direction is due to the asymmetry introduced by the feeding point position, and the asymmetric position of the tag with respect to the blood bag, and will be confirmed in the next section by experiments.

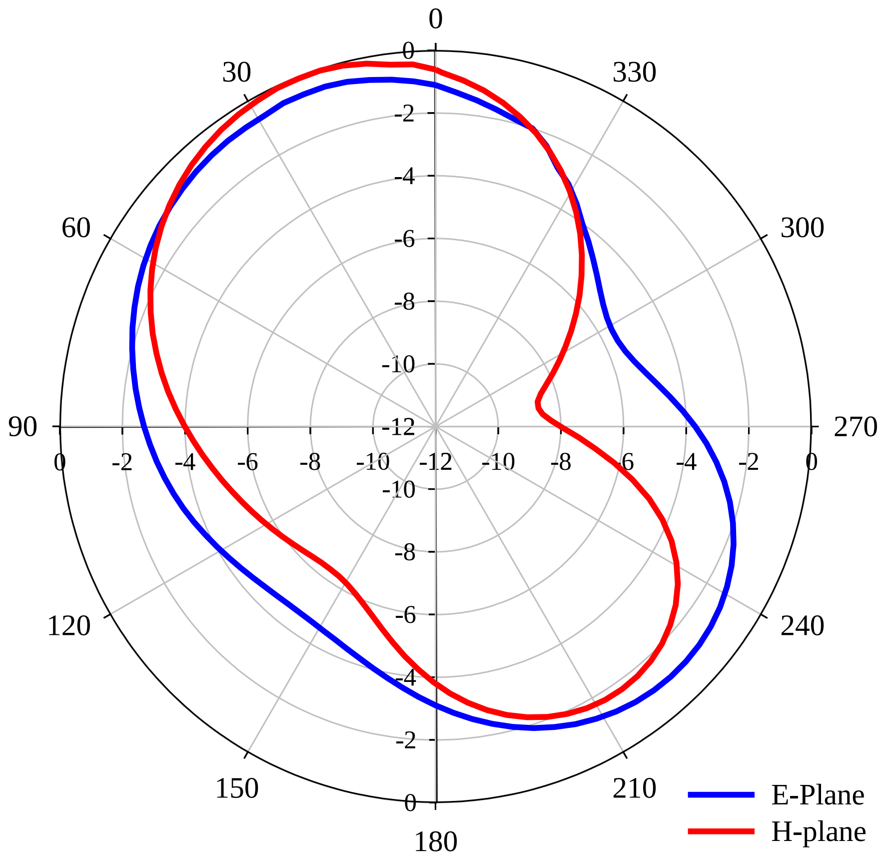


Figure 97: Simulated radiation patterns at fc=867 MHz for the proposed tag attached to a bag full of blood (the horizontal and vertical scales are given in dB, while the circular scale is in degree).

3. Measurement Results and Discussion
3.1 Fabrication and Measurement Setups

The proposed flexible UHF RFID tag antenna (Figure 93) was fabricated with the dimensions included in Table 12 using a laser prototyping system (LPKF Protolaser S) and then characterized from a vector network analyzer (Rhode & Schwarz ZVB 20). In a first step, the UHF RFID tag antenna input impedance was measured by means of a port-extension technique as in [17,39]. Then, in a second step, the reading range was obtained in free space similarly to [40,41]. Both experimental setups are depicted in Figure 98. In Figure 98 (b) we can see a photograph of the antenna slightly bent in a blood bag. We have verified in experiments that a slight bending of the antenna has little influence on its performance. The reading range of the proposed UHF RFID tag antenna placed on the blood bag was measured in horizontal and vertical position (Figure 99). The measurements were realized with a reader output power of 1 W.

(a) (b)

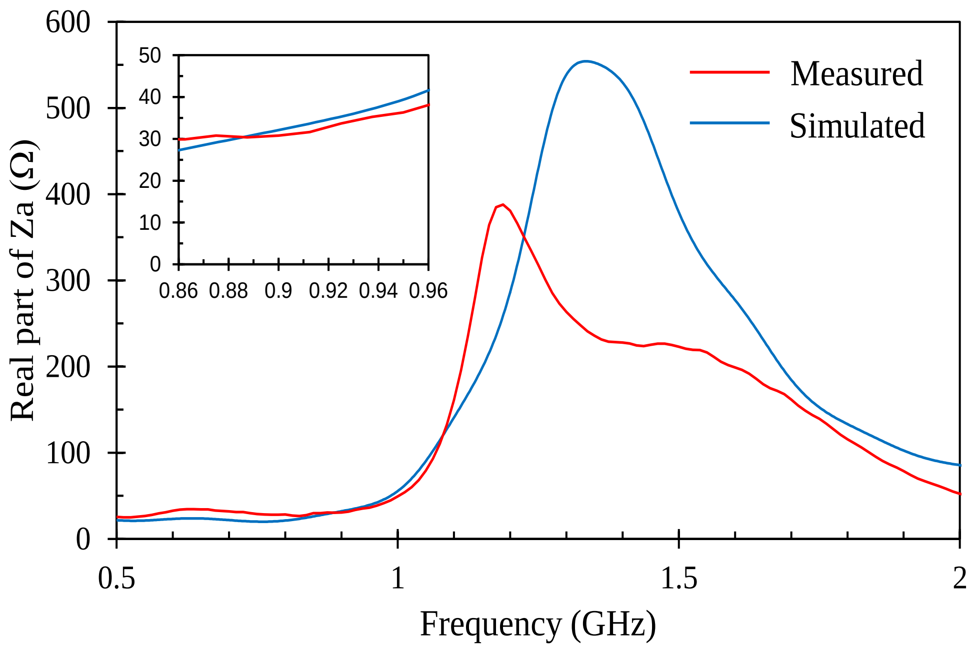
Figure 98: Experimental setups of the UHF RFID tag antenna placed on a blood bag: (a) Input impedance measurement; (b) Reading range measurement.

(a) (b)

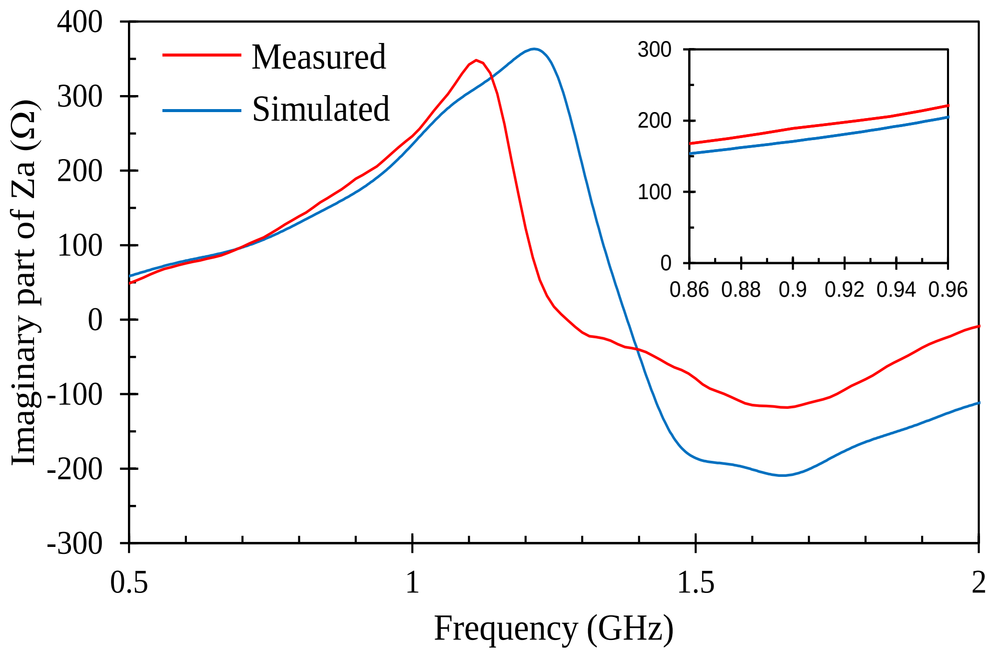
Figure 99: UHF RFID tag antenna placed on the blood bag in (a) vertical position and (b) horizontal position.

3.2. Input Impedance and Power Reflection Coefficient Measurements

Figure 100 displays the simulations and measurements of the input impedance for the proposed UHF RFID tag antenna placed on a blood bag. The insets included in the graphs detail the values of the real and imaginary parts of the input impedance from 0.86 GHz to 0.96 GHz. As can be seen, the measured results of the real and imaginary parts of the input impedance are in good agreement with the simulated data. The measured input impedance at 867 MHz is $Z_a = (30 + j169)\ \Omega$, which is comparable to the conjugate of the IC-chip $Z_C = (28 - j157)\ \Omega$. The mismatch is mainly due to negative mounting and handling effects, since the tag antenna becomes wrinkled on the blood bag, as can be seen in Figure 99.



(**a**)



(**b**)

Figure 100: Simulations and measurements of the input impedance (Za) for the proposed UHF RFID tag antenna placed on a blood bag: (a) Real part; (b) Imaginary part.

Figure 101 shows the simulations and measurements of the power reflection coefficient (1) for the proposed tag antenna placed on the blood bag. As can be seen in Figure 101, simulations and measurements are in good agreement and confirm a good impedance matching between the tag antenna and the IC chip in the UHF European band (865 MHz – 868 MHz). In particular, the antenna achieves Return Losses around 12 dB at the center frequency (867 MHz).

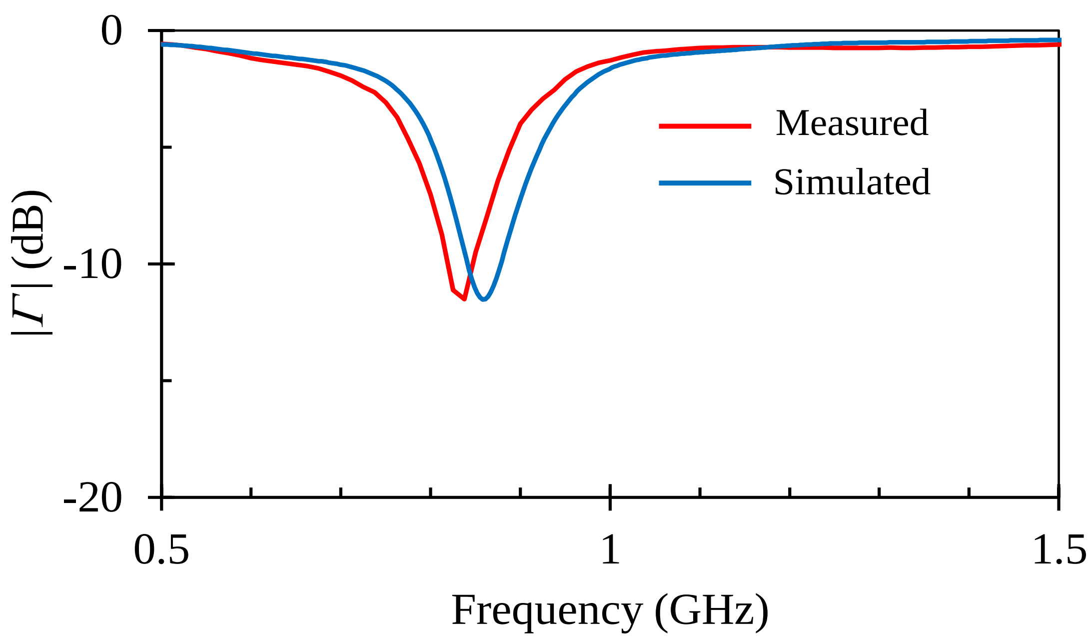


Figure 101: Simulations and measurements of the power reflection coefficient (Γ) for the proposed UHF RFID tag antenna placed on a blood bag.

3.3. Reading Range

The reading ranges for the proposed UHF RFID tag antenna placed horizontally and vertically on the blood bag which were measured in a natural environment from 0.86 GHz to 0.9 GHz are shown in Figure 102. As can be seen, a maximum reading range of 2.22 m or 2.5 m is achieved as the tag is respectively placed vertically or horizontally on the bag full of blood, while it is less than 0.7 m when the tag is located on an empty bag.

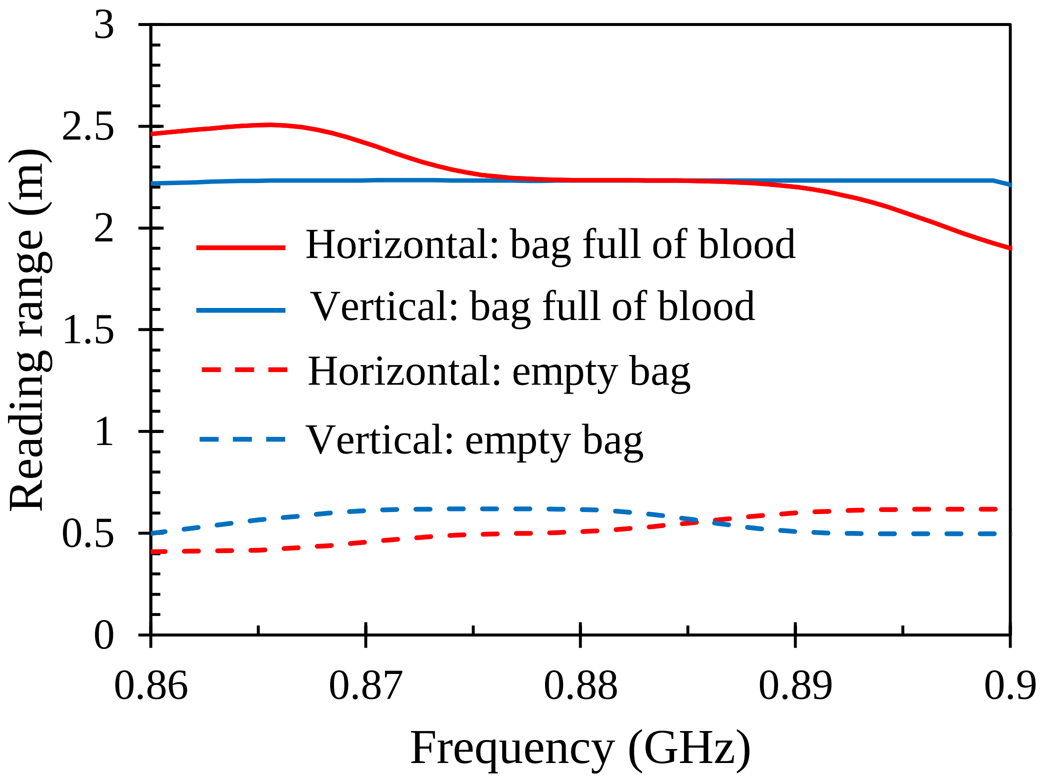


Figure 102: Measured reading ranges in a natural environment for the proposed UHF RFID tag antenna placed horizontally and vertically on the blood bag.

Figure 103 shows the reading patterns at 867 MHz of the designed tag attached horizontally and vertically on the blood bag. A maximum reading range of 2.5 m and 2.22 m is obtained at the angle of 18° when the tag is respectively placed in the horizontal and vertical position on the blood bag. The tilt in the reading range pattern is due to inevitable misalignment between the reader and the UHF RFID tag antenna during the process of measurement. Lower reading ranges in the backward direction are due to higher absorption of the electromagnetic waves when traveling through the blood bag.

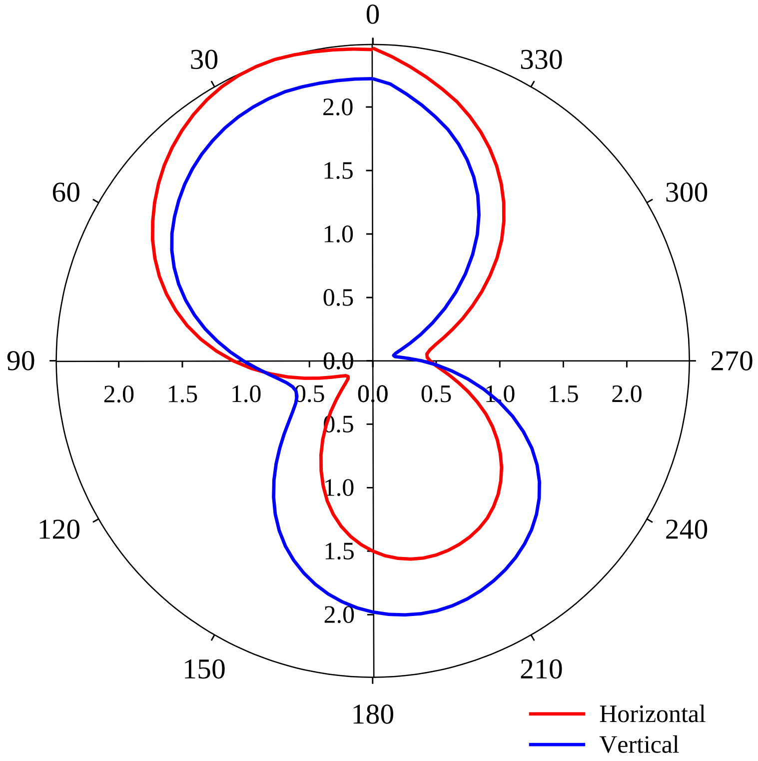


Figure 103: Reading ranges measured at 867 MHz for the proposed UHF RFID tag antenna placed horizontally and vertically on the blood bag and located at different positions in the x-y plane (see coordinate axis in Figure 94; horizontal and vertical scales are given in meters).

3.4. Comparison with other Designs

Table 13 provides a comparison between several previously reported designs and the proposed UHF RFID tag antenna for blood bag traceability in terms of flexibility, antenna type, operating frequency range, output power of the RFID reader, reading range and 2-D size. The proposed RFID tag antenna design reaches a maximum reading range with a small size as compared to the other designs listed in Table 13. In addition, the designs reported in [19,22,23] are not flexible, hence they are not suitable to be attached to blood bags in an easy way. Table 2 also reveals that the proposed RFID tag antenna is the only design that combines inductive and capacitive coupling elements to obtain the conjugate impedance of the IC-chip. Therefore, the proposed RFID antenna can achieve simultaneously high reading range with a suitable small electrical size as compared to prior designs, and can be a good candidate for blood bag traceability applications.

Table 13: Characteristic comparison between different UHF RFID tag antennas for blood bag traceability (λ_0 is free space wavelength at the central frequency of the operation frequency range).

Ref.	Flexible (Yes/Not)	Antenna type	Op. freq. range (MHz)	Reader output power (dBm)	Reading range (m)	2-D size ($\lambda_0 \times \lambda_0$)
[19]	Not	Traveling wave	840 - 960	30	0.015	0.36×0.15
[20]	Yes	Inductive dipole	865 - 868	20	2	0.26×0.17
[21]	Yes	Inductive dipole	912 - 914	-	1.25	0.25×0.04
[22]	Not	Inductive dipole	902 - 928	20	-	0.15×0.15
[23]	Not	Inductive dipole	865 - 868	30	1.28	0.11×0.11
[24]	Yes	Capacitive dipole	890 - 937	28	1.5	0.12×0.04
This work	Yes	Inductive and capacitive dipole	865 - 868	30	2.5	0.18×0.08

3.5. Effect of UHF electromagnetic EM fields on blood bag

The proposed tag antenna for the traceability of blood bags could be used in the health system, only if the blood contained in the bag is not affected by negative effects. The negative effects on the blood for this application could be due to the overheating that would be produced by the electromagnetic fields of the RFID reader. This would involve the blood coagulation, since the electric conductivity decreases [42]. Should this occur, there would be no choice but to discard the blood bag from the system. However, it has been found in previous studies that these negative effects do not occur during a typical reading cycle of the UHF RFID reader [43,44].

4. Conclusions

In this chapter, a novel high-performance flexible tag antenna with a reduced size for blood bag traceability using the UHF RFID system is proposed. Its structure is based on inductive and capacitive parts with nested slots allowing to carry out a good conjugate impedance matching with the IC-chip in the presence of the blood. The designed UHF RFID tag antenna was fabricated on an adhesive, low profile and flexible substrate of Kapton polyimide by means of a fast and low-cost prototyping technique. In this way, it can be easily molded and attached to the blood bags. The measured results have shown that the proposed tag antenna attached to a blood bag exhibits a reading range close to 2.5 m in the European (865 MHz – 868 MHz) UHF band. This flexible tag antenna can be useful for the design of new blood bag traceability systems using RFID UHF technology to improve the patient safety and reliability of healthcare infrastructures.

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CONCLUSION AND FUTURE WORK

1. Conclusions

This thesis deals with RFID technology and has been focused on the design of tag antennas for blood traceability that operate within the European band. For this purpose, the problem of high values of loss and permittivity of the blood has been investigated. It is found that introducing some capacitive parts into the tag can leads to design tags with reasonable size, and good compromise between compactness and radiation efficiency can be achieved. Furthermore, the introduced capacitive part provides higher sensitivity in the presence of blood. Due to these features, the reading range can be increased when the RFID tag antenna is attached directly on the blood bag or tube. An important application of the high sensitivity of the tag antenna to the blood relative permittivity value is also explored in this thesis. Basically, it consists on the use of the tag as a sensor, to monitor the amount of blood contained in clinic bags or tubes. The designed UHF RFID tag antennas are printed on an adhesive, flexible, and resistant substrate of Kapton polyimide thin film (3MTM Kapton polyimide film tape 5413 amber), thus allowing it to be easily molded and attached to blood tubes and bags.

The contents of this manuscript have been split into 5 chapters (excluding the general introduction and conclusions and future work), as follow. After pointing out the motivation and objective of this thesis, a detailed overview about RFID technology, its architecture, and in particular the international regulation and propagation properties in UHF band was given in chapter 1.

In chapter 2, the main parameters of RFID tag antennas such as reading range are presented and explained in detail. The remainder of the chapter is devoted to the description of the RFID tag antennas with sensing capability suitable for a variety of applications.

In chapter 3, different RFID tag antennas mounted on liquid were reviewed and discussed. It is found that liquid alter the input impedance of the antenna and hence affects the impedance matching between the RFID chip and the antenna. Thus, for all cases the research focus was about increasing the directivity of the RFID tag antenna mounted on liquid bottle or avoiding close contact between the liquid and the RFID tag antenna. Furthermore, this review shows that there is a lack of study on the effect of blood on RFID tag antennas for healthcare applications and especially for blood transfusion tracking.

Chapter 4, a novel compact and high-performance tag antenna for blood tube traceability applications, working at the European RFID UHF system, is presented. The proposed tag is based on a capacitive dipole design, which consists of two coupled compact capacitive meandered pads. The design of the tag is carried out by considering the electrical properties of the elements in which it must operate. These elements are blood, the clinic tube and the substrate employed for the tag manufacturing. Thus, a characterization technique based on a coaxial probe has been used to obtain the electrical properties of these elements in the frequency band of interest. The designed tag has been manufactured on a Kapton polyimide substrate by using a low cost and fast prototyping technique. This is a flexible substrate with excellent electrical parameters, which allows the tag to conform to the curved shapes of clinic tubes. The high values of relative permittivity of the blood and the capacitive design of the proposed tag have allowed to achieve a compact structure without sacrificing radiation efficiency. The obtained results have demonstrated that the new tag attached to a clinic tube full of blood exhibits reading ranges above 2 m. Moreover, its capacitive design has shown a strong sensitivity with the presence of the blood inside the tube. Therefore, reading ranges drastically drop when the tube is empty. This property may be interesting for many tracking applications, since it could reduce the amount of information generated from empty tubes. The same property can also be exploited to use the tag as a sensing system to detect and measure the amount of blood in clinic tubes.

Finally, in chapter 5 a novel high-performance flexible tag antenna with a reduced size for blood bag traceability using the UHF RFID system is studied numerically and experimentally. Its structure is based on inductive and capacitive parts with nested slots allowing for good conjugate impedance matching with the IC-chip in the presence of the blood. The designed UHF RFID tag antenna was fabricated on an adhesive, low-profile, and flexible substrate of Kapton polyimide by means of a fast and low-cost prototyping technique. In this way, it can be easily molded and attached to the blood bags. The measured results showed that the proposed tag antenna attached to a blood bag exhibits a reading range close to 2.5 m in the European (865 MHz–868 MHz) UHF band.

As a general conclusion, the work developed within this thesis provided innovative flexible prototypes that can be useful for the design of new blood bag or tubes traceability systems using RFID UHF technology to improve patient safety and the reliability of healthcare infrastructures.

2. Future Work

Regards to the conclusions drawn and the limitations of the work presented, future work can be carried out in the following area:

- It is necessary to improve the reading range of the developed structures. One way is to use artificial magnetic conductor (AMC), which is a 2D metamaterial. Indeed, it is shown that AMC can be used as a ground plane to control the propagation of electromagnetic waves at a specific frequency, which makes them suitable to improve the gain of the tag. The unit cell of the AMC consists of split ring resonator (SRR) well studied in our laboratory.

- An RFID chip with integrated sensors such as temperature is well desired in Blood tracking. We can use for example EM4325 from Microelectronics that integrate temperature sensor. In fact, we have developed and characterized one RFID tag antenna based on this chip. Unfortunately, we couldn't present it in this manuscript owing to the lack of an RFID reader capable of retrieving the temperature from the tag.

- There is a strong demand for wideband RFID tag antenna. It would be desirable if one can develop some new structures of RFID tag antennas that covers both European and American bands for blood tracking applications.

- With the fast growth of Internet of Things (IoT), it will be highly recommended to integrate this application into mobile phones technologies to monitor and collect all data about blood in real time.

- Increasing health care facilitation, especially during the outbreak of covid -19 is primordial. Thus, developing RFID tag antenna for health applications is highly demanded. For example, developing low cost and flexible RFID tag antennas that can be mounted on medical bags such as Sodium chloride solution.

- Regarding the RFID tag antenna with sensing capability, which is now one of the hot topics in the last decade, it can be further studied the first design as sensor to detect the blood types based on the measuring the RSSI. Also, we can use the first design as sensor for continuous blood glucose monitoring.

- The developed structures can be extended to be used on body internet of things (IoT) medical applications.

List of Publications

- **Journals**

- **Khamlichi, M**. El, Melcon, A. A., Mrabet, O. El, Ennasar, M. A., & Hinojosa, J. A Flexible and Low-Cost UHF RFID Tag Antenna for Blood Bag Traceability. Electronics 2022, 11(3), 439. doi.org/10.3390/electronics11030439

- **Khamlichi, M**. El, Melcon, A. A., Mrabet, O. El, Ennasar, M. A., & Hinojosa, J. Flexible UHF RFID Tag for Blood Tubes Monitoring. Sensors 2019, 19(22), 4903. doi.org/10.3390/s19224903

- **Conferences**

- **Khamlichi, M**. El, Melcon, A. A., Mrabet, O. “2019 IEEE 19th Mediterranean Microwave Symposium (MMS) At: Hammamet, Tunisia, Tunisia”, “A Ground Slotted UHF Tag Antenna For Blood Bags Monitoring”.

- **M.El khamlichi,** O. EL Mrabet “6th International Conference on Multimedia Computing and Systems, IEEE Conference - ID 44495, Rabat - Morocco, May 10-12, 2018. ” subtopic” ‘T-Shaped RFID tag antenna for UHF RFID Applications.

- Mohamed EL Bakkali, **M.El khamlichi**, O. EL Mrabet “6th International Conference on Multimedia Computing and Systems, IEEE Conference - ID 44495, Rabat - Morocco, May 10-12, 2018. ” subtopic” ‘Single-Layer UHF RFID Tag Antenna with Multifunctional Characteristics.