
Introduction to Chipless Radio Frequency Identification

1.1. Introduction

In this chapter, we provide an introduction to the chipless RFID technology. After a brief discussion, the recent developments and advancements in the field of chipless RFID technology are presented. In this book, we focus on the development of chipless RFID authentication. For this reason, we also discuss some challenges of the development of robust authentication techniques. This chapter is organized as follows:

- section 1.2 presents the introduction of the chipless RFID technology;
- section 1.3 summarizes the recent developments and advancements from the literature in the field of chipless RFID technology;
- section 1.4 presents numerous challenges of the development of robust authentication techniques;
- section 1.5 concludes this chapter.

1.2. Chipless radio frequency identification

Chipless RFID tags, also called RF barcodes, have several advantages over the conventional passive RFID technology. The absence of any chip (which is the reason it is called chipless) connected to the antenna is the primary revolution of this technology. Chipless RFID is very promising, as it is fully printable, low cost, simple in design and non-line-of-sight operation

technology. This technology has enormous potential to replace the barcode in item-level tagging (Perret 2014, Chap. 1).

Coding techniques for the chipless RFID technology can be classified into two main categories: time-coded and frequency-coded chipless tags, as shown in Figure 1.1.

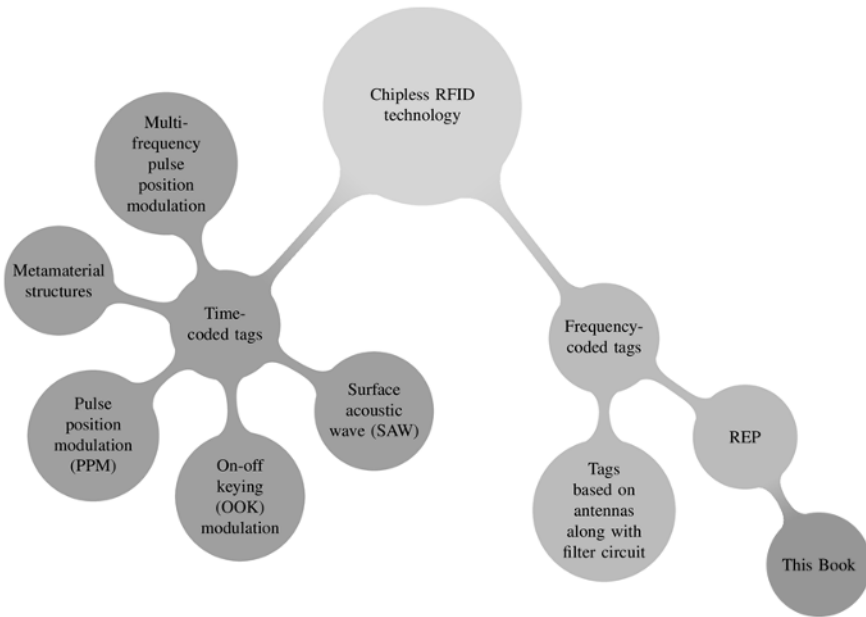


Figure 1.1. Numerous coding techniques for the chipless RFID technology.
For a color version of this figure, see www.iste.co.uk/ali/RFID.zip

The time-coded chipless technique is first based on sending a pulse signal from the reader to the chipless tag, and then on listening to the backscattered echoes of the transmitted pulse from the tag. The tag code is encoded in the reflected pulse train. On the other hand, in the frequency-coded chipless technique, the tag code is usually encoded by the presence or absence of the peak apexes of resonators. This encoding can also be performed using the phase information at a specified frequency position in the spectrum of the tag. Time-coded chipless tags can be further divided into five categories (Forouzandeh and Karmakar 2015): surface acoustic wave, on-off keying modulation, pulse position modulation, metamaterial structures and multi-frequency pulse position modulation. Frequency-coded chipless tags

can be further divided into two categories (Vena *et al.* 2016b, Chap. 4): tags based on dedicated transmission and reception antennas having a filtering circuit between them, and tags based on an RF-encoding particle (REP). An REP is like a scatterer that behaves like a transmitting antenna, a receiving antenna and a filtering circuit simultaneously. The latter technique outperforms the former one in terms of simplicity of design, low cost, low weight and high coding capacity/area. In the former technique, the presence of dedicated transmission and reception antennas causes the mismatching problem, and, ultimately, these antennas do not play their role in increasing the read range. The only advantage of the former technique is that the design of chipless RFID tags shows a separated form.

The radar principle of operation of an REP-based chipless RFID system is schematized in Figure 1.2. A chipless RFID tag is first illuminated by the reader antenna by placing the tag in the field of the reader antenna. The illuminating signal is then coupled with the tag's scatterer. Then, the chipless RFID tag backscatters its response. This backscattered signal is read and stored using the acquisition system.

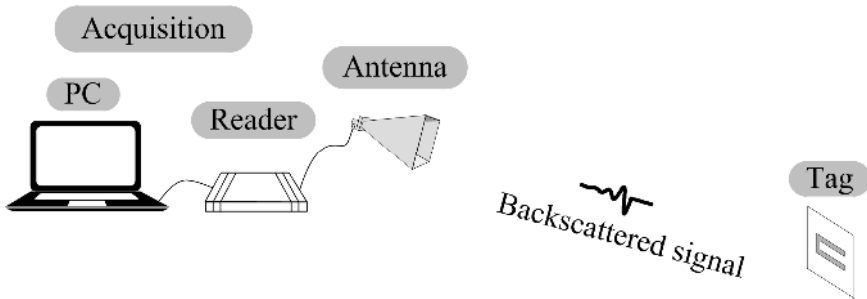


Figure 1.2. Radar principle of operation of an REP-based chipless RFID system

Some examples of REP-based chipless RFID tags (Perret 2014, Chap. 5) are shown in Figure 1.3, where REPs are, for example, C-folded scatterer, nested ring resonator, dual-L dipole and shorted 45° dipole. The nested ring resonators and the nested C-folded scatterers provide promising coding density per surface unit, while the nested ring resonators are also invariant to polarization. The dual-L dipole and the shorted 45° dipole provide a depolarizing operation in the illuminated and backscattered waves. On the other hand, a square-shaped scatterer (Betancourt *et al.* 2015) and an octagonal scatterer (Betancourt *et al.* 2016) are also invariant to

polarization. Other examples of scatterers are open conical resonators (Nair *et al.* 2014a, 2014b) and quick response (QR) codes such as resonators (Betancourt *et al.* 2017).

In the context of this book, we used REP (e.g. C-folded scatterer, dual-L scatterer, shorted 45° dipole) based chipless tags.

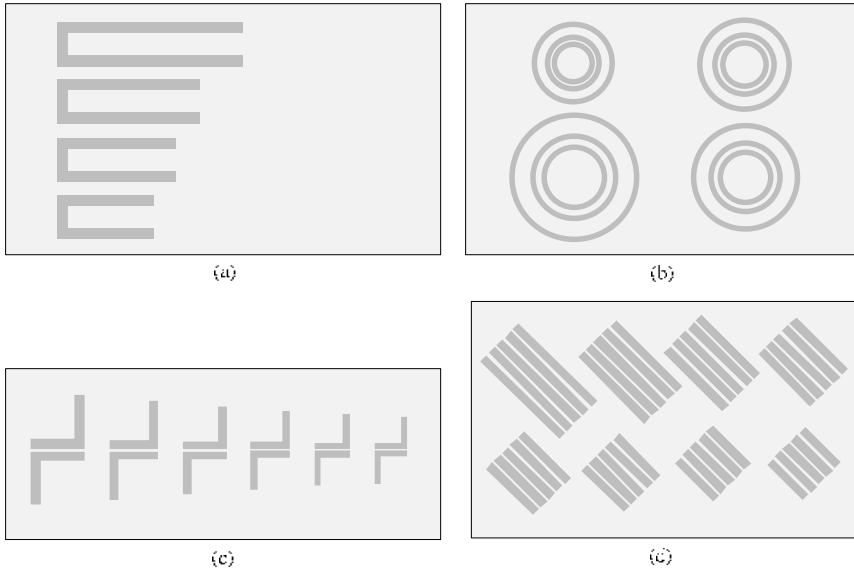


Figure 1.3. Examples of REP-based chipless RFID tags. (a) C-folded scatterer-based tag. (b) Nested ring resonator-based tag. (c) Dual-L dipole-based tag. (d) Shorted 45° dipole-based tag. For a color version of this figure, see www.iste.co.uk/ali/RFID.zip

1.3. Recent developments and advancements

Figure 1.4 outlines the recent developments and advancements in the REP-based chipless RFID. Numerous works to enhance the capability of chipless RFID have been reported that are on the aspects of, for example, the tag, the chipless reader, the robustness of detection, sensing and authentication. For the rest of this book, REP-based chipless RFID is simply referred to as chipless RFID.

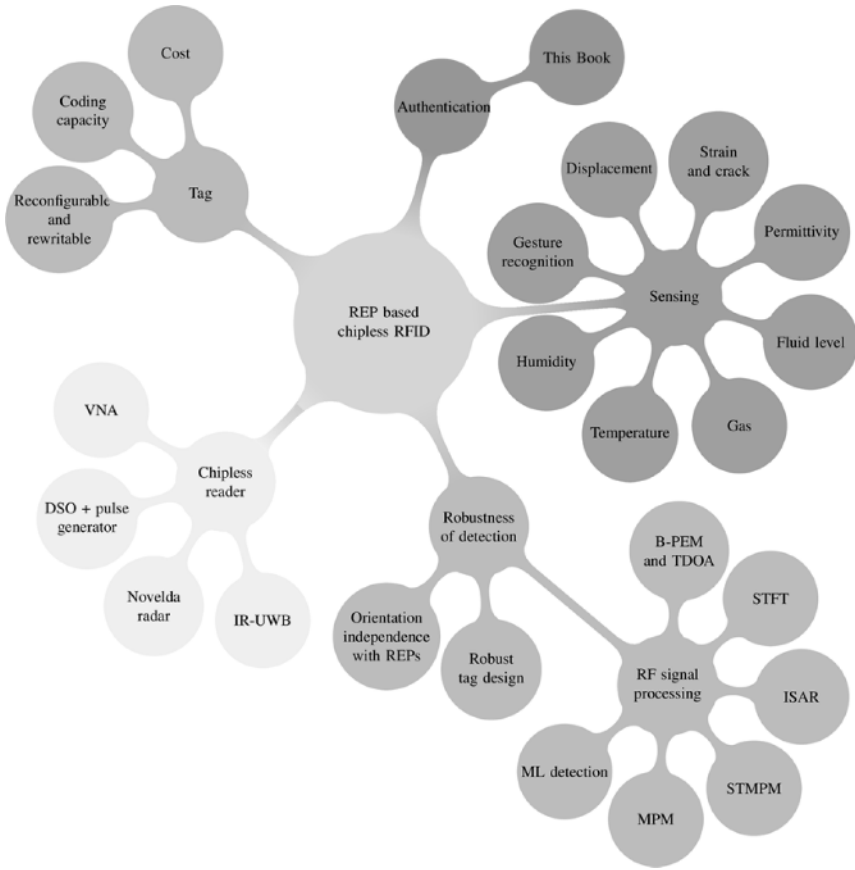


Figure 1.4. The developments and advancements in the REP-based chipless RFID. For a color version of this figure, see www.iste.co.uk/ali/RFID.zip

The cost of the chipless RFID has been brought to a few € cents, e.g. €0.4 cents as found in Perret (2014, Chap. 1) and Perret *et al.* (2013), by using the industrial or laboratory equipment. The techniques used are based on:

- printing the paper-based chipless RFID tags using a flexographic technique (Vena *et al.* 2013b);

- printing the PET-based chipless RFID tags using screen printing for fast mass production of tags (Nair *et al.* 2014a, 2014b; Betancourt *et al.* 2015, 2017). Furthermore, a cost reduction of at least 96% or at least 69%

is expected by respectively replacing silver with copper or copper with aluminum with respect to market prices (Barahona *et al.* 2016a).

For improving the coding capacity of chipless RFID tags, the scientific community has intensified its research efforts. Many examples can be found in Khan *et al.* (2016, Table III). Predominantly, encoding in chipless RFID tags is based on the shift of the peak apexes associated with resonant scatterers. This type of encoding is called frequency position encoding. To further enhance the coding capacity, the tag is coded using phase deviations along with the frequency position, as shown in Vena *et al.* (2011, 2016b, Chap. 4). This type of coding may double the coding capacity even with simple REPs (see Figure 1.3). Further advancement of coding capacity has been discussed in Rance *et al.* (2017, Chap. 4), which introduces magnitude coding based on the radar cross section (RCS).

Reconfigurable chipless RFID tags can be divided into two categories: write-only capable chipless RFID tags and rewritable chipless RFID tags. The activation of reconfigurability can be carried out in the form of additive conductive strips on the resonators in an invasive manner (i.e. by a mechanical trigger) or by applying a voltage or laser pulse to specially designed switches (i.e. by an electrical trigger). In write-only capable chipless RFID tags, many non-effective resonators are added in the design of chipless tags. Without the reconfigurability trigger, the frequencies of resonance of these non-effective resonators do not fall within the frequency band of operation of the chipless RFID tag. When the reconfigurability trigger is applied, these additive (non-effective) resonators become effective, showing their frequencies of resonance within the frequency band of operation of the chipless RFID tag. Hence, this category is called write-only capable chipless RFID tags. On the other hand, in rewritable chipless RFID tags, resonators (in the design of chipless tags) are always effective. When the reconfigurability trigger is applied to these effective resonators, there are shifts in the position of the frequencies of resonance within the frequency band of operation of the chipless RFID tag. Therefore, this category is called rewritable chipless RFID tags.

The write-only capable dual-rhombic loop resonators have been presented in Vena *et al.* (2013a). Strictly speaking, this tag shows write-only capability, which is done for the issue of the tag's realization cost.

This tag is first developed by printing the loop resonators with a conductive silver nanoparticle ink and then printing near-transparent strips on the loop resonators using a resistive carbon nanotube ink. By adding resistive strips, the information is written along the amplitude of the RCS level. In addition, the tag provides anti-counterfeiting capabilities due to the near-transparent resistive strips.

The rewritable chipless RFID tags can be reused, because the tags can be rewritten according to the requirement of the user. In Alves *et al.* (2018), a silicon optical switch is used to present a rewritable chipless RFID tag. The optical switch can change its state when illuminated by a laser source. This concept is proved by using a filter-like configuration that does not fall within the category of REP-based chipless RFID. However, the same concept can also be applied to REPs. Furthermore, this rewritable chipless RFID tag can only maintain the reconfigurability effect in the presence of the laser pulse. Therefore, this proposed rewritable chipless RFID tag is not bistable.

In Jayakrishnan *et al.* (2020), a rewritable chipless tag is presented. This rewritable scatterer is based on a non-volatile memory switch which, in turn, is based on the conductive-bridging random access memory (CBRAM) or metal–insulator–metal switch. The two examples of the reconfigurable scatterer discussed above show a separation of 200 MHz and 140 MHz between the on and off states of the CBRAM switch, respectively. Such values of separation seem to be sufficient to distinguish between the on and off states of the CBRAM switch to develop a rewritable chipless RFID tag. Furthermore, this rewritable chipless RFID tag can maintain the reconfigurability effect even in the absence of the voltage pulse. Therefore, this proposed rewritable chipless RFID tag is bistable.

For laboratory experiments, the most commonly used equipment for chipless RFID readers in the scientific community is based on:

- the vector network analyzer (VNA);
- the digital sampling oscilloscope along with a pulse generator.

This high-cost equipment (several tens of thousands of euros) is not feasible for the practical implementation of the chipless RFID technology for item-level tagging. One solution is to use a Novelda NVA-R640¹

¹ See <https://www.xethru.com/>.

development kit radar as a chipless RFID reader, as discussed in Vena *et al.* (2011, 2015a) and Barahona *et al.* (2017). The cost of the Novelda NVA-R640 development kit radar is €2000, including the low-noise amplifier that is still expensive for low-cost applications. In addition, the Novelda radar shows bandwidth limitations. The 3 dB achievable bandwidth is 4.5 GHz, ranging from 1.5–6 GHz. Therefore, the resonant scatterers in the design of chipless tags operating above a frequency of resonance of 6 GHz cannot be detected precisely using the Novelda radar. To overcome the cost and bandwidth limitations, an impulse radio (IR) ultra-wideband (UWB) reader has been proposed in Garbati *et al.* (2015, 2017). This IR-UWB-based reader is developed using off-the-shelf available components that result in a low-cost device. The cost of this reader is approximately €1000. The band of operation of this reader is 3.1–10.6 GHz.

For the robust detection of chipless RFID tags, two techniques have been discussed in the literature: robust tag design and RF signal processing. A robust tag design is required for the following reasons:

- currently, the majority of the tags’ designs are uniplanar to make them fully printable. In this case, peak apexes associated with resonant scatterers can show random shifts due to random changes in permittivity that occur due to the absence of the ground plane;
- disorientation in the reading process can induce random shifts in peak apexes associated with resonant scatterers.

In Vena *et al.* (2012a, 2012b), frequency shifts are compensated by equipping one resonator as a constant, which means its geometry is the same for all the tags and thus cannot be used for identification.

For the orientation of reading independence, numerous REPs have been proposed in the literature: for example, the nested circular ring resonator (Islam *et al.* 2012; Vena *et al.* 2012c), the dual-L depolarizing scatterer and the shorted 45° depolarizing scatterer (Vena *et al.* 2013c), the nested cross loop resonator (Sajitha *et al.* 2016), the square-shaped scatterer (Betancourt *et al.* 2015) and the octagonal scatterer (Betancourt *et al.* 2016). In Garbati *et al.* (2016), an orientation-independent reading system has been proposed, where the transmitted signal can be rotated electrically with fixed antennas to preserve the cross-polarization for depolarizing chipless tags.

For the robust detection of chipless RFID tags, robust RF signal processing techniques are required for multiple reasons:

- a misalignment between the reader and the tag can lead to a decoding error;
- if the tag is placed on an irregular or asymmetrical surface, the random superposition of the structural mode and the tag mode can create shifts in resonant peak apexes that can again lead to a decoding error;
- until now, most of the decoding techniques for chipless RFID require two measurements: an empty measurement (i.e. a measurement in the absence of the tag) and a tag measurement (i.e. a measurement in the presence of the tag). If the tag is affixed to an object, then the empty measurement is impossible, which finally leads to a decoding error.

For the characterization of tag identification (ID) in chipless RFID tags, an Euclidean distance-based minimum distance detecting method (Barahona *et al.* 2016c) and a maximum likelihood method have been discussed in the literature. On the other hand, to decode chipless RFID tags, complex natural resonances (CNRs) are extracted using the matrix pencil method (MPM) (Blischak and Manteghi 2011) and its variant short-time matrix pencil method (STMPM) (Rezaiesarlak and Manteghi 2013). In Rezaiesarlak and Manteghi (2014a), the STMPM is applied to extract the high-dense tag code. In Rezaiesarlak and Manteghi (2015), the early-time and late-time modes of the transient response from multi-scatterer targets have been distinguished using the STMPM. In Costa *et al.* (2018a), the tag code of mobile chipless RFID tags has been extracted using inverse synthetic aperture radar data processing. However, these techniques are based on two measurements: an empty and a tag measurement. In Ramos *et al.* (2016), tag detection for the chipless RFID technology in different environments using a technique based on the short-time Fourier transform (STFT) is addressed. With this technique, the tag ID is extracted without background normalization (i.e. single measurement) by using an averaged late-time signal. It has been shown that the technique is efficient even without background normalization operating in a realistic outdoor environment. Hence, this technique is very promising for the practical implementation of chipless RFID. For the decoding the same-coded tags, different techniques corresponding to the tag placement have been presented in Barahona *et al.* (2014, 2016b). For decoding the line of sight

and same-coded in-line placed tags in the reader zone, a backscattered pulse energy modulation scheme (i.e. based on the changes in the received RCS level) has been proposed in Barahona *et al.* (2014). For decoding the chipless tags at different distances in the reader zone, the time difference of arrival of backscattered signals has been exploited in Barahona *et al.* (2016b).

Apart from the identification applications, wireless sensing capabilities of the chipless RFID technology have also been discussed in the literature. Such additional sensing capabilities of the chipless RFID technology are very beneficial for environmental monitoring and industrial control. Sensing features in chipless RFID tags are based on the shift of the peak apexes associated with resonant scatterers in most of the studies reported in the literature.

For humidity sensing, in Amin *et al.* (2014), a chipless RFID tag has been proposed for identification and relative humidity (RH) sensing, where a patch loaded with multiple slots is used for the tag code and a single electric inductive–capacitive resonator on a polyvinyl alcohol film is used for RH sensing. In Feng *et al.* (2015), a paper-based chipless RFID tag designed with inductor–capacitor resonators has been presented for humidity sensing. In Borgese *et al.* (2017), humidity sensing has been proposed using a frequency-selective surface (FSS) (i.e. consisting of three concentric loops) based inkjet-printed chipless RFID tag. In Vena *et al.* (2016a), a chipless RFID tag for identification and RH sensing applications has been proposed, where a multiple coupled loop resonator is used for the tag code and a deposited layer of silicon nanowires is used for RH sensing. A similar concept has been presented in Deng *et al.* (2018), where a slotted patch is used for the tag code and a deposited layer of silicon nanowires is used for RH sensing.

For the temperature as well as CO₂ sensing, in Vena *et al.* (2015b), a split-ring resonator (SRR) based inkjet-printed chipless RFID tag with three different inks has been proposed. In the design of this chipless sensor, a deposited layer of a composite polymer/single-walled carbon nanotube ink is used as a transducer. For temperature sensing, in Matbouly *et al.* (2018), a chipless RFID tag compliant with RF emission regulations has been proposed for temperature sensing, where a Rogers RT/Duroid 6010.0LM dielectric substrate is used as a transducer. The tag is based on a C-folded

scatterer with embedded slots operating only in allowed bands: European Telecommunications Standards Institute (ETSI) RFID band and Industrial, Scientific and Medical (ISM) 2.5 GHz and ISM 5.8 GHz bands. In Lu *et al.* (2018), a high-temperature chipless RFID tag based on a gold (Au) microstrip slotted patch has been proposed, where an alumina substrate is used as a transducer. The working range of this proposed sensor is 25–800°C with an average sensor sensitivity of 101.94 kHz/°C.

For the detection of fluid level, in Guillet *et al.* (2012), coplanar stripline (Garg *et al.* 2013, Chap. 7) based C-folded scatterers have been used to determine the water level. In this system, C-folded scatterers are pasted on a water container and the level of water is determined by the diminishing resonant peak apexes by filling the water tank step by step. This technique is very promising because the low-cost C-folded scatterers can be printed on the container during the production process.

For the estimation of the permittivity of different materials, in Perret (2016), a chipless RFID technique based on RCS measurements has been proposed for the first time. Similarly, in Costa *et al.* (2018b), two 45° dipole-based chipless RFID tags have been used to estimate the permittivity of different materials. This proposed technique can also be used for monitoring changes in the electrical properties over time. In Lázaro *et al.* (2018), a chipless RFID tag based on an FSS loaded with printed capacitors has been proposed to estimate the permittivity of the material to which the tag is attached. The main application of this chipless sensor tag is to monitor civil structural health.

For strain and crack sensing, in Vena *et al.* (2014a, 2014b), an SRR-based inkjet-printed chipless RFID tag on a polyimide substrate has been proposed. In this chipless sensor, deformations in printed strips due to applied strain produce amplitude variations in the RCS. This variability is used for strain and crack sensing. In Marindra and Tian (2018), a chipless RFID tag has been proposed to detect and characterize cracks in metallic structures. This sensor tag is based on four dipoles along with a circular microstrip patch antenna (CMPA) resonator, where the orientation and width of cracks can be detected using the behavior of shifts in the peak apexes associated with resonators.

For sub-millimeter displacement sensing, in Perret (2017), the phase of the backscattered signal from a chipless RFID tag has been exploited. This

proposed system has shown that displacements of the object can be detected using chipless RFID with a possible resolution of less than 1 mm, even in a realistic outdoor environment with the surrounding objects or obscured by opaque objects. This feature of displacement sensing has been added to the predesigned chipless RFID tag for identification applications (see Figure 1.3(c) and (d)) without compromising the coding capacity.

For gesture recognition, in Barbot and Perret (2017), a human–computer interaction system has been proposed to detect and localize a human finger on a chipless RFID tag. In this system, a dielectric paste is placed on different scatterers on a chipless RFID tag, and the position of the dielectric paste can be detected by the presence or absence of the peak apexes associated with the resonant scatterer. This feature of gesture recognition has been added to the predesigned chipless RFID tag for identification applications (see Figure 1.3(d)) without compromising the coding capacity.

For 2D localization sensing, in Hu *et al.* (2010), a chipless RFID tag based on a coplanar waveguide-fed monopole antenna has been proposed. Then, tag detection and localization have been demonstrated using a differential delay-and-integrate receiver. In Anee and Karmakar (2013), three different antennas have been used to localize the chipless tag by analyzing the early-time response (structural mode) using the trilateration algorithm. In Rezaiesarlak and Manteghi (2014b), a cellular technique has been used, where each cell has a triangular geometry with three antennas at the vertices. Then, chipless tags are localized by calculating the roundtrip time by applying the narrow-frequency matrix pencil method to the early-time response (the structural mode in the frequency domain). In Barbot and Perret (2018), the phase offset of the backscattered signal from a known position to an unknown position has been exploited to localize a chipless RFID tag (or the object to which the tag is attached) on a 2D plane. In this system, a simple search method (multilateration algorithm) is used to localize the chipless tag with an accuracy of less than 4 mm. This feature of localization is added to the predesigned chipless RFID tag for identification applications (see Figure 1.3(d)) without compromising the coding capacity.

Finally, this book discusses a novel aspect of the chipless RFID technology that is extended to the chipless authentication. The basic idea of the proposed chipless authentication can be explained by the arrangement of paper fibers. Figure 1.5 shows the scanning electron microscope (SEM) photograph of an ordinary paper. The unique arrangement of paper fibers

naturally occurs during the realization process. Copying such a naturally occurring pattern in an exact manner is virtually impossible. Similarly, Figure 1.6 presents an overview of the chipless authentication concept. Any two RFID tags developed using the same digital design (e.g. film mask for printed circuit board (PCB) chipless tags) will show process variations in their geometrical dimensions. These variations can be:

- the non-systematic over- or under-etching in the case of the PCB;
- the randomness of ink drops in the case of inkjet printing.

These independent variations can produce unique signatures that can be used for authentication. A comparison among the signals from the same device will produce a theoretical value of similarity level equal to 1. Moreover, a comparison between two different devices will produce a theoretical value of similarity level equal to 0.

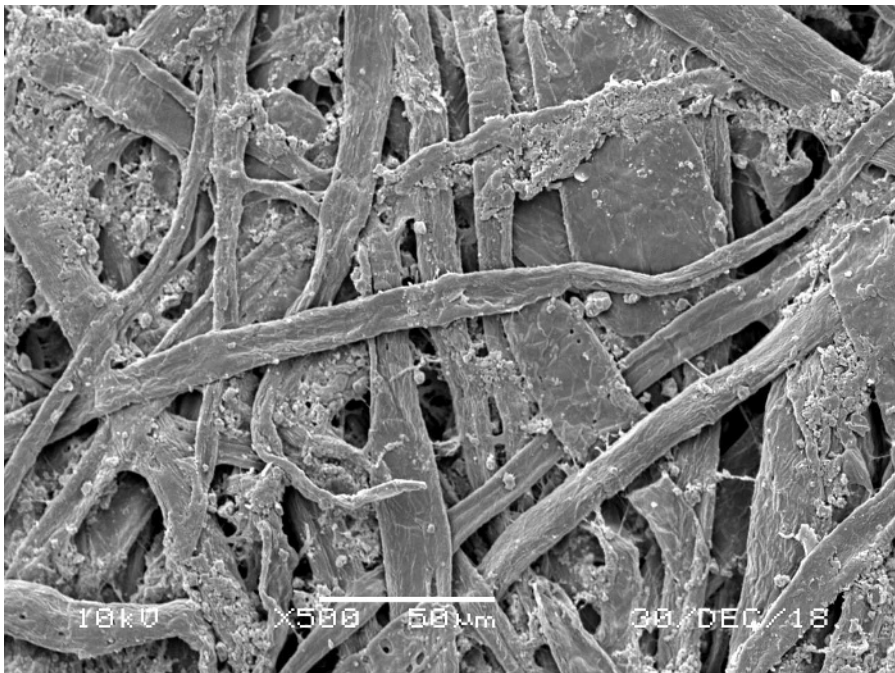


Figure 1.5. SEM photograph of a normal paper. For a color version of this figure, see www.iste.co.uk/ali/RFID.zip

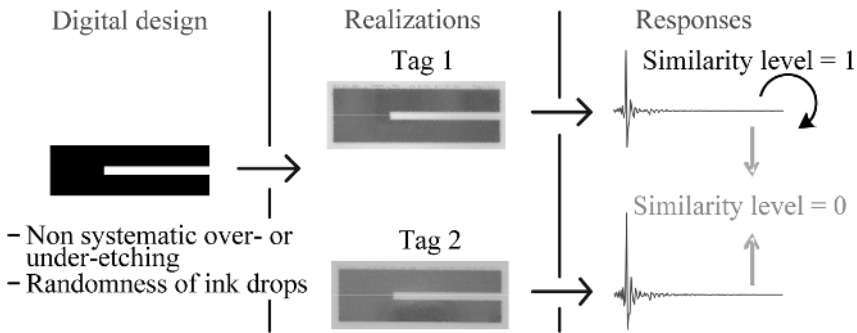


Figure 1.6. Overview of the chipless authentication concept

1.4. Authentication

Anti-counterfeiting and authentication techniques are widely used in the industry to evaluate the authenticity of the products. Various techniques ranging from less secure visible markers (e.g. labels) to highly secure biological elements (e.g. DNA – deoxyribonucleic acid) are currently being used. The robustness of an authentication technique can be defined as follows:

- highly secure;
- non-invasive or non-intrusive operation;
- difficult to duplicate;
- simple in operation;
- low cost;
- ease of fabrication.

The development of robust authentication techniques remains a challenge because of the numerous requirements mentioned above.

This book is focused on taking the next step with the aim of developing chipless tags for authentication applications. The concept of chipless RFID is extended to authentication where each tag has to present a unique signature that can never be reproduced even if someone tries to copy the tag.

For this purpose, natural randomness (i.e. inherent in the fabrication process) along the dimensional parameters of resonators is used. Such natural randomness can produce unique electromagnetic (EM) signatures that can be used for authentication.

1.5. Conclusion

In this chapter, the chipless RFID technology and its sub-branches were briefly explained. In addition, the recent developments and advancements from the literature in the field of chipless RFID technology were summarized. Finally, the challenges of the development of robust authentication techniques were discussed.

