1.

INTRODUCTION

1.1. Introduction

Radio-frequency identification (RFID) is one of the fastest growing wireless technologies in recent decades. This technology is currently being used in numerous applications throughout the world such as supply chain management (SCM), health care, traffic monitoring, retail, access control, etc. [Stockman (1948), Xiao *et al.* (2007), White *et al*. (2007), Khandokar *et al.* (2010), Perret *et al.* (2012)]. The idea behind the RFID tag is to store a unique identification number, same as that of a bar code or a magnetic strip on the credit card or ATM card. To retrieve the information stored in the bar code or magnetic strip, the device must be scanned in close proximity to its scanning device. While in RFID, the data transfer between tag and reader is done wirelessly and hence enables remote identification.

It was initially implemented during World War II to identify and authenticate allied planes, and is still being used today for the same purposes. The RFID systems allow for non-line-of-sight and noncontact reading of data from electronic labels by the means of electromagnetic signals. Consequently, they became attractive for several tracking and tagging scenarios [Karmakar (2010), Lehpamer (2008)].

1.2. RFID System

RFID system consists of mainly three components as shown in Figure 1.1.

- RFID Reader
- RFID Tag
- Middleware software

1.2.1. *RFID Reader*

A RFID reader is a device that enables the communication between the tag and the system software. The reader communicates with tags within its range of operation and performs the tasks including sending an interrogation signal, filtering (searching for tags that meet certain criteria), decoding data from the tag, writing (or encoding by rewriting the IC) to selected tags, etc.

The reader uses an antenna to capture data from tags. Further, it passes the data to a computer for processing. Readers are available in different forms such as handheld, mobile or stationary.

1.2.2. *RFID Tag*

RFID tag contains the identification code which is stored in the Silicon chip. The tags memory can be read-only, read-write, or write-once and read many. The simplest tags contain only read-only memory (ROM), while more advanced tags include random access memory (RAM) and nonvolatile programmable read-only memory (PROM) or electrically erasable programmable read-only memory (EEPROM). Generally, ROM contains identification string for the specific tags and instructions for its operating system. RAM is typically used for temporary data storage during communication with the reader [Nieto *et al.* (2011)].

RIFD tags are available in different frequency bands like low frequency (LF), high frequency (HF) to the microwave bands, as shown in Figure 1.2. LF (usually in 125 kHz) and HF (with 13.56 MHz) RFID systems can communicate up to 1m read range with the use of inductive coupling. Due to the large operating wavelength compared with tag size, RFID tags operating in these bands are less prone to the effect of metal/liquid environments, thus offering robust readability in practice. UHF RFID tags, typically operating in 866-868MHz (European (EU) countries) and 902-928MHz (North American Continent) have a longer read range up to 10 m or more, with a faster data rate. On the other hand, the reading performance of UHF tags depends on the working environment. They are incapable of penetrating materials such as metals, liquids, dust and fog. Commonly used frequencies at SHF and microwave band for RFID technologies are 2.45GHz and 5.8 GHz, respectively.

Depending on the power handling method in the tag, RFID can be classified as Passive, Semi-Passive, and Active Tags.

(i) Passive RFID systems,
(ii) Active RFID system, and
(iii) Semi-passive or battery-assisted tags.

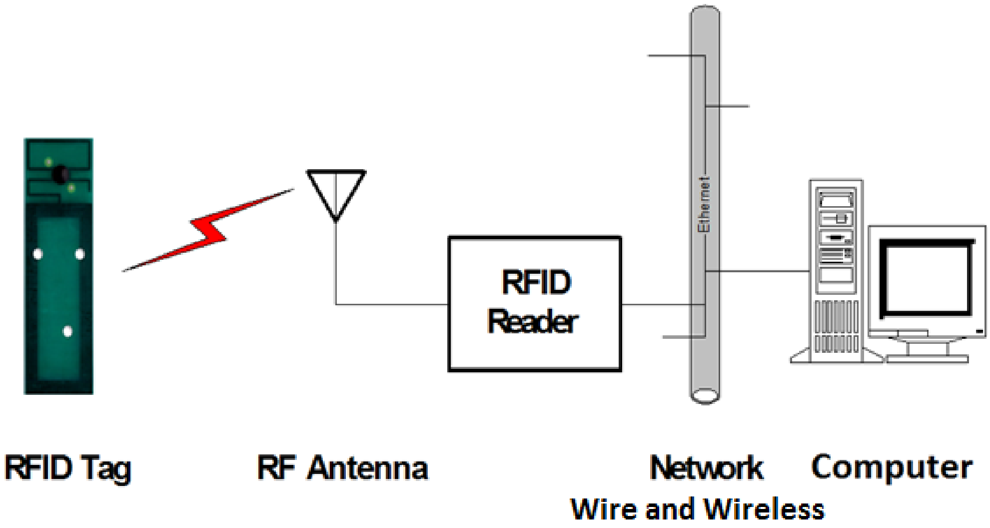
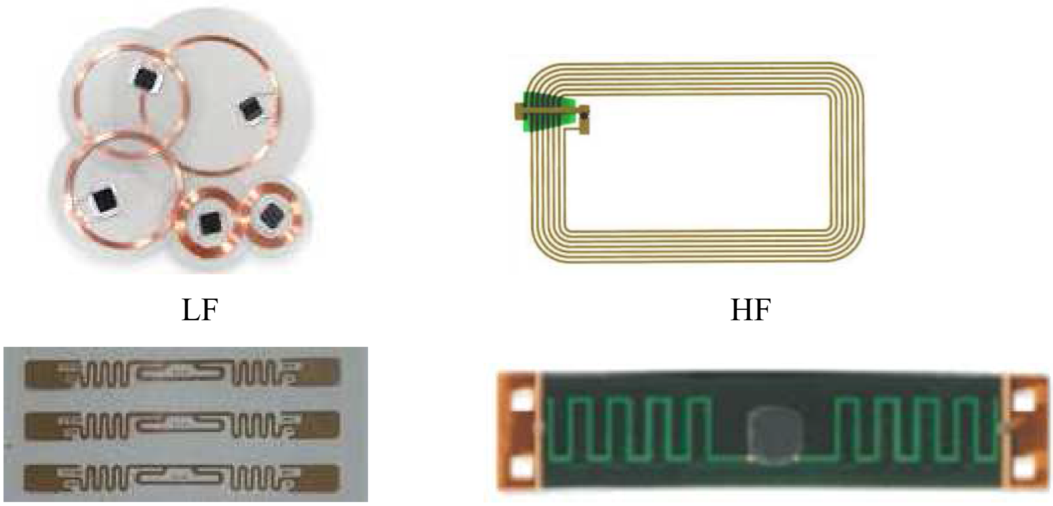


Figure 1.1: Information retrieval from an automatic identification system



LF HF

UHF 2.45 GHz

Figure 1.2: Several types of transponders used in RFID systems

Passive RFID systems use passive tags. Passive tags do not have an internal power source. They harvest the energy from the electromagnetic field generated by the reader needed by their internal circuits. Therefore, they have a short range, limited to a few feet and often, more realistically, to a few inches. Also, their manufacturing and production costs are very low.

On the other hand, active RFID systems use active tags. They have an internal power source, typically a battery. It allows broadcasting the signal to the reader. They do not utilize the antenna to harvest the power. Therefore, they have an extended read range, typically several hundred feet. However, the inclusion of the power source increases the cost of the systems. The cost of active tags is approximately 100 times higher than the cost of a passive tag. Active tags typically operate in the ultra-high-frequency (UHF) and super high frequency (SHF) ranges.

The third type of tags is known as semi-passive or battery-assisted tags. These tags also include a battery, but contrary to active tags, the battery is not utilized to transmit the signal to the reader. Instead, the battery is utilized to support secondary functions like the data logging from different types of sensors.

1.2.3. *Middleware Software*

The interface and the software protocol are maintained by middleware software to encode and decode the stored data from the reader into a mainframe or personal computer. It is the intermediate between the interrogator and the enterprise layer. Middleware sends and collects data directly from the interrogator, performs a business-related process regarding the data, read data, stores the data as per the requirement and sends data to the enterprise applications. Middleware also comprises the software used to monitor, configure, and manage the hardware of the interrogator. Data gathered from middleware are sent to the enterprise application stored in the computer. After the process application software can update the data in the server through the internet [Ahson and Ilyas (2008)].

1.3. Applications of RFID System

Nowadays, RFID tags are applied in almost every business process and are projected to be implemented everywhere that exists in the real world. Because of the use of radio waves in RFID, it does not require line-of-sight communication to operate. That means the tag can be hidden inside the item or box that is to be identified and still be read. Another feature of RFID system is the ability to read many tags at the same time. Again, there is a tremendous savings potential by not having to present the reader manually with each item to be identified. Applications fall into two broad categories: short range applications in which the reader and the tag must be in proximity (such as access control), and medium to long-range applications (such as reading across a distribution centre, access control, electronic toll collection, etc.) [Xiao *et al.* (2007), Perret *et al.* (2012)].

1.4. Literature Review

RFID can be traced back into the 1948 work on using RF modulated backscatter for communication (basic principle of passive RFID) [Stockman (1948)]. While the general theory of scattering from loaded antenna has been developed by Harington [Harington (1963)]. After three decades, a low-powered CMOS integrated circuit was developed for RFID passive tags by Friedman *et al.* [Friedman *et al.* (1997)]. Further, Au *et al.* investigated the narrow loop resonators for RFID applications. He showed that the RCS bandwidth can be increased by varying the dimensions. The peak RCS was achieved without shifting of resonance frequency when using an array of a narrow rectangular loop [Au *et al.* (1997)].

Thereafter in 1999, Foster and Burberry [Foster and Burberry (1999)] designed antennas for RFID system which works on 435 MHz, 2.45 GHz, and 5.8 GHz. The antenna was designed to maximize the transfer of power into and out of the device on the protected object. In the same year, a new RFID system for the ISM band at 24 GHz employing quasi-optical beam forming was presented by Kaleja *et al.* in [Kaleja *et al.* (1999)]. Active integrated antennas were used as transmitters resulting in exceptionally small size of the ID-tags. After that, the aperture coupled patch (ACP) antennas for a RFID system in the 2.4 GHz ISM using circular polarization modulation was reported by Kossel *et al.* in [Kossel *et al.* (1999)]. Further, Rao *et al.* in [Rao *et al.* (1999)], presented a systematic approach to analyze the read zone of a RFID system where the base station antennas were a pair of switchable circularly polarized antennas and the transponder antennas were linearly-polarized and oriented in arbitrary directions. Later, investigation in the packaging of RFID transponders at microwave frequencies was done by Brady *et al.* in [Brady *et al.* (1999)]. They presented two packaging methods such as chip-on-board (COB) and chip-in-board (CIB), which allowed designers to utilize the existing semiconductor facility to achieve a reliable microwave tag and provide high volume manufacturing capabilities. For both methods, the tag package includes a single chip integrated circuit, a small resonant antenna, chip attach, wire bonding, chip encapsulation, and various substrate materials.

In the year 2000, Dou and Chia [Dou and Chia (2000)] presented a novel meandered planar inverted-F antenna with a single feed for 900 MHz, 1.9 GHz, and 2.4 GHz bands. Using two shorting strips, proper impedance matching is achieved in three bands. This compact low-profile design shows characteristics of near-omnidirectional radiation patterns with minimal hand effects.

In 2001, Chen and Thomas [Chen and Thomas (2001)] identified the technical parameters that affect the RFID performance and evaluated measures to enhance performance. They addressed issues related to read range, algorithms for communication between tag and reader, the theory behind powering a passive tag via an LC circuit antenna, the process by which the tag modulates the carrier signal, and the algorithm for simultaneously receiving and decoding information from more than one tag. Soon after, Siden *et al.* investigated the performance degradation in passive RFID systems due to the distortion of the tag antenna caused by geometrical bending of the antenna. This bending was likely to occur when tags were attached to flexible substrates. It was shown that the performance of RFID system, characterized by operating range, can be degraded significantly due to the distortion [Siden *et al.* (2001)].

In 2002, Marrocco *et al.* designed a miniaturized meandered line antenna using the genetic algorithm for RFID applications at UHF. Improvement in the gain of up to 0.45 dB was achieved by tuning both the vertical and horizontal segments of meandered line [Marrocco *et al.* (2002)]. After that, Cichos *et al.* performed the analysis of polymer based antenna-coils for RFID. It was shown how the ohmic losses of conductive thick film paste affect the functionality of transponder systems [Cichos *et al.* (2002)].

In 2003, Strassner and Chang reported a new integrated antenna system for a 5.8 GHz RFID tag to predict the pipe's lifetime and to provide inventory control [Strassner and Chang (2003)]. After that, Marrocco proposed a meander line antenna with improved gain as low-profile self-resonant tags for application in passive radio frequency identification. Antenna shape and size was optimized by the genetic algorithm taking into account the conductor losses [Marrocco (2003)]. After that, Padhi *et al.* proposed an electromagnetic-coupled dual-polarized microstrip patch antenna for RFID applications. Two different antennas, Antenna-1, and Antenna-2, for RFID tag and reader applications were presented at the C and S bands, respectively. The antennas used two symmetric coupling apertures to excite two orthogonal modes for dual-polarization operation. High isolation of the order of -35 dB was obtained by proper selection of the shape and positions of the coupling aperture [Padhi *et al.* (2003)].

In 2004, a small and low-cost antenna solution for UHF RFID tags was presented by Hirvonen *et al.* The impedance of the antenna was designed to match directly to the impedance of the RFID microchip. The impedance of the antenna was also immune to the platform [Hirvonen *et al.* (2004)]. After that, Keskilammi and Kivikoski proposed a novel meander line comprises with text, for size reduction of the dipole antennas used in passive transponders for RFID system. Three different structures of text dipole antennas for 869 MHz RFID applications had been examined [Keskilammi and Kivikoski (2004)]. In the same year, Chen and Hsu presented a coplanar waveguide (CPW)-fed capacitive folded-slot antenna for the RFID application at 5.8 GHz. The proposed antenna was mechanically robust and easy to fabricate and design [Chen and Hsu (2004)].

In 2005, Liu and Hu proposed a broadband CPW-fed folded-slot monopole antenna for 5.8 GHz RFID application. A folded slot was introduced to expand the impedance bandwidth and miniaturize the size [Liu and Hu (2005)]. Soon after, an inductively coupled feed concept had been introduced to design RFID tag antennas by Son and Pyo. It was shown that using an analytical model, the antenna could be designed to be directly matched to a RFID tag chip and had wideband characteristics [Son and Pyo (2005)]. After that, Nikitin *et al.* presented a power reflection coefficient analysis for complex impedances in RFID tag design. The performance analysis of a specific RFID tag was presented together with experimental data, which was in close agreement with the theory [Nikitin *et al.* (2005)]. Later on, Cho *et al.* proposed broadband UHF RFID tag antenna with quasi-isotropic radiation pattern. The antenna was composed of two bent dipoles and a modified double T-matching network to improve the bandwidth [Cho *et al.* (2005)].

In 2006, Palmer and Rooyen presented a simple broadband network analyzer technique for measuring balanced loads, such as antennas for RFID tags, without a balun. The technique used the normal two-port calibration of the network analyzer, which was extended by the addition of two short lengths of cable [Palmer and Rooyen (2006)]. After that, Griffin *et al.* presented two new useful forms of the radio link budget that described the power link of an RF tag system when the tag was attached to an object. A series of measurements was performed on several 915 MHz flexible antennas when attached to the various materials such as cardboard, pine plywood, acrylic, deionized water, ethylene glycol, ground beef, and an aluminium slab to measure the far-field gain pattern and gain penalty [Griffin *et al.* (2006)]. Later on, Son *et al.* presented a low-cost wideband antenna for RFID tags mountable on metallic surfaces. A novel proximity-coupled feed structure was explored to perform simple and wideband impedance matching, in which the direction of the microstripline was orthogonal to that of the resonant length of the radiating patch [Son *et al.* (2006)]. Further, Zhang *et al.* introduced dual-band CPW-fed folded-slot monopole antenna for RFID application. The folded slot with open end was introduced to achieve dual-band at the 2.45 and 5.8 GHz bands [Zhang *et al.* (2006)]. Thereafter, Jeon *et al.* proposed a slot-coupled dipole antenna for 900 MHz and 2.45 GHz RFID tag applications. A slot-coupled feed was explored to achieve dual-band operation [Jeon *et al.* (2006)]. Again, a capacitively coupled structure to design broadband RFID tag antennas for the UHF band was investigated by Chang and Lo [Chang and Lo (2006)]. Unlike the popular inductively coupled structure, the capacitively coupled structure offered an alternative method for impedance matching over a broad frequency bandwidth.

In 2007, Stupf *et al.* extensively investigated the number of UHF/RFID tag designs including the hybrid loop, dual crossed-dipoles, and dual crossed-dipoles utilizing an inductively coupled feed for their performance enhancement with metamaterial such as artificial magnetic conductor (AMC) [Stupf *et al.* (2007)]. After that, Nikitin *et al.* presented both theoretical and experimental results for the vector differential radar cross section (RCS) of a UHF RFID tag which agreed well and demonstrated the validity of the theory [Nikitin *et al.* (2007)]. Thereafter, Yen *et al.* presented a graphical method which is based on Green's analysis of scattering antennas to optimize the load impedances for achieving maximum modulated RCS of backscattering semi-passive RFID tags. A planar tag antenna designed at the UHF band was used experimentally to validate the method [Yen *et al.* (2007)]. Later on, Ahn *et al.* [Ahn *et al.* (2007)] presented a compact UHF RFID tag antenna which has near-isotropic RCS patterns and easy conjugate impedance matching property by virtue of an inductively coupled feeding. Further, Fan *et al.* proposed a miniaturized 2.45 GHz RFID tag antenna consisting of a dipole radiator and a planar impedance transformer formed on a copper foil layer cladding on FR4 substrate. The impedance transformer comprised of two inductively coupled spiral inductor is utilized to realize both resistance boosting and inductive compensation for the short dipole radiator to be conjugately matched to the microchip. The length of the dipole radiator and the side length of the spiral inductor could be easily adjusted to tune the input resistance and inductance of the tag antenna [Fan *et al.* (2007)]. In the same year, Camp *et al.* showed a new method to determine the input impedance of RFID transponder antennas with a combination of on-wafer-prober and a network analyzer [Camp *et al.* (2007)].

In 2008, Chen *et al.* demonstrated a 2.45 GHz near field RFID system with passive on-chip antenna (OCA) tags. The passive tag chip with 128-bit non-volatile memory had been realized using CMOS technology [Chen *et al.* (2008)]. After that, Chen and Lin proposed a slim UHF RFID tag antenna design for metallic objects application. The antenna design was based on a high-impedance surface (HIS) unit cell structure directly rather than adopting a large HIS ground plane [Chen and Lin (2008)]. Later on, Bae *et al.* proposed a dual resonance meander antenna that had a bandwidth enhanced characteristic without any additional matching circuit for a UHF RFID tag. The antenna consisted of two radiators that create dual resonance in adjacent frequencies [Bae *et al.*(2008)]. Thereafter, a method of complex input impedance measurement for RFID tag antenna based on a differential probe was presented by Kuo *et al.* The proposed method using the differential probe was explained based the well-known two port network model [Kuo *et al.* (2008)]. Again, Mo *et al.* presented a broadband UHF RFID tag patch antenna with a pair of U-shaped slots. By embedding a pair of U-shaped slots on the patch, a new resonant mode adjacent to the origin mode was excited, and a broadband characteristic was achieved [Mo *et al.* (2008)]. In the same year, Lee and Yu designed a new type of a compact RFID tag antenna in UHF band, which was effectively mountable on various sizes of metallic objects. The proposed antenna had a very thin and simple structure of microstrip patch antenna compared with the conventional metallic tag antennas [Lee and Yu (2008)]. Soon after, in order to increase the RFID operation distance, read range analysis was performed based on a simple equivalent circuit of the UHF-band passive RFID tag by Lee and Lee. The analysis showed that a tag with a large Q-factor lead to an increased input voltage in the tag chip and thus enhanced the efficiency. Based on this analysis, a compact UHF RFID antenna employing inductive coupling between the radiation and feeding portions was designed [Lee and Lee (2008)]. Further, Cho *et al.* proposed a novel UHF RFID tag antenna suitable for metallic objects, consisting of an inner spiral dipole, an outer bent dipole, and a double T-matching network [Cho *et al.* (2008)]. Again, Son presented a novel low-cost antenna design suitable for RFID tags mountable on metallic surfaces. The proposed design reduced the substrate loss and improved the radiation efficiency by more than double compared with a conventional PIFA [Son (2008)]. After that, Fang *et al.* proposed dual band transponder antenna which covered the ETSI standard in UHF band and ISO 18000-4 standard in microwave band had been designed and implemented. The antenna was simple and very suitable for directly matching a commercial chip without additional impedance matching network [Fang *et al.* (2008)]. Later, Park and Woo presented a miniaturized metallic surface-mountable dual-band S-shaped UHF RFID tag antenna. The antenna was designed with a meander and spiral structure, by modifying the microstrip feeding line and ground line [Park and Woo (2008)]. In the same year, Kim *et al.* presented a very small ceramic material patch-type RFID tag antenna (UHF band) mountable on metallic surfaces. The impedance of the antenna could be easily matched to the tag chip impedance by adjusting the size of the shorting plate of the patch and the size of the feeding loop [Kim *et al.* (2008)].

In 2009, Or *et al.* proposed a new passive RFID tag antenna for the UHF band. It consisted of a modified inductive feed and a radiating slotted copper trace (SCT). A ground plane was used in the design to make the tag antenna platform-tolerant [Or *et al.* (2009)]. Soon after, Tang and He proposed a novel single-layer passive RFID tag antenna for 2.45/2.41 GHz applications using a square microstrip patch with a pair of U- and T-shaped slots. The proposed tag antenna was suitable for attaching to metallic objects [Tang and He (2009)]. Thereafter, Rida *et al.* presented an overview of design requirements and novel approaches for improved performance UHF RFID tags. Two matching techniques such as an inductively coupled structure and a serial stub structure were also discussed [Rida *et al.* (2009)]. In the same year, Cho *et al.* introduced a novel circularly polarized UHF RFID tag antenna, consisted of a truncated patch, a shorting plate, and a ground plane, to increase the reading range while remaining in compliance with EIRP regulations. The reading range of the proposed tag was twice that of linearly polarized tags, due to the decreased polarization mismatch between the reader and tag antennas [Cho *et al.* (2009)]. Later on, Kimouche *et al.* presented a dual-band fractal shape antenna design for RFID applications at 915 MHz and 2.4 GHz frequency bands. The proposed antenna was a dipole antenna consisted of a combination of two kinds of fractal shapes with the aim of reducing antenna size. A double T-match structure was used to provide conjugate matching with the complex impedance of the chip [Kimouche *et al.* (2009)]. Again, Iliev *et al.* presented a dual-band HF and UHF RFID tag antenna with two feeding points. Antenna was composed of an S-shaped dipole integrated with the HF coils [Iliev *et al.* (2009)]. After that, Qing *et al.* presented an experimental methodology for the characterization of the impedance of balanced RFID tag antennas and demonstrated the application of the proposed method in RFID tag co-design. The proposed method was useful in practical RFID applications for co-designing the RFID tag with the attached platforms for enhancing the tag performance [Qing *et al.* (2009)b]. Soon after, Toscano and Vegni outlined a generic design process and showed how RFID tags loaded with a metamaterial slab were able to increase the read range and to decouple the tag with the tagged objects [Toscano and Vegni (2009)]. In the same year, Lao *et al.* presented a novel method to measure the radiation pattern of unwired small dipole-like antennas such as RFID tag antennas by optically modulated scatterer (OMS) technique. The radiation pattern could be measured by this technique without any metallic feeding wire that would disturb the field pattern. Measurement results of a small dipole antenna and a RFID tag antenna showed good agreement with the simulated data [Lao *et al.* (2009)]. Again, Nikitin *et al.* describe the sensitivity and impedance measurement method for UHF RFID chips. The measurements are performed using a RFID tester having RFID reader with variable output power and frequency and a vector network analyser. No special impedance matching was required: chips could be connected to standard 50 Ω connectors allowing the sensitivity and threshold impedance to be measured directly in a fast and efficient way [Nikitin *et al.* (2009)]. Further, Mats *et al.* presented an indirect non-invasive method for measuring input impedance and the variations in the assembly of the interconnect and packaging between the antenna and the integrated circuit effects of passive RFID tag antennas [Mats *et al.* (2009)].

In 2010, Lin et al. described a capacitively coupled multi-feed slot antenna consisted of a slot radiator and a small dipole as a coupling source for metallic plate RFID tag design. The tag antenna could function effectively with three different RFID chips, whose impedances varied widely, and the design of the conjugate matched RFID tag could be easily achieved [Lin *et al*. (2010)]. After that, Chen et al. proposed a measurement method for verifying the match condition of the assembled RFID tag. The proposed method could verify the final impedance match condition of the assembled RFID tags which identify the impedance mismatch condition between the RFID chip and the antenna. The verification method was used to obtained the measurement data to estimate the assembly error introduced by different mounting methods [Chen *et al.* (2010)]. Further, Huang *et al.* proposed a compact broadband patch antenna for global UHF RFID applications. The antenna was composed of four synchronous shorted patches that resonate at four different frequencies resulted in broadband impedance characteristics. A central loop was incorporated to feed the four patches simultaneously, which provided the required input reactance for matching to the chip [Huang *et al.* (2010)]. Thereafter, Liu *et al.* presented a novel miniaturized monopole tag antenna for passive UHF RFID operation. The antenna possessed a two-sided structure printed on an FR4 substrate and fed by a microstrip line. The antenna size was reduced by properly using helical strips and vias. A miniaturized quasi-lumped circuit was also designed to attain a good impedance matching between the antenna and the chip [Liu *et al.* (2010)]. Soon after, Kim and Yeo, proposed a passive RFID tag antenna in a recessed cavity in metallic objects such as vehicles, aircraft, and metallic containers, and an impedance matching technique. The tag antenna was a cavity backed antenna and was comprised of a bowtie antenna installed in a recessed large metallic object. The input impedance of the bowtie antenna could be easily matched by adjusting the coupling effect between the tag antenna and the cavity [Kim and Yeo (2010)]. Later on, Koskinen *et al.* presented a RFID multi-slotted dual patch tag antenna for 902–928 MHz band. The antenna could be mounted on metal without degradation in performance. Due to a low-profile and simple structure, the antenna had more potential for mass production compared to earlier antenna design [Koskinen *et al.* (2010)]. Thereafter, Chen and Tsao presented a design of a capacitively coupled meandered patch antenna for UHF band RFID tag mountable on metallic objects. The antenna was fabricated on a very thin substrate. The capacitively coupled feeding technique was used to perform a broadband operation [Chen and Tsao (2010)]. Further, Cho *et al.* designed an embedded-feed type microstrip patch antenna mountable on metallic objects for UHF RFID. The structure consisted of an embedded feed with T-matching networks and a symmetrical radiating rectangular loop patch. The impedance of the presented antenna could be changed to match the impedance values of tag chips by using the T-matching network [Cho *et al.* (2010)]. Soon after, Son and Kim proposed a new antenna design method UHF RFID tags on metallic surfaces, using a low-cost and high-loss substrate. The proposed method improved the radiation efficiency of the tag antenna by almost double compared with a conventional planar inverted-F antenna significantly by reducing the dielectric loss of the substrate [Son and Kim (2010)]. Again, Bletsas *et al.* studied tag properties for optimized tag-to-reader backscatter communication. They provided a general tag load selection methodology applicable to any tag antenna, including minimum scattering antennas as a special case. The method was based on tag antenna structural mode closed-form calculation, employs simple antenna theory, and applies to both passive, as well as semi-passive RFID tags [Bletsas *et al.* (2010)]. In the same year, Chen and Mittra proposed a broadband UHF RFID tag antenna in which complex conjugate of the chip impedance was conveniently implemented using indirect coupling method. An equivalent circuit model of the coupling method was also presented to characterize the performance of the antenna [Chen and Mittra (2010)]. After that, Hadarig *et al.* showed a novel combination of CPW-fed double bow-tie slot antenna and artificial magnetic conductor (AMC), for 5.8 GHz super high frequency (SHF) RFID tag antenna usable on metallic objects [Hadarig *et al.* (2010)]. Thereafter, Virtanen *et al.*

presented a novel RFID tag design optimized especially for the inkjet printing process. Those tags were printed using narrow conductors, which enabled low cost and fast manufacturing rate [Virtanen *et al.* (2010)]. Later, Qing *et al.* proposed a segmented loop antenna with capacitive couplers is proposed for UHF near-field RFID applications, which was capable of generating a strong and uniform magnetic field in a near-field zone even though the perimeter of the loop was comparable to the operating wavelength [Qing *et al.* (2010)].

In 2011, Chen *et al.* proposed a novel dual-antenna tag structure for UHF RFID systems. The tag antenna was formed by two linearly tapered meander dipole antennas that were perpendicular to each other and connected to the slightly modified tag chip. One of the antennas was for receiving, whereas the other is for backscattering. The input impedance of the receiving antenna was designed to be conjugate matched to the highly capacitive chip impedance for the maximum power transfer. However, the backscattering antenna was alternatively terminated by an open or a short circuit to modulate the backscattered field. The differential RCS of the dual-antenna structure was demonstrated to be much larger than that of the conventional tag design [Chen *et al.* (2011)a]. After that, Lai and Li proposed a novel low-profile broadband UHF RFID tag antenna with two parasitic patches. By adding parasitic patches with lengths slightly different from the driven patch, two additional resonant modes were excited; thus, the bandwidth of tag antenna was enhanced [Lai and Li (2011)]. Thereafter, Kim *et al.* proposed a compact tag antenna for UHF RFID systems. The proposed antenna consisted of a T-matching network, meandered dipole, and an inverted-U shaped parasitic element. The tag antenna was miniaturized by utilizing inductive coupling between the meandered dipole and the parasitic element [Kim *et al.* (2011)]. Soon after, Koo *et al.* proposed a label-typed UHF RFID antenna for metallic object applications along with its design methodology. To enhance the gain of the proposed antenna, an additional loop had been placed to surround the original meandered folded dipole antenna [Koo *et al.* (2011)]. Again, Park *et al.* proposed a novel UHF RFID metal tag antenna mountable on the metallic surface. Three techniques such as T-shaped slot, two rectangular slots for impedance matching, and air gap technique for reading distance enhancement were used to obtain a good performance of metal tag antenna on the metallic surface [Park *et al.* (2011)]. Later on, Paredes *et al.* implement dual-band tags for UHF RFID applications. They demonstrated that the performance of dual-band tags operated at the frequency bands of interest is superior to that of the broadband (monoband) tags. A meander-line antenna had been considered for tag implementation. The dual-band functionality was achieved through a perturbation method consisting of coupling an electrically small resonator to the antenna [Paredes *et al.* (2011)]. In the same year, Makimura *et al.* presented evolutional antenna design for wireless environmental or physical sensor devices based on passive RFID. Genotypes are introduced to generate shapes of planar lattice antenna (PLA) and spiral meander line antenna (SMLA) for the genetic algorithm. It was shown that the feeding powers of the optimized antennas were about ten times as great as that of the dipole antenna. The sizes of optimized PLA and SMLA were smaller than that of meander line antenna [Makimura *et al.* (2011)]. Further, Seigneuret *et al.* presented a study of a multi-antenna tag in a RFID UHF system. It was demonstrated that double dipole tag minimized the loss during the backscattering modulation and has improved read range as compared to a single antenna [Seigneuret *et al.* (2011)]. Thereafter, Eldek presented a miniaturized RFID patch tag design to operate on metallic surfaces. Two balanced feedlines with microstrip short circuit are housed inside a patch antenna with a long quasi-Σ slot. The new shape of the slot and feeding circuit made the antenna size compact [Eldek (2011)]. Later, Gao and Yuen disclosed a new method to insulate the UHF RFID tag from backside objects using an electromagnetic band gap (EBG) material so that the tag could still work on the metallic surface. The designed EBG material for UHF RFID operated at 915 MHz under federal communications commission (FCC) regulation was discussed. It was also shown that the RFID tag read range with EBG material increased with the number of EBG unit cells [Gao and Yuen (2011)]. Soon after, Liu *et al.* proposed a novel dual-antenna passive UHF RFID tag with polarization-time coded backscatter diversity to mitigate the performance degradation caused by multipath fading channel. The proposed polarization-time coding scheme reduced the complexity of the corresponding RFID tag design and effectively reduced detection errors of modulated backscatter signal [Liu *et al.* (2011)]. Again, Lu and Zheng derived a new resonant mode that was excited with frequency shifting to enhance the operating bandwidth for broadband operation using the shorting pins posted at the corner of the proposed tag antenna which was mountable on metallic surfaces [Lu and Zheng (2011)]. Further, Lu and Su proposed a novel planar loop tag antenna mounted on the plastic pallets for UHF RFID system. By inserting the U-shaped slot and a pair of rectangular parasitic strips into the proposed tag antenna, the resonant mode close to UHF 900-MHz band was excited to enhance the operating bandwidth [Lu and Su (2011)]. After that, Ziai and Batchelor presented a passive UHF RFID tag design in the form of a transfer of patch similar to a temporary tattoo that was mountable directly onto the skin surface. The transfer tag was also suitable for monitoring of people over time [Ziai and Batchelor (2011)]. Again, Son and Jeong presented a low-cost, wideband patch antenna for RFID tags mountable on metallic surfaces. A novel proximity-coupled feed structure, having the direction of the microstrip feedline parallel to that of the resonant length of the radiating patch and one end of the feed line shorted to the ground, was proposed to perform wideband impedance matching between the antenna and tag chip without any additional matching networks [Son and Jeong (2011)].

In 2012, Ma *et al.* presented a single-layer compact HF-UHF dual-band RFID tag antenna. The antenna was designed on a credit-card-size single layer support using a spiral coil along the edges of the card for the HF (13.56 MHz) near-field coupling and the UHF antenna was placed inside the coil. A diagonal symmetric design consisting of two meander lines inside the spiral coil was adopted for UHF band to supports multiple resonances around 915 MHz to broaden the bandwidth [Ma *et al.* (2012)]. Further, Chen *et al.* implemented a microstrip patch-type UHF RFID tag antenna with circular polarization (CP) radiation. The broad CP bandwidth attained was determined by applying two different techniques such as the dual-offset coupling feed and loading of perturbation element [Chen *et al.* (2012)b]. Again, Chen *et al.* designed a square patch passive RFID tag antenna for UHF band. The square patch was embedded with a cross-shaped slot, while an L-shaped open-end microstrip line linked to a tag chip and terminated by a shorting pin was capacitively coupled to the patch to achieve a compact size and circular polarization radiation. By selecting an appropriate length of the microstrip line and its coupling distance with the radiating element, the matching of the input impedance of the proposed tag antenna is easily achieved [Chen *et al.* (2012)a]. After that, Abdulhadi and Abhari reported the design and experimental evaluation of three compact printed monopole antennas for UHF RFID applications. The antennas were included folded 2-D meander and 3-D meander monopole designs which were inductively coupled to RFID chips. A method for measuring the radiation pattern of an assembled UHF RFID tag without the use of any additional matching circuits or feeding wires was also presented [Abdulhadi and Abhari (2011)]. Further, Lin *et al.* designed an UHF RFID tag antenna comprised of a trapezoidal loop and a dual-dipole radiator with an L-slit for omnidirectional polarized reading patterns. For a conjugate match to the chip impedance, an orthogonal dual-dipole tag antenna with L-slit on each dipole arm was designed [Lin *et al.* (2012)]. After that, Kim and Yeo proposed long read range dual-band passive UHF RFID tag antenna using an artificial magnetic conductor (AMC) ground plane applicable for a recessed cavity in metallic objects such as heavy equipment, vehicles, aircraft, and containers. The proposed tag antenna consisted of a bowtie antenna and a recessed cavity with the AMC ground plane installed on the bottom side of the cavity [Kim and Yeo (2012)]. Thereafter, Son *et al.* presented a low-cost, wideband, flexible antenna for RFID tags mountable on curved metal surfaces. The antenna consisted of a label-type patch adhering to a flexible polyvinyl chloride substrate. To perform simple and wideband impedance matching between the antenna and a tag chip, a novel balanced feed method using two orthogonal slits on the patch was proposed [Son *et al.* (2012)]. Soon after, Chen *et al.* described a high impedance-matched dipole antenna composed of an inductive T-loop and a small bent dipole radiator with a slit for UHF RFID tag design. Simple adjustments of the T-loop and dipole radiator of the antenna allowed for easy control of the antenna resistance and inductive reactance, from which a high chip reactance (or high Q-factor) requirement was attained [Chen *et al.* (2012)c]. Later on, Soliman *et al.* introduced a novel miniaturized RFID tag antenna operated at 915 MHz. The electrical size of the antenna was λ/30 × λ/30, which made it very compact. The antenna had a "Vivaldi-like" aperture fed with a slot line coupled to a microstrip line. The aperture is loaded with a meander line [Soliman *et al.* (2012)]. In the same year, Ryoo *et al.* designed a low-cost wideband antenna for RFID tags for use with metallic foil packages. A proximity inductively coupled feed structure was used to perform wideband impedance matching between a slot on a metallic foil package and a small rectangular feeding loop connected to a microchip [Ryoo *et al.* (2012)]. In the same year, Babar *et al.* presented a possible method of utilizing paraffin wax as a substrate material in developing a threshold heat sensing RFID tag. A small narrowband passive UHF RFID tag was made on top of a multilayer substrate. Paraffin wax acted as the main heat sensitive layer of the substrate. The narrowband tag on top of the substrate was designed to be sensitive enough to detect any structural and physical changes of the substrate material [Babar *et al.* (2012)].

In 2013, Lin *et al.* proposed a design of a long read-range, reconfigurable, and metal mountable UHF RFID tag antenna. The antenna structure consisted of two non-connected load bars and two bowtie patches electrically connected through four pairs of vias to a conducting backplane to form a looped-bowtie RFID tag antenna. The design offers more degrees of freedom to tune the input impedance of the proposed antenna [Lin *et al.* (2013)]. After that, Casula *et al.* proposed a new antenna as a passive tag antenna for UHF RFID, designed on a polyethylene terephthalate (PET) substrate and fabricated by inkjet printing using a conductive ink. The operating bandwidth of the proposed antenna was very large. It had a very simple geometry and could be easily tuned to feed many of the commercial RFID chips [Casula *et al.* (2013)]. Thereafter, Santiago *et al.* presented a new improved design of a RFID passive tag antenna which performs well near problematic surfaces such as human body, liquids, and metal) across most of the universal UHF RFID band. The antenna was based on a low-profile printed configuration with slots [Santiago *et al.* (2013)]. Soon after, Chen *et al.* proposed a novel circularly polarized (CP) loop antenna design for a UHF RFID tag to overcome the polarization mismatch problem between the reader antenna and tag antenna. The structure of the proposed tag antenna was a square-loop type loaded with an open gap, two feeding strips, and a matching stub [Chen *et al.* (2013)]. Again, Du *et al.* proposed a novel dual-band metal skin UHF RFID tag antenna suitable for attaching to metallic objects. The antenna was designed with two patch arrays printed on a flexible substrate polypropylene for low-cost production to achieve long read ranges within dual band on an ultra-thin substrate [Du *et al.* (2013)]. In the same year, Cruz *et al.* proposed a new planar antenna operating in the UHF-RFID and the FCC UWB band for hybrid passive tag systems. The co-designed UHF and UWB antenna elements were printed back-to-back on each side of a common substrate for future integration with a single UHF-UWB RFID chip [Cruz *et al.* (2013)]. Later on, Sun *et al.* proposed an improved coupling source structure for RFID tag antenna for broadband operation. The antenna could also easily carry out a complex conjugate impedance match between antenna and RFID chip [Sun *et al.* (2013)]. Thereafter, Varadhan *et al.* proposed a tri-band antenna structure for RFID systems with both the reader and tag deploying fractal geometry. The main property of the fractal antenna was to obtain multiband, maintain low profile, and remain small in size [Varadhan *et al.* (2013)].

In 2014, Choo and Ryoo proposed a label tag and a radiator for both the dielectric and metallic target objects in UHF RFID. By the use of a cross-shaped loop placed on dielectric objects and the inserted radiator, proper impedance matching was achieved. The radiator was printed on the plastic substrate with a finite ground plane [Choo and Ryoo (2014)]. After that, Sabesan *et al.* presented a long range and effectively error-free UHF RFID interrogation system based on a novel technique where two or more spatially separated transmitter and receiver antennas were used to enable greatly enhanced tag detection performance over longer distances utilizing antenna diversity combined with frequency and phase hopping [Sabesan *et al.* (2014)]. Thereafter, Pan *et al.* presented a low-profile

RFID tag antenna with a compact size and circular polarization (CP) for metallic surfaces. A star-shaped slot was etched onto the antenna for the CP and antenna size reduction. A terminal-grounded L-shaped feed line was embedded in the etched slot to efficiently excite the wideband CP mode, complexly match the tag-antenna impedance, and further reduce the antenna size [Pan *et al.* (2014)]. Soon after, Salmerón *et al.* developed a sensing RFID tag on flexible foil compatible with tag chip. The integration of different types of the sensor on printed UHF RFID tags was investigated for taking advantage of the sensor interface capabilities of a RFID chip [Salmerón *et al.*(2014)]. Later on, Zhang and Long proposed a novel dual-layer electrically small RFID tag antenna for metallic object applications. Two rotationally symmetric loaded via-patches were fed through an embedded dual-element planar inverted-F antenna (PIFA) array which made the antenna size compact [Zhang and Long (2014)]. Further, Goudos *et al.* designed and optimized a new planar spiral antenna for passive RFID tag application at UHF band using the Artificial Bee Colony (ABC) algorithm [Goudos *et al.* (2014)]. In the same year, Saarinen *et al.* studied the effects of changing humidity conditions on the performance of a passive UHF RFID tag with anisotropic conductive adhesive joints. The tags were tested in a humidity where the humidity varied from 85%RH to 10%RH and temperature from 85 °C to 25 °C. Tags with four different sets of bonding parameters were tested. Significant differences in reliability between tags with different bonding parameters were observed [Saarinen *et al.* (2014)].

In 2015, Tran *et al.* proposed a compact circularly polarized (CP) crossed-dipole antenna for UHF RFID tag. The antenna consisted of two orthogonal dipoles with an arm composed of a meander line and triangular-shaped ending for achieving a compact size. By incorporating two semi-circular curves inserted between the orthogonally arranged dipole arms, the CP excitation was achieved [Tran *et al.* (2015)]. Further, Malek *et al.* proposed a dual-band coplanar-waveguide (CPW)-fed transparent antenna for active RFID tags working at 2.45 GHz and 5.8 GHz. AgHT-8 thin film, included with the silver-coated polyester as the conductive layer and polyethylene terephthalate as the substrate was used to design and fabricate the antenna with high transparency [Malek *et al.* (2015)]. After that, Shao *et al.* designed a textile-based broadband elastic UHF RFID tag antenna. It was also demonstrated that the designed antenna maintained its tuned behavior when placed on dielectrics with varying permittivity [Shao *et al.* (2015)]. Thereafter, Polivka and Svanda introduced a low-profile platform-tolerant UHF RFID tag antenna composed of a pair of three-step impedance sections of shorted patches coupled by a slot, which was differentially fed by a RFID chip. Its input impedance was also analytically investigated using transmission line (TL) modeling [Polivka and Svanda (2015)]. Soon after, Chang *et al.* proposed a compact single-feed dual mode antenna for active RFID tag application. The proposed antenna consisted of a slotted patch on a substrate, a feeding microstrip line, and a foam spacer. The antenna operated as a dipole in free space and as a patch when placed on a metallic surface [Chang *et al.* (2015)]. In the same year, Islam and Karmakar presented two novel compact printable chipless RFID systems. One was a dual-polarized (DP) system and other was an orientation insensitive (OI) system. Chipless tags for both the DP and OI systems consisted of horizontally (H) and vertically (V) polarized "I" shaped slot resonators of different lengths to create frequency signatures in the backscattered signal. To achieve orientation insensitivity, different V–H slots were used in the DP tag to double the encoding capacity within a fixed bandwidth and same V–H slots were used in the OI tag. Further, for reading these DP and OI tags, a low-profile low-cost wideband DP aperture coupled microstrip patch antenna (ACMPA) with high port-to-port isolation was also developed [Islam and Karmakar (2015)].

In 2016, Colella *et al.* presented an accurate and cost-effective measurement platform for the performance analysis of UHF passive RFID tags. The platform was based on a commercial multi-programmable UHF RFID reader provided with general purpose input output ports and controlling a stepper motor. In this way, it can perform the measurement of the minimum emitted power capable of turning ON the tag under test when varying the angle between the reader antenna and tag itself. Based on a rigorous theoretical formulation, tag sensitivity, working range, and radiation pattern can be automatically derived. The system guarantees high versatility since the tag performance can be completely evaluated by varying, besides angle and frequency, also protocol parameters, and interrogation power [Colella *et al.* (2016)]. After that, Michel and Nepa proposed the normalized power density as a metric for numerically assess the performance of near-field UHF-RFID antennas. A proper normalization factor was also included to allow for the performance comparison among reader antennas with different size. It was also demonstrated that NPD numerical data could be used for the prediction of the performance of near-field reader antennas [Michel and Nepa (2016)].

1.5. Scope of the Thesis

In addition to several advantages of RFID systems, they have some limitation. In many RFID applications, the tag needs to be placed on a metallic objects. However, the reading performances of tags, such as read range and reading stability depends on the characteristics of the surface materials on which tag is mounted. For example, if the surfaces are made of dielectric materials, then the read range is decreased due to the shift of the resonant frequency. The radiation efficiency also decreases due to the electrical property of the surface materials. Moreover, if the objects have high conductivity, as in the case of metallic objects, then significant degradation of the reading performance observed due to cancellation of the tangential components of electrical currents on the metallic surface [Chihyun *et al.* (2006)]. Therefore, it is always desirable for RFID tag to be platform tolerant i.e., tag performances do not affect severely when mounted on different objects including metals and lossy objects.

Furthermore, there are several bands on which RFID systems can work such as LF, HF, UHF, SHF and Microwave. In the different regions of the world and depending on the applications, different frequency bands for RFID applications are used. In view of this, it is desirable to have RFID systems that can be worked on different frequency band simultaneously. To accommodate several bands in a single RFID system, the antennas and the electronics circuits should be compatible to work on multi-band or broadband environment.

Furthermore, the RFID systems based on the far-field communication generally suffer from the limitation of short read range. The short read range problem arrives during the backscattering process of tag. Since, during the back scattering process, reader gets the information in term of differential RCS which depends on the maximum and minimum impedance loading of the input port of tag antenna. In case of only a single antenna for a tag the difference of impedance is limited between short and complex conjugate of the chip. It limits the overall read range of the RFID system.

In view of the above limitations of the RFID systems, in the present thesis endeavor has been made to design and develop RFID tag antennas with improved characteristics. To improve the read range of the RFID tag, tag antennas with dual antenna structure is proposed for separate receiving and backscattering antennas. So that the back scattering antennas can be switched between open and short to provide maximum differential RCS, responsible for increased read range. Further, some multiband and broadband dual antenna structure for RFID tag is also presented. After that, some platform tolerant RFID tag antennas are also presented with enhanced read range and multi-band capability. The platform tolerant RFID tag antennas are designed on the PEC backed dielectric substrate to work effectively on the metallic objects.