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1 Context analysis

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1.1 Introduction

This chapter addresses the present challenges facing radio frequency identification (RFID) systems and aims to highlight the perspective and potential of this technology which, due to attractive properties such as low power, low cost, and ability to integrate sensing functionality, is enjoying widespread application and a growing market potential. The simplicity and minimalist approach in the design of RFID tag circuits has led to their widespread utilization in supply chain and logistics applications. IDTechEX reported that the total RFID hardware market value was 5.56 billion US$ in 2009 and is expected to increase above 25 billion US$ by 2019 [1]. In 2005 the large volume electronic product code (EPC) tag cost was US$0.13 [2], while the recent volume pricing of UHF RFID transponders is approximately US$0.10 (for example [3]). A further price reduction below US$0.05 is desired in order to achieve additional market penetration [4]. The World Wide Research Forum (WWRF) estimates that 7 trillion wireless devices will be serving 7 billion people by 2017 [5]. RFID systems with sensing functionality are a fundamental technology for realizing a network of interconnected devices, which represents the vision of ubiquitous sensing and communication.

This chapter aims to set out the background to the exciting technological advances and properties that RFID systems are required to accomplish, demonstrating how RFID technology is capable of providing a solution towards ubiquitous sensing smart environments. It begins with a brief historical perspective, showing the major milestones in the evolution and commercialization of RFID technology. The remaining paragraphs highlight existing performance challenges and problems, from a brief description of networking and security issues to more detailed circuit, system, material, and computer aided design (CAD) topics, which will be addressed in more detail in the rest of this book.

1.2 Historical perspective of RFID

RFID systems operate based on the principle of *back-scatter communication* which has its roots in radar technology [6, 7]. The principle of radar is to transmit a radio signal which is then reflected or scattered by objects present in its trajectory, and subsequently received by a receiver placed at the same or different location from the transmitter [8].

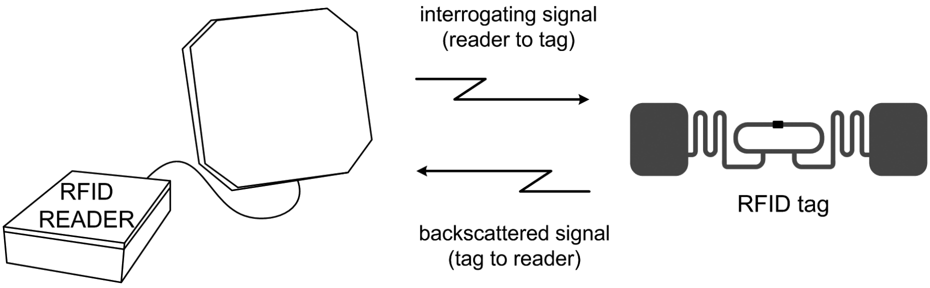

Figure 1.1 Back-scatter communication.

Signal processing is then applied in order to identify the nature of the objects which have interfered with the originally transmitted signal.

Radar technology developed during World War II was widely utilized in identifying incoming planes. The challenge for the technology was to determine whether it was a friendly or an enemy plane approaching, in other words to create an identify friend or foe (IFF) system. As an example, the German military utilized the fact that if the pilots rolled their planes when approaching their base, the reflected radar signal could be distinguished and therefore they could be identified. This is reported as a first implementation of a passive RFID system [6]. Alternatively, the British planes utilized a transmitter which, when interrogated by an incoming radar signal would transmit back a special signal used to identify the plane. This, in turn, represents an implementation of an active RFID system [6].

The 1948 paper by Stockman [9] is, however, arguably the first proposal to utilize the back-scattered signal for communication purposes, by modulating the reflected signal with some selected time-varying signal, and this represents to many the foundation of RFID communication technology. Following the work of Stockman, in the next two decades, more fundamental publications appeared studying back-scatter communication systems [8], notably the 1964 paper by Harrington on the “Theory of loaded scatterers” [10], as well as a number of patents such as the 1960 filing by Harris “Radio transmission systems with modulatable passive transponder” [11] exploring and demonstrating the potential of the technology.

The principle of back-scatter communications is shown in Figure 1.1. The interrogating transmitter – *reader* – sends a signal which is captured by all RFID *tag* antennas in the vicinity of the reader. The scattered signal from the tag antenna has a particular signature in the frequency or time domain (or both), which allows the reader to identify the tag.

Essential to the development of RFID technology has been the invention of the integrated circuit, originally envisioned by Dummer in 1952 [12]. Subsequently, Jack Kilby at Texas Instruments filed the first patent in 1959 [13] and was awarded the Nobel Prize in Physics in 2000 [14]. Independently from Kilby, and only six months later, Robert Noyce of Fairchild Semiconductor filed a patent for a “semiconductor-device-and-lead structure” [15]. The realization of integrated circuits or chips in silicon and other substrates has enabled the *low cost fabrication* and *mass production* of RFID tag

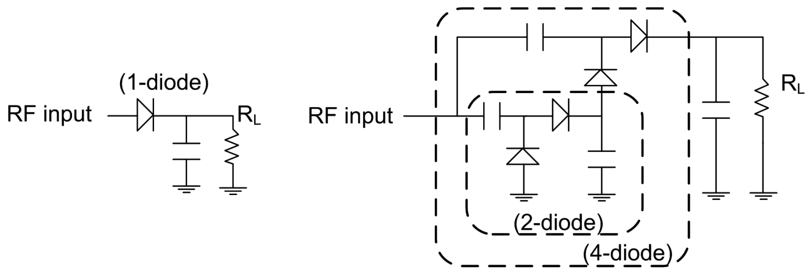

Figure 1.2 Rectifier circuits used in RFID tags.

chips, which ensured their widespread application. The tag chip is a core element of RFID technology, which has led to the introduction of a programmable memory and subsequently identification features, and modulation and detection circuits, as well as the capability of sensing through analog-to-digital (ADC) and digital-to-analog (DAC) conversion circuitry.

RFID technology owes much of its popularity and great potential for emerging applications to the simplicity of the tag circuit, especially when looking towards green technologies that place emphasis on limiting environmental pollution by not requiring the use of batteries and their associated waste treatment. Passive RFID tags extract the DC power required to activate their circuitry from the transmitted reader signal. Key to RFID technology is therefore the concept of wireless power transmission (WPT), which is attributed to the original work of Hertz and Tesla [16]. A fundamental component of the radio front-end of RFID tag chips is the rectenna, an active antenna consisting of a radiating structure and a rectifier circuit, which in its simplest form consists of a single diode, as shown in Figure 1.2. The rectenna was patented by Brown in 1969 [17], and is responsible for powering the circuitry of passive tags. A great challenge in modern RFID circuits is to come up with improved diode devices and original rectenna circuit topologies in order to maximize the efficiency in converting microwave power to DC power sufficient to activate the RFID tag circuits.

Electronic article surveillance (EAS) systems were the first commercial application of RFID technology, which began in the 60s with companies such as Sensormatic, Checkpoint, and Knogo [8]. In the 70s further developments of RFID systems were reported as the number of research laboratories such as Los Alamos Scientific Laboratory and companies such as Raytheon working on RFID systems increased significantly. The paper by Landt [8] presents an excellent historical overview of the technology. Notable publications include the first patent proposing an active RFID system with memory by Cardullo and Parks in 1973 [18], and the 1975 paper by Koelle, Depp, and Freyman from Los Alamos Scientific Laboratory, demonstrating a passive RFID system with temperature sensing capability in addition to identification functionality [19]. RFID was considered in applications such as animal tracking, vehicle identification, and factory automation.

In the 80s and 90s RFID commercialization grew significantly especially in terms of transportation applications. A characteristic example is the first open highway electronic

Table 1.1 RFID technology timeline.

Time	Milestone
1940s	radar technology [6, 7], first publication on back-scattered signals for communication [9]
1950s	integrated circuit vision [12]
1960s	patent on back-scattered communication systems [11], rectenna patent [17]
1970s	active RFID system patent [18], passive RFID system with temperature sensing capability [19]
1980s/1990s	first open highway electronic toll system in Oklahoma
2000s	GS1 launching [21], Auto-ID Labs [22], EPCglobal development [23]

toll system installed in Oklahoma in 1991. The development of the personal computer (PC) further assisted in the widespread utilization of the technology as it provided an efficient way to manage data collection from RFID systems. In 1997, the Uniform Code Council (UCC) and European Article Number (EAN) International initiated discussions about global standardization activities [20]. In 1999, the Massachusetts Institute of Technology (MIT) Auto-ID Center was founded with support from Procter & Gamble, Gillette, and UCC, in order to develop a universal RFID system, the Electronic Product Code (EPC). In 2003 EAN International underwent a significant reorganization and its management board agreed to change its name to GS1 [21]. GS1 was eventually launched in 2005 and UCC became GS1 US. The Auto-ID Center evolved into Auto-ID Labs in 2003 [22], responsible for research activities, and EPCglobal [23] responsible for standardization activities, related to Electronic Product Code technology. Presently Auto-ID Labs has seven laboratories in USA, UK, Australia, China, Republic of Korea, Japan, and Switzerland [22]. Standardization has helped the widespread application of the technology, which is now used by some of the biggest organizations in the world, one of the most notable examples being Wal-Mart, which in 2003 announced that its top 100 suppliers would be required to use EPC compatible RFID tags on all their pallets and cases of goods beginning January 2005 [24]. A summary of the timeline of the major milestones that have led to the mainstream deployment of RFID systems is shown in Table 1.1.

1.3 RFID towards a networked society

Technology advances towards increased processing power together with low cost, low profile, and low power electronics are making possible notions such as ambient intelligence, pervasive computing and communication, and Internet of Things. These concepts aim to improve the quality of life through a network of sensing devices communicating with each other and providing useful information to the network user [25]. Ubiquitous communications and sensing are becoming more and more part of everyday life by embedding wireless transceivers into an increasing array of appliances.

Sensing capability, jointly with communication and networking, leads to an array of smart objects ranging from clothes to cars, to buildings and to cities, with applications from health monitoring and assisted living to energy efficient operation, minimizing environmental pollution. All of these concepts imply everyday all-day communication, *anytime*, but also available connectivity *anywhere*, and effectively by *anything*, by introducing an increasing number of interconnected devices [25].

A characteristic example of the increasing number of communication links among smart objects, is the deployment of near-field communication (NFC) [26] and specifically its introduction in smart phones. In contrast to the traditional trend of communication networks towards high data rate and large range, a significant interest in *low data rate* and *short range* communications has been established, while placing emphasis on a low energy requirement and energy efficient operation. Networks of smart objects, based on back-scatter communication, are envisioned, placing emphasis on minimizing tag circuit complexity and energy requirements, based on a continuous, unidirectional communication from a reader to a large number of nearby tags, with a very low bit rate operation of a few bits per sec [27]. RFID technology is widely considered as the enabling technology for the implementation of such networks of smart objects, due to attributes such as low cost, low complexity circuit architecture, and low power operation [28]. RFID tags are able to provide much more than a simple identification, they can track location, store new information, and provide environmental sensing information [29].

RFID is also a key component in the concepts of augmented reality (AR) [30], where real world scenarios are overlaid with computerized graphics, sounds, videos, or 3D images to create a more informative or entertaining reality. In AR the RFID tags are used to activate these additional layers containing animations or information. AR finds application in a wide range of scenarios, such as urban, educational, cultural, architecture, design, and logistics fields. Further applications include autonomous logistics [31], where RFID technology can be used to achieve unmanned and autonomous control of goods being transported. The use of RFID tags can be considered not only to identify but also to locate and provide additional information about the goods being transported.

More recent solutions include networked RFID (NRFID), where RFID tags identify themselves and provide information to their associated readers that forward it to a central node to create a centralized database [27, 32]. NRFID makes it possible for data obtained by a certain reader to be reached by a network of authorized users that have access to the central database. This type of scheme can be used to improve the efficiency of the supply chain cycles.

In a standard application scenario, a large number of RFID tags are situated within the range of a reader. As a result, multiple tags receive and respond simultaneously to a reader interrogation transmission and, consequently, the reader is receiving simultaneously a large number of interfering responses, which lead to what is known as tag collisions. The result of tag collisions is a delay in the response, as well as wasted bandwidth and power resources. A challenge for RFID systems is that of developing protocols and system architectures which minimize the collisions between the responses of the various tags [33]. Furthermore, the widespread use of RFID technology is resulting in a more general scenario where multiple readers are also simultaneously operating. As a result, one should also consider the reader to reader collision problem [34], where the interrogation signal of one reader interferes with the operation of another reader, and also the reader-to-tag interference scenario, where a single tag is being detected by two readers [33].

In addition to the collision problem, an important challenge for RFID systems is that of security and privacy [35, 36]. Juels [35] identifies two main privacy concerns in covert tracking and inventorying. Directly because of the added functionality of RFID systems, user privacy can be compromised when identification is combined with personal information. Characteristic examples, where user privacy is of concern, include vehicle tolls, libraries, passports, and human implants [35]. Stanford [29] reports a case where user concerns that RFID clothing tags, being able to identify the purchaser and included in databases, have led a well-known commercial retailer to withdraw its plan for deploying RFID systems. In addition to the issue of privacy, which relates to potentially undesired interrogation or utilization of tag information by a reader, a second important issue is that of authentication, which deals with the problem of identifying counterfeit tags. With alarming reports estimating that roughly 8% of world trade yearly is in counterfeit goods [37], authentification is an important problem that RFID systems need to address, as replicating low-end RFID tags does not pose a difficult challenge [35]. While RFID technology already finds application in scenarios where authentification is required [36], there are several challenges that need to be addressed in terms of security and privacy, and RFID technology can profit from RF-based techniques in addition to cryptography and encryption algorithms. As an example, RF fingerprinting, generating certificates of authenticity based on the RF transmission or reflection characteristics of quasi-randomly printed or generated conductive objects, has been proposed to support identification [37].

1.4 Standardization

The International Organization for Standardization (ISO) is a global network of national standards bodies with members such as the American National Standards Institute (ANSI) from USA, the UK British Standards Institution (BSI), the Standardization Administration of the People’s Republic of China (SAC), and the Asociación Española de Normalización y Certificación (AENOR) in Spain to name a few [38]. ISO has developed a number of different air protocol standards pertaining to RFID systems based on different applications, as a result of the widespread utilization of the technology [39]. As noted in Section 1.2, in addition to ISO, EPCglobal has defined a set of standards for RFID systems operating at 13.56 MHz and at UHF (860MHz – 960MHz) frequency bands. Table 1.2 includes a non-exhaustive list of existing standards. The present framework of standards facilitates the widespread utilization of RFID technology in an increasing number of applications and consequently the implementation of an Internet of Things.

Table 1.2 RFID standards [24, 39].

Standard	Frequency	Application	Communication
ISO/IEC 11784/5 ISO/IEC 14223 ISO/IEC 18000–2	125/134 kHz	animal identification	passive
ISO/IEC 10536 ISO/IEC 14443 ISO/IEC 15693 ISO/IEC 18000–3 EPC Class 1 [23]	4.9152 MHz 13.56 MHz	contactless smart cards	passive
ISO/IEC 18092	13.56 MHz	near-field communication	passive and active [40]
ISO/IEC 18000–7	433 MHz	item management	active
ISO/IEC 18000–6 EPC Class 0,1 [23]	860–960 MHz	item management	passive
ISO/IEC 18000–4	2.45 GHz	item management	various
IEEE 1451.7–2011	various	smart transducers	various [39]

Nonetheless, the integration of sensing functionality and networking between RFID tags remains a challenge in terms of standardization of the technology. The Institute of Electrical and Electronics Engineers Standards Association (IEEE-SA) has a formal agreement with ISO to cooperate in the development of international standards [41]. Specifically, the Instrumentation and Measurement Society TC9 Sensor Technology (IM/ST) Committee has introduced the IEEE 1451.7 standard for a smart transducer interface, which defines the communication interface between different transducers and RFID systems supporting a number of ISO/IEC air interface specifications such as ISO/IEC 18000–2,3,4,6,7 included in Table 1.2 The standard supports a number of sensors from accelerometers to humidity and temperature sensors, and can be considered as a preliminary step towards standardization of the technology [42].

1.5 Circuit challenges for RFID systems

In order to implement these concepts, issues such as miniaturization, conformal and flexible materials, low power, low cost, mass production fabrication, and environmentally friendly, passive or battery-less operation are fundamental, and lead to critical technological as well as circuit and system design challenges. Such attributes frequently lead to incompatible specifications; however, RFID technology comes with a plurality of categories, each one able to address a suitable subset of the sought for applications and specifications. RFID tags can be loosely classified based on their market objectives into low-end and high-end tags, ranging from chipless tags with no local memory all the way to battery powered transceivers with microcontrollers, multiple sensors, and complete radio front-ends [29]. More accurately, one can classify RFID systems based on the type of electromagnetic interaction into near-field and far-field systems [39], or otherwise based on their operating frequency and corresponding operating standard (Table 1.2).

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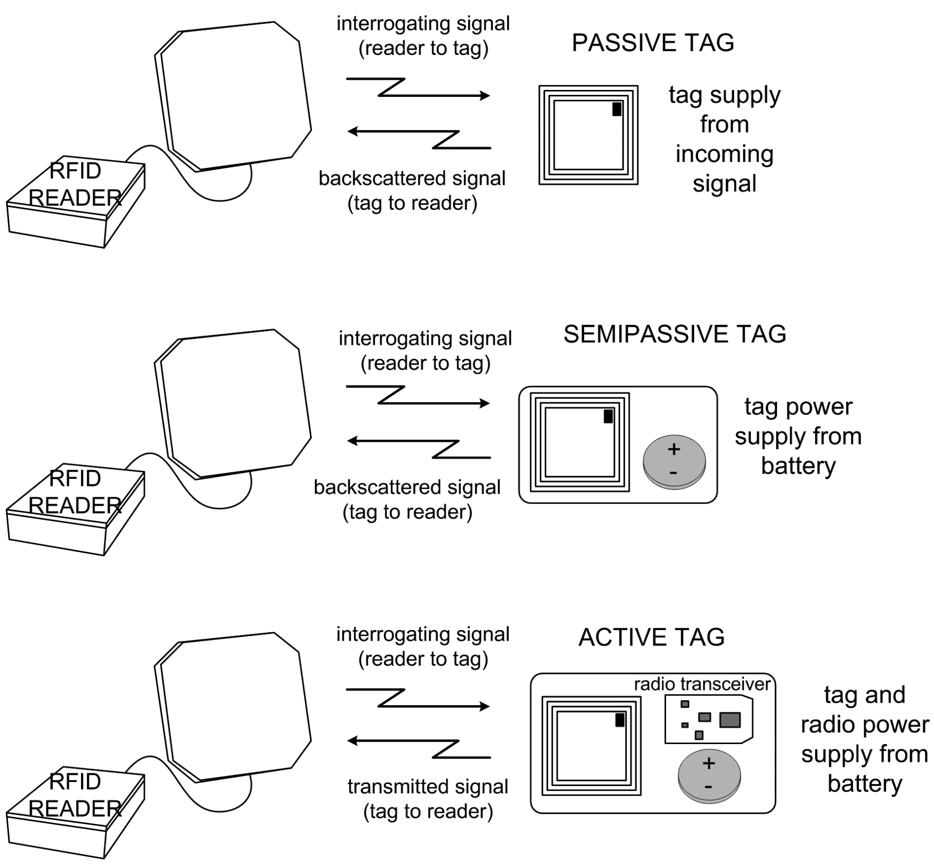

Figure 1.3 Classification of RFID systems.

An alternative classification of RFID systems is based on their functionality, and divides them into passive, semi-passive, and active tags (Figure 1.3) [1, 28, 39]. Passive tags rely on the transmitted power from the reader to both power their circuitry and communicate a response back to the reader. As a result, the operating range of such systems is limited by the minimum required power to operate the tag circuitry, rather than the sensitivity of the reader. The main challenge therefore becomes that of minimizing the dissipated power of the tag circuitry as well as that of maximizing the efficiency of converting the electromagnetic power transmitted by the reader into electrical DC power used by the tag [24]. Furthermore, the inclusion of sensing capability may further reduce the operating range of passive RFID systems, due to the additional power dissipated by the sensor circuits. Consequently, passive sensor design is receiving significant scientific interest, which is further boosted by advances in nanotechnology, with examples such as gas sensors exploring the dependence of the electrical properties of carbon nanotube thin films on the presence of ammonia gas [43]. Chipless RFID systems are a very promising technology, where tags do not require any (silicon) chip [1]. Chipless tags consist of purely passive circuitry or utilize printed thin film transistors and are thus able to minimize cost and energy requirements, leading to an increased recent scientific and market interest [1].

Semi-passive tags utilize an additional power source, a battery, to power-up their circuitry, however, communication is still done passively, by reflecting or scattering the reader signal which arrives at the tag terminals. The use of a power supply maximizes the operating range to the limit set by the reader sensitivity, and therefore the challenge then becomes that of improving the corresponding sensitivity specification of the reader. Furthermore, sensing functionality is additionally enhanced by the inclusion of an auxiliary power source. While the extra power source in its simplest form is a battery, there is a significant environmental concern associated with the disposal of spent batteries, corresponding to an exceptionally large number of sensor tags. As a result, energy harvesting technologies can be utilized as auxiliary power sources.

Finally, fully active tags utilize an auxiliary power source to both power their circuitry and amplify and transmit back the incoming signals from the reader. Such tags combine multiple functionalities with a large operating range at the expense of added circuit complexity, and higher cost. They can also benefit from energy harvesting technologies, but their power requirements are higher than semi-passive, or passive tags.

Researchers from the University of Washington have recently proposed utilizing solar energy as an auxiliary source to power the RFID tag circuitry and therefore extend its operating range [44]. DC power generated from solar cells can be provided to commercial tags utilizing an auxiliary DC terminal and corresponding power management circuitry. Commercially available tag chips with an external supply mode are already on the market [45]. Alternatively, the solar cell output DC electrical power can be efficiently converted to RF power, and the RF power can be directly fed into the RF port of any commercial tag. This was proposed in [46], where a high efficiency class-E oscillator was used to perform the DC–RF power conversion. A suitable matching circuit can be printed on the tag antenna substrate in order to maximize the RF power into the tag at the operating frequency of the oscillator. The oscillator frequency can be chosen so that it does not interfere with the reader signal. The possibility of utilizing RF beacon signals as auxiliary power sources for commercial RFID tags presents yet another new possibility for deploying wireless power nodes separated from the reader in an RFID network scenario. Solar, thermal, vibrational, or even ambient electromagnetic energy harvesters, can be utilized to provide additional power to the sensor tag [47].

The challenge of maximizing the operating range of RFID systems has inspired several circuit and system improvements. The efficiency of a rectifier circuit can be significantly improved by taking advantage of its nonlinear nature. It was found that there is a strong dependence of the rectifier efficiency on the peak-to-average power ratio of the input RF signal. Consequently, an RF signal with a time-varying envelope can result in a higher RF-to-DC conversion efficiency, compared to a simple RF tone signal. RF signals with strongly varying envelope, such as multi-tone signals [48, 49], or chaotic waveforms [50], can be used to increase the range of RFID systems by utilizing the time-varying nature of the RF signal envelope to maximize the RF-to-DC conversion efficiency of the rectifying circuitry of the RFID tags. Trotter *et al*. reported measured gains in the read range of 24% by using four subcarriers compared to a single tone carrier signal [48].

Similarly, Boaventura and Carvalho reported a 3 dB improvement in the conversion gain of a rectifier circuit by utilizing a four tone signal, and a 5 dB improvement using 16 tones [49]. Utilizing a very low complexity circuit consisting of a single transistor Colpitts-based oscillator to generate a chaotic signal, resulted in a 20% efficiency improvement in the rectifier efficiency over a single tone carrier [50].

Another significant challenge consists of maximizing the range of RFID tags when placed on metal or highly conductive surfaces. Placing an electrical dipole very close to a large conductive surface results in a significant reduction of its gain [51]. This is explained by applying image theory, where the electromagnetic problem of an electric dipole near a large conductive surface is equivalent to one where the conductive surface is removed but a second dipole, an image of the original dipole, excited with opposite phase, is placed symmetrically behind the conductive surface and at the same distance from it as the electrical dipole. The total field radiated from the two dipoles tends to zero as their separation is minimized [51]. Consequently, it is customary to use a thick substrate of spacer material such as foam in order to mitigate the effect of the conductive surface on the tag antenna performance [24]. An electromagnetic bandgap (EBG) surface can alternatively be used to eliminate the image phase inversion and, as a result, the antenna gain degradation due to the effect of the metallic ground plane [52]. EBG surfaces have been proposed to minimize the required spacer material thickness in situations where RFID dipole type tags are placed on top of metallic objects [53], as well as to mitigate the effect of the metallic surface size on the performance of patch antenna type tags [54].

Finally, an important challenge is that associated with optimizing the range of RFID systems with respect to the relative alignment of the tag and the reader, and in the presence of multipath propagation. Multiple tag antennas can be used to provide diversity and mitigate the effect of multipath propagation [55]. Tag chips with two antenna terminals are also available commercially [56]. The use of retro-directive array principles, such as the Van-Atta topology, can be used to maximize the signal back-scattered by the tag in the direction of the reader and has been shown to improve the read range by making it less sensitive to the tag alignment with respect to the reader [57].

1.6 Materials and technology

Typically, low cost materials such as polyethylene terephthalate (PET) or paper are used as substrates to host a silicon RFIC chip and its radiating tag antenna circuit. Recently, additional materials have been investigated as suitable candidates for RFID tags such as textiles and conductive threads [58]. The development of organic RFID (ORFID) is also being explored with a view to minimizing the cost of RFID tags by utilizing organic semiconductors for the synthesis of the RFIC chip instead of silicon [59].

In addition to investigating low cost, widely available substrate materials, an important challenge consists of exploring the possibility of using fabrication technologies which permit a low cost, large volume electronic circuit production. Inkjet printing is emerging as a popular alternative to traditional circuit board fabrication techniques,