CHAPTER 2: ANALYSIS OF RADIO FREQUENCY IDENTIFICATION SYSTEM

2.1 Introduction

Radio frequency identification has emerged as one of the key players in the automatic identification industry making its presence felt across different sectors including supply chain management, product tracking, security systems, health care, and logistics. A typical RFID system consists of a tag attached to the item to be tracked and a reader connected to the host computer. The tag has an antenna and a reprogrammable microchip to store information about the tagged object. In this chapter, the basics of RFID systems have been introduced focusing primarily on UHF RFID systems. It introduces RFID system components which incorporate tag, reader, and data processing systems. Thereafter, various operating frequency ranges of RFID systems and their working principles are also discussed. The historical development of RFID technology has been presented in a chronological manner. Furthermore, a detailed literature survey on the RFID tag antennas and reader antennas are carried out in four subsections.

2.2 RFID System Components

Although a variety of RFID technologies exist today, the fundamental components of every RFID system include: tag, reader and data processing systems. A tree diagram of the different components of an RFID system is shown in figure 2.1.

- A tag (or transponder) is located on the object to be tracked. Each tag comes with a unique identification code. The tag comprises an integrated circuit with an antenna. It transmits data by employing radio-frequency signals without any physical contact.

- A reader (or interrogator) is attached to a data processing system through different interfaces (wired or wireless). A reader consists of one or more antennas.
- Data processing systems are networked with readers. They receive the unique tag ID to extract the corresponding information from its database. The application software running on a work station, interprets the collected data from the tag to user-readable messages.

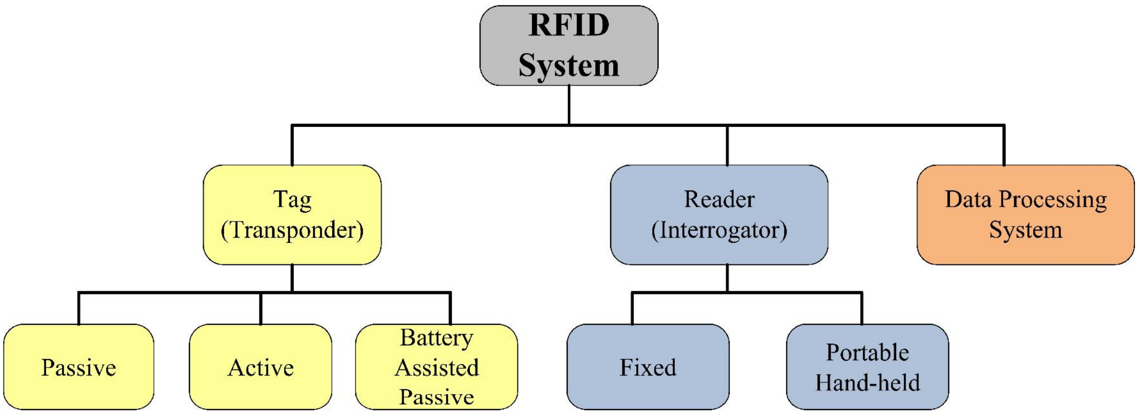


Figure 2.1 RFID system components

2.2.1 Transponder (Tag)

An RFID tag or transponder is a small device that is attached to the objects of interest. A passive RFID tag consists of an application specific integrated circuit (ASIC) and an antenna. The exclusive data about the tagged item is stored in the IC. The ASIC also provides backscattering modulation to the interrogatory signal according to the stored data in it. On account of the available power supply, RFID transponders are broadly categorized into active, passive and semi-passive tags [7].

Passive Tags: Passive RFID tags do not have any on-board power source to energies their internal circuitry. A passive tag receives the operational power from the interrogatory electromagnetic signal from the RFID readers. When an electromagnetic signal reach the tag, a voltage is developed across the tag antenna terminals. The chip collects power from the antenna and responds back by fluctuating its input impedance. Due to the absence of an internal battery, passive tags have a smaller size and longer life in comparison to the active RFID tags. However, the passive tags require high power RFID readers, and they have a shorter read range than the active tags. Passive tags are economical, therefore usually employed for tagging low-cost items in large volume.

Active tags: Active RFID tags have their own internal power source to energies microchip. Active tags can initiate communication by transmitting signal towards their reader. Due to the internal power source, active tags have a larger read range. Thus, they not only detect the presence of an object but can also track its position. Active tags also have a large user-defined memory. However, active tags are expensive. The presence of on-board power source increases the size of the tags in addition to limiting their lifetime by the battery life.

Battery Assisted Passive (BAP) Tags: BAP tags also called semi-passive tags and have an on-board power source, but they cannot initiate communication with readers. The internal battery is only used to energies the tag IC. The communication between semi-passive tags and reader take place using backscattered modulation principle. Thus, the battery life of semi-passive tags is longer than the active tags. Due to the internal battery source, they are expensive and bigger in size in comparison to passive tags. However, the durability of semi-passive tags is limited by battery, but they fill the gap between expensive active tags and short-range passive tags.

2.2.2 Reader

An RFID reader or transceiver consists of antennas which are used to transmit and receive signals simultaneously from a tag. An RFID reader receives data sent from active tags and or reflected from passive tags. The received data contains information about the tagged items, and it is transmitted to the data processing units. The reader antenna radiates maximum allowable equivalent isotropic radiated power (EIRP) to maximise the communication distance between the tag and the reader. More than one antenna can be used at the reader end to enhance the communication distance. RFID readers can be divided into two categories; fixed readers and handheld readers. A wired connection is used to connect fixed reader and the data processing unit whereas; a handheld reader uses a wireless connection to communicate with a data processing unit. In the case of active RFID tags, readers collect the signal sent from transponders. However, in case of passive tags, readers are transceivers which transmit and collect signals at the same time at the same frequency. In a passive RFID system, readers also power up the tags with magnetic field coupling or electromagnetic fields. Based on the isolation between the transmitting and receiving antennas, readers can be divided into bistatic and monostatic antenna configurations. A bistatic reader uses separate transmitting and receiving antennas. Whereas, a monostatic reader uses a single antenna for both transmission and reception. In bistatic reader, two opposite sense circularly polarised (left hand circularly polarised and right hand circularly polarised) antennas are used for isolation between two antennas. In monostatic reader circulator or directional couplers are used for the isolation between transmitting and receiving channels. In portable RFID readers, a monostatic configuration is used due to their compact size [8].

2.3 Operating Frequency Ranges and Principle

Four different frequency bands are assigned for RFID applications; namely, low frequency (LF, 125-134 kHz), high frequency (HF, 13.56 MHz), ultra-high frequency (UHF, 433MHz and 840-960 MHz) and super high frequency (SHF, 2.45 and 5.8 GHz) [9].

Low-frequency RFID systems are largely used for automotive industry and livestock industry. Due to the electromagnetic properties of low frequencies, LF tags work properly even when they are tagged to the objects containing water, animal tissue, and conductive surfaces. The reader-tag link is based on inductive coupling between their antennas, with the same principle of two coils in a transformer. Read range for passive LF tags is in general limited to the diameter of reader's antenna, because the intensity of magnetic field decreases inversely with the third power of distance. Therefore, the power coming back from the tag is inversely proportional to the sixth power of distance. The performance of high-frequency tags is adversely affected by conductive objects. The metallic surfaces cancel the normal component of incoming magnetic fields, which is necessary for the communication with the tag. Thus, HF tags do not work properly on metallic objects. Applications of HF tags include smart cards, library books, airport baggage tracking, etc.

The ultra-high frequency RFID systems have garnered more popularity than the RFID systems used in other frequency bands as they offer longer read ranges, higher reading speeds, enable simultaneous detection of many tags, and require smaller antennas compared to the low frequency (LF) and high frequency (HF) RFID systems. Furthermore, they are less prone to multipath interference and signal diffraction compared to RFID systems used in the microwave frequency band. UHF RFID systems operate in 433 MHz (active tags) and 840-960 MHz (passive tags), but each country has been allocated a specific frequency band for UHF RFID system: India (865 - 867 MHz), Australia (920 - 926 MHz), Taiwan (922 – 928 MHz), Japan (916.7 – 923.5 MHz), North America (902 - 928 MHz), Korea (908.5 - 910 MHz), Europe (865.6 – 867.6 MHz), China (920.5 - 924.5 MHz), Singapore (866 - 869 MHz and 923 - 925 MHz), etc [10].

There are two different working principles of RFID systems based upon the operating frequency. Low frequency and high-frequency band RFID systems work on near-field coupling with load modulation principle, and UHF RFID system works on backscattered modulation in the far field. In near-field coupling, both reader and tag have coil antennas with power coupling between them based on the principle of transformer. In far field communication, the reader sends a modulated signal with unmodulated carrier pulses, which energizes the passive tag. When these unmodulated carrier pulses are converted to DC at the ends of the tag antenna, then a potential difference is developed across its terminals. The chip receives power from the antenna and replies back to the antenna by switching its input impedance between two states. One of them is the match state when the chip impedance is maximally matched with the tag antenna. In this state, the chip is powered up. The other is a strongly mismatched state when the backscattering modulation takes place [11].

2.4 Passive UHF-RFID Tags: An Overview

As discussed in section 2.3, UHF RFID systems are more attractive than others due to fast data transfer speed, more storage capability and higher reading range. A passive UHF RFID tag is comprised of an application specific integrated circuit (ASIC) and an antenna.

2.4.1 UHF-RFID ASIC

Due to the advancement in CMOS technology, the size, cost, and threshold power of the tag IC have been significantly reduced in the last few decades. As the passive tag does not contain any internal power source, so the IC is powered up by the incoming electromagnetic signal from the reader. The first stage of an RFID tag IC is a voltage multiplier, which produces the rectified DC voltage required to energies the IC. Schottky diodes and capacitors, which were earlier used in the rectifier stage, have now been replaced by CMOS technology. The input impedance and threshold power of a tag IC are the most crucial parameters as they affect the read range and bandwidth of the RFID system. The threshold power or sensitivity (P_{th}) of a tag IC is described as the minimum power required to awaken it. The first stage of tag IC decides the input impedance (Z_c) and for good energy harvesting efficiency; a large input capacitance is required. Thus, the input impedance of tag IC (Z_c) contains a strong reactive component, and it varies with frequency and applied voltage. In order to transfer maximum power to the microchip, the input impedance of the tag antenna should be complex conjugate to the impedance of the tag IC. For good impedance matching and larger bandwidth, the input capacitance of tag IC should be as low as possible. Therefore, a trade-off between the input capacitance and energy harvesting efficiency is considered, and the input capacitance cannot be decreased indefinitely [5]. The input impedance of tag IC is modelled by a parallel combination of resistance (R_c) which accounts for the power dissipated by load and capacitance (C_c) which account for the effects due to rectifier stage. A UHF RFID microchip has strongly capacitive reactance with reactance in order of hundreds of ohm and resistance in the order of a few ohms. Table 2.1 shows input impedance and sensitivity of some commercially available UHF RFID tag ICs.

Table 2.1 Input characteristics of some UHF RFID tag ICs

UHF RFID tag IC	**P_{th} (dBm)**	**Z_c (Ω) at 866 MHz**	**Z_c (Ω) at 915 MHz**
NXP UCODE 7 [12]	-21	14.5-j293	12.5-j277
NXP UCODE G2XM [13]	-15	24-j207	22-j195
Impinj Monza 4 [14]	-17.4	13-j151	11-j143
Impinj Monza X-2K Dura [15]	-17	21-j182	19-j172

2.4.2 Passive UHF-RFID Tag Antenna

The overall performance of a passive UHF RFID system depends on the tag antenna. Thus, the tag antenna forms a crucial element. In this section, important tag antenna parameters for a passive RFID are presented.

Radiation Pattern: Radiation pattern of a tag antenna describes how it is able to receive or backscatter reader signals from different directions. For an arbitrarily oriented general purpose tag, ideally an isotropic radiation pattern is desirable. The isotropic like pattern provides reliable detection of the tag from all directions irrespective of its orientation. However, a directional pattern is preferred for a tag whose orientation is fixed and is prior-known for some dedicated applications. Directional patterns provide enhanced read range only in a particular direction.

Polarization: Polarization is an important parameter for a tag antenna. The polarization of tag and reader antenna should be matched in order to get efficient coupling between them for optimum read range. Generally, tag antennas are designed with linear polarization (LP) to keep size and cost of tag low. In most of the RFID applications, orientation of tag does not remain fixed. Thus, a circularly polarized (CP) reader antenna is required, for the reliable communication between the arbitrarily oriented linearly polarized tag and reader. This combination of polarizations provides reliable detection capabilities with reduced read range. A LP tag is able to receive only half of the available power from CP reader, which reduces the read range of RFID system. If the orientation of LP tag antenna remains fixed and is known in advance, then the use of an LP reader provides larger read range.

Bandwidth: A smaller bandwidth of the order of a few MHz is required for the UHF tag antenna to operate in one region and a noticeable wider bandwidth (840 MHz to 960 MHz) is required to cover whole UHF band which can be used all over the world. The input impedance of a tag antenna varies with frequency and the impedance mismatching with tag IC limits the bandwidth. Thus, it is troublesome to design a tag antenna that provides same performance in different regions. Wideband tag antennas are less sensitive to detuning, which may occur due to metallic object tagging.

Input Impedance: Tag antenna is also used for energy harvesting to energies the ASIC of a passive RFID system. Thus, the input impedance of a tag antenna is a fundamental parameter, since the energy transfer between the antenna and microchip depends upon the impedance matching between them. The input impedance of microchip is strongly capacitive because of the presence of rectifier and energy-storage stage at the input of microchip. To achieve maximum power transfer between antenna and ASIC, the tag antenna input impedance must be inductive in order to provide complex conjugate impedance matching. External impedance matching networks involving lumped components are not feasible for low cost and miniaturized passive tags. Therefore, the matching mechanism must be included in tag antenna design. Some feeding mechanism like T-match network [16] and inductively coupled loop [17] may be adopted with tag antenna for conjugate impedance matching.

Size: Since most UHF RFID tags have to be attached with small objects, tag antenna size must be miniaturized with allowable degradation in characteristics. In order to reduce the length of an antenna, one can bend the straight conductor of dipole type antenna. Multiple bending produces a meandered dipole with size reduction. The folded arms of the meandered dipole produce distributed capacitance and inductance that also affects the input impedance of the antenna. Since the conductor of meander line is not straight, the equivalent inductance of each segment is reduced in comparison to a straight dipole. Therefore, at the same resonant frequency, the total length of the meander line antenna is increased compared to a straight dipole but the projected length is reduced. A consequence of reduced size of the antenna due to meandering is reduced radiated fields. The currents in the adjacent vertical segments of a meander line antenna are in the opposite direction, which cancels the radiation in the far field. Radiation from antenna are mainly contributed by segments oriented along the length of the structure. The vertical segments produce losses and the radiation resistance scales with horizontal segments rather than the total length of the antenna. The reduced dissipated energy of meander line antenna in comparison to a straight dipole antenna implies a high ratio of stored to dissipated energy, which gives a high-quality factor and narrow bandwidth. Size miniaturization can be achieved with meandering technique at the expense of narrow bandwidth and low efficiency. Therefore, a trade-off between meandering and antenna performance should be considered for tag antenna design. Another efficient size reduction method for tag antenna is capacitive tip loading. In a straight dipole antenna, most of the current flows near the centre of the antenna and most of the charge are stored at the ends. Resonant frequency can be shifted at lower side by broadening the conductor at the end to provide more space to store charge. Two more benefits with size reduction may be expected due to capacitive tip loading. First, the capacitance of the structure increases, which reduces the capacitive reactance of the antenna. Second, the current falls off less rapidly at the ends, and this increases radiation resistance. Often, a combination of meandering and tip loading is used for size reduction and performance enhancement of tag antennas.

2.5 Passive Tag Performance

This section deals with the main performance indicators of passive UHF-RFID tags. Read range and the input impedance measurement techniques are discussed.

2.5.1 Impedance Measurement

Accurate impedance measurement plays a crucial role in RFID antenna designs. However, most of the UHF RFID tag antennas are balanced structures. These antennas are fed by differential input signals without a real ground. Therefore, input impedance of balanced antennas cannot be measured directly by using a single ended two-port vector network analyzer which are terminated with unbalanced ports like coaxial port. Unequal current flows through the terminals of a balanced RFID tag antenna when it is connected to an unbalanced port. Thus, accurate measurement of antenna impedance becomes very difficult.

Balun method [18], mirror image method [19], and differential probe method [20] are the most common methods for the input impedance measurement of an RFID tag antenna. Balun is a balanced to unbalanced converter that provides differential currents at end port. In external baluns, the measurement accuracy relies on the accuracy of the baluns itself. In the mirror image method, half of the symmetric antenna is placed over a large conducting ground plane and its input impedance is measured using a network analyzer. The complex input impedance of the full antenna is twice the measured impedance of half antenna. Measurement accuracy in mirror theory relies on the size of the ground plane as compared to the antenna, and connection between measurement cable and tag antenna. In this thesis, differential probe method is used for measurement. A differential probe test fixture is made of two semi-rigid coaxial cables which are soldered together on the outer conductor, as shown in figure 2.2. One end of the differential probe has small-extended inner connectors that are connected to the antenna under test, and the other end of the test fixture is connected to a VNA with cables. The errors introduced by the test fixture in the measurement of parameters are taken care of by adopting port extension technique, as shown in figure 2.3.

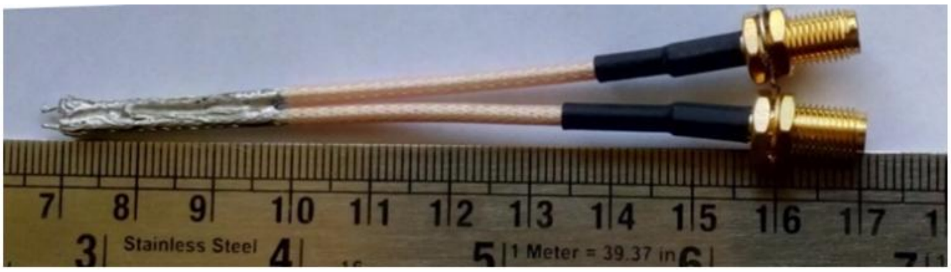
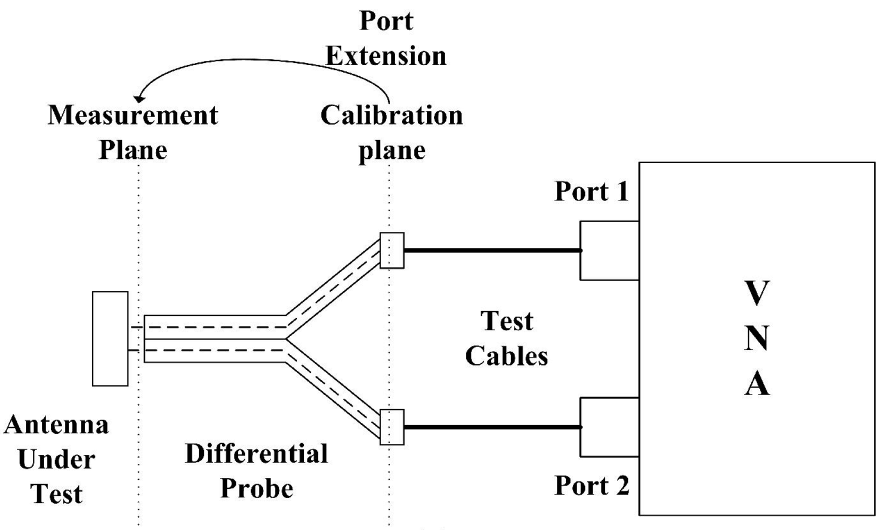
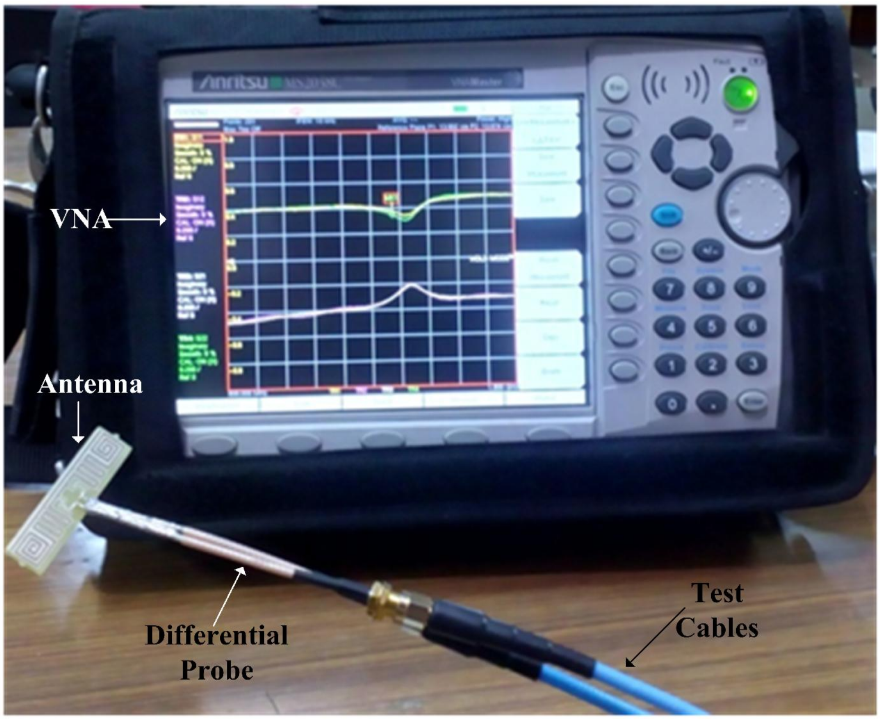


Figure 2.2 A semi-rigid differential probe test fixture



(a)



(b)

Figure 2.3 (a) Schematic configuration of measurement setup with differential probe, (b) impedance measurement setup with VNA

2.5.1.1 Differential Probe Method

Differential probe method, proposed by Palmer and Rooyen [21], is an effective and wideband method to calculate the input impedance of balanced antennas from measured data.

The measurement can be conducted via the following steps

1. Conduct standard VNA parameters setting and calibration.
2. Connect the differential probe to the test cables and shift the calibration plane through the port-extension technique to de-embed the influence of the text fixture.
3. Connect the antenna under test (AUT) with a differential probe and measure S-parameters.
4. Calculate the impedance of AUT using the conversion formulas.

   The differential input impedance (Z_d) of tag antenna can be calculated by using measured S-parameters with formulas [22]:

$$Z_d = \frac{2Z_0(1 - S_{11}S_{22} + S_{12}S_{21} - S_{12} - S_{21})}{(1 - S_{11})(1 - S_{22}) - (S_{21}S_{12})} \tag{2.1}$$

   For a symmetrically balanced antenna, the equivalent network is symmetrical as well; thus equation (2.1) can be modified by having $S_{11}=S_{22}$ and $S_{21}=S_{12}$:

$$Z_d = \frac{2Z_0\left(1 - S_{11}^2 + S_{12}^2 - 2S_{12}\right)}{\left(1 - S_{11}\right)^2 - S_{12}^2} \tag{2.2}$$

2.5.2 The Read Range

Read range is an important performance characteristic of an RFID system. Read range is the maximum possible communication range between reader and tag, i.e., the maximum distance at which the reader can detect the tag. Read range depends on many factors like impedance matching between tag antenna and IC, antenna gain, communication environment, tag orientation, platform material on which tag is connected and regional regulations on EM emissions. Maximum read range R_{max} can be determined as follows [23]:

$$R_{\max} = \frac{\lambda}{4\pi}\sqrt{\frac{P_r G_r G_t (1-|\Gamma|^2)\rho}{P_{th}}} \tag{2.3}$$

Where λ is the wavelength at the working frequency, P_r is the transmitted power from the reader and G_r is the gain of the reader antenna, G_t is the gain of tag antenna, ρ is the polarization efficiency and P_{th} is the threshold power.

Γ is the reflection coefficient and τ is the power transmission coefficient.

$$\tau = 1-|\Gamma|^2, \Gamma = \frac{Z_c - Z_a^*}{Z_c + Z_a} \tag{2.4}$$

Z_c and Z_a are the chip and antenna impedance, respectively. The product of the power transmitted by the reader and the gain of the transmitting antenna (i.e., P_tG_t) is the transmitter's effective radiated power, which is allotted for different regions as per the regulations of regulatory authorities. In order to avoid the effects of RFID power transmitter to other radio wave devices, individual countries impose a limitation on power uses. The radiated power limitation is usually expressed in the terms EIRP and ERP. EIPR and ERP are the acronyms of equivalent isotropic radiated power and effective radiated power, respectively. 4 W EIRP is used in United States, Japan, Australia and South America; while a value of 2 W ERP is used in Europe, China and Singapore. A maximum of 4 W ERP power limitation is settled in India and Russia.

EIRP and ERP are related as:

$$P_{EIRP} = 1.64 * P_{ERP} \tag{2.5}$$

The maximum detection range of a RFID system can also be found by using the classical radar range equation [24]:

$$R_{\max} = \left(\frac{P_r G_r^2 \lambda^2}{(4\pi)^3 S_R} \Delta\sigma \right)^{1/4} \qquad (2.6)$$

Where, P_r and G_r are the radiated power and gain of the reader antenna, respectively. λ is the wavelength and S_R is the sensitivity of the reader. Δσ is the radar cross section difference of the backscattered antenna signal for the two loading states. For the polarisation-matched reader and tag antennas, the backscattered radar cross section (σ) of the tag antenna is expressed as [25]:

$$\sigma = \frac{\lambda^2 G_t^2 R_a^2}{\pi |Z_a + Z_L|^2} \qquad (2.7)$$

Where, Z_L and $Z_a=R_a+jX_a$ are the terminated load impedance and the input impedance of the tag antenna, respectively.

2.6 History of RFID

Although RFID technology has gained popularity in recent years, its operating principle (backscatter modulation) was introduced many decades ago. RFID did not experience the same process of development and evolution common among the most known wireless technologies, such as Bluetooth, WIFI, GSM and so on. Modern RFID systems were developed by military research programme during World War II. Europeans used reflected radio waves to detect aircraft by using radar, which were discovered in 1935 by Sir Robert Alexander Watson-Watt. The Germans identified that the reflected back radio signal changes if pilots rolled their planes when returned to base. This raw method was used by the ground crew to identify German planes [26]. The British developed an active identification system by using a transmitter on each plane to Identify friend or foe (IFF) aircraft. These transmitters were as big as suitcases and used to transmit RF signals in order to communicate with their base station.

Table 2.2 Evolution of RFID system

Year	Event
1935	Discovery of RADAR by Sir Robert Alexander Watson-Watt
1939	First RFID concept for IFF systems in WWII
1948	First technical idea behind RFID was published in the paper entitled "Communication by Means of Reflected Power" by Harry Stockman
1973	Mario Cardullo received the first patent for an active RFID tag with rewritable memory
	Charles Walton received a patent for a passive RFID tag used to unlock a door without a key
1975	Extensive research and development of passive/semi-passive RFIDs in Los Alamos National Laboratory
1987	The first commercial application of electronic toll collection began in Norway
1990-2000	RFID technology enters the mainstream, emergence of RFID standards
2002	FCC approved UWB technology for commercial applications
2003	EPC technology adopted by Walmart and DoD, first UWB RFID developed

The historical development of IFF systems shows that the RFID technology developed by military research, and they were related to the identification applications implemented with RADARs and transponders. In 1948, Harry Stockman published the first paper on basic principles of RFID entitled "Communication by Means of Reflected Power" [27], but the electronic technology suitable for a low-cost realization was not mature enough. It took several decades to develop the first transponder. The first active RFID was invented by Mario Cardullo in 1973. He patented an active transponder with rewritable memory where transfer of data took place either by using RF, acoustic, or light signals [28]. In the same year, the first passive RFID system was invented by Charles Walton of Proximity Devices. With the passive RFID system, keyless door lock was developed [29]. A key to the rapid expansion of RFID technology was the development of the personal computer (PC) that allowed convenient and economical collection and management of data from RFID systems. Tests of RFID for collecting tolls had been going on for many years, and the first commercial application began in Europe in 1987 in Norway and was adopted quickly in the United States by the Dallas North Turnpike in 1989 [30]. However, it was not until 1990s that the RFID technology saw widespread application in mainstream business. This can be attributed to the advancements in the semiconductor industry, which saw an improvement in the performance of semiconductor chips while reducing their size and cost. This breakthrough enabled massive commercialization of RFID systems in security and access control, transportation, toll systems, supply chain management and tracking. The development of RFID transponders found a key advancement when the first microwave Schottky diodes could be integrated with the CMOS technology, at the end of the 90s. This breakthrough allowed the transponder circuitry to be entirely contained within a single integrated circuit (RFID ASIC), covering an insignificant portion of the tag area. For the first time, the antenna size was the limiting factor of passive RFID tags, which continues to be a major limitation [30]. In 1999, the Auto-ID center at MIT was founded to establish an open standard for RFID networking. The auto-id center has introduced an electronic product code (EPC) concept. In this concept, each tag only contains a unique 96 bit long code and all the other information is stored in the database. The adaptation of this concept avoids the requirement of a large memory for storing object information in tag chips and results in low tag cost. 2003 was very important for RFID as both Wal-Mart and the U.S. Department of Defence (DoD) adopted EPC (Electronic Product Code) technology for supply chain management in this year. Furthermore, with the FCC approval of commercialization of UWB technology in 2002, several companies introduced UWB RFID systems. The limiting factor to the expansion of the RFID technology is the cost of the tag. As the tags are intended to label virtually any kind of object, including everyday consumables, their cost must be fairly lower than the cost of the tagged items. Table 2.2 summarizes the evolution of RFID.

2.7 Literature Review

The objective of the present thesis is to design antennas for passive UHF RFID tags with longer read range and to design a compact antenna for handheld UHF RFID reader system. In order to outline the scope of the thesis, we will now review some important literature on the RFID tag antennas and the RFID reader antennas in the following sub-sections.

- Review of passive UHF RFID tag antennas
- Review of circularly polarised UHF RFID tag antennas
- Review of dual antennas for RFID tags
- Review of RFID reader antennas

2.7.1 Review of Passive UHF RFID Tag Antennas

In passive RFID, the performance of the system is dependent on the tag antenna. Conjugate impedance matching between the tag antenna and the microchip is of principal importance for the reliable performance of an RFID system. The size of a passive tag is also limited by the tag antenna. Thus in this section, the previously reported passive RFID tag antennas are presented with focused on impedance matching and size miniaturization.

In **2003**, G. Marrocco proposed a gain optimised non-uniformed meander line antenna for application in passive radio frequency identification [31]. The meander line technique is used for size miniaturisation, and antenna shape is optimized using a genetic algorithm. This paper concludes that a fixed height standard meander line antenna with uniform meanders does not provide optimum gain and for a fixed maximum available space an optimised non-uniformed meander line antenna performs better than the same order uniform meander line antenna.

In **2004**, a platform tolerant inverted-F antenna for RFID tags at 869 MHz was presented by Hirvonen *et al.* [32]. The performance of the antenna has been studied with different platforms showing that the variation in bandwidth is only from 15 to 17 MHz against different platforms, indicating a very good tolerance to different platforms. In the same year, Keskilammi *et al.* proposed a new technique to use text as a meander line antenna in RFID tag systems at 869 MHz [33]. A miniaturised dipole antenna was formed by joining letters of text. Handwriting fonts are suitable to form meander line antenna and shortening ratios of 16% and 22% were reported for two text antennas. Chen *et al.* reported a folded slot CPW fed antenna for 5.8 GHz frequency band [34]. The total length of the slot is comparable to the guided wavelength in order to generate resonance. A 7.5% bandwidth and 4.2 dBi gain are reported, but the antenna is designed for 50 Ω input impedance. Thus a matching network is required to get impedance matching with the microchip.

In **2005**, Son *et al.* explored an inductively coupled feed method to design UHF RFID tag antennas resonating at 915 MHz [35]. An analytical model for the inductively coupled feed structure is discussed for wideband impedance matching between an antenna and a microchip without any additional matching networks. Feed network and the radiating element are designed separately. After optimising the impedance matching between feed loop and microchip, the feed structure can be coupled with the different radiating body. In [36], a passive broadband RFID tag antenna with quasi-isotropic radiation pattern in the UHF band has been proposed by Cho *et al.* The antenna is fabricated with two bent dipoles and a modified double T-matching network. Double T-match network was used to enhance inductive reactance of the antenna and the bent dipoles provided size miniaturisation. Kwon *et al.* investigated a compact slotted planar inverted-F antenna mountable on metallic objects at 900 MHz [37]. Input impedance of the antenna is immune to metallic surfaces. The resistance and the reactance of the antenna can be varied by the width of U-shaped slot in order to get complex conjugate impedance matching with the microchip. Liu *et al.* designed a CPW fed monopole antenna for 5.8 GHz RFID applications [38] with 50 Ω input impedance. Thus, an additional matching network is required to get impedance matching with microchip. In [39], an overview for antenna design for passive RFID tag is studied by Rao *et al*. The design requirements, design process and measurement setup for an RFID tag is discussed in the paper. A loaded meander line antenna is also investigated for tagging a cardboard box in warehouse tracking. Impedance of the antenna can be varied without disturbing the main radiating body by varying the length of the loading bar.

In **2006**, Son *et al.* presented a proximity-coupled wideband tag antenna mountable on metallic surfaces operating at 915 MHz [40]. The antenna consists of a microstrip feed line orthogonal to radiating patch to get impedance matching with microchip. One end of the radiating patch was shorted with the ground plane. In the same year, Chang *et al.* investigated a capacitive coupled broadband RFID tag antenna for UHF band [41]. The capacitive coupler is also a radiating element which improves the efficiency of the antenna. Therefore, capacitive coupled antennas provide better radiation efficiency than inductively coupled antennas. In [42], Hirvonen *et al.* reported a dual-band platform tolerant tag antenna. A technique was discussed to get dual-band behaviour by tuning a single element planar inverted F-antenna. The platform tolerance of the antenna was realized by dominating horizontal surface current density. Jeon *et al.* achieved dual band resonance with a slot coupled dipole antenna at 900 MHz and 2.45 GHz for RFID applications [43]. By inserting a coupled slot in a dipole antenna, a second resonating band was achieved. Zhang *et al.* [44] and Ma *et al.* [45] proposed CPW fed folded dipole antennas for ISM band RFID applications. The antennas are designed with 50 Ω input impedance. Miniaturisation of a circular loop antenna was provided by Ryu *et al.* with the use of shorting stubs [46]. Shorting stubs increase the current length. Therefore, meandered stubs were inserted into the inner part of the circular loop.

In **2007**, Ahn *et al.* proposed a compact RFID tag antenna at 910 MHz [47]. The antenna provides easy conjugate impedance matching by the integrity of an inductively coupled feed loop and near-isotropic radar cross-section pattern which makes the antenna reliable for arbitrarily oriented tag detection applications. In [48], a compact planar antenna for RFID applications at 915 MHz is described. The half-Sierpinski fractal antenna was derived from Sierpinski bow-tie antenna with the modification of ground plane. The antenna has an advantage of its unique topology to achieve conjugate impedance matching with the complex impedance of microchip by varying the feed shape. A novel fork-shaped RFID tag antenna mountable on metallic surfaces to operate at 902-928 MHz band [49] has been reported by Kim *et al*. The fork-shaped structure with two parasitic patches on top of the substrate provided the required complex impedance matching. With the help of parasitic patches, the antenna input impedance can be matched with various tag ICs without disturbing the main radiator. A small rectangular loop antenna for UHF RFID tag was designed by Ryu *et al.* [50]. Meander line and folded meander line were used to get 85.4 and 92.2 % size miniaturisation compared to a general loop antenna.

In **2008**, Xu *et al.* developed a symmetrical broadband RFID tag antenna for UHF band [51]. A T-match network has been used with double symmetrical radiating patches for easy impedance matching and two shorting strips have been used between the patch and the ground plane for acceptable performance on the metallic surfaces. In the same year, a tag antenna for metallic surfaces without a ground plane and shorting pins was reported by Cho *et al.* [52]. The structure consists of two elements with a T-match network; one was a spiral end dipole and second was a bent dipole. The reactance of these elements changes in the opposite direction when attached with highly conductive surfaces. In [53], a low-profile passive RFID tag antenna with artificial magnetic conductor substrate was investigated by Kim *et al*. A modified rectangular patch shaped AMC substrate with offset via was used to significantly increase the gain of the tag antenna. AMC substrate provides high impedance at selective frequencies which makes it platform tolerant. In [54], H.W. Son reported an antenna with two shorted patches printed on FR-4 substrate. Tag IC was placed between two patches and stacked capacitance formed to compensate the impedance. The measured result shows a 2 dB gain improvement and better cross-polarization compared to conventional PIFA of similar size. In [55], Mo *et al.* proposed a broadband patch antenna with a pair of U-slots. The pair of U-slots were used to generate a new resonating mode close to the original mode for bandwidth enhancement. An inset feed with a short line were used to connect the tag IC. Later in 2008, Park *et al.* reported a miniaturized dual band S-shaped RFID tag antenna in the 866-868 MHz (European) band and 908.5-914 MHz (Korean) band [56]. The antenna has parasitic microstrip ground lines on both sides of the feed line. Meander and spiral shape were used for size miniaturisation. Fang *et al*. investigated an asymmetric dipole antenna for 2.45 GHz active tag applications [57]. The antenna was comprised of a short rectangular dipole and a bent T-shaped monopole directly integrated to the electronic components such as battery. A balloon-shaped passive antenna was demonstrated by Hu *et al.* for UWB RFID applications [58]. Theoretical and experimental study of radar cross section with different kind of loads was presented with omnidirectional scattering pattern. Kim *et al*. investigated a circular antenna for metallic platforms [59], which uses ceramic material and PIFA type patch antennas for the UHF RFID tags. Both the feeding part and the radiating part with horizontal slits were on the same side of the substrate so the implementation is simple and the cost is low.

In **2009**, Dacuna *et al.* proposed an inductively coupled bow-tie patch antenna mountable on metallic objects [60]. Bow-tie shape provides a reduction of the patch size and a further reduction can be accomplished by cutting a slot in the patch. The antenna was fed through a rectangular loop by means of an inductive coupling which does not require any shorting plate or via-hole. Feeding loop was placed between two radiating bow tie elements of slightly different size for bandwidth enhancement. In [61], Choi *et al.* reported a simple tag antenna using a modified folded dipole structure for the Korean band (908–914 MHz), providing nearly independent tuning mechanisms for input resistance and input reactance. Input impedance of the antenna can be matched with any microchip with variation in inner and outer lobs of the circular ends of the dipole. Radiation pattern has been recorded similar to that of a standard dipole antenna with a maximum gain of 2 dBi in the desired frequency band. You *et al.* discussed the use of a photonic band gap (PBG) structure to broaden the working bandwidth of the antenna [62]. A dual-frequency printed folded dipole antenna with PBG structure carved in the antenna's arms was designed. PBG structure enhanced the radiation characteristics of the antenna and increased the working bandwidth adequately. Kimouche *et al.* reported a compact printed dipole antenna for dual-band RFID applications at UHF and microwave bands [63]. The antenna consists of a combination of two kinds of fractal shapes for size reduction. A double T-match structure was used for conjugate impedance matching with microchip. Omnidirectional radiation patterns comparable to those reported for a conventional dipole antenna were obtained. Xi *et al.* presented an on-chip antenna design for UHF RFID tags [64]. However, the communication distance of the tag is low, but the on-chip antenna design methodology has an advantage of small size and enhanced reliability. Galehdar *et al*. described a tapered meander line antenna for enhanced efficiency and reduced environmental effects [65]. With a growing number of applications of the disposable RFID tags, the environmental impact of mass-produced antenna was considered. The proposed study provided a design methodology based on tapering meander line antennas to achieve maximum efficiency within a fixed volume. An iterative optimization technique was used in which the thickness of each segment was optimised according to the current in each segment of the meander line. A dual-band antenna for high frequency and ultra-high frequency RFID tag was designed by Iliev *et al.* [66]. Two separate radiating elements with separate feeding points were proposed for HF and UHF ASIC. An S-shaped dipole was inserted within the HF coil, and mutual coupling between these elements was controlled for good performance. A 3-D cubic antenna for environmental sensing applications has been developed by Kruesi *et al*. [67]. The cubic shape of the antenna provided miniaturised packaging as the sensors were integrated inside the cube. The antenna structure comprised of folded meander line with a T-match network. Ziai et al. came forward with a tag antenna for metallic surfaces which is designed to fit on the neck of a small gas cylinder [68]. The antenna consists of a folded dipole with parasitic element, placed on a flexible substrate and operates at the European and American UHF RFID bands. A miniaturised tag antenna with omnidirectional radiation pattern was designed by Chen *et al.* [69]. The antenna consists of an inductively coupled feeding loop which was placed within a radiating open loop. The feeding loop provided freedom to optimise the input impedance of the antenna by varying geometrical parameters. Tang *et al*. developed a single layer RFID tag antenna for microwave band [70]. A pair of U and T-shaped slots on the rectangular patch was used with grounded FR4 substrate which made it suitable for the conductive surfaces. The antenna attained a good trade-off between bandwidth and gain. S. L. Chen designed an antenna for metallic object tagging applications [71]. The antenna consists of two rectangular patches, electrically connected to ground plane with shorting pins. A metallic layer was inserted between the patch and the ground to increase the reactive impedance of the antenna, which helped to attain the conjugate impedance matching with microchip.

In **2010**, Chen *et al.* presented an indirect coupling method for designing an RFID tag antenna, which can attain a complex conjugate impedance match with tag IC [72]. In case of an inductively coupled feed loop, the resistance cannot be controlled easily, and a large size loop is required to achieve input reactance. With indirectly coupled feed, the problems associated with loop feed can be mitigated. The bandwidth of the proposed antenna was covering the entire UHF RFID frequency band. In [73], Chen *et al.* presented two PIFA array antennas mountable on metallic objects for UHF RFID applications. The first array has shorting pins placed at the outer edges of PIFAs and fed by two quarter-wavelength microstrip lines. The second array has shorting pins located at the inner edges of PIFAs. The second array was also incorporating additional matching stubs into the quarter-wavelength microstrip lines to attain conjugate impedance matching. Performance of the first array degraded when the antenna was mounted on a metal object but the performance of second array remained unaffected. Later in the same year, Lin *et al.* reported a capacitive coupled multi-feed antenna for conductive surfaces [74]. The antenna consists of a slot radiator and can function efficiently with three different tag ICs. The conjugate impedance matching for three different ICs can be attained by varying the feed position around the slot. Chen *et al.*

presented a meander line patch antenna for conductive surfaces [75][76]. Both antennas were made up of a tapered meander line with a ground plane. At UHF band, the long radiator meandered into several half wavelength long elements which made the surface current of each element in phase. Thus, the antenna efficiency was increased and an enhanced read range was achieved. In [77][78], Braaten *et al.* explored the use of open complementary split ring resonator rather than meander line technique for miniaturisation of the antennas. Split ring resonators were used in a similar manner to the series connected meander-line sections which provided enhanced gain with a smaller size. Hu *et al*. studied a monopole antenna for chip less UWB RFID systems [79]. Six different antennas were designed and their backscattering characteristics evaluated. A trimmed elliptical-ring patch was employed as the radiation element with meandered CPW fed; therefore, the size of the monopole became small. Ryu *et al*. presented an electrically small spherical UHF RFID tag antenna [80]. A dipole-typed RFID tag antenna was wound into a spherical shape to attain size miniaturisation. Quasi-isotropic radiation pattern was achieved by adjusting the current in the desired direction. A small size monopole antenna for UHF RFID has been proposed by Liu *et al.* [81]. Size of the antenna was reduced by using helical strips with shorting pins. Unlike conventional antennas, a matching structure connecting to the IC was not combined with antenna, but a miniaturized quasi-lumped circuit was used to attain conjugate impedance matching between the antenna and the IC. Mo *et al*. presented a tag antenna mountable on conductive surfaces [82]. An open stub line and inset feed were used to connect the tag IC. The open stub feed line provided a large tuning range of the input impedance of the antenna in comparison to short stub line. Difference between the open stub feed line and short stub feed line was discussed. Lu *et al.* presented a planar inverted-E antenna for UHF RFID tag applications [83]. A narrow slit was etched out from one of the radiating edges of the patch to generate a new resonating mode near to fundamental mode which enhanced the bandwidth of the antenna. A short stub line with inset feed was used to get conjugate impedance matching of the antenna with microchip. Kim *et al*. investigated a UHF tag antenna in a recessed cavity in metallic objects such as vehicles, aircraft and metallic containers [84]. The cavity backed antenna comprised of hollow bow-tie antenna and the input impedance of the antenna was matched with microchip by adjusting the coupling effect between the antenna and the cavity.

In **2011**, Son *et al.* reported a multi-layered, wideband tag antenna for radio frequency identification applications [85]. A rectangular metal plate was used as a radiating element, whose one edge was shorted with the ground plane. A novel proximity-coupled feed structure between ground and the radiating element was implemented, in which the direction of the feed line was parallel to that of the resonant length of the radiating patch. One end of the feed line was shorted to the ground with shorting pin for the wideband impedance matching with the microchip, and the other end of the feed line was kept open to connect microchip. In the same year, Paredes *et al.* [86] reported a novel dual-band RFID tag antenna by cascading an impedance matching network (split-ring resonator) between the tag chip and the antenna using artificial transmission lines. A two-turn spiral resonator was coupled to a meander line antenna operating at 891 MHz to split the tag resonance into two (one beyond and the other one below 891 MHz) by perturbing the line impedance and the electrical length of the antenna. The antenna resonates at 867 MHz and 915 MHz. In [87], Lu *et al*. designed a meandered broadband tag antenna. The antenna can be mounted on conductive surfaces at UHF frequency band. The operating bandwidth of the antenna was increased by generating a new resonating mode with shorting pins at the corner of the antenna. The new resonating mode was excited near to the fundamental mode. A T-match network was used for impedance matching. Deng *et al*. proposed a new optimisation technique for RFID tag antenna design [88]. The technique was a combination of space mapping and jumping-gene genetic algorithm technology. The antenna structure consists of a meander line dipole with hollow rectangular tip loading. An artificial magnetic conductor (AMC) ground plane was used to make antenna platform tolerant. Aghdam *et al*. described a small-sized antenna set including one scavenging antenna and one UWB antenna [89]. This antenna set was integrated with the same wireless-powered RFID chip in 5.8 GHz. Both the antennas were designed with separate T-match networks for impedance matching. The spiral end loading with dipole was used for size miniaturisation. Jeong *et al*. proposed a UHF RFID tag antenna suitable for the concrete floor [90]. The tag antenna was used to identify and track the location of a shipyard transporter. A shipyard floor is usually made up of concrete which is highly lossy dielectric at UHF band thus produce adverse effects on tag antenna performances. The antenna comprised of a ceramic patch, a parasitic patch and a metal cavity. The parasitic patch and metallic cavity improved the gain of antenna by removing the energy flow in concrete floor. Bjorninen *et al*. investigate a conformal tag antenna suitable for water bottle tagging [91]. The antenna was fabricated on a thin flexible substrate for easy integration with a bottle. To account the influence of water on the antenna, the water bottle was considered as part of the antenna. Double T-match structure was used for impedance matching with microchip and folded dipole for the size miniaturisation. Koo *et al*. proposed a label type tag antenna for conductive surfaces [92]. First, a folded dipole antenna with meandering was designed without consideration for metallic objects. A T-matching network was used to increase the inductive reactance of the antenna. In order to improve the tag performance on the metallic plates, the gain of antenna improved with an additional loop which surrounds the original meandered antenna. Yang *et al*. presented an antenna with loop-fed suitable for metallic objects [93]. The antenna consists of two radiating patches with shorting plates and a loop. The small loop provides the needed inductance to the antenna and attached to the microchip.

In **2012**, Abdulhadi *et al.* reported an experimental evaluation of three small sized monopoles (folded dipole, 2-D meander line antenna and 3-D meander line antenna) transponder antennas [94]. All antennas inductively coupled to the microchip for better impedance matching. 3-D meander line antenna had the smallest dimension and designed by using shorting pins. In the same year, Son *et al.* investigated a low-cost, wideband, flexible antenna mountable on curved metal surfaces [95]. A square patch with slits was printed on a flexible polyvinyl chloride substrate for cylindrical conductive surfaces. Two orthogonal slits were used to provide a required inductive impedance to antenna for conjugate impedance matching with tag IC. Later in the same year, a miniaturized wearable UHF RFID transponder antenna has been reported by Manzari *et al.* by engraving a 'square-smile' slot shape on a folded patch [96]. An H-shaped slot was used to connect the microchip. The form factor of this slot provided the required inductive impedance to the antenna. Remaining two slots were used to lengthen the current path for size miniaturisation. Ma *et al*. proposed a single layer dual-band antenna [97]. For the high-frequency RFID operation, a spiral coil antenna was designed at the edge of the substrate and for UHF band, a folded meandered structure was designed inside the coil. Zuazola *et al*. presented an RFID tag antenna for vehicle chassis applications [98]. The planar inverted-F antenna was designed for hidden applications which can be used on metallic surfaces. Ryoo *et al*. investigated a transponder antenna for metallic foil packages [99]. The tag antenna consists of a slot radiator and a loop feeder. The slot was made by cutting a slit in the metallic foil surface of the package and the inductively coupled loop feeder was used to attach the microchip at the centre. Chen *et al*. proposed a UHF RFID tag antenna with high chip reactance matching for the livestock industry [100]. The antenna was composed of an inductive T-loop and a small bent dipole radiator with a slit. Lin *et al*. presented a UHF RFID tag antenna, which was comprised of a trapezoidal loop and a dual-dipole radiator with an L-slit [101]. In general, most conventional RFID tag antennas are dipole like structures which provides null in a particular direction. Thus, the read range in those directions reduces. To mitigate this problem, the antenna provided an omnidirectional polarized reading pattern.

In **2013**, Du *et al.* reported an electrically small planar dual-band tag antenna for 866/915 MHz applications, suitable for mounting on conductive surfaces [102]. In order to increase the read range of RFID system, the gain of the tag antenna was increased by using arrays on the ultra-thin flexible substrate polypropylene. The antenna was cross-connected with the tag IC. In [103], Chen *et al.* proposed a compact strip dipole coupled split-ring resonator transponder antenna. A dipole was integrated with microchip and inductively coupled with a split ring resonator. The uniplanar structure makes the antenna easy to integrate with different passive tag ICs. Lin *et al*. investigated a looped-bowtie antenna for metallic objects [104]. The antenna structure made up of two parasitic load bars and two bowtie patches. The two load bars were placed on both sides of bowtie elements with cut-off points on each bar. The resonating frequency of the antenna can be changed by optimising the cut-off space of the load bar. Four shorting pins were used to connect the bow tie antenna with ground plane which made it looped bowtie and suitable for metallic surfaces. Liang *et al*. designed a low profile tag antenna with quasi-isotropic radiation pattern [105]. The antenna was proposed for active UHF RFID applications which consist of a bent dipole and a ground plane with two slots. A

T-match network was used to provide impedance matching with microchip. The isotropic radiation pattern of the antenna makes it suitable for arbitrarily oriented tag applications. Sun *et al*. proposed a UHF tag antenna with improved coupling loop shape [106]. The inductively coupled loop consists of a small loop connected with two parallel split ring resonators. The structure of the new feeding source has two advantages, easy change of the imaginary part of the input impedance and extended bandwidth because of the two resonant frequencies. A meandered dipole was used as a radiating element. Zhang *et al*. reported a broadband small sized transponder antenna for metallic objects [107]. The antenna has a multi-layered structure. The top layer consists of two directly coupled planar inverted-F antennas and the middle layer consists of two parasitic planar inverted-F antennas. The antenna produced four resonating frequencies to make antenna broadband. Liu *et al*. presented a metal mountable UHF RFID tag antenna [108]. An inductively coupled feed loop was used for conjugate impedance matching with microchip. Loaded capacitors in the radiating and feeding loops allowed for easy control of the resonant frequency. The omnidirectional radiation pattern on the horizontal plane made the proposed tag insensitive to be mounted on different target objects.

In **2014**, Park *et al.* reported a passive tag antenna mountable on metallic and highly dielectric platforms [109]. The antenna was designed inside a cavity to increase the communication distance between the reader and the tag. An artificial magnetic conductor was used at the bottom to reduce the antenna size and to make antenna usable at metallic objects. A hollow bow-tie structure was used as a radiating element. In the same year, Zhang *et al*. proposed a small sized UHF RFID tag antenna with design guidelines for metallic objects [110]. A proximity coupled feed was used to energies two planar inverted-F antenna array. The feed network was embedded in the middle layer for the proposed dual layer structure. Dubok *et al*. presented design guidelines for tag antennas attachable on decomposable objects and human bodies [111]. A balanced slot antenna was used and the slot shape was optimised for impedance matching with tag IC and for maximum efficiency. Goudos *et al*. demonstrated a spiral tag antenna using an artificial bee colony optimisation technique [112]. The optimisation technique was used to achieve maximum read distance, better impedance matching and size miniaturisation. A spiral shape was chosen for the radiating element because the spiral conductor has the attribute of space filling. Therefore, spiral shape meets two purposes; the shape capture small size and the enhanced length of the element would permit the antenna to resonate at a frequency inside the UHF band. Gupta *et al*. proposed a passive chipless RFID tag [113]. The antenna consists of log periodic dipole array which was formed with a large number of resonant dipoles. The dimensions of those dipoles were scaled by a constant factor. The antenna was fed at the centre with differential feed.

In **2015**, an impedance matching technique for extremely low-profile on-body tag antennas was proposed by Svanda *et al.* [114]. This approach excites the higher order mode that affects the field distribution of the fundamental mode and sets the input impedance to the required complex values of UHF RFID chips over the range of 5−50 Ω for the real part and 100−200 Ω for the imaginary part. In the same year, S. Shao *et al.* presented a broadband textile-based UHF RFID tag antenna [115]. Its wide bandwidth makes the tag less susceptible to objects and materials in the vicinity. High conductive textile material (E-fiber) was used to introduce elasticity, flexibility and mechanical strength. As a result, the designed tag antenna operates in a wide range of dielectric materials and various environments. Also, the designed tag achieved the same good performance after being stretched by nearly 10%.

In **2016**, Zuffanelli *et al.* reported an electrically small planar RFID tag antenna, based on an edge-coupled split ring resonator [116]. An analytical study of the SRR radiation properties at its fundamental resonance was presented for the first time. The antenna also features mitigation of the blind spots, providing a minimum measured read range of 4.2 m. In the same year, Kopyt *et al.* proposed a graphene-based dipole antenna for RFID tag operating in the UHF band in [117]. The read range for the graphene-based antenna has been limited in comparison to copper antennas because of the increased sheet resistance of a graphene layer and also due to significant dielectric losses of the substrate material in case of tags fabricated on paper. However, for applications where the interrogation range is not crucial graphene-based antennas can be an alternative to much more expensive circuits printed with silver-based inks. Sohrab *et al.* investigated the effect of liquid on the performance of a UHF RFID tag and an antenna with improved performance on a liquid bottle is proposed [118]. A resonant RLC circuit was added with tag antenna to compensate the effects of liquid. Lin *et al.* proposed a transponder antenna for metallic objects [119]. The antenna consists of a Z-shaped slot on a rectangular radiating plate which works as a half wavelength slot resonator. The impedance of the antenna can be conjugately matched with different microchip by varying length and width of the slot. Svanda *et al.* designed an impedance-flexible on-body semi-electrically-small tag antenna for UHF RFID tags [114]. The radiator was based on differentially-fed coupled shorted-patches and vertical folding techniques, using a loop excitation. Loop excitation provided the required impedance matching to the antenna with microchip. Sun et *al.* investigated a proximity coupled cavity backed antenna for longer read range [120]. The proximity feed and RFID chip were fully enclosed inside the cavity to provide protection. The patch structure also offers a way to tune the resonant frequency of the antenna. K. Jaakkola proposed a small RFID tag antenna for metallic objects [121]. The impedance matching between antenna and the microchip was achieved by using antenna integrated components. The communication range between tag and reader was enhanced by using the most efficient radiator within the given maximum dimensions. Alibakhshi-Kenari *et al.* presented a tag antenna based on the Hilbert-curve fractal structure [122]. The antenna was designed for high frequency and ultra-high frequency dual-band RFID applications. A Hilbert-curve was used as the high-frequency coil antenna in series with square loop structure which worked as a UHF antenna.

In **2017**, Hamani *et al*. proposed a compact broadband tag antenna for use in a UHF band [123]. The antenna has been designed with two substrates; upper substrate contained a modified folded dipole and a meander bar, while the second substrate was a double face with parallel bars printed on the top face and a metal plane on the bottom to isolate the antenna from metallic surfaces. The antenna provided multi-resonance and can be used in three UHF band. An *et al*. presented a compact dual-band tag antenna which operates in UHF (881-913 MHz) and UWB (2.9-5.35 GHz) [124]. For UHF band, a U-shaped planar inverted-F antenna was designed to surround the dipole for the UWB band. For UWB band, a symmetrical feeding strip was used to energise the ellipse-shaped dipole. Ginestet *et al*. studied the possibilities of embroidered antenna and microchip connections for UHF RFID textile tags [125]. A planar dipole type structure with a T-match network was investigated on two different fabrics. The tags with the embroidered interconnections showed similar or superior performance in comparison to identical tags with ICs attached with conductive epoxy. Ramirez *et al*. proposed passive 2D and 3D tags for on/off metal applications [126]. For the impedance matching between the antenna and the microchip, a matching loop was used which consisting of two parallel stubs to ground. Lopez-Soriano *et al*. presented a normal mode helical tag antenna [127]. The antenna was designed for UHF RFID wristband applications which can be used for identification and tracking of patients inside hospital. Normal mode helical antenna was used to reduce the size and the cost of a wristband.

In **2018**, the radiation properties of the split-ring resonator (SRR) working at its second resonance to design an RFID tag were exploited for the first time by G. Zamora *et al.* in [128]. A T-match network was used for impedance matching. The measured read range was higher than 13 m within the whole UHF-RFID band with a peak value of 16 m at 915 MHz. Bong *et al.* described an orientation insensitive dipolar patch antenna for metal mountable RFID tags [129]. The antenna consists of two pairs of orthogonal dipolar patches, which were placed in such a way that their inherent blind spots and null points were removed. The tag antenna was readable in all directions in the boresight. Michel *et al.* outlined design considerations on the placement of a wearable UHF-RFID PIFA on a compact ground plane [130]. The effect of the position of the radiating element of a wearable antenna with respect to its ground plane was investigated. Choudhary *et al*. reported a compact long read range UHF RFID tag [131]. A novel technique of designing an RFID tag antenna with an alphabetical pattern was explored. A double T-matching approach was used to enhance the impedance matching, radiation efficiency and gain in the UHF band.

In 2019, Ng *et al.* presented a semi-flexible E-shaped folded patch antenna for metallic surface tagging [132]. The top and the bottom arms of the E-shaped patch radiator were interconnected to the ground plane by a narrow inductive stub and a capacitive shorting wall, respectively. Lee *et al*. described a compact folded C-shaped antenna for on-metal UHF RFID [133]. The tag was designed by combining a loop antenna and a planar inverted-L antenna. Michel *et al.* proposed a compact in-metal

UHF RFID tag antenna [134]. The structure consists of two rectangular quarter-mode patch antennas properly arranged to make the tag performance robust in small cavities.

2.7.2 Review of Circularly Polarised UHF RFID Tag Antennas

A design of CP tag antenna for increased read range [135] was presented for UHF RFID applications. The proposed tag antenna consists of a single radiating patch, a shorting plate and a ground plane. For impedance matching with commercial tag chips, a feed line was added between the patch and the ground plane. To obtain right hand circularly polarised radiation, lower left and upper right corners of the rectangular patch were truncated. Even though the antenna has 8 m read range, it was a multi-layered structure, which makes the tag bulky.

In [136], a comparative study of the read range of linearly and circularly polarized tag antenna was carried out and a 17.9 % read range enhancement has been examined with circularly polarized tag antenna. Circularly polarised tag antenna can enhance the performance of an RFID system than a linearly polarised tag antenna due to reduced multipath loss and polarisation mismatch loss.

Square microstrip CP tag antennas, with unequal cross slots, fed by a coupling feed line have been proposed in [137], [138]. In [137], two microstrip feed-lines of suitable lengths were used, in which one of the feed-lines was a quarter-wavelength longer than the other and the enhancement in CP bandwidth was found by a combination of two techniques, dual-offset coupling feed and cross slot (perturbation element) loading. In [138], an L-shaped microstrip line was used to provide impedance matching between antenna and microchip.

A circularly polarized circular microstrip antenna was presented in [139] with cross slot and coupling feed technique. In the design, the compact CP operation can easily be obtained by only adjusting the unequal arm lengths of a cross slot. Also, the complex impedance matching of the proposed tag antenna was achieved by properly selecting the dimensions of the two short-circuited arc microstrip lines.

Although the reported antennas [137]–[139] exhibit circularly polarized radiation on a metallic surface with longer read range, the use of shorting pins in the coupling feed lines makes the antenna structures complicated for fabrication. Furthermore, a compact circularly polarized structure of UHF RFID tag antenna has been presented by J.H. Lu *et al*. in [140] by introducing a Y-shaped slit and two orthogonal N-shaped slits to provide wider half power operating bandwidth (135 MHz); but the obtained 3-dB AR bandwidth is less than 10 MHz. The Y-shaped slit on a circular patch was used for impedance matching and two orthogonal N-shaped slits were used for circularly polarised radiation.

Square-loop [23] and meandered-loop [141] CP antennas have also been studied for long read range UHF RFID systems. The meandered-loop antenna [141] exhibits antenna size miniaturization in comparison to square-loop [23] antenna. Circularly polarised radiation was realized by introducing an open gap and two feeding strips to the square loop and meander line.

A CP square ring tag with meander strip [142] was proposed for the automatic toll collection system. It reported 64% smaller size than the antennas attached to safety glass, but with a shorter read range of 8.3 m. A shorting oblique stub was connected to the ring arms of the antenna to get conjugate impedance matching with microchip, and a meander section with a small gap was embedded to square loop to get the circularly polarised radiation.

In [143], a compact circularly polarised antenna was described. The proposed structure contains a T-match network for the impedance matching and cross-dipole structure for CP radiation. A meander line section with triangular endings was used for the size miniaturisation of the antenna.

2.7.3 Review of Dual Antennas for RFID Tags

Chen *et al*. proposed the concept of the dual antenna [144] which was formed by two independent linearly tapered meander line antennas; one for receiving power and the other for backscattering purpose at 915 MHz. The two antennas were perpendicular to each other and designed on both sides of the substrate to reduce the mutual coupling. The opposite side printed design on the substrate make it unsuitable for metallic objects. A dual antenna design [145] for 5.8 GHz RFID system has been reported with bow-tie structures. The fractal geometry was introduced in the structure for antenna size miniaturization. In practical RFID applications, an antenna should be designed on single side of the substrate. Antennas which are printed on both side of the substrate, to reduce mutual coupling, are difficult to use with metallic surfaces.

Platform tolerant single-sided dual antenna structures for UHF RFID tags have been proposed in [146]. The antenna was composed of two L-shaped strips and a square patch loaded with a cross slot. One L-shape strip along with square patch was used for receiving electromagnetic energy from the reader and the other was used for the backscattering. Electromagnetic band gap structure was used around the antenna for increasing the gain.

A single sided dual band tag antenna for UHF (915 MHz) and SHF (2.45 GHz) has been presented in [147]. At UHF band, this antenna works as a dual antenna but at SHF band, it works only as a conventional antenna. The receiving antenna was made up with an F-shaped slot and an inverted L-shaped slot loaded with rectangular patch whereas the backscattering antenna was composed of meander line. Due to the complete ground plane, the antenna can also be used with metallic objects.

A single-sided meandered dual antenna for 915 MHz UHF RFID tag has been proposed in [148]. The receiving antenna consists of a parasitic meander line with a rectangular loop. The rectangular loop was used for inductively coupled feeding to the meander line section. The backscattering antenna was made up with another meander line loaded with a rectangular strip.

2.7.4 Review of RFID Reader Antennas

To encompass the full UHF (840-960 MHz) RFID frequency band, a wideband circularly polarised antenna is required [149]. However, this type of antenna is bulky in size and unsuitable for portable handheld RFID readers. Recently, a design was proposed [150] with broadband circularly polarised antenna covering the entire UHF RFID frequency band (791-998 MHz). The antenna has three L-shaped strips, one strip for feeding and two L-strip lines into the circular slot at the ground plane for wideband CP bandwidth. Despite being the smallest available antenna in literature to cover the entire UHF RFID band, the size of the antenna ($120 \times 120 \times 0.8$ mm^3) is too large rendering it unsuitable for handheld readers. Single-feed type CP antennas, which cover at least one UHF RFID band, have been used for compact handheld RFID readers because the main constraint for handheld readers is compactness rather than antenna gain and bandwidth. Numerous circularly polarised structures with single-feed have been proposed in the literature for UHF RFID reader antenna.

In [151] a single-feed technique for the circularly polarised antenna was introduced with diagonally feed square, truncated corner square and square with the diagonal slot. But no size reduction was obtained by the truncated corner method. Multi-stacked antennas were presented in [152], [153] for UHF RFID readers. Although they are single feed, they are bulky thus not suitable for handheld readers. A proximity coupled antenna was presented in [154] which is based on a cross-slot with unequal slot lengths on a circular patch giving circularly polarised radiation with 36 % antenna size miniaturization due to the cross slot. The symmetric-slit [155] and asymmetric-slit [156] along the diagonal directions on a square radiator were reported for small circularly polarised antennas. A cross-shaped slotted antenna [157] was proposed for circularly polarised radiation with size miniaturization. The circular-, square- and cross-shaped slot antennas have been compared, where the slot perimeter limits the 3-dB AR frequency. This work [157] was extended for further size miniaturization by having diagonally symmetric slot antenna [158] and asymmetric slot antenna [159].

From the brief literature survey, it is observed that a lot of works on the designing of RFID tag antenna and reader antenna have been described. Tag antenna designs have been concentrated to the various techniques of conjugate impedance matching between the tag antenna and the microchip. Numerous methods of enhancing the read range and miniaturization of the antenna have been also investigated. Still, there is a scope to further miniaturize the antenna size for both tag and reader with enhanced read range. In view of this, author has endeavoured to take up this topic for the investigation. Consequently, the details of both simulation and experimental investigations embody the thesis. After the detailed study of literature survey of various methods, geometries, etc. used to design a circularly polarised antenna for UHF RFID tag applications, the design and analysis of meandered cross dipole antenna structure is taken up in detail in next chapter.