1

INTRODUCTION

The area of contactless identification systems is growing rapidly into a multi-billion dollar market. It covers a broad range of applications including supply chain management, manufacturing, and distribution services. Examples of these applications include consumer packaged goods, postal items, drugs, books, airbag management, animal tracking, pharmaceuticals, waste disposal, clothes, defense, smart tickets, people tracking such as prisoners, hospital patients, patients in care homes, and leisure visitors as shown in Figure 1.1. Tough trading conditions due to the global competition strive industries to attain more process efficiencies. Therefore, effective goods tracking systems are required to assist the implementation of the modern management system.

In general terms, any application that involves object identification, tracking, navigation, or surveillance would benefit from an identification system. Several hundred billion tags per year are required by this wide area of applications [1].

In this market, every application has its own technical and financial specifications. Main applications, those that need a huge number of tags, require high data encoding capacity and survive only with a very cheap tag solution. For others, secure identification and antitheft tagging is more important. In some cases, the tag size is a key factor and for some others proper identification of highly reflective items such as liquid containers or metal objects is of more importance. Reading range would be another imperative factor for many applications.

Advanced Chipless RFID: MIMO-Based Imaging at 60 GHz–ML Detection, First Edition.
Nemai Chandra Karmakar, Mohammad Zomorrodi, and Chamath Divarathne.

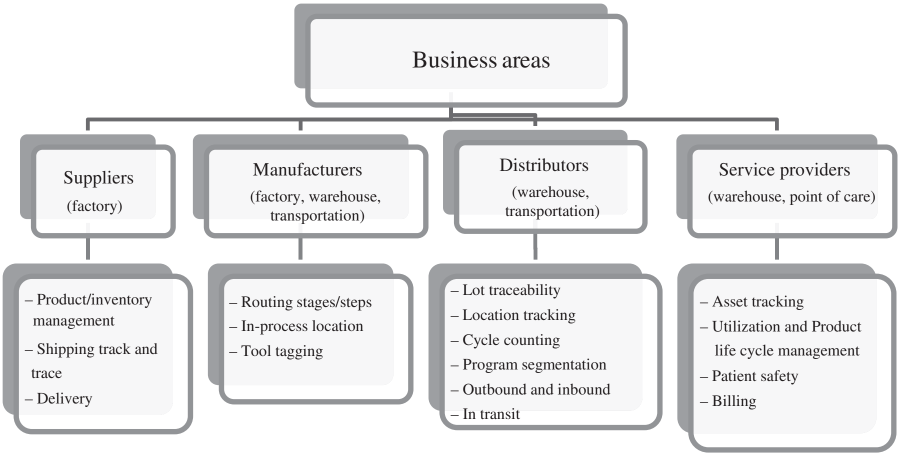

Figure 1.1 Application areas of identification systems.

Irrespective of all priorities, there are two main factors that significantly matter in all applications: the *data encoding capacity* and the *system cost*. For applications with millions of items for tagging, high data capacity of the identification system is a must. For applications with a limited number of objects, high data encoding capacity would be also beneficial to secure the identification process or provide higher reading reliability by sacrificing some of the available bits. The cost reduction is the main initiative for the usage of identification systems in industry; hence, the cost of the identification system and its tagging price must be low and competitive enough to initiate the request for the system. Otherwise, there would be no demand for such systems.

The cost of identification systems, like any other broadcasting service, has two parts: the reader and the tag. The reader cost is normally a fixed cost irrespective of the number of tags. However, the price of the tag attached to every individual item is the most costly part of the whole system. Specifically when the number of items is in the order of millions, the tag price plays a major role in the system's total cost. For such applications, a tag price of only $1 would increase the total cost of the system to a level that restricts the usage of identification systems. Therefore, the tag price should be kept as small as possible to offer a reasonably low identification system cost.

1.1 BARCODES AS IDENTIFICATION TECHNOLOGY

Barcode is an optical-based, machine-readable technique for identification purposes. It has been established in various industries for many decades with proven applicability. Barcode provides an *extremely low-cost* solution for identification of items to which it attaches. Originally, barcode are comprised of many parallel printed dark lines. The tag's data are systematically represented by varying the widths and

Figure 1.2 Data encoding limitation of a 1D barcode tag due to diffraction effect.

spacing of those parallel lines. This type of barcode, dominant in many applications, is normally referred to as linear or one-dimensional (1D) barcode. Data encoding capacity of the barcode tag is restricted by the diffraction of light through the edges of the lines, the reader sensitivity, and the reading distance, as shown in Figure 1.2. Diffraction restricts the minimum detectable line width as well as the minimum distance between two adjacent lines. This means that for increasing the data encoding capacity of the barcode, the only way is to increase the length of the tag. As the data encoding capacity of barcodes is proportional to the tag's size, it may result in an unreasonable tag size for many applications. This issue is considered as the main limitation of the barcode systems. The 1D barcodes have evolved into rectangles, circles, dots, hexagons and other two-dimensional (2D) geometric patterns to enhance the data encoding capacity. This has resulted in new machine-readable optical labels known as quick response (QR) code. QR codes use four standardized encoding modes to efficiently store data. The maximum storage capacity of QR codes can be up to 7000 characters, which is better than that of barcodes [2]. However, barcodes and QR have many operational limitations. They are very labor intensive as every tag needs to be read/scanned individually. Moreover, being an optical-based system, a clear line-of-sight (LoS), known as optical LoS, is also necessary for proper reading. This means that the tag shall be always printed and exposed on the products and the scanner requires clear optical LoS to read the barcodes or QR codes. Barcodes inside clear polyethylene bags cannot be read due to the light reflection of the bags. Any damage or dirt on the barcode results in improper reading. The reading distance between the optical scanner and the tag is also limited when considering the light dispersion/attenuation in free space and diffraction effect on the tag surface. Normal reading distance in optical systems is limited to few centimeters. Moreover, barcode is not a secure means of communication as tags can be easily reproduced by a cheap inkjet printer. The reading errors of barcodes depend on applications and many industries lose billions of dollars as compensations and damages each year. For example, optical barcode-based luggage handling has approximately 20%

reading errors and airlines are paying more than $2 billion/year as compensations to passengers.

To address positive aspects of barcodes, no doubt a very cheap tag solution and proven applicability in identification systems are the most important factors. Its few cents tagging solution is very attractive for many applications, specifically for industries with millions of products. Being accepted globally for almost half a century also provides it a unique superior opportunity that makes it very difficult for other technologies to compete. The globally accepted international barcode quality specification standards, ISO/IEC-15416 (linear) and ISO/IEC 15415 (2-D) [3], and no privacy issues involved with the barcodes usage are highly regarded by many users.

Moreover, barcode systems provide a fairly good reading accuracy that is almost comparable with what other new techniques are offering [3]. Another good aspect of the barcode is that the accuracy of the reading process is almost independent of the items on which tags are placed.

1.2 RFID SYSTEMS

The usage of light waves as communication mean in the barcode systems causes many technical and operational limitations as discussed before. As an alternative approach, the use of EM waves for identification and tracking of objects was first proposed by Watson-Watt in 1935 [4] and coined as the radio frequency identification (RFID) system. In an RFID system, the reader sends an electromagnetic (EM)-wave interrogating signal toward the tag. This signal is then processed by the tag's microchip unit and backscatters the signal toward the reader. This backscattered signal carries the tag identification information and is received and processed by the reader to retrieve the data.

Figure 1.3 shows the generic configuration of the RFID system. As the EM wave is not obstructed by barriers, the system does not need a LoS link between the reader and tag. This provides a number of opportunities for an RFID system. For example, the tag may hide inside the item and not necessarily be exposed on the object as the barcode system does. Moreover, many reader antennas are omnidirectional; hence, they can detect tags irrespective of their position with respect to the reader. Multiple

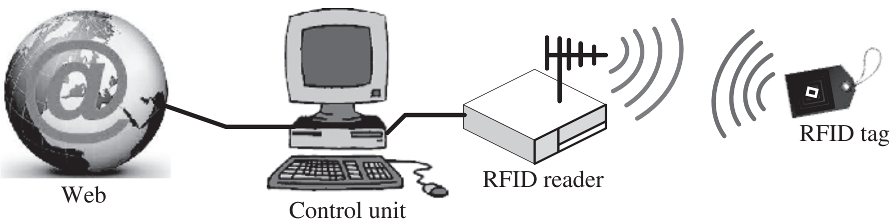

Figure 1.3 RFID general system structure.

tag reading is also feasible in an RFID system, bulk detection scenario. The RFID reading distance may be much greater than that of barcodes as the EM waves are much less attenuated in free space than light waves. The more attractive part of an RFID system is its higher data encoding capacity, which is not comparable to the barcode, as the data are encoded by a microchip. Moreover, many security codes can be easily manipulated inside the microchip to provide more secure communication.

1.3 BARCODES VERSUS RFID

Optical-based identification systems, barcodes and QR codes, and RFID systems all have their own advantages and limitations. This means that each system would be suitable for different purposes and under different circumstances. Although the majority of users still consider barcode systems as the most cost-effective way to handle the circulation and inventory management of equipment, the indication of changing market occurred in 2003, when Walmart adopted and mandated RFID tagging for all its suppliers. Walmart's motto of mandating RFID is to obtain seamless information from the manufacturing point to the ends of sales when the goods are sold and the boxes are crashed. There are numerous discussions and studies in industry and academia about the suitability of these three systems [5–9]. It is almost agreed that there is no clear superiority of one technology over others when both the cost and operational flexibility are considered simultaneously. In general, it is upon each specific industry to select the most suitable technology based on their needs and budgets. The benefit of barcode technology comes from their low-cost implementation. It is well established in industry and has fairly enough content capacity for many industrial and commercial applications. QR codes offer higher data encoding capacity while working almost on the same basis as barcodes. RFIDs are popular and more appropriate technology than barcodes for many industries as it can provide higher content capacity and much more operational flexibilities. For example, Cisco recently announced its new idea of Internet-of-everything (IoE) based on RFID systems [10]. However, conventional RFID systems are associated with limitations too. The main issue for RFID is that many industries cannot afford the system cost. To mitigate the potentials of RFID systems to compete with optical barcodes and being accepted by more applications, it is required to reduce the cost of the RFID tag to a level similar to optical barcodes, say less than a cent. A fully printable tag that is still able to provide the same or higher data encoding capacity compared to 1D barcodes with more operational flexibility would be highly welcomed by industries. A fair comparison among barcode, QR codes, and RFID systems is provided in Table 1.1.

1.4 CHIPLESS RFID TAG FOR LOW-COST ITEM TAGGING

As addressed in the previous section, RFID systems show many technical and operational superiorities over barcodes and, therefore, are suggested as the most promising technique for barcode replacement. However, to date, this has not

TABLE 1.1 Barcode, QR codes, and RFID [8,9]

	Data Capacity (max)	Tag Cost (¢)	Reading Speed	Unique Advantage	Operational Limitation	Reading Distance
Barcodes	20 bits	0.5–1	Relatively quick	Cheap and accurate	Optical LoS	Few centimeters
QR codes	7000 characters	1	Relatively quick (depends on device)	Versatile	Optical LoS	Few centimeters
RFID	4 million characters	>30	Very fast	Many technical superiorities	EM LoS or NLoS	Tens of meters

happened for main applications with billions of yearly tag requirements because of the higher cost of the RFID system. The RFID system cost mainly depends on its tag expense like any other broadcasting system. The total cost of identification system is mainly governed by the tag's cost only when the tag number is significant. Normally, the reader system does not contribute significantly in operational cost as it is a fixed cost.

$$\begin{aligned}
&\text{System cost} = \text{fixed cost} + N \times \text{tag cost}\\
&N:\ \text{number of tags; fixed cost} = \text{reader electronic} + \text{middleware costs}\\
&\text{if } N \to \infty\\
&\text{then}:\ \text{total system cost} \approx \text{tag cost} \times N
\end{aligned} \quad (1.1)$$

In RFID systems, every tag needs a silicon chip to encode data. This results in an RFID tag cost that is many times more expensive than the barcodes. Significant investments and research have been spent on lowering the price of microchips to less than a cent and thus make it comparable to that of barcodes. However, the application-specific integrated circuit (ASIC or IC for short) design and testing along with the tag antenna and ASIC assembly still result in a costly manufacturing process [11–13]. Furthermore, as the price of every silicon chip directly depends on its size on the wafer, the minimum predictable cost of an RFID chip with the quantity of billion cannot be less than 5¢, which is still not competitive with 1¢ tag price of barcodes [11,14]. Despite all recent improvements in silicon chip technology, silicon chips remain too expensive to be part of every RFID tag [15]. Considering the minimum predictable cost of a chipped tag, the total cost of an RFID system in applications with millions of tagging requirements would be much higher than that of barcodes. Therefore, the price of chipped RFID tags remains as the first and foremost hurdle for their deployment in applications with low product costs, for example, groceries. Based on the company's potential and system affordability, the relation between the tag cost and its volume is shown in Figure 1.4 [1]. Based

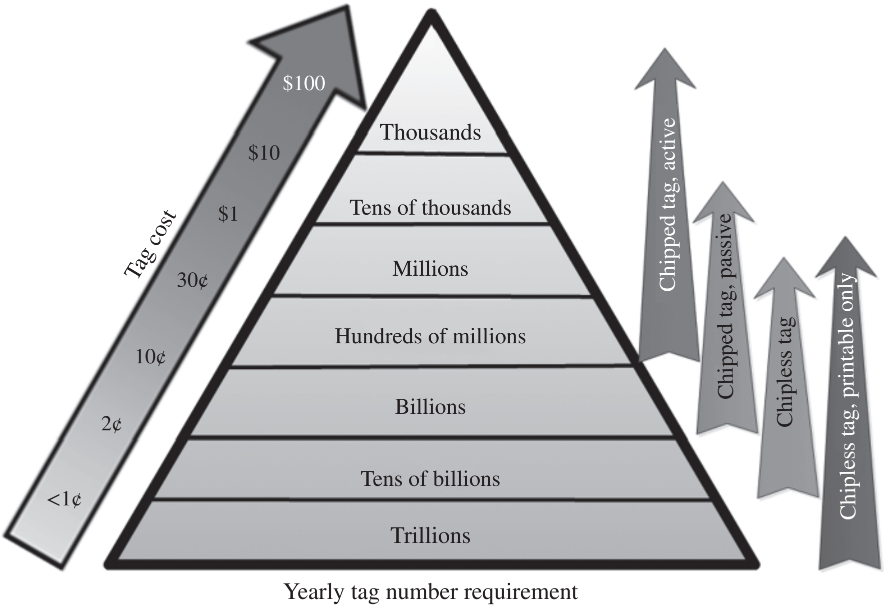

Figure 1.4 Expected tag volume versus tag cost. *Source*: IDTechEx [1].

on this model, the RFID tag cost would be a large barrier in organizations with high tagging requirements. Therefore, RFID tags without a chip, named as chipless tags, appear to be necessary for the commercialization of RFID systems in main applications with billions of yearly tag requirements [1]. As shown in Figure 1.4, the chipless tags are necessary to satisfy the requirements of medium- to large-sized organizations, with a tag price to be down to 1¢. Although the chipless tags eliminate the need for the silicon chip, the most expensive element of the tag structure, there are other factors that may surge the tag cost. The tag fabrication process, the requirement of tag to be affixed with other costly elements rather silicon chip, and their installation procedure may elevate the tag cost higher than the targeted value of 1¢, radiofrequency surface acoustic wave (RFSAW), for example [16]. Therefore, based on the worldwide well-accepted model, the main stream industries with billions of yearly tag requirements will only be satisfied through a *fully printable chipless* tag structure. Any technique or suggested solution for a chipless RFID system must consider this critical point of the industries for a printed tag; otherwise, the proposed technique finds no place in the identification market or at least in main stream industries.

However, the way the data can be encoded in a fully printable chipless tag is a big challenge that opens a new area of research. To date, many techniques and approaches have been proposed for a data encoding scheme in a chipless tag structure [11,17–19]; however, very few products are available on the market.

1.5 CHIPLESS RFID SYSTEMS

Reducing the RFID tag price to below 1¢, printable chipless tags appear to be the only solution. There are many proposed techniques in the open literature on designing a chipless and passive tag structure with the mandated data encoding capability for identification purposes. This section mainly focuses on reviewing those techniques and approaches and exploring their potential advantages and limitations.

The communication between the RFID reader and the tag is accomplished through the use of EM waves. For the RFID chipless systems, the tag does not require any processor unit; hence, all the reading and coding processes are accomplished in the reader. The basis of the chipless system is that the reader receives the tag's backscattered signal in different domains and processes the signal in different domain to retrieve its encoded data. This leads to the time-domain-based, frequency-domain-based, phase-based, or hybrid systems [20–22]. Figure 1.5 shows the classifications of the chipless RFID systems that are reviewed in this section.

1.5.1 Time-Domain-Based Chipless RFID Systems

In a time-domain-based system, the reader interrogates the tag with a series of pulses [23,24]. The tag then retransmits the signal as a train of echoes with some time delays with the data encoded in the delayed responses. Manipulation of the delays can be handled directly on the EM waves domain. It is possible to convert the EM wave to another type of medium, acoustic wave, for example, and then delays are deployed in the signal. After manipulation of the data as delayed responses, the EM wave is retransmitted to the reader. When an alternative medium is used for data encoding purposes other than the EM wave, extra elements are needed for conversion [25]. For instance, in the surface acoustic wave (SAW) technique, the interdigital transducer element is used to convert an electromagnetic wave into a mechanical wave, which travels much slower than EM waves. This surface acoustic wave propagates through a piezoelectric element and then it is reflected back by a number of reflectors toward the reader. The requirements for extra elements in the SAW system elevate the tag

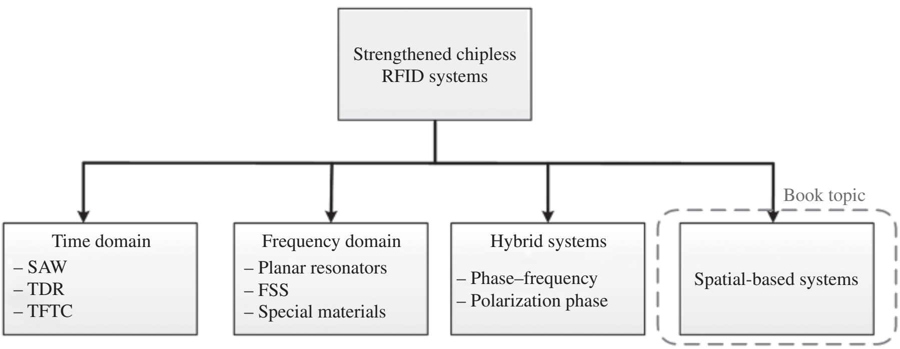

Figure 1.5 General classifications of chipless RFID systems.

price. Lowering the tag cost in time-domain-based systems mandates a printable tag structure without conversion of EM waves to other types of media. In this approach, the tag operates on the time-domain reflectometry (TDR) principle. The TDR tag normally consists of different types of transmission lines with multiple discontinuities [23,24,26–28]. Every discontinuity creates a reflection in the passing signal that shall be detected by the reader as the encoding technique. This approach provides the planar version of the tag structure; hence, a very low tag cost expectation through direct printing is claimed to be feasible. There are, however, some basic limitations that restrict their usage in real scenarios. Considering the much higher speed of EM waves than mechanical/acoustic waves, the required circuit size is remarkably large in creating detectable delays in the backscattered signal. For example, almost an $80 \times 30\,\text{mm}^2$ board size is required to encode only 4 bits of data, with the tag size rapidly increasing with a higher amount of data [24]. Moreover, the claimed 4-bit capacity is also based on the fabricated tag structure with PCB technology, and no information on the printed tag using conductive ink on paper were declared. The structure also includes some via holes that are not possible to mount on the commercial tag structure that is fully printable. In another work, the use of a transmission line of 2 m is reported to have a 4-bit coding capacity [29], which results in a tag size of $112 \times 53\,\text{mm}^2$ while the FR9151, Dupont was used as the substrate. The tag also includes the ground plane that increases the tag cost. No information was revealed on the performance of such a printed tag. There are some techniques proposed by other researchers to decrease the tag size in time-domain-based systems; however, the total performance of the system was significantly degraded [30,31].

In summary, it can be concluded that the time-domain-based systems have major limitations in tag cost reduction and on providing enough data encoding capacity in a reasonable tag size. Although SAW tag, the most successful chipless RFID product available in the market [32], is time domain based, it appears that the main application of RFID systems will not be solely satisfied by the time-domain-based approaches.

1.5.2 Frequency-Domain-Based Chipless RFID Systems

The reader in a frequency-domain-based RFID system normally interrogates the tag with a wide band signal. The interrogation signal is reflected back toward the reader, while specific resonances based on the tag structure are manipulated in the frequency domain of the backscattered signal. Alteration of the frequency domain of the interrogation signal is normally known as the tag's frequency signature. This process is figuratively shown in Figure 1.6. The reader then extracts the encoded data on the tag structure based on the detected resonances of the tag frequency signature [17,33,34]. To create specific resonances on the frequency domain of the interrogation signal, there are different types of approaches:

(i) Planar structure resonators [17]
(ii) Frequency-selective surface (FSS)-based resonators [35,36]
(iii) Special materials usage for resonant purposes [37–42].

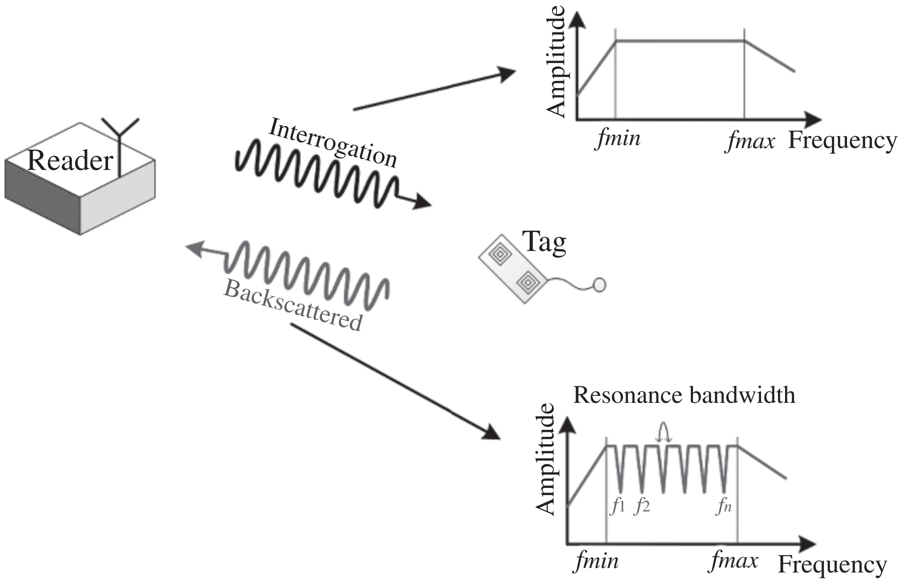

Figure 1.6 Working basis of the frequency-domain chipless RFID systems.

1.5.2.1 Planar Structure Resonators Jalaly and Robertson [43] proposed some RF barcode-type structures for data encoding. The structure is composed of planar dipoles, similar to barcodes that resonate at different frequency bands. To enhance the content capacity of the tag, it was proposed to use all available industrial, scientific, and medical (ISM) radio frequency bands. Based on the proposal, every ISM band is capable of encoding a maximum of 5 bits. This expectation is based on simulation results. The precisely fabricated tag on the Taconic-TLY ($\varepsilon_r = 2.2$) substrate creates detectable resonances. However, based on the simulation results, the occurred resonances have 4–6 dB resonance deep that would be difficult for detection purposes in real scenarios. It is very obvious that the same structure is not capable of creating detectable resonances if the tag is printed on a lossy paper substrate with low conductive ink. Moreover, system reliability decreases when multipath and clutter interferences are considered. The effect of printing inaccuracy on the length of the dipoles, which creates a resonance shift, is also another factor that affects the consistency of the system performance.

Microstrip spiral resonators were proposed to create sharp resonances on the frequency domain of the backscattered signal [17]. The chipless tag also comprises a cross-polarized transmitting and receiving microstrip ultra-wideband (UWB) disk-loaded monopole antenna. It was shown that the system is capable of encoding up to 35 bits at 4 GHz frequency bandwidth. This is a significant success in the content capacity of the chipless RFID systems. However, certain circumstances were considered for the measured data capacity. First, the tag was fabricated through a costly process using the printed circuit board (PCB) technology on the low loss material of Taconic TLX-0 ($\varepsilon_r = 2.45$). Moreover, the printed tag with conductive ink on a paper base will experience significant Q-factor drop due to the printing errors, high loss of the paper, and low conductivity of the ink. These factors may limit the actual data encoding capacity of the proposed structure. However, the proposed idea in this work suggests a wide range of potentials for chipless RFID systems.

Fractal structures, as the load section of a wideband monopole antenna with encoding capability, were proposed by Balbin [44]. Based on the type and length of the fractal structures, multiple resonances would be detectable in the backscattered signal. However, due to the complex coupling behavior among the branches of a fractal structure, the resonance frequencies alteration seems to be unpredictable. This may restrict the actual usage of the fractal structure for the RFID applications. Moreover, in the proposed work, the behavior of precise fabricated structures was only considered and there was no study on the printable version of the fractal resonators. Considering the very tiny and complex shape of fractal structures, it is expected that printing issue may cause more complexity on the frequency resonances of the tag. No further results have been reported on the fractal resonators for the RFID applications.

Using split ring resonators (SRRs) was also proposed for the data encoding purposes on the chipless RFID systems [45]. The proposed tag structure was printed on the polycarbonate ($\varepsilon_r = 3.25$) material and measured on the frequency range 8–12 GHz. The tag was capable of encoding 4 bits of data on a 4 GHz spectrum bandwidth. The authors suggested using waveguide antennas to create a small illumination zone. By repeating the SRRs on the tag surface, more encoding capacity would be feasible. The proposed technique would be suitable for security of credit/personnel cards. However, due to the low encoding capacity, the proposed approach is not practical for identification purposes.

As an advanced approach, the usage of complex natural resonances was proposed to enhance the content capacity of a chipless RFID system [46]. Based on the singularity expansion method (SEM), complex natural resonances are aspect-independent parameters that include some structural information of the scattering target. This technique suggests encoding of up to 24 bits in a small area of $24 \times 24\,\text{mm}^2$ that would be an extensive encoding enhancement compared with other available approaches in the chipless RFID systems. However, the system requires complex signal processing as multiple switching between time and frequency domains are required to decode the tag's content. Moreover, the performance of the printed tag was not shown in the proposed communication. The limited conductivity of the conductive ink and high loss tangent of the paper significantly changes the poles' positions of the tag responses; hence, the proposed data encoding scheme is challenged. In addition, the tag structure is very tolerance dependent as it comprises the line width and gaps in submillimeters (0.2–0.7 mm). This precise structure cannot be manipulated successfully through commercial printing facilities for low-cost tag production purposes. The effect of printing inaccuracy was not also considered in the proposed approach. However, the SEM approach opens up a new area of research for chipless RFID systems and may be combined with other conventional techniques for enhancing their potentials for massive commercialization.

1.5.2.2 Frequency-Selective Surface-Based Resonators Frequency-selective surfaces (FSSs) are constructed as the rows and columns of a particular resonant structure designed to perform a (or a combination of) low-pass, band-pass, high-pass, and band-stop filtering functions on the incident plane wave passing through, in a measurement known as “transmittance” [43,47]. Although barcodes and RFID systems are reflection-based structures, sometimes the FSS are used for creating resonances in the reflection direction and hence are suitable for RFID applications.

Costa *et al.* [35] proposed the usage of high-impedance surface-based multiresonators. The structure is based on a finite metallic FSS comprising of several concentric square loop resonators. The reported tag structure occupies an area of $45 \times 45\,\text{mm}^2$ and is capable of encoding 5 bits of data content. Therefore, the data encoding density is $0.25\,\text{bit/cm}^2$, which is very low considering the requirements of the main RFID applications. The tags are readable from 55 cm distance with 0 dBm transmit power. The system had a good performance for different tag orientation scenarios. However, the system needs a calibration measurement process for proper reading to cancel out the effect of multipath interference and the effect of antennas; otherwise, the system fails to read and detect the tag’s data. Moreover, all measured data in the published work is based on the fabricated tag structure with PCB standards on an FR4 substrate. No result based on the printed tag structure was revealed.

In another work, a stacked multilayer patch antennas is used as an all-pass network to provide more robustness with respect to multipath and clutter interferences [36]. In the proposed theory, instead of relying on an amplitude–frequency response of the multilayer structure, the phase–frequency response is considered. A three-layer structure with an area of $18 \times 18\,\text{mm}^2$ is able to decode 2 bits of data content based on the simulation results. No measurement of the proposed tag structure was shown. However, the performance of the proposed structure is directly linked to the conductivity and loss tangent of the substrate. This suggests that the printed tag may show significant performance degradation with respect to the simulation result. Moreover, printing of a three-layer structure increases the tag fabrication cost and may not meet the low-cost expectation of the RFID tag for the main industries.

1.5.2.3 Material-Based Resonators CorssID [37], a telecommunication company, has reported developing a chipless RFID system that provides a reliable authentic approach for valuable documents, such as intelligence agency reports, financial securities, and banknotes. The system uses “nanometric” materials, tiny particles of chemicals with varying degrees of magnetism, that resonate when bombarded with electromagnetic waves from a reader. Each chemical emits its own distinct radio frequency, or “note,” that is picked up by the reader, and all the notes emitted by a specific mix of different chemicals are then interpreted as a binary number. Since the system uses up to 70 different chemicals, each chemical is assigned its own position in a 70-digit binary number [37]. No further information about the working prototype and its applicable tag cost has been released since it was introduced in 2004.

In 2007, Somark Innovation declared that it has a special readable ink as a chipless RFID tag that can be used to track animals, for example, cattle, or even human beings. No further discussion is disclosed by the company and no information is also available on its encoding capacity or the ink (tag) cost [38,39].

A fair comparison among different chipless RFID system techniques with or without metamaterials are provided by Mandel *et al*. [41]. In this communication, various approaches were studied in terms of their merits, frequency band usage, and tag size for one bit of content; then they concluded that the metamaterials can shrink the tag size hence enhancing the merits of the structure. Although in their study the time- and frequency-based systems were considered with the application of metamaterials, no information about the tag cost utilizing metamaterials was provided.

1.5.3 Phase-Domain-Based and Hybrid Chipless RFID Systems

Phase-domain-based system is proposed as a method of data encoding to rely on the phase information of the backscattered signal. In one proposal, the tag consists of some plurality of antenna elements with different dimensions and orientations that provide polarization and phase information [48]. The interrogator device scans the area and uses radar imaging techniques to create an image of the scanned scene. The reradiated RF signals of the tag preferably include polarization and phase information of each antenna element. The proposed tag shapes are presented in Figure 1.7 with dipoles of different length and width. Four different orientations are suggested for each antenna size at angles 0°, ±45°, and 90°, which control their particular phase and polarization responses. It has been also proposed to use some reflective rectangles with two (or more) reactive stub loading that are extended from rectangle antennas. One is perpendicular to the antenna and the other is parallel to the antenna polarization. In this case, the length and position of the reactive stub elements control the phase and polarization parameters of the reflected signal, respectively. It is claimed that the proposed system has the ability to read and track chipless tags 100 m away

Bow-tie dipole elements

Rectangular reactively loaded patch

Figure 1.7 Phase-domain-based chipless RFID tags.

and to read thousands of tags per second [1,48]. However, no commercial product is available on the market based on this approach yet. This is probably because the content encoding in RFID systems through phase and polarization is very expensive and sometimes impractical. The phase of the reflection by a given element is dependent on its distance to the reader. This means that a slight bending of the tag surface causes a significant phase shift specifically in higher frequencies. There are suggestions to mitigate the phase ambiguity; however, the solutions only apply to chipped tags for low frequencies, below 1 GHz, and no work is reported on chipless systems [49,50].

As a hybrid-based system, the combination of phase deviation and frequency position of the resonances was proposed as the data encoding approach in a chipless RFID system [19]. The tag consists of multiple "C"-shaped resonators that are interrogated through a wideband signal in the band 2.5–7.5 GHz. The claimed content encoding capacity is 23 bits with five "C"-shape resonators. The encoding is based on a matrix of frequency and phase shift deviation. However, the tag was tested in the anechoic chamber and no further discussion was communicated to explore the effect of multipath interference on the system performance. This would be an important aspect of the proposed approach as the reflection from other objects will cause significant effects on the phase shift. There is a need for premeasurement of the scene to calibrate the system as well. This means that the system is vulnerable to errors if any changes happen in the surrounding area of the tag. Moreover, the performance of the tag is not clear regarding to the bending effect. The performance of a real printed tag structure was also not discussed.

In another work, the amplitude- and frequency-based encoding scheme is proposed as a new encoding approach for enhancing the content capacity of the chipless RFID systems [51]. The SRR is the proposed resonator type, and based on the received signal level and the position of the resonances, the data can be encoded. Although the system content capacity is increased, the system complexity and also its sensitive performance toward noise and multipath interference may prevent its actual usage.

1.6 SPATIAL-BASED CHIPLESS RFID SYSTEM

A quick review of the identification technologies, mainly barcodes, QR codes, and RFID systems (chipped and chipless), shows that the market is still waiting for a product meeting all requirements of the industry. While the optical systems, barcodes, and QR codes are suffering from many technological limitations, the chipped RFID systems are not able to reduce their tag price to an acceptable level by industries for main applications. Chipless RFID systems have also limitations on providing a reliable approach for data encoding based on a real printed tag structure with subcent expense. In this situation, any suggestion that fulfils all or main parts of expectations would be welcomed by industries. The new technique of spatial-based system has potentials and abilities that may attract many involved parties in identification field. Moreover, the proposed technique may be combined with other conventional techniques in chipless RFID systems to complement them for a more practical system.

In the spatial-based technique, the tag surface is scanned very precisely by the reader antenna to provide a fine image resolution. Hence, each small section of the tag surface may independently encode the data. The tag is comprised of tiny conductive printable strip or meander lines as EM polarizers. The EM polarizers on the tag surface create a high crosspolar radar cross section (RCS) on the backscattered signal while being interrogated by a linearly polarized signal. The reader utilizes two orthogonally oriented arrays of double-side printed dipole (DSPD) antennas [52,53]. The reader may move around the tag to create a synthetic aperture and provide a fine EM image of the tag using synthetic aperture radar (SAR) signal processing. Alternatively, a multiple input and multiple output (MIMO)-based system may be used for the same effect as SAR technique.

In comparison to other techniques in chipless RFID systems, the tag structure is fully passive and printable. The expected tag printing cost is even less than that of barcodes as the tag size in the proposed technique is smaller than the barcodes. The system does not require any calibration or reference tag. Changing the background of the environment around the tag has no effect on the performance of the proposed system. The tag also provides higher data encoding capacity in a smaller tag size as reported to date by other chipless RFID systems [19,27,46]. The system is very robust to multipath and clutter interference as it is a crosspolar-based system. Moreover, the highly reflective items tagged with the proposed tag structure show a very satisfactory result. All printing inaccuracies are also considered in the proposed system and appropriate solutions are suggested.

1.7 BOOK OUTLINE

The book is divided into two main parts. Part I labeled as “EM Image-Based Chipless RFID System” introduces the novel EM imaging concept for data extraction from chipless RFID tag. The EM-imaging technique exploits advantages of flexible non-line-of-sight (NLoS) operation, high data capacity, low-cost advantages, and fully printable features of the barcodes on low-grade packaging materials. Part II entitled “Advanced Tag Detection Techniques for Chipless RFID Systems” presents smart tag detection techniques for existing chipless RFID systems and an innovative MIMO-based tag detection technique for high content capacity and zero guard-band tag detection. These approaches have been fully developed and tested in Monash Microwave, Antenna RFID, and Sensor Research Group (M.M.A.R.S.) at Monash University.

1.7.1 Part I, EM Image-Based Chipless RFID System

In Part I, the fundamental of EM imaging at the millimeter-wave band for data extraction is introduced followed by the SAR technique. It is shown that the millimeter-wave EM imaging has significant potentials for commercialization of chipless RFID. In this pursuit, the system elements and technical requirements are discussed in detail. The proposed approach to the SAR-based EM-imaging technique enhances the content capacity of the chipless systems to a commercial level, for example, EPC Global Class 1 Generation 2 with 64 data bits. A credit card size EM image-based chipless RFID can encode more than 90 data bits at 60 GHz frequency band. Next, the limitation of the conventional SAR is discussed with MIMO system as solution for addressing the drawbacks of the system. Then the MIMO system is optimized through genetic algorithm approach for minimum hardware complexity. Breakdown of Part I is as follows.

The basics of EM imaging are introduced in Chapter 2. The definitions of range and azimuth resolutions are introduced and their relation with the technical parameter of the system is presented. It is shown that for RFID application, the range resolution suggests impractical requirements while the cross range or azimuth resolution provides a meaningful technique for data retrieval of a chipless RFID tag.

The miniaturized EM polarizers are introduced in Chapter 3. The theoretical working basis of the polarizers on resonance and diffraction basis are discussed. The result of simulation and measurement for strip-line- and meander-line-based polarizers are presented. Then the polarizers are fabricated through different techniques and they are compared regarding their performance.

The advantages of the crosspolar working basis is discussed in Chapter 4. First, the system model is provided for studying the reliability of the system toward noise, multipath, and other environmental factors. Then the fabricated tag is measured to confirm the theoretical expectation. This chapter shows the attributes of the crosspolar working basis for the RFID application.

The reasons and advantages of using the ISM band 60 GHz are discussed in Chapter 5. It is shown that the suggested band provides an acceptable reading range for a chipless RFID system, lowers the tag cost to below the barcode level, and finally suggests high data encoding capacity tag structure. In the second part of this chapter, the reader antenna is introduced along with its technical requirements. A fully printed reader antenna is shown including its design, measurement, and results.

Chapter 6 introduces the conventional SAR technique for imaging of the tag. Technical parameters of the SAR approach for chipless RFID systems are derived. Then tag samples with different encoded data are imaged through the proposed approach. The effect of the synthetic aperture length on the image quality is also studied. Then high data capacity tag is considered in the imaging process, which confirms the ultimate ability of the proposed technique for data encoding purpose of the chipless RFID tag. The downsides of the SAR technique are presented at the end of this chapter.

Chapter 7 addresses the limitations of the SAR technique for a practical application of the spatial-based chipless RFID system. It suggests the MIMO technique to provide a solution for the physical movement of the reader around the tag. While the proposed MIMO system is able to replace the conventional SAR technique, it still requires noticeable reader antennas. The mathematical model of the MIMO system is then considered and it is shown that the suggested MIMO system is not optimized. The genetic algorithm is then applied to the MIMO system to provide the same effect as that of the SAR approach with minimum number of reader antennas. The final system utilizing optimized MIMO system is tested and compared with SAR technique to prove the applicability of the proposed system with minimum hardware complexity.

1.7.2 Part II, Advanced Tag Detection Techniques for Chipless RFID Systems

Part II focuses on advanced tag detection techniques for chipless RFID systems based on maximum likelihood. Chapter 8 gives a brief introduction to Part II and a review of the tag detection techniques reported. Chapter 9 involves both SISO and MIMO tag design and experimental verifications of the proposed tag detection techniques. Chapters 10–12 discuss the proposed tag detection techniques for chipless RFID systems. Chapters 10 and 12 present tag detection techniques for SISO- and MIMO-based chipless RFID systems, respectively, while Chapter 11 presents computationally feasible tag detection techniques. Finally, Chapter 13 summarizes Part II and shares the potential applications, future directions, and recommendations.

In Chapter 8, an introduction to RFID systems and the research aims are presented. The first part of the chapter focuses on two areas in SISO chipless RFID systems. First, it reviews the available chipless RFID tag types and identifies the potential candidate tag types for further investigation. Next, the existing tag detection techniques for chipless RFID systems, their limitations, and areas for improvements are listed. Last part of the chapter presents the state-of-the-art MIMO-based chipped RFID systems followed by the major challenges of MIMO-based chipless RFID systems.

Chapter 9: This chapter presents the designing of two chipless RFID tag types for experimental verification of the proposed detection techniques. The first type is a circular resonator-based SISO chipless RFID tag. The tag is printed on a paper film using a printer with conductive ink. Its performance is verified using measurement data. Then a novel MIMO-based chipless RFID tag was designed in CST and the results were presented.

In Chapter 10, four likelihood-based detection techniques have been presented and their performances have been verified using CST and MATLAB simulation. A fifth tag detection technique is developed for an existing chipless RFID reader and its performances are verified using empirical measurements. The superior performances of the proposed tag detection techniques are compared with the existing detection techniques. The disadvantages of these detection methods are identified and solutions to them are presented in Chapter 11.

Two computationally feasible tag detection techniques are introduced in Chapter 11. The first detection technique is a suboptimal bit-by-bit detection (serial bit reading) in contrast to detecting all the tag bits once (parallel bit reading). The next detection technique is based on trellis tree and Viterbi decoding. This detection method can be incorporated into the proposed tag detection techniques in Chapters 10 and 12.

In Chapter 12, a MIMO-based chipless RFID system is proposed and a MIMO decomposing technique is used for separating the tag responses in each branch. Next, an ML-based tag detection technique is introduced to detect the tag bits encoded in each branch. Its performances are evaluated using MATLAB simulations and then further verified using measurement data.

Chapter 13 summarizes the content provided in Part II on tag detection techniques. Finally, future directions of the research and potential applications are presented.

REFERENCES

1. P. Harrop and R. Das, "Printed and Chipless RFID Forecasts, Technologies & Players 2009–2029," *IDTechEx, USA*, 2009.
2. BiQRious. (2015). *QR Code Capacity*. Available: http://qrcodetracking.com/qr-code-capacity/.
3. *IDAutomation group*. Available: http://www.idautomation.com/barcoding4beginners.html.
4. C. Turcu, *Current Trends and Challenges in RFID*, InTech, 2011.
5. T. Lotlikar, R. Kankapurkar, A. Parekar, and A. Mohite, "Comparative Study of Barcode, QR-Code and RFID System," *International Journal Computer Technology & Applications*, vol. 4, pp. 817-821, 2013.
6. E. Arendarenko, "A Study of Comparing RFID and 2D Barcode Tag Technologies for Pervasive Mobile Applications," Master, Department of Computer Science and Statistics, University of Joensuu, 2009.
7. G. White, G. Gardiner, G. P. Prabhakar, and A. Razak, "A comparison of barcoding and RFID technologies in practice," *Journal of Information, Information Technology and Organizations*, vol. 2, pp. 119-132, 2007.
8. Cartman. (Feb 5, 2015). *Asset Tracking: RFIDs, Barcodes or QR Codes?* Available: https://www.webcheckout.net/blog/rfid-asset-tracking/.
9. A. Campbell. (2011). *QR Codes, Barcodes and RFID: What's the Difference?* Available: http://smallbiztrends.com/2011/02/qr-codes-barcodes-rfid-difference.html.
10. Cisco. (Oct 14, 2014). *Internet-of-Everything*. Available: http://www.cisco.com/c/r/en/anz/internet-of-everything-ioe/tomorrow-starts-here/index.html.
11. S. Preradovic and N. Karmakar, "Chipless RFID, Bar Code of the Future," *IEEE Microwave Magazine*, vol. 11, pp. 87-97, 2010.
12. R.R. Fletcher. (2002). *Low-Cost Electromagnetic Tagging: Design and Implementation. PhD thesis*. Available: www.media.mit.edu/physics/publications/theses/97.02.fletcher.pdf.
13. S. Preradovic, "Chipless RFID System for Barcode Replacement," PhD, ECSE, Monash University, 2009.
14. V. Chawla and D.S. Ha, "An Overview of Passive RFID," *Communications Magazine, IEEE*, vol. 45, pp. 11-17.
15. P. Harrop. (2006). *The Price-Sensitivity Curve for RFID*. Available: http://www.printedelectronicsworld.com/articles/the-price-sensitivity-curve-for-rfid-00000488.asp?sessionid=1.
16. C. S. Hartmann, "A global SAW ID tag with large data capacity," in *IEEE Ultrasonic Symposium*, 2002.

17. S. Preradovic, I. Balbin, N.C. Karmakar, and G.F. Swiegers, "Multiresonator-Based Chipless RFID System for Low-Cost Item Tracking," *IEEE Transactions on Microwave Theory and Techniques*, vol. 57, pp. 1411–1419, 2009.
18. T. Singh, S. Tedjini, E. Perret, and A. Vena, "A frequency signature based method for the RF identification of letters," in *2011 IEEE International Conference on RFID*, 2011, pp. 1–5.
19. A. Vena, E. Perret, and S. Tedjini, "Chipless RFID Tag Using Hybrid Coding Technique," *IEEE Transactions on Microwave Theory and Techniques*, vol. 59, pp. 3356–3364, 2011.
20. M.S. Bhuiyan, R.E. Azim, and N. Karmakar, "A novel frequency reused based ID generation circuit for chipless RFID applications," in *Asia-Pacific Microwave Conference (APMC)*, Melbourne, Australia, 2011, pp. 1470–1473.
21. I. Balbin and N.C. Karmakar, "Phase-Encoded Chipless RFID Transponder for Large-Scale Low-Cost Applications," *IEEE Microwave and Wireless Components Letters*, vol. 19, pp. 509-511, 2009.
22. Md. Aminul Islam and N.C. Karmakar, "A Novel Compact Printable Dual-Polarized Chipless RFID System," *IEEE Transactions on Microwave Theory and Techniques*, vol. 60, pp. 2142-2151, 2012.
23. A. Ramos, A. Lazaro, D. Girbau, and R. Villarino, "Time-Domain Measurement of Time-Coded UWB Chipless RFID Tags," *Progress in Electromagnetics Research*, vol. 116, pp. 313–331, 2011.
24. Z. Lu, S. Rodriguez, H. Tenhunen, and Z. Li-Rong, "An innovative fully printable RFID technology based on high speed time-domain reflections," in *High Density Microsystem Design and Packaging and Component Failure Analysis*, 2006, pp. 166–170.
25. V.P. Plessky and L.M. Reindl, "Review on SAW RFID Tags," *IEEE Transactions on Ultrasonics, Ferroelectrics, and Frequency Control*, vol. 57, pp. 14-23, 2010.
26. C. Mandel, M. Schüßler, M. Maasch, and R. Jakoby, "A novel passive phase modulator based on LH delay lines for chipless microwave RFID applications," in *IEEE MTT-S International Microwave Workshop on Wireless Sensing, Local Positioning, and RFID*, Croatia, 2009.
27. S. Gupta, B. Nikfal, and C. Caloz, "Chipless RFID System Based on Group Delay Engineered Dispersive Delay Structures," *IEEE Antenna and Wireless Propagation letters*, vol. 10, pp. 1366-1368, 2011.
28. F.J.H. Martínez, F. Paredes, and G. Zamora, "Printed Magnetoinductive-Wave (MIW) Delay Lines for Chipless RFID Applications," *IEEE Transactions on Antennas and Propagation*, vol. 60, pp. 5075–5082, 2012.
29. A. Chamarti and K. Varahramyan, "Transmission Delay Line Based ID Generation Circuit for RFID Applications," *IEEE Microwave and Wireless Components Letters*, vol. 16, pp. 588-590, 2006.
30. M. Schüußler, C. Damm, M. Maasch, and R. Jakoby, "Performance Evaluation of Left-Handed Delay Lines for RFID Backscatter Applications," in *Microwave Symposium Digest*, 2008.
31. J. Vemagiri, A. Chamarti, M. Agarwal, and K. Varahramyan, "Transmission Line Delay-Based Radio Frequency Identification (RFID) Tag," *Microwave and Optical Technology Letters*, vol. 49, p. 1900, 2007.
32. RF SAW, Inc. (14 July 2014). *RF SAw Inc.* Available: http://www.rfsaw.com.

33. S. Preradovic, I. Balbin, N.C. Karmakar, and G. Swiegers, "Chipless Frequency Signature Based RFID Transponders," in *1st European Wireless Technology Conference,* Amsterdam, 2008, pp. 302-305.

34. D. Girbau, J. Lorenzo, A. Lázaro, C. Ferrater, and R. Villarino, "Frequency-Coded Chipless RFID Tag Based on Dual-Band Resonators," *IEEE Antennas and Wireless Propagation Letters*, vol. 11, pp. 126-128, 2012.

35. F. Costa, S. Genovesi, and A. Monorchio, "A Chipless RFID Based on Multiresonant High-Impedance Surfaces," *IEEE Transactions on Microwave Theory and Techniques*, vol. 61, 2013.

36. S. Mukherjee and G. Chakraborty, "Chipless RFID Using Stacked Multilayer Patches," in *Applied Electromagnetics Conference (AEMC), 2009*, *Kolkata*, 2009.

37. M. Glickstein, "Firewall Protection for Paper Documents," *RFID Journal Internet Article*, 2004.

38. K.C. Jones, "Invisible RFID Ink Safe For Cattle And People, Company Says," *InformationWeek*, 2007.

39. St. Louis, "SOMARK's Chipless RFID Ink Tattoo Field Demo Brings the Company Closer to Launch," 2008.

40. C. Mandel, B. Kubina, M. Schussler, and R. Jakoby, "Group-Delay Modulation with Metamaterial-Inspired Coding Particles for Passive Chipless RFID," presented at the *RFID-TA*, Nice, 2012.

41. C. Mandel, B. Kubina, M. Schüßler, and R. Jakoby, "Metamaterial-inspired Passive Chipless Radio-Frequency Identification and Wireless Sensing," *Annals of Telecommunications*, vol. 68, pp. 385-399, 2013.

42. S. Kim, A. Georgiadis, A. Collado, and M.M. Tentzeris, "An Inkjet-Printed Solar-Powered Wireless Beacon on Paper for Identification and Wireless Power Transmission Applications," *IEEE Transactions on Microwave Theory and Techniques*, vol. 60, 4178–4186.

43. I. Jalaly and I.D. Robertson, "RF Barcodes Using Multiple Frequency Bands," in *International Microwave Symposium Digest, IEEE MTT-S*, 2005.

44. I. Balbin, "Chipless RFID Transponder Design," PhD, Monash University, 2010.

45. H.S. Jang, W.G. Lim, K.S. Oh, S.M. Moon, and J.W. Yu, "Design of Low-Cost Chipless System Using Printable Chipless Tag With Electromagnetic Code," *IEEE Microwave and Wireless Components Letters*, vol. 20, 2010.

46. R. Rezaiesarlak and M. Manteghi, "Complex-Natural-Resonance-Based Design of Chipless RFID Tag for High-Density Data," *IEEE Transactions on Antenna and Propagation*, vol. 62, 2014.

47. B.A. Munk, *Frequency Selective Surfaces, Theory and Design*: John Wiley & Sons, Inc., 2000.

48. M.G. Pettus, "RFID System Utilizing Parametric Reflective Technology," USA Patent, 2005.

49. S. Särkkä, V.E.V. Viikari, M. Huusko, and K. Jaakkola, "Phase-Based UHF RFID Tracking With Nonlinear Kalman Filtering and Smoothing," *IEEE Sensors Journal*, vol. 12, 904–910, 2012.

50. P.V. Nikitin, R. Martinez, S. Ramamurthy, H. Leland, G. Spiess, and K.V.S. Rao, "Phase Based Spatial Identification of UHF RFID Tags," presented at the *IEEE RFID*, 2010.

51. Md. S. Bhuiyan, A. Azad, and N. Karmakar, “Dual-band Modified Complementary Split Ring Resonator (MCSRR) Based Multi-resonator Circuit for Chipless RFID Tag,” in *IEEE – Intelligent Sensors, Sensor Networks and Information Processing*, Melbourne, Australia, 2013.

52. M. Zomorrodi and N.C. Karmakar, “An Array of Printed Dipoles at 60 GHz,” in *IEEE International Symposium on Antennas and Propagation*, Memphis, Tennessee, USA, July 2014, pp. 73–74.

53. M. Zomorrodi and N. Karmakar, “A Low Cost Wideband Printed Dipole Array Antenna for 60 GHz Image-Based Chipless RFID Reader,” *IEEE Antennas and Propagation Magazine*, vol. 57, p. 13, 2015.