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Chipless labels detection by backscattering for identification and sensing applications

Détection d'étiquettes sans puce par rétrodiffusion pour des applications d'identification et de détection

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Abstract. There is currently a growing interest in the development of communication systems that consume as little energy as possible, with the idea of eliminating the presence of batteries, which are a very polluting component. This is why the principles of communication based on backscatter modulation, or even more simply on backscattering by a device that takes the form of a label, like a barcode, are being studied more and more. In the latter case, the idea is to use the radar signature of this totally passive label, the geometry of the elements printed on it having been specially designed to perform the desired functions. These new systems cannot claim to do the same things as those working with a power supply or a chip, but they may be of interest for certain applications where the reading distances do not exceed one metre. Compared to barcodes, the main advantages are related to the use of RF waves to communicate, which makes it possible to read through certain objects that are opaque to light, or to significantly reduce the acquisition time of identifiers by being able to scan larger reading areas more easily.

Résumé. Il existe actuellement un intérêt croissant pour le développement de systèmes de communication consommant le moins d'énergie possible, avec l'idée d'éliminer la présence de batteries, qui sont des composants très polluants. C'est pourquoi on étudie de plus en plus les principes de communication RF basés sur la retro-modulation, ou même plus simplement sur la rétrodiffusion d'une onde par un dispositif qui prend la forme d'une étiquette, comme un code-barres. Dans ce dernier cas, il s'agit d'utiliser la signature radar de cette étiquette totalement passive; la géométrie des éléments imprimés sur celle-ci ayant été spécialement conçue pour remplir les fonctions souhaitées. Ces nouveaux systèmes ne peuvent prétendre faire les mêmes choses que ceux fonctionnant avec une alimentation ou une puce, mais ils peuvent être intéressants pour certaines applications où les distances de lecture ne dépassent pas un mètre. Par rapport aux code-barres, les principaux avantages sont liés à l'utilisation des ondes RF pour communiquer, ce qui permet de lire à travers certains objets opaques à la lumière ou encore de réduire significativement le temps d'acquisition des identifiants en pouvant balayer plus facilement de plus grandes zones de lecture.

Keywords. Chipless radio frequency (RF) identification (RFID), Backscattering communication, Sensor tags, Aspect-independent parameters extraction, Radar cross section (RCS), RF scatterer.

Mots-clés. Identification par radiofréquence (RFID) sans puce, Communication par rétrodiffusion, Étiquettes-capteurs, Extraction de paramètres indépendante de l'orientation, Surface équivalente radar (SER), Diffuseur RF.

1. Introduction

Despite our advanced communication systems, humans lack an easy way of interacting with everyday objects. Over centuries human beings interacted mechanically with physical, non-electronic, objects. The development of electronic devices has introduced non-natural interactions, with cumbersome, wire connected devices requiring a significant expertise and time investment. With the advent of wireless technologies, one would expect more natural handlings of objects to replace these non-ergonomic interactions. Although considerable progress has been made in recent years, particularly in smartphones, the fact that these devices need a battery to operate still makes their use restrictive. Today, the objective of more and more researchers is to develop electronic systems that communicate without wires and without batteries. From an application point of view, such systems already exist but remain confined to the field of identification as it is the case for Radio Frequency IDentification (RFID).

In RFID, the tag consists of an antenna and a chip that is self-powered by the EM wave emitted by the reader. A considerable number of studies have been carried out in recent years to extend the number of functionalities of these tags, in particular to allow them to have a sensor function. However, even if these systems consume much less energy than systems with a battery, they are still based on the use of a silicon chip, which has also a strong impact on the environment, especially when we are talking about tens of billions of tags sold per year. It therefore seems interesting to wonder what can be done in terms of applications with a system of tags without chips. Could wireless electronic systems be turned into chipless devices that can be printed with common printers, even simpler than a common passive RFID tag? Could this new technology be compatible with easier interactions with physical objects, and be able to connect them wirelessly to the internet? Indeed, can't we introduce a chipless RF reading technology closer to the barcode application that is currently very popular? Barcodes are very present around us for the identification and tracking of objects. They work on an optical principle where the information is coded by the geometry of the printed patterns (for example the width of the black strips printed next to each other for EAN13 codes, or the position of the black squares in the case of datamatrix) [1]. Unfortunately, barcodes have significant limitations in that they often have to be read by a human operator. This significantly reduces the reading time when a large number of labels are present on a pallet for example.

Achieving this goal will allow everyone to produce smart electronic labels that could be used for different applications (like identification, sensing or remote control of common electronic devices), with their own printer. To this end, models for "artificial" radar target need to be rethought from a theoretical and practical point of view. Specifically, we propose the new paradigm of "smart chipless electronic labels", that can replace current applications based on classical chipped devices.

Scientifically, while the problem we address is in the field of Radio Frequency communications, this calls for a new convergence with radar approaches, reflectometry principle, and wave interaction with objects. In terms of impact, the resulting "smart paper based electronic label" for human-machine interface will not only serve the needs of scientists or engineers but also of anyone interested in changing the way they interact with objects.

2. Context and state-of-the-art of chipless RFID radar approaches

2.1. *A failure of standard RF identification technologies?*

RFID is one of the major technologies in the field of identification and has grown considerably, since its principle was introduced more than 60 years ago [2]. This is a technique for automatic capture of information contained in a label, by radio waves with a remote reading facility. The label consists of a chip that contains the data and an antenna that allows a communication with a dedicated reader. Many prospective studies show that in coming years the world's demand for traceability is expected to increase considerably, as a result of economic development. However, despite the benefits of RFID deployment, this technology is affected by several economic, technological or societal factors. These obstacles include the tags' cost which is too high for some application sectors, but also the lack of reliability and security in the information contained in the RFID chip. Furthermore, RFID remains a relatively complex technology when compared to the barcodes. Indeed, the barcodes are very simple to implement or to use. They are perfectly standardized and universal in their operating principle. They are also extremely low cost for both the tags and the reader part. However, the main drawback of this technology relies in the way of capturing the information, which most often requires human intervention. In contrast, the main advantage of RFID is the use of radio waves to transfer data, for the purposes of automatically identifying and tracking tags attached to objects. In addition to the flexibility of reading, multiple tags can be read at once. Similarly, it is possible to obtain a substantial read range. However, the RFID solution is complex; it requires the use of a chip and a communication protocol which induces costly tags. Moreover, this solution is not universal, since it requires different frequency bands from one country to another. All these reasons explain why more and more research projects seek to develop new identification systems. Among them, a solution without any chip is very promising.

2.2. *Chipless RFID and state-of-the-art of chipless radar approaches*

The development of chipless radar tags in RF has grown significantly in recent years [3–5]. The principle of information encoding, that is to say the ID label, is based on the generation of a specific electromagnetic signature, a bit like the radar principle: a wave is sent to the tag, a portion of the tag backscattered signal—what we call his EM signature—is retrieved by the reader. The main difference here is that the shape of the conductive pattern forming the tag is imposed (RCS Synthesis) in order to have a specific and perfectly recognizable signature (see Figure 1). Thus, the information is no longer stored within an electronic chip in a classical memory, as can be done in traditional RFID tags, but directly "written" in the label like a barcode.

Figure 1a shows the chipless technology from an application point of view. It shows a pallet with 16 cardboards (marked objects in the figure) on which tags have been placed (on the outside of the carton, like the barcode, each tag has a different geometry/identifier) to identify each cardboard. In the figure, the tag has been shown on the outside of the cardboard for ease of understanding, however unlike barcodes, a chipless tag based on an RF approach can be read through the cardboard. Also, for practical purposes, the tags could still be read if the cardboards were wrapped in a protective plastic film. Similarly, for product integrity reasons, it would also be possible to put the tags inside the cardboards to make them invisible. Another undeniable advantage of RFID chipless technology over barcodes is the ability to significantly increase the speed of reading of the tags on the pallet. Whereas with a barcode, the reader has to be positioned in direct view of each label, chipless tags can be read at greater distances (e.g. 40 cm) and therefore by scanning the area with a handheld reader for example. Figure 1a shows

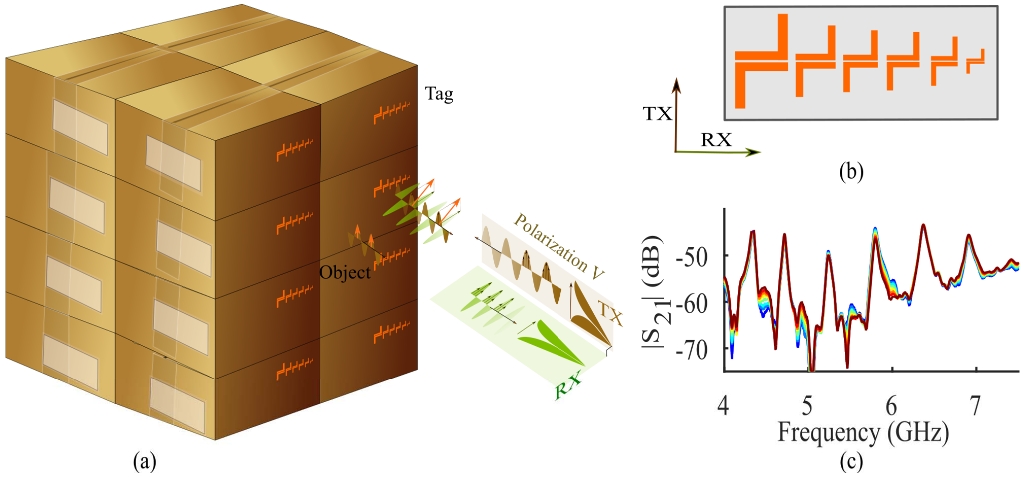


Figure 1. Chipless RFID application principle: (a) Example of the use of chipless technology. Each cardboard is identified by a chipless tag (orange pattern). The identification is done by means of RF waves. The wave backscattered by the object and the tag contains the information that will allow to obtain the identification. Like the barcode, each tag has a different geometry/identifier. (b) Example of a REP chipless tag with 6 independent resonators. (c) Spectrum of the backscattered signal measured for the chipless tag (b) and showing 6 resonance frequencies.

the interaction between the waves sent by the chipless reader (not shown in the figure) and the tag, as well as the backscattered wave which contains the information on the ID of the chipless tag. The tag is shown in Figure 1b. There are many different types of chipless tags, most often consisting of a rectangular plastic (or paper) support with conductive patterns (shown in orange in the figure) printed on it. Some tags have a third metal layer which acts as a ground plane for the structure and which usually isolates the tag from the object and improves the quality factor of the resonators. The shapes of the resonators are obtained from a specific RF design work based mostly on the use of RF simulators [3, 6]. There are many constraints to be taken into account in the design of the tag, such as the amplitude of the backscattered signal (or the radar cross section (RCS) of the tag, a quantity that describes the ability of the tag to reradiate in one direction in space), or the quality factor, which must be as large as possible. The coding capacity of a chipless tag as well as the reading distance are directly linked to this design work. Therefore, a key point is the relationship between the geometry of the conductor pattern and the RF signature expected. To encode information in chipless solutions consists in:

- Detecting the presence or absence of a distinctive portion of signal observed in the time or in the frequency domain (for example a peak or dip associated with a resonance of the conductive pattern of the label—see Figure 1c).
- Measuring precisely the duration or the frequency interval (respectively from the signal represented in the time or the spectral domain) between the presence of distinctive parts of the signal. This physical quantity must be independent of the measurement, for example the distance between the reader and the tag or the presence of objects next to the tag. In this case, the use of resonant devices (resonators), and therefore the detection of their resonance frequency (which is an independent parameter), is of particular interest. This is why the vast majority of chipless tags currently in use are based on the printing of resonant patterns on the label (see Figure 1b). From this, it is possible to establish a bijective link between their resonant frequencies and the corresponding tag ID. This link

can be made in both directions, allowing both the generation of a tag corresponding to a given ID, or the association of an ID with the EM signature of a tag.

- Making these physical quantities extracted from the tag signature totally independent. Indeed, in the case where the tag comprises several resonant patterns, these structures must be decoupled from each other, i.e. the modification of one of the resonance frequencies (and therefore the modification of a specific geometric quantity) must not have any effect on the resonances of the other patterns. These conditions are indispensable for coding information according to this label principle. Note that to increase the coding capacity of the tag, more advanced design methods based on RCS synthesis have also been proposed [6].

One of the first frequency tags was designed on the principle of antennas loaded by resonant structures. In order to decouple transmission from reception as much as possible, these tags were usually made up of two antennas oriented at 90° to each other and connected by a transmission line on which resonators were placed [3, 4]. These cumbersome structures made it possible to demonstrate the principle of information coding but proved to be too inefficient for applications in a real environment.

A decisive turning point for the practical implementation of this technology is linked to the introduction of tags based on the use of resonant patterns. In this case, we no longer try to recover or retransmit the signal with antennas and modify the signal by placing a specific circuit between the antennas. Instead, the emitted signal is directly interacted with the presence of a resonator that stores energy and then backscatters it over a period of time that is related to its quality factor. These "artificial" objects with remarkable properties thus operate on the principle of RF Encoding Particles (REP) and can intrinsically have a characteristic radar signature and thus be directly associated with an identifier [3, 7]. The functions of receiving, signal processing and transmitting are not separated from each other, both in terms of the concept and the geometry of the tag (see Figure 1b). In this case, REP tags act as transmitting, receiving and filtering devices at the same time [8, 9]. Also, these tags do not have antennas, or transmission lines, which are too cumbersome and restrictive for the development of chipless RFID tags. Thus, like RF barcodes, tags designed on this principle are extremely simple and most often the resonant frequency is directly linked to a characteristic pattern length that can be modified to change the tag ID. Similarly, to increase the coding capacity, it is possible to place several resonators on the same tag and thus reach several tens of bits (see Figure 1b).

Based on the REP approach a substantial amount of research work was focused on demonstrating the potential of chipless radar approaches for scientific (remote characterization of RF devices [10–12]) and engineering applications (identification—chipless RFID [5]). An important number of these articles have addressed technical challenges, such as the tag encoding capacity [9, 13], the robustness of detection [14–17], the sensitivity of detection based on the relative orientation between the reader and the tag [18–21], the cost of both the tag and the reader [22–24], and finally, compliance with RF emission regulations [25]. A tag demonstrated a capacity of 49 bits [18], proving for the first time that chipless technology can have a comparable encoding capacity to the well-known international article number EAN 13 [(EAN), formerly the European article number] bar code technology. The widespread application of chipless RFID is intimately linked to the manufacturing cost of the tags. The feasibility of large scale chipless tag production has been shown with a unit cost of about €0.004 [24]. These figures are following some institutes' forecast. Indeed, it has been demonstrated that a REP chipless tag based on a paper substrate can be manufactured using the flexography technique, which is an industrial high-speed printing process. Everyone can also use a common low-cost component off the shelf (COTS) inkjet printer to produce such tags. Here, the only difference with the barcodes is the use of a conductive ink which is at the origin of the specific EM signature of the tag.

In practical terms, it is now expected to show that it is possible to associate the chipless label ID with other features like the ability to: (1) write and rewrite the information (ID) [26], (2) associate an ID with a sensor function [27, 28], (3) associate an ID with gesture recognition [29, 30]. As compared to the barcodes, the chipless technology must bring other features that are impossible to implement with the optical approach, while remaining a very low-cost approach, that is to say, a printable one. This is why the writing/rewriting, sensor capabilities and gesture recognition are crucial features for the large-scale development of such a technology. For instance, the development of very low-cost sensor tags is now eagerly awaited for.

Could wireless electronic systems be turned into chipless devices that can be printed, and even simpler to use than a common passive RFID tag? Could it be possible to rewrite data using only a paper label and a common inkjet printer? Could these chipless labels replace classical remote control for specific applications? These are the questions we are asking ourselves and to which we are seeking to provide concrete answers, particularly within the framework of the ScattererID project [31].

3. Challenge: retrieve the label data from its backscattered wave in an unknown environment

To achieve this goal, developing these smart chipless labels based only on the extension of existing approaches is far from sufficient. Existing models need to be totally re-thought, in order to give the possibility to add these awaited new functionalities. In other words, rewritable capability needs to borrow a concept from memory and revisit tag models from a user-centered perspective. It is the same thing for the sensing and gesture recognition part. Therefore, we will explore the new paradigm of "smart chipless electronic label", namely, a paper-based green electronic compatible solution with advanced functionalities and designed to allow an intuitive interaction with users.

We will then discuss some essential aspects relating to the challenge of retrieving the label data from its backscattered wave in an unknown environment. We will be interested in: (a) the isolation between the signals reflected by the tag and the much more significant ones reflected by the environment around the tag, (b) aspect-independent parameters extraction, which is essential to recover the ID of the tag, (c) the level of sensitivity on the measurement, which can be achieved and which allows to determine possible sensor applications.

3.1. *Spatial isolation of signals*

The vast majority of objects are characterised by RCS values that increase with their geometric dimensions and with the frequency of the EM wave. Thus, we have around us objects with very different RCS values, some of which (such as metallic objects) can be very large when compared to the RCS values of chipless tags (at best the RCS of a chipless tag is less than −10 dBm at UWB frequencies between 3 and 10 GHz). Therefore, an important task when designing chipless tags is to find shapes that allow the highest RCS values to be obtained with the highest possible quality factors. However, the limitations imposed by the application (geometry of the tags with a credit card format—frequencies in the UWB band...) mean that it is not possible to obtain tags with RCS values that are much higher than the ones of surrounding objects. In fact, we usually end up with tag RCS that can be a thousand or even a million times weaker than the surrounding object ones. This is why, in order to be able to read a chipless tag in a real environment, without a complex calibration system (which would mean imposing that we know the environment), we need to implement specific strategies such as the isolation of signals between the tag and

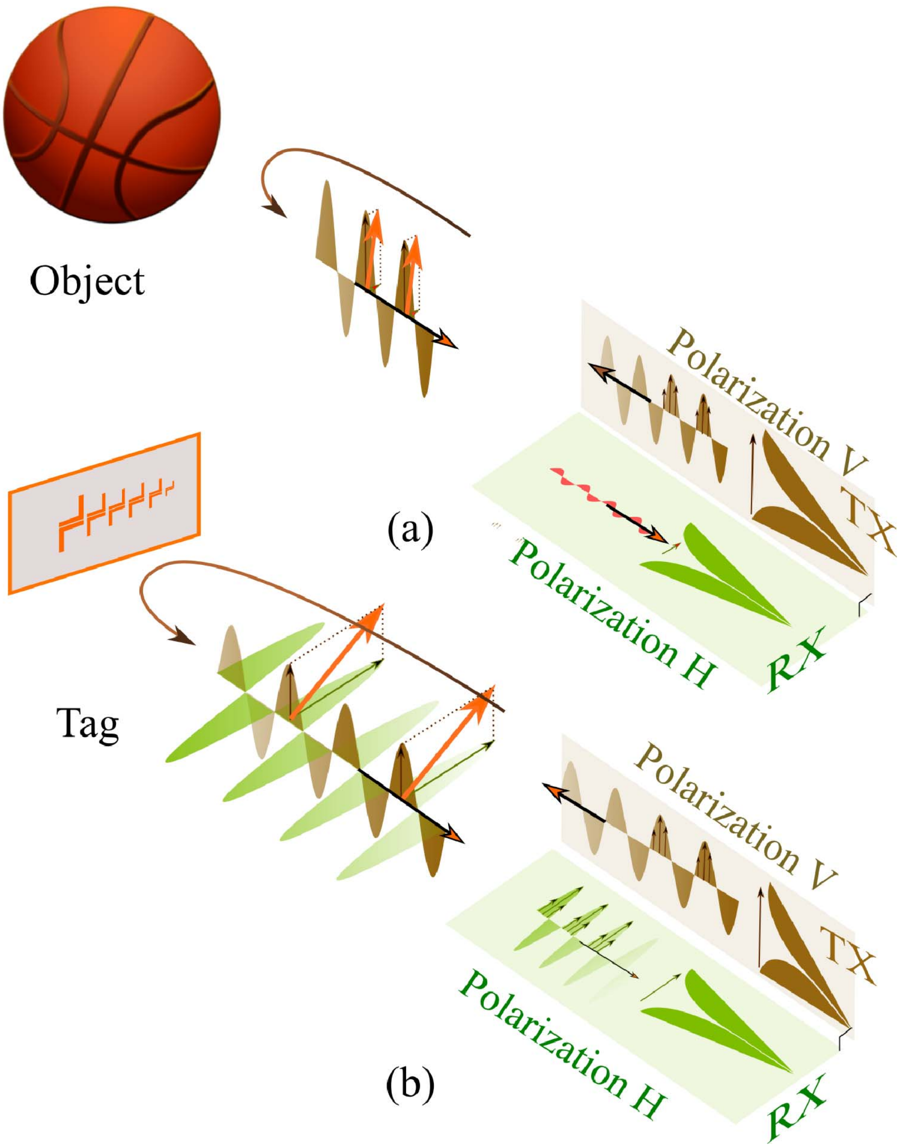


Figure 2. Principle of cross polarisation measurement applied to chipless RFID. (a) The field backscattered by a large number of objects has the same polarisation as the incident wave. (b) The chipless tag is designed to backscatter a field perpendicular to the incident field. In practice, the tag is surrounded by objects, and the situation (a) and (b) are superimposed, which makes it possible to isolate the tag signal from the total backscattered signal.

those linked to the environment, from a spatial and temporal point of view. A good spatial isolation is achieved by working in cross-polarisation [3, 32]. The principle is illustrated in Figure 2. Indeed, a vertically polarised signal is transmitted and only the horizontally polarised backscattered component is recovered at the reader. The advantage here is to seek to put oneself in an environment that contains objects that tend not to change the polarisation of the incident wave as it is the case with the balloon in Figure 2a. This constraint is relatively simple to respect in practice as objects are often oriented vertically or horizontally (especially metallic structures which have high RCS), which allows to respect the case described by the Figure 2a. In this case, the tag must be able to change the polarisation of the incident wave. The first generation of chipless tags with two antennas were directly compatible with this approach as it was sufficient to impose a 90° angle between the two antennas. For REP tags, specific design work has shown that by simply modifying the geometry of the scatterers [32], it is possible to obtain the same effect (see Figure 2b). It has even been recently shown that with the REP approach (as opposed to the two-antenna approach) it is possible to design resonators that depolarise the incident wave regardless of the orientation of the tag with respect to the incident wave [33]. It is thus shown that it is possible to have either tags of this type that are totally invariant (backscattered wave of constant amplitude regardless of the orientation of the emission), or tags that guarantee a certain level of signal (non-zero) in cross-polarisation regardless of their orientation with respect to the emission. With this approach based on a cross-polarisation measurement, we show that we can reduce the importance of the surrounding objects by 20 to 30 dB, which is a way to isolate the signal backscattered by the tag from the total backscattered field.

3.2. *Temporal isolation of signals—aspect-independent parameters extraction*

In order to be able to carry out a measurement without any calibration (i.e. a measurement in which the tag has been removed from the scene and which will be subtracted from the following measurements in which the tag will be present), the spatial isolation described above must be completed by a temporal isolation whose basis is the resonant character of the scatterers used to make the tag. Indeed, the resonant character of the tag has a double importance. As described above, it is the basis of the coding used for this type of tag, where the resonant frequencies will enable the information to be coded. It will also play a discriminating role in the tag's reading robustness. Indeed, as shown in Figure 3, it is possible to use the resonant character of the scatterers to temporally isolate the tag from its environment and thus be able to measure the resonance frequencies precisely. The principle is also based on the idea that this resonant character is not present in everyday objects. In this respect, it should be noted that a great deal of design work, particularly in the choice of materials and geometries, is necessary to have good resonators on chipless RFID tags. The signal backscattered by these everyday objects (which, as previously mentioned, can have very high RCS) will have a duration similar to that of the incident pulse. This is known as a quasi-optical reflection; an illustration is given in Figure 3b. This behaviour is very different from that of a good resonator (quality factors between 100 and 150 can be obtained in the UWB band with printed techniques). These will act as a very selective filter and the backscattered field will have a much longer duration than the incident pulse. For example, a UWB pulse emitted by a chipless reader will have a duration of a few nanoseconds (less than 5 ns) whereas the duration of the field backscattered by the chipless tag from this same pulse will have a duration of around 20 ns. Also, on this principle, as illustrated in Figure 3b, it is possible to separate the signal backscattered by the tag from other signals which may have higher amplitudes. It is possible to perform cross-polarisation readings and time windowing in order to cumulate both effects (see Figure 3b). However, as shown in Figure 3c, it is also possible to recover the useful signal from the backscattered signal in co-polarisation. However, the amplitude variations between the tag signal and the other signals are much greater, which can cause problems, particularly in the reader's receiver amplification chain. It has been shown that this temporal windowing is nothing other than a method allowing aspect-independent parameters extraction, i.e. we can recover the characteristics specific to the tag's resonators, i.e. their resonance frequency and their quality factor [34]. These characteristics are

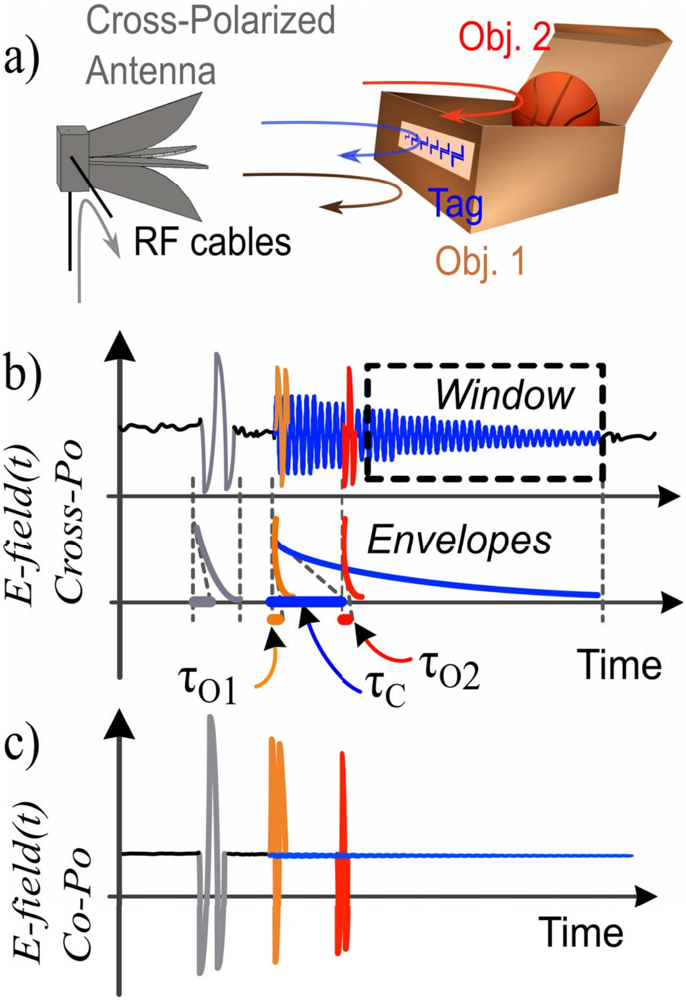


Figure 3. Illustration of the time separation used in chipless RFID technology. (a) The tag is read with an antenna that will be characterised by an isolation between the horizontal and vertical polarisation. This imperfection causes a replica of the transmission pulse in grey on the figure. The presence of objects will also send back signals with a duration similar to that of the incident pulse, which is very different for the tag, which is composed of resonant scatterers. (b) Temporal presentation of the signals reflected by the objects and the tag for a cross-polarisation reading. It is possible to define a time window where the signal corresponds almost exclusively to that linked to the tag. (c) Same as (b) but for a co-polarisation reading. The signals reflected by the objects have a much greater amplitude than the one linked to the tag.

essential for coding the information as they do not depend on the measurement itself, i.e. the distance, the orientation of the tag, the surrounding objects or even the type of antenna used. It is therefore important to be able to retrieve them as accurately as possible. However, at the level of information recovery, it is possible at first sight to associate the resonance frequency with the search for a maximum in the spectrum of the backscattered signal. However, if we look more precisely, without any particular signal processing, this maximum does not only describe

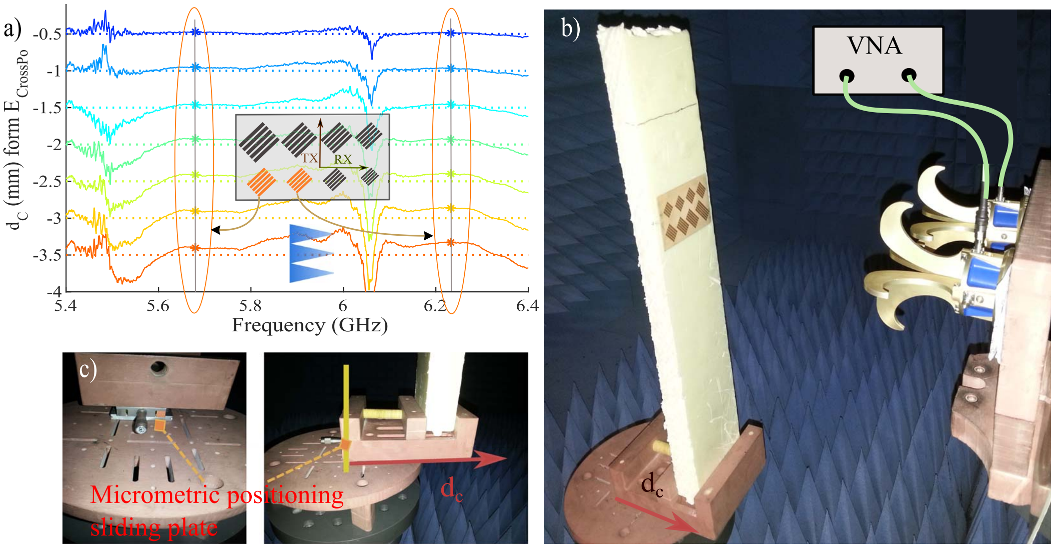


Figure 4. Illustration of the level of accuracy achievable with a chipless tag. Application to displacement measurement. The tag used has 8 scatterers with resonance frequencies between 3.34 to 6.8 GHz. (a) Extraction of the displacement d_c from the measurement of S-parameters (S21) in an anechoic chamber. (b) Bench used, description of the measurement using a VNA. (c) Details on how displacements of 100 to 500 µm were achieved in practice.

the resonance mode of the tag but also the quasi-optical mode of the tag itself, not to mention the effect of surrounding objects when they are present. So, the frequency associated with this maximum can move as a function of the reading itself, which shows that this approach does not detect the resonant frequency of the tag [34]. The temporal windowing approach coupled with a spectrogram representation has been used to recover tag information in real environments and even without any calibration, which is very complicated to do in practice [34]. This approach is essential to efficiently read a tag in a real environment and is all the more relevant when the quality factor of the tag is important.

3.3. *Level of accuracy of the backscattered signals from a chipless RFID tag*

Particular attention has been paid to the possibility of identification with this radar approach, where the identifier is linked to the geometry of the resonators present on the tag. However, like the radar applications known to allow the remote recovery of potentially very precise information such as the speed of a vehicle, to name but one, the signals retrieved by a chipless reader can contain much more than an identifier [3]. This is particularly interesting in chipless RFID as the radar target in this case is specifically designed to have special properties. Thus, we were able to show that this approach is compatible with the remote measurement of a large number of physical quantities ranging from temperature, humidity, or electrical/thermal quantities of materials such as permittivity/thermal expansion coefficient. This idea of using a radar approach on resonant targets to make precise measurements of physical quantities follows a first characterisation which aimed to measure the smallest possible displacement (noted d_c in Figure 4) of a tag. Indeed, if we are interested, in this case, in the variation of the phase of the backscattered signal, it is possible to derive analytically the displacement of the tag (see Figure 4a). By exploiting resonance frequencies, cross-polarisation and time windowing, we have been able to show that it is possible to measure these displacements even through objects (such as a cardboard box or plastic tab) or even to identify individually the displacement of different tags positioned at the same time in front of the reader [35, 36]. Figure 4 shows some results obtained in an anechoic chamber where one can see the procedure used to make the measurements. It can be seen in Figure 4a that around the resonance frequencies (vertical lines), the extracted displacement value is the smoothest and flattest part of the curve, this being due to the fact that it is at these frequencies that the best SNR is obtained. The results obtained in terms of accuracy are remarkable. Indeed, a displacement of 100 μm can be measured with this approach [36]. The error of the displacement measurement can be reduced by using several resonators, each of them allowing to recover a displacement value. Finally, it was found that for displacements greater than or equal to 400 μm, the error on the measurement is less than 15 μm.

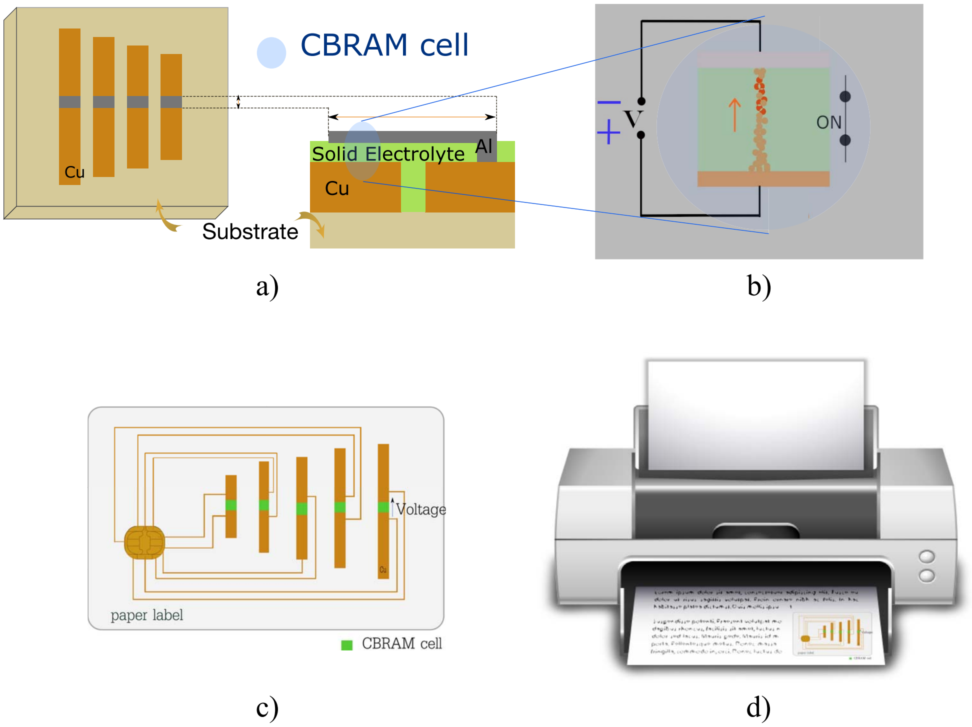
Thus, this example illustrates the potentially high sensitivity of the chipless approach, and several application areas are possible. Indeed, by perfectly controlling the environment, for example by positioning the tag in an anechoic environment, by choosing a highly resonant tag (with a quality factor of the order of 150), as well as a very precise measuring device such as a network analyser (VNA), it is possible to measure variations in resonance frequency of less than 1 MHz when the measurement is reproduced identically by removing the tag each time. If we compare these values with those related to the effect on the length of a 3 cm metal loop for a temperature variation of a few degrees, we realise that we are on the same order of magnitude. Indeed, the thermal expansion modifies the geometric dimension of the loop and thus its resonance frequency. Thus, based on this principle, it is possible to carry out very precise measurements, remotely, such as the characterisation of the dilation coefficients of metals [12]. If, on the other hand, the temperature dependence of the materials that make up the tag is considered to be known, it is possible to use it as a temperature sensor [27, 37]. Results on tags with no specific material (i.e. known to be particularly temperature sensitive) have shown that it is already possible to trace the temperature, simply by modelling the effect of thermal expansion and the temperature dependence of the dielectric. As these input data are usually present in the material datasheets, this shows that it is very simple to create a sensor with the chipless approach. Recent studies also show that a conventional chipless tag can be used to measure temperature and humidity at the same time. Taking advantage of the simple geometry, it is possible in this case to have an analytical approach to model both the temperature and humidity dependence of the resonant frequency and to extract these two physical quantities [37].

4. New features in RFID chipless

4.1. *Rewritable chipless RFID label*

As said previously, advances in the field of chipless RFID applications are primarily based on significant technological breakthroughs. For instance, the possibility of designing rewritable and low-cost printable tags involves the development of original approaches at the forefront of progress, like the use of structures from conductive-bridging random-access memories (CBRAM) microelectronics technology, allowing to achieve reconfigurable elements based on Nano-switches [38, 39].

Like the barcodes, the chipless tags' information cannot be changed: once the tag has been printed, the information is recorded in hard copy. To obtain the "writing/rewriting" function, a specific element presenting two clearly distinct states must be implemented in the label. This element must be perfectly controllable and must allow modifying the EM signature of the tag, that is to say its ID. This behaviour can be obtained with a RF switch; the major differences here are that (1) this device must be printed simultaneously with the label conductive pattern and



a) b) c) d)

Figure 5. Use of CBRAM technology to produce rewritable RFID chipless labels. (a) Example of the implementation of a CBRAM cell at the level of a resonator. (b) Operating principle of the CBRAM cell, the formation of a filament ensures electrical conductivity between the two electrodes (ON state). (c) Example of an RFID chipless label printed in credit card format with the supply lines. (d) Illustration of the problem of manufacturing these labels where the objective is to be able to print them with conventional printing means.

(2) the switch must keep its state even in the absence of any applied power. A simple and flexible technology in terms of manufacturing is needed. Such a function can be obtained with a physical principle currently being studied to realize the future non-volatile fast access memories (known under different names including Memristors or CBRAM) [40]. It was particularly interesting to work on the principle of CBRAM in order to perform RF switches that could be used to rewrite our chipless tags (see Figure 5). The CBRAM technology has shown the potential to operate at lower energies and voltage (couple of volts), making it particularly interesting for embedded applications [40].

4.1.1. *Operating principles of CBRAM*

The RF switches that have been developed are based on MIM structures (Metal Insulator Metal—Figure 5b), that is to say a stack of three layers, with no moving parts. Moreover, they are fully compatible with many low cost fabrication approaches and simple to implement [41,42] (see Figure 5c, d). By carefully choosing materials and their thicknesses, it is possible to show that such a structure acts as a programmable resistor that keeps its value in the absence of any power control (see Figure 5b). Under the action of an electric field between the two electrodes, the insulator (which is a solid electrolyte) allows the migration of ions, which come from the active electrode, towards the inert electrode. The ions are then deposited on the inert electrode and are reduced with electrons to obtain the Cu or Ag metal .... This way, a conductive filament grows

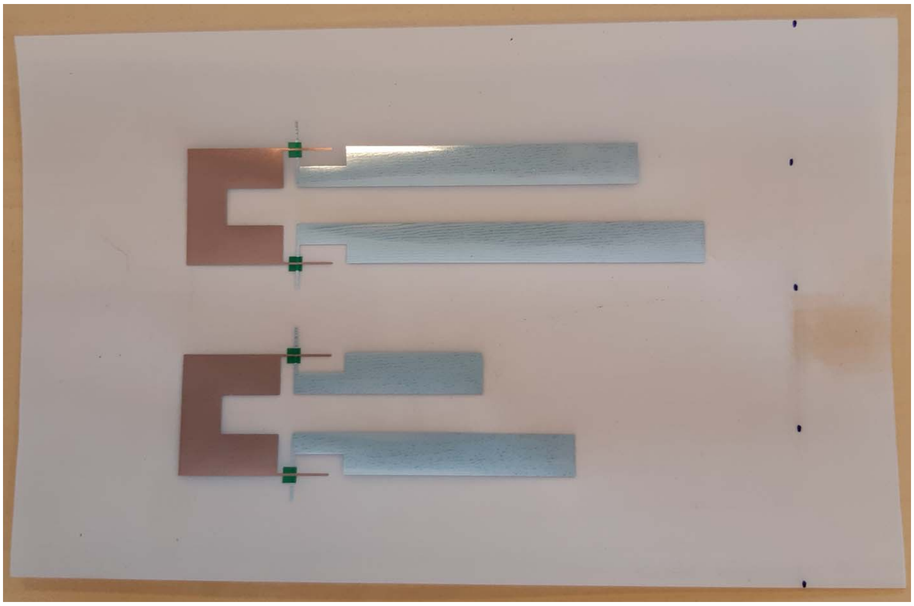


Figure 6. Photo of the first rewritable chipless tags made entirely through printing. The metals used are copper and aluminium.

until it touches the active electrode (see Figure 5b). The device then switches to a conducting state (ON). To break the filament and return to the OFF state, we simply have to reverse the voltage.

We will note here the significant divergences that exist in terms of specifications and desired performance between memories and RF switches, which are very different applications from an applicative point of view. In the case of memories, consumption and time of switching/memory access are determining factors, while in RF, it is above all frequency behaviour and particularly the insertion loss in the ON state that is decisive. The main differences between memories and the RF switch version can be found in the dimensions of structures. In RF, the lowest COFF capacity possible must be reached. We must also seek configurations in which the dielectric is as thick as possible; that is, it must absolutely be significantly thicker than 100 nm, generally used for memories. Studies have shown that it is possible to execute switching with thicknesses of several hundred nanometers [43]. A work closer in nature to the function desired for chipless tags has shown the possibility of producing an RF switch operating between 1 and 6 GHz [44]. A comparison with switches based on classic approaches is presented in [44], and the results are spectacular. To provide proof-of-concept for the integration of RF switches using CBRAM in a chipless tag, the use of common, printable materials is expected. A photograph of a tag made entirely by printing is shown in Figure 6. The tag is made on flexible PET laminates with copper and aluminium as metals. A complete study of the performance of this tag is given in [26].

4.1.2. *Example of a reconfigurable chipless tag*

The CBRAM structure is extremely simple. Figure 5a shows an example of the implementation of this technology in a chipless tag in order to make it rewritable. The RF switch is used to modify the geometric length of the tag and thus its resonance frequency. As an example, in Figure 5a, the arrangement of switches at the centre of the dipoles makes it possible to obtain basic OOK coding in frequency. We can see in this figure how the reconfigurable element, the CBRAM cell, could be integrated. With the Cu/Nafion/Al layers, filaments inside the solid electrolyte dielectric can be created to produce a short circuit. In terms of realization, if we start from a classical chipless tag (that is, a substrate with a conductive pattern), we must begin by depositing the dielectric layer, being careful to leave a copper access area on the arm that does not contain the MIM structure. After this, we must deposit aluminium in such a way as to cover part of the arm of the antenna, thus creating the MIM stacking and ensuring electrical contact with the other arm. This results in a horizontal stacking of layers (out-of-plane RF switch). It is also possible to create a vertical MIM structure (in-line RF switch), but the thinness of the dielectric (typically of the order of a few hundred nanometers) makes this second configuration more difficult to achieve in practice. Next, to create the dielectric layer, various solutions are possible (such as, for example, the deposit of resins (PMMA/Nafion) via spin coating to preserve simple production techniques [41]), and need to be tested to improve the RF switch performances for chipless applications.

The principal result obtained is that it is possible to obtain very low ON-state resistances of the order of a few ohms, which makes this technology compatible with RF applications. With several volts (from 1 to 20 V depending on the dielectrics and thicknesses used), an ON state can be obtained, and an OFF state achieved by reversing the voltage.

4.2. *Remote sensor based on chipless label*

Still on the idea of low cost printed labels, it would be quite relevant to perform a new generation of sensors that are identifiable, easy to use, and able to fulfill the pressing need to make objects able to communicate with one another. It would be of particular interest to be able to read an identification code providing information about the content of an object—data on its hygrometry, for example (see Figure 7). We would have access to an object-tracking system that would be remote and extremely complete, all using low-cost technology. For this, the production of chipless tag-sensors is a very attractive solution. Compared to the classic RFID solution, besides increased precision, the ability to avoid chip-related constraints reduces cost, increases life span, and results in tags that are more mechanically robust overall, with much higher resistance to vibration and temperature. Based on the chipless technology, the idea here is to add a sensor function. Various materials can be used to do this, for example nanomaterials. Silicon nanowires have geometries and dimensions with a very high surface-to-volume ratio, thus encouraging surface interactions. Given the very small dimensions of these structures (the diameter of a nanowire can be of the order of a few dozen nanometers), exchanges or harnessing of molecules can take place on the surface, permitting a modification of electrical properties depending on the environment in which they are placed (see Figure 7).

These nanomaterials have been studied for several years already, and the possibility of using them as sensors, particularly wireless sensors, has been demonstrated [28].

Figure 8 describes the operating principle used to produce a chipless tag comprising an ID and a sensor function. The principle of associating an ID with an RF signature (backscattered field or RCS) is shown in Figure 8a. We can see in Figure 8b that for the sensor function, the idea is to use, in contact with a resonator, a material sensitive to the quantity to be measured. The electrical variations (permittivity and losses) of this material as a function of the quantity to be measured will directly impact the resonance frequency (as well as the amplitude/phase of the corresponding peak—resonance frequency—obtained on the field backscattered by the resonator). Thus, it is possible to trace the value of the physical quantity through the measurement of this backscattered field, most often through the value of the resonance frequency. The correspondence between the resonance frequency and the value of the physical quantity is usually done using a lookup table or, when the problem is simple enough, by a direct analytical model [27, 37].

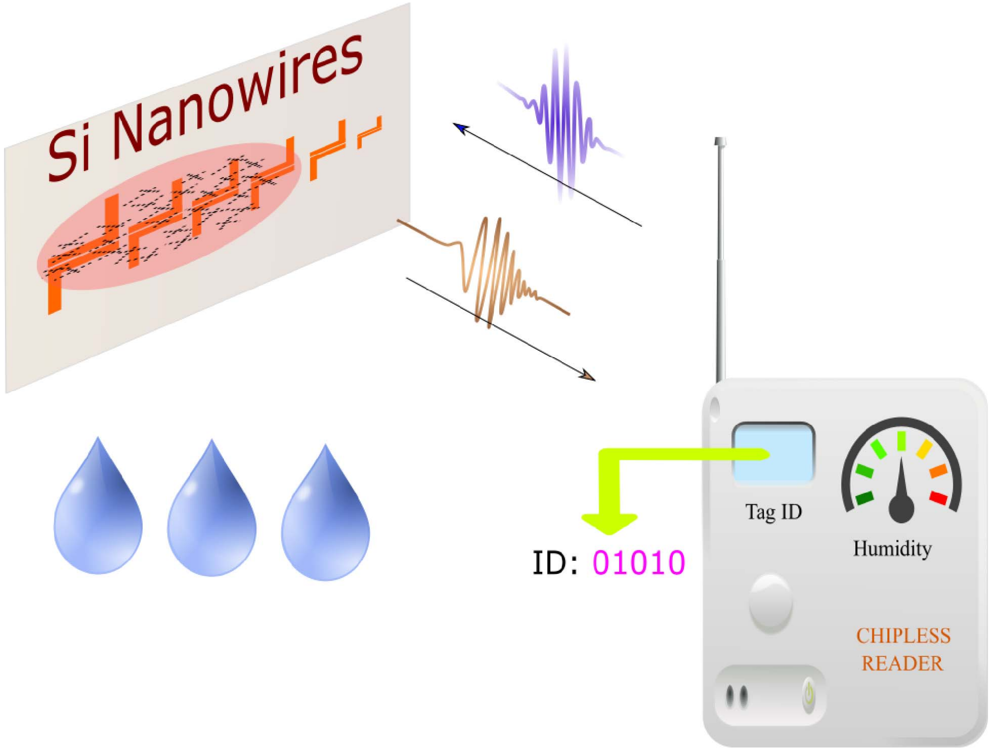


Figure 7. Illustration of the reading of a chipless tag with an identifier and a humidity sensor. Resonators are either used to encode the information or to read the relative humidity in the air. In this example, a humidity-sensitive material (silicon nanowires—SiNw) has been deposited on these resonators. Therefore, the resonance frequency associated with these specific resonators (with SiNw) will change according to the relative humidity level. The measurement of the 6 resonance frequencies allows the recovery of the tag's ID and the humidity value in one go.

Figure 8c, d show measurements made on resonators where drops of silicon nanowire have been deposited [28]. Indeed, a dozen drops of solutions containing silicon nanowires were deposited on a specific resonator of the tag. A climate chamber or a sealed container into which water was placed (to simulate a more realistic environment) made it possible to cause the relative humidity (HR) to vary in time inside the box, between around 70% and 100%. Significant variations have been observed around the resonant frequency of the chipless tag (35 MHz of frequency shift). For example, by comparing the measurement results with the EM simulations, it has been possible to understand the electrical behavior of the silicon nanowires: we can deduce that the presence of humidity will simultaneously modify permittivity and losses. A measurement of the same structure but without the presence of nanowires (see Figure 8d), under the same conditions, does not display any significant variations in RCS, which shows that it is the nanowires that are exacerbating this phenomenon. A last important point is that it has been observed that the variations are reproducible from one day to the next [45]. In fact, the same tag was measured under the same conditions several weeks later, and the results obtained are comparable.

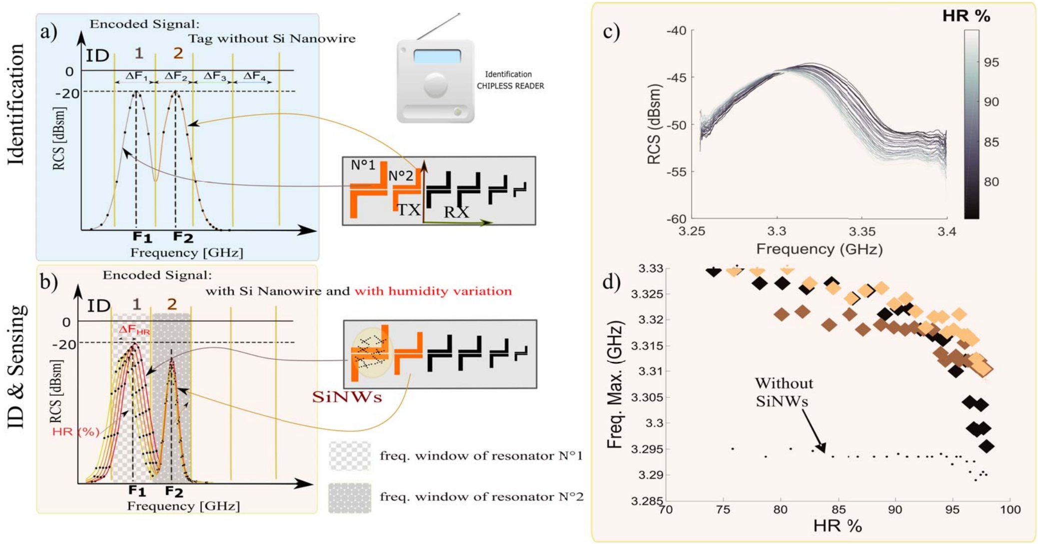


Figure 8. Operating principle of a chipless tag comprising an ID and a sensor function. (a) Tag used for identification—in this case the ID is determined by looking in which ΔFi sub-windows the peaks relating to the resonance frequencies of the tags are present. (b) Sensor function: a material sensitive to the physical quantity to be measured is added to resonators. The information on the physical quantity will be obtained by measuring precisely the value of the resonance frequency and by using either an analytical model or a lookup table to find the required value. (c) Example of the variation of the RCS as a function of humidity (measurements—resonator with SiNw). (d) Variations of the resonance frequency as a function of the relative humidity for 3 identical sensors and a resonator without SiNw.

4.3. *Gesture recognition*

As previously shown, chipless tags are sensitive to their surrounding environment. It means that, if desired, they can be affected by the position of the user's hands or fingers on the top of the label. Moreover, a radar approach is used to read these tags, which means that it is fully adapted for localization purposes. If we combine these two statements, we will see that chipless tags can be used to introduce a new kind of application, i.e. for gesture recognition as illustrated in Figure 9. So the question is: can a simple chipless label be used to control electronic equipment?

Contactless human-computer interactions (HCI) using EM waves have already been investigated in the literature. Project Soli is developed by Google ATAP since 2015 [46]. As compared to Project Soli, our solution would operate in UWB band and would use chipless paper tag to identify the label, and thus the user itself. The WISP (Wireless Identification and Sensing Platform) is another project which can produce contactless HCI [47]. This platform is based on the use of a low power microcontroller coupled with sensors. The whole system can be powered by standard RFID readers and can communicate using backscatter modulation. Unlike WISP, our solution proposes a simple chipless tag to sense the environment, that is to say without any electronic component. Initial studies show that it is possible to developed the concept of HCI based on the use of radar chipless labels [29, 30, 48]. Our system has to detect specific user gesture like the displacement of the label (see Figure 9a) or the position of the finger on a tag's surface (see Figure 9b) [30]. The chipless tag, made on paper is playing the role of a remote control but without any electronic component.

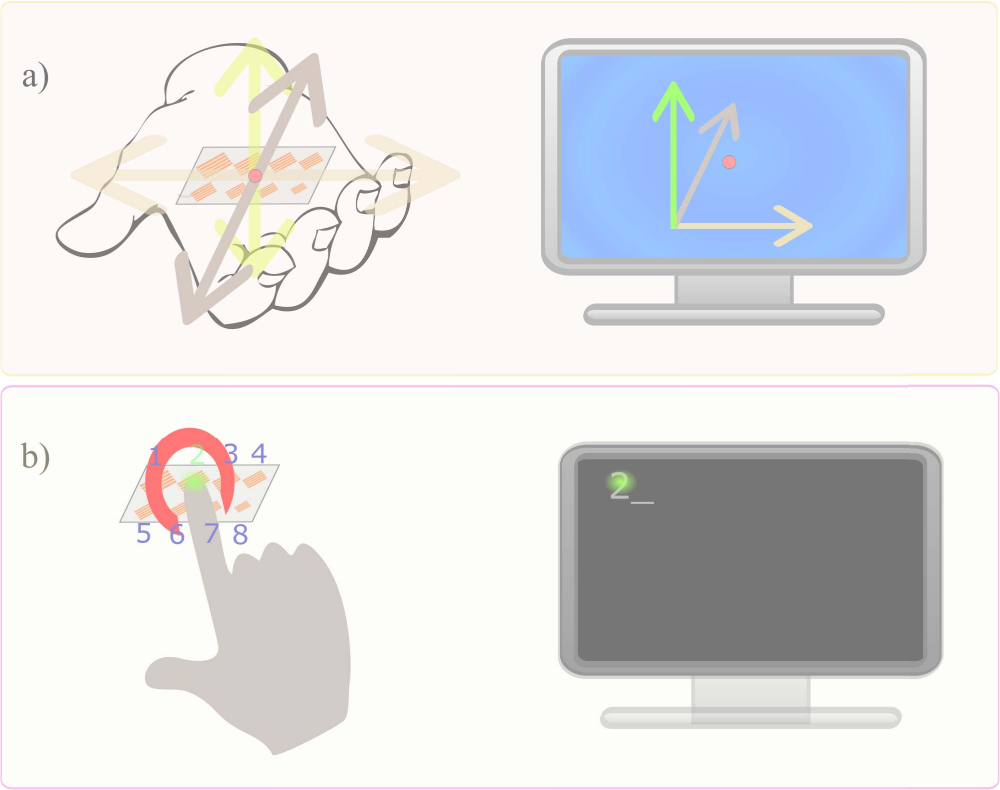


Figure 9. Gesture recognition applications: chipless label acting as a remote control. (a) Joystick mode, (b) keyboard mode.

This is based on the observation that it is possible to extract the displacement of chipless labels with submillimeter precision [35]. So, as it is possible to measure in real time the position of the tag, gesture recognition can be considered. Moreover, the identification function of the chipless tag is still available in the signature and can be used to separate various users.

Figure 10 explains the principle of operation of a label that can be used in keyboard mode. One can imagine a two-phase operation. (1) The user approaches the tag to the reader to read the identifier so that the reader recognises the user in front of it. (2) By pressing the finger on different areas of the tag, one area after the other—like using a keyboard—the user can communicate information to the reader. The principle is based on the fact that the finger has a high effective permittivity, which causes the resonance frequency to vary by several GHz, making it disappear from the frequency band and thus allowing the reader to detect this disappearance. Since the geometrical position of the resonator is perfectly known, it is possible to print a keyboard like numbers on the label in a perfectly visible way (see Figure 9b) [30].

5. Conclusion

The development of the new paradigm of RF communication system based on chipless labels is now highly expected. This means a totally passive tag without any chip, bringing an ID, able to communicate with radio wave and having extremely low costs. With comparable costs to a barcode, this new technology should stand out by providing more functionalities than the optical approach.

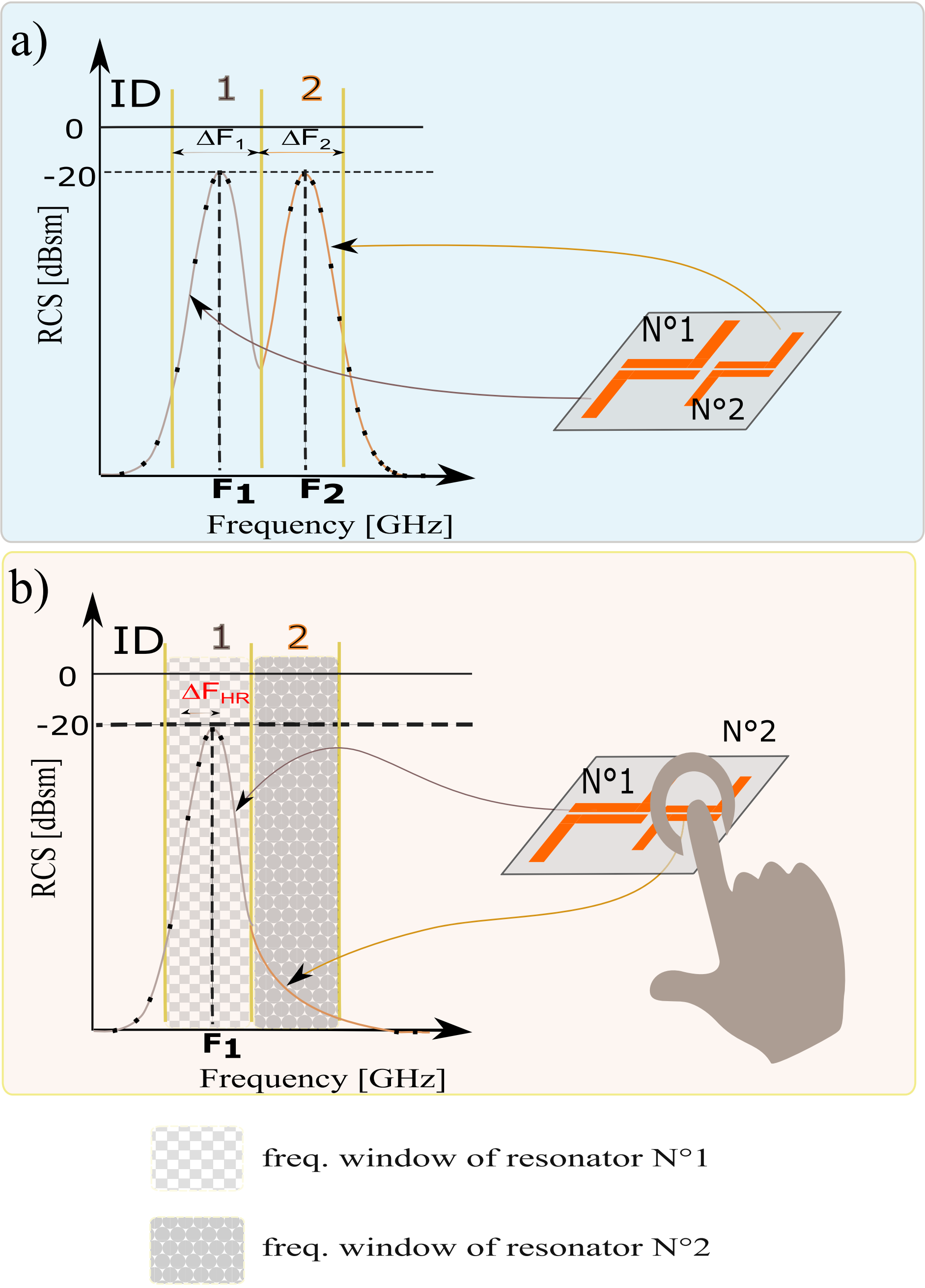


Figure 10. Operating principle of a chipless tag usable in keyboard mode. (a) RCS of the tag presented to the reader for identification. (b) Once the identification has been carried out, the user can interact with the reader by pressing on a specific zone of the tag (where a keyboard can be printed). The action of the finger on the tag will cause the peak related to the resonance frequency of the touched resonator to disappear.

The use of CBRAM technology nowadays provides a non-volatile RF behaviour in such a simple manner. Similarly, it seems to be the only approach that would allow (i) to control the RF switches activation remotely (by radio wave); which is due to the low power needed to change the state, (ii) to manufacture switches entirely through printing techniques. It is obvious that scientific challenges have to be addressed and solved such as: a better understanding of the filament creation, the role that the dielectric plays in it, how to reduce the inherent MIM capacity in order to increase the frequency range of use, how to minimize the equivalent resistance of the conductive state, how to increase the manufacturing reliability.... In all cases, the use of this technology to achieve printable, reconfigurable chipless tags, is original and promising for future applications in the field of identification and sensing of totally passive and printable labels. Chipless RFID technology is also very interesting to achieve sensor functions. This is based on the use of the radar approach coupled with the use of particular targets, that is to say resonant targets that allow to significantly increase the signal to noise ratio around the resonance frequencies as well as to perform time windowing. Numerous conceptual possibilities for such a use are currently being studied. Concerning gesture recognition, the goal is to develop a system that can detect the specific user gesture, like the position of the finger on a tag's surface. The chipless tag, made on paper with an inkjet printer would play the role of a remote control but without any electronic component. Indeed, since the architecture is based on a chipless tag, the system is entirely passive and does not need any battery. With the radar approach used in chipless, lots of accurate and useful data can be deduced form that type of reading. For example, as it is possible to measure in real time the position of the tag (the distance between the tag and the reader but also lots of other relevant data), gesture recognition can be considered. Moreover, the identification function of the chipless tag is still available in the signature and can be used to separate various users. Chipless paper tags could have a huge impact in the development of the concept of "smart packaging" or "smart paper". New progresses in conductive inks give the possibility for printer companies to think about new applications for their printers now able to print on paper with conductor ink.

Conflicts of interest

The author has no conflict of interest to declare.

Acknowledgments

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