Chapter 2

Analysis of RFID Tag Antennas

2.1 Introduction

This chapter delves into the intricacies of UHF band tag antennas, a critical component that determines the performance and reliability of an RFID system. It begins by providing an overview of the essential elements that constitute an RFID system, including tags, readers, and middleware. The discussion then shifts to the different frequency bands used in RFID and their respective characteristics, with a particular emphasis on the UHF band. The chapter explores the design and functionality of passive UHF tag antennas, highlighting their advantages and limitations. It also examines the unique features that make UHF tag antennas suitable for various applications. Critical parameters that influence the performance of UHF tag antennas, such as impedance matching, gain, and radiation pattern, are thoroughly analyzed. Lastly, a comprehensive review of existing research and developments in the field of UHF RFID tag antennas is presented, providing a foundation for the subsequent discussions. By focusing on these key areas, this chapter aims to provide a thorough understanding of UHF RFID tag antennas and their pivotal role in enhancing the efficiency and effectiveness of RFID systems.

2.2 RFID System Components

RFID systems consist of three main components: the tag, the reader and the computer database. Each component plays a crucial role in the functionality of the system, enabling efficient and accurate identification and tracking of items. Figure 2.1 illustrates a tree diagram depicting the various components of an RFID system.

- The RFID tag is a small device attached to the item that needs to be tracked. It consists of a microchip and an antenna. The microchip stores information about the item, such as a unique identifier or other relevant data. When the tag comes within the range of a reader, it receives the radio waves and transmits its stored information back to the reader. Tags can be active, semi-passive or passive.
- The reader, also known as the interrogator, is a device that emits radio waves to communicate with the RFID tags. It sends out signals to detect the tags within its range and then receives the data stored on them. Readers can be either fixed or mobile, depending on the application. They are equipped with antennas to transmit and receive signals from the tags.
- The computer database is where the collected data from the RFID readers is stored and managed. It processes the information received from the tags and organizes it for easy access and analysis. The database can be part of a larger system that integrates with inventory management, supply chain logistics, or other applications, providing real-time updates and insights based on the data collected by the readers.

These components work together seamlessly to create an efficient RFID system capable of tracking and managing items accurately and in real-time.

2.2.1 RFID Reader

An RFID reader is a crucial component of an RFID system, responsible for communicating with RFID tags. It consists of antennas used for transmitting and receiving electromagnetic signals to and from the RFID tag. The reader radiates the maximum allowable

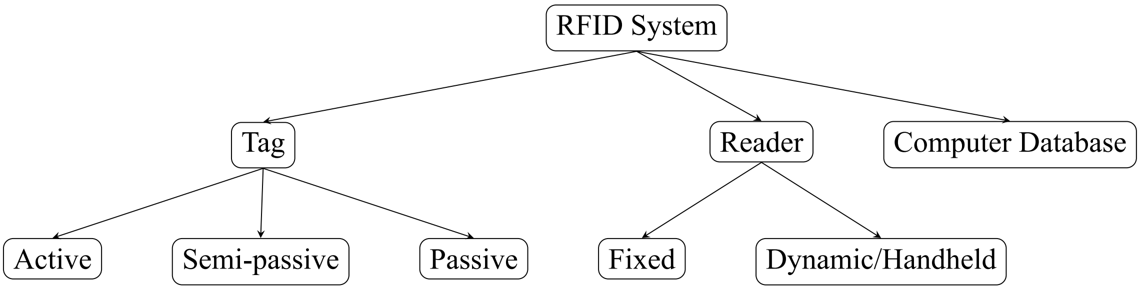

Figure 2.1: RFID system components

Equivalent Isotropically Radiated Power (EIRP) to communicate with tags from the maximum possible range. RFID readers come in two types: fixed and dynamic (handheld).

Fixed RFID readers are typically installed in specific locations and are used for applications where items pass through designated points, such as warehouse entrances, retail checkout points, or conveyor systems. They often have multiple antennas to cover larger areas and can handle high tag densities and fast-moving tags. Fixed readers are designed to provide robust performance, high read accuracy, and can be integrated with existing systems for seamless operations.

Dynamic or handheld RFID readers are portable devices used for on-the-go scanning and inventory management. These readers are often used in retail stores, logistics, and field operations, providing flexibility to scan tags in various locations. Handheld readers usually come with built-in antennas and can connect wirelessly to other devices for real-time data access. They are designed for ease of use, ergonomic handling, and often include features like touch screens, Wi-Fi, and Bluetooth connectivity.

For active RFID tags, the reader collects signals sent from the active tag. In the case of passive tags, the reader sends and receives signals at the same frequency. It powers up the passive tag using magnetic field coupling or electromagnetic fields, enabling the tag to transmit its data back to the reader. Depending on the isolation between transmitting and receiving antennas, RFID readers have either bistatic or monostatic antenna configurations. A bistatic reader has separate antennas for transmitting and receiving signals, which can help improve read performance and reduce interference. This configuration is often used in applications where high accuracy and long-range communication are required. On the other hand, a monostatic reader uses a single antenna for both transmitting and receiving purposes, making the system simpler and more cost-effective. Monostatic configurations are suitable for applications where space is limited and the read range is moderate. They are designed to cater to various applications with fixed and dynamic options, and their performance can be optimized through the use of bistatic or monostatic antenna configurations.

2.2.2 RFID Tag

An RFID tag is a small electronic device that consists of a microchip called as Application Specific Integrated Circuit and an antenna. It stores information about an object and communicates with an RFID reader through radio waves. RFID tags come in various forms and can be attached to or embedded in objects to facilitate automatic identification and tracking. RFID tags are categorized into active, semi-passive, and passive types, each with distinct features and applications.

***Active tags**:*Active RFID tags are equipped with their own battery, which powers both the tag's circuitry and its signal transmission. This allows them to actively broadcast signals at regular intervals or in response to a reader's query, enabling communication over longer distances—typically from 30 to 100 meters or more. The internal battery also supports on-board processing and data storage, enhancing the tag's performance and capabilities. Active tags are well-suited for applications requiring long-range communication and frequent updates, such as asset tracking, vehicle identification, and environmental monitoring. Although they offer extended range and functionality, active tags are generally more expensive and have a limited lifespan due to their reliance on battery power.

***Semi-passive tags**:*Semi-passive RFID tags, also known as battery-assisted passive tags, use a battery to power their internal circuitry but rely on the reader's signal for communication. The battery in semi-passive tags supports functions like signal amplification and data storage, enhancing their performance and extending their range compared to fully passive tags. However, unlike active tags, semi-passive tags do not use the battery to transmit signals; instead, they only use it to boost the signal received from the reader. This setup allows semi-passive tags to offer improved read distances and better performance in challenging environments. They are commonly used in applications requiring moderate range and reliability, such as inventory management and asset tracking. Semi-passive tags balance the advantages of active and passive tags, offering a cost-effective solution with extended read range and functionality. However, their main disadvantage is the limited battery life, which can affect long-term maintenance and operational costs.

Passive tags:Passive RFID tags operate without their own power source, relying entirely on the RFID reader to energize them. When the reader emits radio frequency signals, the tag's antenna captures these electromagnetic waves, causing a voltage to develop across the antenna terminals. This voltage powers the tag's ASIC (Application-Specific Integrated Circuit), which then reflects back the signal by changing its input impedance after impedance matching. This backscattered signal carries the tag's unique data to the reader. The absence of an internal battery makes passive tags smaller, lighter, and cheaper than active and semi-passive tags, making them ideal for cost-sensitive and space-constrained applications. The read range of passive tags typically spans from a few centimeters to several meters, depending on the frequency and reader power. They are widely used in applications like retail inventory management, library book tracking, and access control due to their simplicity and affordability. However, passive tags have limitations in requiring high power readers or where longer read ranges are needed. Despite these limitations, their low cost, small size, and lightweight nature make them advantageous over active and semi-passive tags in many scenarios.

2.3 Operating Frequency Bands and Principle

RFID systems operate across several frequency bands, each with distinct characteristics and applications. The four primary frequency bands assigned for RFID are Low-Frequency (LF), High-Frequency (HF), and Ultra-High Frequency (UHF) and Microwave Frequency.

LF RFID systems operate in the frequency range of 125-134 kHz. They use near-field coupling, where the reader generates a magnetic field that induces a current in the tag's coil antenna. This current powers the tag, allowing it to communicate with the reader and function effectively in close proximity to the reader. However, their read range is limited, usually up to 10 cm. LF RFID systems are largely used in the automotive industry for vehicle immobilization. LF RFID tags are embedded in car keys, which interact with the vehicle's RFID reader to verify the key's authenticity and enable access thus enhancing security. In the livestock industry, LF RFID tags attached to ear tags or collars help track and manage animals, improving herd management and record-keeping. HF RFID systems operate at 13.56 MHz. HF RFID systems also use near-field coupling. In both LF and HF RFID systems, the tag uses load modulation to communicate back to the reader, altering the impedance of its antenna to vary the load seen by the reader. HF RFID tags can experience reduced performance when used in proximity to conductive objects. Metallic surfaces disrupt the normal component of the incoming magnetic fields essential for communication with the tag. As a result, HF RFID tags do not function effectively on metallic surfaces. HF RFID is widely used in applications like smart cards, library book tracking, and ticketing.

Ultra-High Frequency (UHF) RFID (433 MHz, 860-960 MHz): UHF RFID systems operate in the frequency ranges of 433 MHz and 860-960 MHz. The frequency bands allocated for UHF RFID vary by region. For instance, in India, the allocated frequency band is 865-867 MHz, while in the United States, it is 902-928 MHz. In China, the range is 920.5-924.5 MHz, and Singapore uses two bands: 866-869 MHz and 920-925 MHz. Australia has allocated 920-925 MHz. In Japan, the frequency band for UHF RFID is 916.7-920.9 MHz. South Africa has been allocated two UHF RFID bands: 865.6-867.6 MHz and 915.4-921 MHz. Jordan uses 865-868 MHz. Some of region-wise RFID UHF band alloted is shown in Table 2.1. Each region's allocation supports a variety of RFID applications while aiming to comply with international standards for interoperability and efficiency. These frequencies are beneficial over LF and HF systems due to their longer read range (up to 12 meters) and faster data transfer rates, making them ideal for applications such as supply chain management, asset tracking, and vehicle identification. UHF RFID systems use far-field communication, where the reader sends out electromagnetic waves that propagate through space. The tag's antenna captures these waves, and the tag's

Table 2.1: Region-wise UHF band frequency allocation

Region	**Frequency(MHz)**	**Power**	**Region**	**Frequency(MHz)**	**Power**
America	902-928	4W EIRP	Jordan	865-868	2W ERP
China	920.5-924.5	2W ERP	Russia	866-867.6	100mW ERP
				866-868	500mW ERP
				866-867.6	2W ERP
				915-921	1W ERP
Denmark	865.6-867.6	2W ERP	Singapore	866-869	0.5W ERP
				920-925	2W ERP
Hong kong	865-868	2W ERP	South Africa	865.6-867.6	2W ERP
				915.4-921	4W EIRP
India	865-867	4W ERP	Vietnam	866-868	0.5W ERP
				918-923	0.5W ERP
				920-923	2W ERP

ASIC (Application-Specific Integrated Circuit) harvests the energy to power the tag. The tag communicates back to the reader using backscatter modulation, where it changes the impedance of its antenna to reflect the reader's signal in a modulated manner. This modulation technique involves the ASIC switching its input impedance between two states: matched and mismatched to the antenna. When the impedance is matched, the tag absorbs more power, and when it is mismatched, the tag reflects more power. This switching creates a modulated signal that the reader can detect and decode, containing the tag's unique information.

2.4 Passive RFID Tags for UHF band

As discussed in section 2.3 , passive UHF RFID tags provide advantages like extended read ranges and faster data transfer rates. They operate without an internal power source, using the reader's electromagnetic waves to power the tag. The tag's ASIC modulates the reflected signal by switching its input impedance, facilitating efficient communication. This makes passive UHF RFID tags suitable for diverse applications, including asset tracking and supply chain management.

2.4.1 UHF RFID-ASIC

Advancements in CMOS technology have significantly reduced the size, cost, and threshold power of integrated circuits (ICs) over the past few decades. In UHF RFID systems, the IC is powered by the incoming electromagnetic signals from the reader. The Application-Specific Integrated Circuit (ASIC) in these tags is primarily a data storage device composed of resistive-capacitive (RC) components. The initial stage of the RFID microchip is a voltage multiplier, which converts the received RF signal into rectified DC voltage necessary to activate the chip. The input impedance and threshold power of the IC are critical parameters. The threshold power, or sensitivity, is the minimum power level required to activate the ASIC. For efficient power transfer, the input impedance of the tag's antenna and the ASIC should be a complex conjugate match. Additionally, the ASIC's input capacitance should be minimized to ensure a reasonable bandwidth. However, higher capacitance is needed for better energy storage, resulting in a trade-off between low capacitance and high energy harvesting efficiency. The input impedance of the tag is modeled as a parallel combination of resistance and capacitance. The resistance is kept low, typically in the order of a few ohms, to minimize power dissipation. The ASIC, on the other hand, has a high capacitive reactance, often in the order of hundreds of ohms, due to its lower capacitance. This balance ensures efficient power transfer and optimal performance of the RFID system. Table 2.2 shows some of ASIC's sensitivity and input impedances at two different frequencies.

Table 2.2: Different ASIC specification

ASIC	$P_{th,chip}$	$Z_c(\Omega)$ at 865 MHz	$Z_c(\Omega)$ at 915 MHz
Alien Higgs 4 SOT [5]	-18.5 dBm	20.6-j191.26	18.42-j181
RI_UHF_0001_01 TI chip [6]	-13 dBm	9.42-j63.8	8.44-j60.45
NXP UCODE 7 [7]	-21 dBm	14.66-j291	12.8-j277
Impinj Monza 4 [8]	-17.4 dBm	14- j150.3	12.4- j142.6
Impinj Monza X-2K Dura [9]	-17 dBm	21- j182	19- j172

2.4.2 Passive UHF Tag Antenna Features

The overall performance of a passive RFID system heavily relies on the tag antenna. Key parameters for a desirable tag antenna include radiation pattern, polarization, impedance matching and size miniaturization. In this section, we present the critical design parameters and performance metrics essential for optimizing passive UHF RFID tag antennas.

***Polarization*:** In passive RFID systems, tag antennas are generally designed with linear polarization to minimize size and cost. Linear polarization is often adequate for applications where the tag orientation remains constant, ensuring a larger detection range. However, in scenarios where the tag antenna's orientation is dynamic, a circularly polarized tag antenna is required to maintain consistent performance. This is because circularly polarized antennas can effectively receive signals regardless of their orientation, making them suitable for dynamic environments. When a circularly polarized (CP) reader antenna interacts with a linearly polarized (LP) tag antenna, only half of the incoming power is received by the tag. This mismatch significantly deteriorates the detection range. Conversely, if both the reader and tag antennas are linearly polarized and their orientations are aligned, the system achieves optimal power transfer, resulting in an enhanced detection range. Therefore, the choice between linear and circular polarization for tag antennas should be carefully considered based on the specific application requirements and the anticipated variability in tag orientation.

***Radiation Pattern*:** The radiation pattern of a passive UHF RFID tag antenna is a critical factor in determining the overall system performance. Ideally, the antenna should exhibit an omnidirectional radiation pattern to ensure consistent tag readability from multiple angles. This helps in applications where the orientation of the tag relative to the reader cannot be controlled, allowing for reliable detection regardless of positioning. In contrast, for applications with a fixed orientation or where tags are placed on specific items with predictable alignment, a more directional radiation pattern may be advantageous. A directional pattern can focus energy in a particular direction, enhancing the read range and detection sensitivity in that specific area. Therefore, the design of the tag antenna's radiation pattern must align with the intended application, balancing between omnidirectional coverage for versatility and directional focus for enhanced performance in controlled scenarios.

***Impedance Matching*:** Impedance matching between the UHF tag antenna and the ASIC is crucial for efficient energy transfer. The ASIC, being a storage device, typically has a highly capacitive reactance, necessitating that the tag antenna have an inductive input impedance for proper matching. This ensures maximum power transfer and optimal tag performance. Using external impedance matching networks with lumped components is impractical due to size and cost constraints. Consequently, impedance matching techniques must be integrated into the tag antenna design. Several methods are employed for this purpose: Nested Slots, T-Match Network, and Inductively-Coupled Loop. Nested slots are particularly effective in microstrip patch antennas, where the slot area is comparable to the patch area. This technique helps achieve the necessary impedance transformation by altering the current path and distribution on the antenna. The T-Match Network involves creating a balanced input by adding a parallel conductive strip, which helps in adjusting the antenna impedance to match the ASIC's impedance. The Inductively-Coupled Loop method uses a loop to inductively couple the antenna to the ASIC, providing the necessary impedance matching by fine-tuning the inductive reactance. These integrated impedance matching techniques are essential for designing efficient and cost-effective UHF tag antennas, ensuring reliable performance across various applications.

***Size*:** The size of a UHF RFID tag antenna is a critical design parameter, particularly because RFID tags are often used in applications requiring compact and unobtrusive form factors. Minimizing the antenna size is essential to facilitate easy integration onto various items, such as retail products, luggage, and electronic devices, without affecting their functionality or aesthetics. Smaller antennas also reduce material costs and enable more efficient manufacturing processes.

One effective technique for size miniaturization is meandering, which involves folding the antenna's conductive path into a compact, serpentine pattern. By increasing the electrical length of the antenna without significantly enlarging its physical dimensions, meandering helps maintain the resonant frequency required for UHF operation. This allows the antenna to fit into smaller spaces while still performing adequately at the desired frequency band. However, there is a trade-off between meandering and antenna performance. While meandering effectively reduces the antenna size, it can also introduce additional losses and reduce the antenna's efficiency. The bends and turns in the meandered design can lead to increased resistance and reduced radiation efficiency, potentially diminishing the read range and overall performance of the RFID system. Additionally, meandered antennas can exhibit narrower bandwidths, which may impact their ability to operate effectively across the entire UHF band. To mitigate these issues, careful design and optimization are required. This involves balancing the degree of meandering with the need to maintain acceptable performance metrics, such as gain, efficiency, and bandwidth. Advanced simulation tools and design techniques can help identify the optimal meander pattern that minimizes size while still achieving satisfactory performance. In some cases, hybrid approaches combining meandering with other matching networks, can provide better overall results.

Ultimately, while size reduction is crucial for many RFID applications, it is essential to carefully consider and address the associated performance trade-offs to ensure the tag antenna meets the required specifications and delivers reliable performance in real-world conditions.

2.5 Passive UHF Tag Performance

The performance of passive UHF RFID tags is critical for effective system operation, encompassing parameters such as read range and impedance matching. In this section, we discuss impedance measurement methods and detection range to evaluate and optimize tag performance.

2.5.1 Impedance Measurement

Measuring the input impedance of passive UHF RFID tag antennas is essential for ensuring optimal performance, but it presents unique challenges, especially for balanced antennas. Directly using a single-ended two-port Vector Network Analyzer (VNA) is not feasible because the VNA is terminated by unbalanced ports, leading to unequal current flows in the antenna terminals and resulting in inaccurate measurements. For balanced tag antennas, two primary methods can be employed: the mirror image method and the differential probe method. The mirror image method involves mounting half of the antenna's radiators on a ground plane, which acts as a mirror to configure the other half as shown in figure 2.2. This technique is suitable for symmetrical balanced antennas, where the ground plane provides a mirror image, effectively creating an equivalent monopole antenna. The impedance measured from this configuration is then multiplied by a factor of two to obtain the actual impedance of the balanced antenna. However, the accuracy of this method depends on the size of the ground plane relative to the antenna, which can introduce errors if the ground plane is not adequately large.

In contrast, the differential probe method offers a more direct and potentially more accurate means of measuring impedance. This approach is particularly suitable for use in this thesis. The differential probe is constructed using two coaxial cables, where the outer conductors are soldered together, effectively creating a balanced measurement system as shown in figure 2.4. By connecting the inner conducting wires of both coaxial cables to the antenna terminals, the differential probe can measure the tag antenna's impedance. This probe is then connected to the VNA, allowing for accurate impedance measurement of the balanced antenna. This method overcomes the limitations of unbalanced ports and

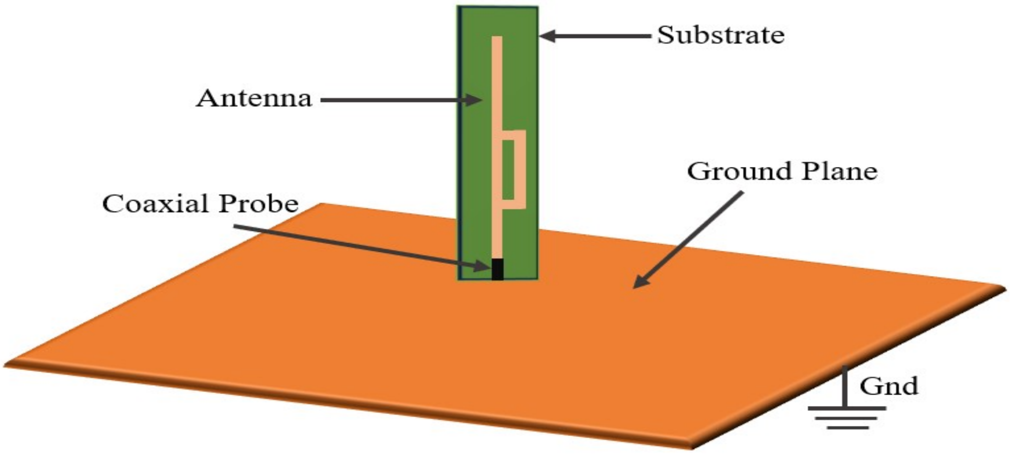

Figure 2.2: Antenna impedance measurement with mirror image method

unequal current flows, providing a reliable means of assessing the antenna's impedance. The choice of impedance measurement method is crucial for the accurate characterization of UHF RFID tag antennas. The mirror image method is beneficial for its simplicity and effectiveness with symmetrical designs but requires careful consideration of ground plane size. On the other hand, the differential probe method, used in this thesis, provides a robust solution for balanced antennas, ensuring precise impedance measurements critical for optimizing tag performance. The measurement errors introduced by this test fixture are mitigated by employing the port extension technique as shown in figure 2.3. By accurately measuring the impedance, designers can ensure better impedance matching, leading to improved energy transfer between the antenna and the ASIC, thereby enhancing the overall performance of the passive UHF RFID system.

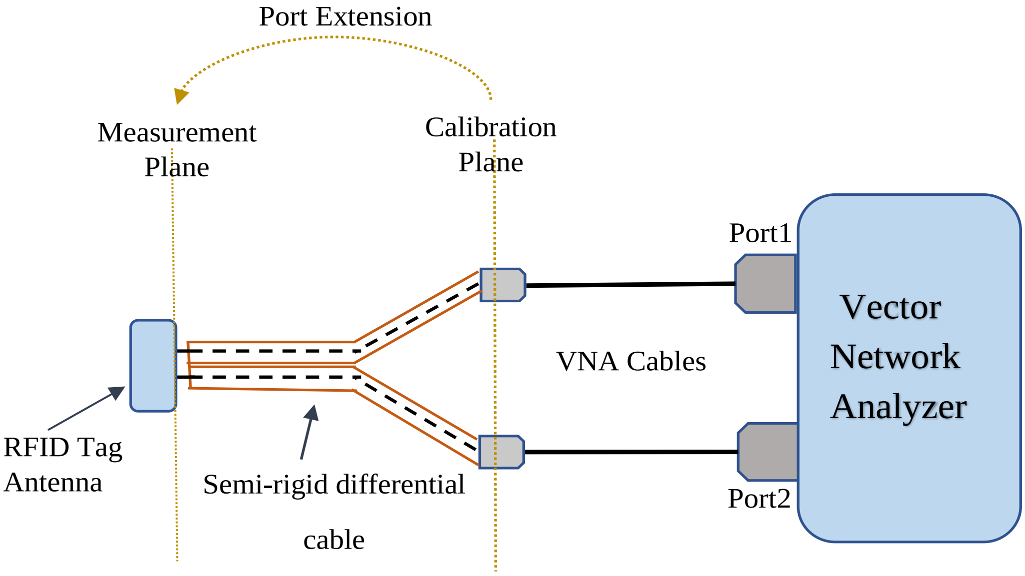

Figure 2.3: Measurement schematic setup with differential probe

Differential probe method steps

The impedance measurement steps by using differential probe are given below:

1. Attach Probe to Antenna:
    - Connect the inner conductors of the coaxial cables to the two terminals of the balanced tag antenna.

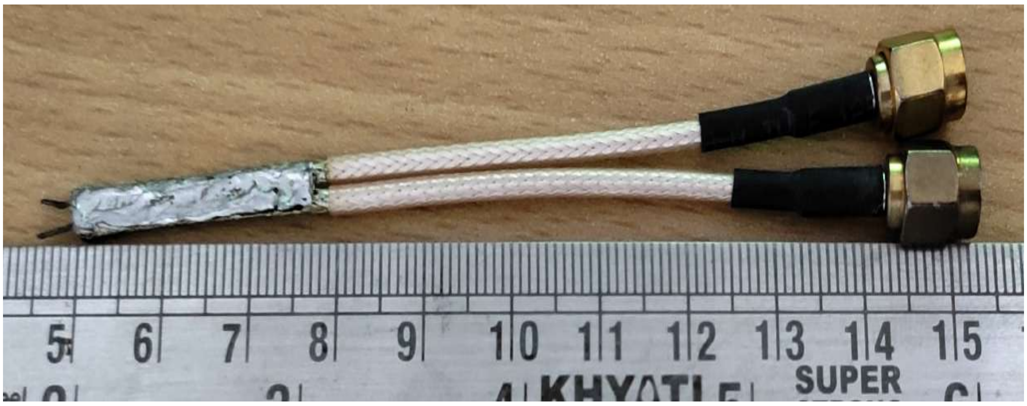

Figure 2.4: A differential probe test fixture for impedance measurement

2. Attach Probe to VNA:
    - Connect the other ends of the coaxial cables to the VNA's ports.
3. Perform Calibration:
    - Perform a standard calibration procedure to account for system errors. Use appropriate calibration standards (open, short, load) to ensure accuracy.
4. Apply Port Extension:
    - Use the port extension technique to correct any errors introduced by the test fixture. This technique helps to eliminate the effects of probe length and shiftes the calibration plane to tag antenna measurement plane.
5. Calculate impedance of tag antenna under test using the conversion formula by measured S-parameters as given below:

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

However, In the case of a symmetrical balanced antenna, the equivalent network is also symmetrical, allowing equation 2.1 to be modified such that S11 equals S22 and S21 equals S12:

$$Z_{diff} = \frac{2Z_0\left(1 - S_{11}^2 + S_{12}^2 - 2S_{12}\right)}{\left(1 - S_{11}\right)^2 - S_{21}^2} \tag{2.2}$$

2.5.2 Detection Range

The detection range of a tag antenna is a critical parameter in RFID systems, determining the maximum distance at which the tag can be reliably detected by the reader. This range is influenced by various factors including the antenna's design for impedance matching, power transmitted by the reader, orientation of tag and environmental conditions. The maximum detection range S_{max} can be determined by given formula:

$$S_{max}(\theta,\phi) = \frac{\lambda}{4\pi}\sqrt{\frac{EIRP_R}{P_{th,chip}}(1-|\Gamma|^2)G_t(\theta,\phi)\rho} \tag{2.3}$$

where, λ is wavelengh of operating frequency, $G_t(\theta,\phi)$ is gain of rfid tag antenna, ρ is polarization efficiency of tag antenna and $P_{th,chip}$ is sensitivity of ASIC. $EIRP_R$ is Effective Isotropic Radiated Power of reader which is product of transmitted power and gain of reader. Effective Isotropic Radiated Power (EIRP) is a measure of the power radiated by an antenna in the direction of its strongest signal. It is regulated with limitations in individual countries to minimize interference with other communication systems and ensure safe levels of electromagnetic exposure. For example, in the United States, the maximum allowed EIRP for UHF RFID systems is 4 watts (36 dBm), while in Europe, it is limited to 2 watts (33 dBm) ERP. The relation between EIRP and ERP is given by:

$$P_{EIRP} = 1.64 \times P_{ERP} \tag{2.4}$$

Γ is reflection coefficient of tag antenna and it is given by 2.5.

$$\Gamma_{tag} = \frac{Z_{chip} - Z_T^*}{Z_{chip} + Z_T} \tag{2.5}$$

where, Z_{chip} and Z_T are chip and tag antenna impedance respectively.

2.6 Literature Review

The objective of this thesis is to design passive UHF RFID meandered tag antennas with an extended detection range and compact size, as well as to develop a circularly polarized tag antenna that can be attached to metallic objects. To outline the scope of the thesis, we will review significant literature on RFID tag antennas in the following subsections, focusing on advancements and methodologies relevant to enhancing detection range and adapting to challenging environments.

- Review of Passive UHF RFID meandered tag antennas
- Review of Circularly polarised UHF RFID tag antennas for metallic surfaces

2.6.1 Review of Passive UHF RFID meandered tag antennas

Passive RFID tag antennas are crucial for enabling the functionality of RFID systems. They operate by harvesting energy from the RFID reader's transmitted signal, which powers the tag and allows it to send back data. These antennas must be efficiently designed to maximize the read range and ensure reliable communication. Meandering techniques are often used to increase the electrical length of the antenna without enlarging its physical dimensions, making them compact and robust. This design is essential for applications like inventory management and asset tracking, where space is limited but performance cannot be compromised.

In **2011**, Ferran Paredes *et al.* explored the development of dual-band tags for UHF RFID applications targeting the regulated frequency bands in Europe (867 MHz) and the US (915 MHz) [10]. The study demonstrated that dual-band tags exhibit superior performance compared to broadband (monoband) tags designed for the same frequency bands. The authors utilized a meander-line antenna (MLA) coupled with a two-turn spiral resonator (2-SR) to achieve dual-band functionality through a perturbation method, thus eliminating the need for an impedance matching network. The design, analysis, and fabrication of the dual-band UHF RFID tag showed that the fabricated prototype's performance closely matched theoretical predictions, with measured read ranges of 6 meters for the European band and 8 meters for the US band. This research highlights the effectiveness of the dual-band approach in improving read ranges over traditional broadband designs, offering significant advancements for UHF RFID applications.

In **2012**, Soliman *et al.* introduced a novel miniaturized RFID tag antenna designed for 915 MHz operation, notable for its compact electrical size [11]. The antenna features a ”Vivaldi-like” aperture, a slot line coupled to a microstrip line, and a meander line for loading. Theoretical and experimental investigations demonstrated its compact size, low profile, flexible impedance tuning, good impedance bandwidth, omnidirectional radiation patterns, low cross-polarization, and reasonable gain. The design was validated through simulations and measurements, showing excellent agreement and confirming the antenna’s suitability for RFID tags with stringent size constraints and the ability to tune to other frequencies.

In **2013**, Xu-Bao Sun *et al.* proposed an enhanced coupling source structure for RFID tag antennas, achieving broadband operation and facilitating complex conjugate impedance matching between the antenna and RFID chip. The proposed antenna features an impedance bandwidth of approximately 15% (842–985 MHz) relative to a 925 MHz center frequency, effectively covering the entire UHF RFID band [12]. This design ensures compatibility with various RFID tag applications. Both simulated and measured results validated the antenna’s functionality, demonstrating its suitability for diverse RFID systems by providing reliable broadband performance and efficient impedance matching across the entire UHF frequency spectrum.

In **2014**, S. Gupta *et al.* introduced a passive RFID tag based on a log-periodic (LP) dipole array, utilizing the LP aperture’s band-rejection properties to generate numerous codes [13]. This approach was validated through measurements, demonstrating that the presence or absence of band-rejection could encode bit information. The tag was implemented on a flexible substrate, showcasing its fabrication simplicity. Additionally, two tag formation schemes based on specific resonance suppressions were explored, indicating that the number of possible codes depends on the chosen suppression scheme. This chipless tag solution offers design flexibility, simplicity, and a vast number of code combinations, making it suitable for large bandwidth RFID systems.

In **2015**, Milan Polivka *et al.* introduced a low-profile, platform-tolerant UHF RFID tag antenna [14]. The antenna comprises three-step impedance sections of shorted patches, coupled by a slot, and differentially fed by an RFID chip. Analytical investigation of the input impedance was conducted using transmission line (TL) modeling. Electromagnetic simulations confirmed the flexibility in achieving the required complex impedance for UHF RFID chips. The manufactured and measured antenna demonstrated good agreement with analytical values. The design allows quick preliminary impedance calculations and exhibits flexibility for impedance retuning. Compared to other commercially available UHF tags under 1 mm thickness, this antenna provides a significantly larger read range. The study underscores the antenna's suitability for optimization approaches.

In **2016**, Pawel Kopyt *et al.* presented a graphene-based dipole antenna for UHF RFID tags [15]. The antenna, compliant with the EPC Global Class 1 Gen. 2 standard, was designed and tested with standard RFID readers. The graphene-based tags, although fully operational, had a limited interrogation range compared to copper antennas. This limitation was due to the increased sheet resistance of graphene and dielectric losses of the paper substrate. Despite this, the tags still achieved over 10 cm of interrogation range with 17 dBm reader output power. The study suggests that graphene-based antennas can be a cost-effective alternative to silver-printed circuits for applications where interrogation range is not critical.

In **2017**, Sergio Lopez *et al.* addressed the need for specific antenna solutions for UHF RFID applications, focusing on patient identification and tracking in hospitals using wristbands [16]. They proposed a normal-mode helical antenna (NMHA) for passive tags, offering a low-cost and compact alternative to existing bulky and expensive solutions. The NMHA design is versatile and easily adaptable to various ICs. The study demonstrated that the NMHA wristbands maintained a minimum read range of 2 meters, even in the challenging environment of the human body. Measurements showed robust performance across different wrist sizes and arm positions, confirming the design's suitability for diverse patient constitutions and strict application requirements.

In **2018**, Choudhary *et al.* proposed a compact, wideband UHF RFID tag with an innovative alphabetical pattern design. The tag employs a double T-matching approach to enhance impedance matching, radiation efficiency, and gain [17]. It was optimized for both hard and flexible substrates and tested with Impinj Monja R6 and Higgs 4 ICs. The tag, measuring 89.5 mm × 25 mm, achieved maximum read ranges of 15.5 meters on a hard substrate and 18 meters on a flexible substrate. The ”Uiet” pattern tag demonstrated superior performance with double T-matching compared to single T-matching. The flexible polycarbonate substrate exhibited a maximum read range of 18 meters in the ETSI band and 14.8 meters in the FCC band, showcasing its suitability for various practical applications.

In **2019**, Paul S. Taylor *et al.* designed and tested a passive UHF RFID tag worn as a ring, targeting healthcare and secure environments. The rings, designed for the European UHF RFID band, were tested on an adult male finger across various angles of RF illumination [18]. Despite the challenge of body-mounted antennas, read ranges between 2 and 5 meters were achieved depending on the ring’s substrate height. The prototypes demonstrated effective performance near the lossy human body. Future work includes testing on other digits and potential applications for premature babies and animals. The design could be manufactured using conductive inks, and integration with sensor-type RFID chips may add functionalities like patient health monitoring.

In **2020**, Bianco *et al.* introduced self-tuning RFID tags that adjust the input impedance of the embedded microchip transponder to counteract impedance mismatches with the antenna, ensuring stable communication performance despite environmental changes [19]. They presented a general design method for these tags, particularly for scenarios where the tag is close to the interrogating antenna and free-space assumptions don’t apply. A two-port system and network-oriented reformulation were used to optimize interrogation power under various conditions. Experimental validation with an R-FAD system showed consistent antenna responses even with high dielectric contrast materials. This method could enhance IC retuning for different objects, offering potential applications in sense augmentation, soft robotics, and the tactile internet. Fuad Erman *et al.* proposed a U-shaped inductively coupled UHF RFID tag antenna with a defected microstrip surface (DMS) for metallic surfaces [20]. The design includes symmetrical U-shaped feeder structures, enhancing flexibility for matching with various IC chips by adjusting the U-shaped dimensions. The DMS, achieved by etching a rectangular slot, improves antenna performance, increasing realized gain by 5.7 dB. The tag achieves a detection distance of 8.44 m on metallic surfaces and 6.2 m in free space. The study found good agreement between simulated and measured results, demonstrating the effectiveness of the proposed design.

In **2021**, Zhidan *Yan et al.* introduced an embedded metal UHF RFID tag using a planar inverted F antenna (PIFA) structure to enhance anti-metal performance [21]. The tag, with dimensions of 19.8 mm × 25.8 mm × 2 mm, achieves optimal impedance matching through an embedded feed design. Electromagnetic simulations and practical tests were conducted, showing a maximum gain of -9.7 dB and a reading distance of 1.26 m in metal grooves. Key findings indicate the significance of tag structural parameters and packaging materials on performance. The design demonstrates practical value in long-distance reading and writing for embedded metal applications, offering a robust solution for the IoT field.

In **2022**, Fuad Erman *et al.* introduced a miniature interdigitated UHF RFID tag antenna designed for metallic objects. The tag features two horizontal strip lines with seven identical open stubs, achieving a perfect match to the IC chip's impedance through adjustable stub lengths and spaces [22]. Fabricated on a PTFE substrate, it lacks metallic vias or shorting walls, simplifying construction for mass production. The tag measures 55.2 mm × 44.2 mm × 1.5 mm and achieves a realized gain of -4.11 dB at 902-928 MHz. It demonstrated a detection distance of 8.14 m on metallic objects and 5 m in free space, showing good agreement between measured and simulated results.

In **2023**, Al Ka'bi *et al.* proposed a compact broadband meander antenna for RFID applications. This design uses bent inductive strips to generate capacitive effects and achieve impedance matching at 876 MHz [23]. The antenna, made from a copper strip on an FR4 epoxy substrate, measures $75{\times}25{\times}1.6\ \text{mm}^3$ and is optimized for the European band of 867 MHz. Simulations showed excellent performance in free space with a reading range of 12.6 m and good performance in various media like plastic, glass, wood, and foam. Performance degrades on liquid surfaces but can be improved using a ground plane and multiple antenna prototypes.

In **2024**, Casula *et al.* introduced a compact AMC structure for wearable UHF RFID tags, aimed at on-body applications [24]. This AMC design, with a footprint of 41.4 × 82.8 mm^2, enhances tag antenna gain and reading range by an order of magnitude compared to conventional tags. The AMC structure is crafted on a flexible, biocompatible, silicone-doped dielectric substrate, featuring apertures for skin transpiration. The device, designed using CST Studio Suite, demonstrates high reliability and platform tolerance. It is suitable for epidermal use, enabling on-skin health parameter monitoring. The prototype's measured results closely align with simulations, confirming the design's effectiveness in improving healthcare RFID applications.

2.6.2 Review of Circularly Polarized UHF RFID tag antennas for Metallic surfaces

Circularly polarized UHF RFID tag antennas are designed to maintain consistent readability regardless of orientation, making them ideal for metallic surfaces. These antennas counteract signal degradation caused by metal, ensuring robust performance. They are particularly useful in dynamic environments, enhancing reliability and efficiency in industrial and logistics applications.

A circularly polarized (CP) loop antenna for UHF RFID tags was introduced by *Chen et al.* in **2013**, addressing polarization mismatch issues between reader and tag antennas [25]. The design features a square-loop with an open gap, feeding strips, and a matching stub for impedance tuning. The antenna achieved a 3-dB axial-ratio bandwidth of 50 MHz and an impedance bandwidth of 52 MHz. It demonstrated good performance with a gain variation of 2.64 to 2.95 dBic and a maximum reading range of 16.3 meters. This makes it a strong candidate for UHF RFID applications requiring long reading distances.

In **2014**, Ching-Han Tsai *et al.* proposed a simple circularly polarized (CP) square loop antenna [26] for UHF RFID tags, addressing polarization mismatch issues. The design incorporates an open gap and a matching stub for good CP radiation and impedance matching with the RFID chip. The antenna achieved an impedance bandwidth of 70 MHz and a CP bandwidth of 55 MHz. It demonstrated a maximum gain of 4.2 dBic at 915 MHz and a reading distance of up to 17.6 meters. This makes the proposed antenna an excellent candidate for long-distance RFID applications in the UHF band.

In **2015**, Marco Fantuzzi *et al.* introduced a compact, single-port antenna combining UWB and UHF bands for next-generation passive RFID tags[27]. The design utilizes an Archimedean spiral for UWB communication and extended spiral arms for UHF energy harvesting, maintaining compatibility with previous RFID generations. The antenna, designed for integration with future UWB-UHF chips or standard RFID chips, is validated through prototypes on FR-4 and paper substrates. It demonstrated effective performance in both UWB (3.1–4.8 GHz) and UHF (868 MHz) bands. This compact, eco-compatible antenna is a potential candidate for future smart tags, supporting UWB communication and UHF energy harvesting.

In **2016**, Chen *et al.* proposed a compact planar loop antenna for UHF RFID applications operating in the 922–928 MHz band [28]. The antenna, measuring 58.6 × 58.6 mm^2, features a meandered-loop structure with an open gap to achieve good circularly polarized (CP) radiation. A matching stub is used to ensure desirable impedance matching between the antenna and RFID chip. The antenna demonstrates a 3-dB axial-ratio bandwidth of 921–929 MHz, a 10-dB impedance bandwidth of 915–942 MHz, and an antenna gain of 1.73 dBic. The maximum read range achieved is 20.5 meters, making this antenna a strong candidate for UHF RFID applications requiring long reading distances.

In **2017**, Zaid *et al.* introduced a circular polarized patch antenna for UHF RFID tag-based sensor applications, utilizing an asymmetric stars-shaped slotted microstrip patch antenna (CP-ASSSMP) [29]. The design generates circular polarization and reduces the antenna size by 20%. It employs inductive-loop matching to connect two RFID chips: one for sensing and the other as a reference. This configuration allows simultaneous reading of both tags in any orientation, with a measured reading range of 25 meters. Operating in the 902–929 MHz band, the antenna demonstrates an axial-ratio bandwidth of 7 MHz. It effectively detects temperature changes and offers simple fabrication and low cost, showing good agreement between measured and simulated results.

In **2018**, Jhih-Han Hong *et al.* proposed a circularly polarized tag using a 3 × 3 AMC structure to enhance read range for UHF RFID on-body applications [30]. The design employs a modified T-matching transformer to achieve conjugate matching with the Monza 4 microchip. The cross-dipole tag antenna, implemented on the AMC structure, effectively isolates the influence of the human body and increases antenna gain by 3.34 dB. The measured impedance bandwidth is 3.2%, covering the UHF RFID bands of North America and Taiwan. The tag demonstrated a measured read range of 15.7 meters on the human body and up to 18 meters in free space, showing excellent performance for on-body RFID applications.

In **2019**, Wei Hu *et al.* proposed a 2 × 2 circularly polarized (CP) microstrip patch antenna array for long-range UHF RFID communication [31]. The design utilizes a two-level sequential rotation structure to meet the 840–960 MHz operational frequency band and enhance broadside gain. A series power divider, implemented with substrate-integrated coaxial line technology, minimizes radiation losses. The prototype demonstrates a peak gain of 12.5 dBic at 900 MHz and an axial ratio bandwidth of 18.2% from 828 to 994 MHz. This antenna array offers an excellent gain/size trade-off, making it a suitable candidate for long-range UHF RFID applications.

An optically transparent and flexible UHF RFID tag antenna with circular polarization was introduced by Sayem *et al.* in **2020**. This antenna, made from a flexible conductive-mesh-polymer composite, is encapsulated in a transparent polymer for protection against environmental factors [32]. The design is based on a planar square ring, achieving a maximum read range of 8.3 m and a 3 dB axial-ratio bandwidth of 47 MHz. The CP nature ensures reliable communication even with orientation mismatches between the tag and reader. The antenna performs well on both flat and curved surfaces, maintaining excellent read range and CP performance under various bending states, making it ideal for applications requiring unobtrusive and durable tracking solutions.

In **2021**, Sim *et al.* proposed a circularly polarized (CP) UHF RFID tag antenna with a 100×100 mm^3 size, featuring an eccentric circular slot patch and a coupled arc-shaped feeding strip [33]. The design achieves good impedance matching and CP characteristics through its specific structure and slot positioning. The antenna operates within the 914-929 MHz band with a 10-dB impedance bandwidth of 1.62% and a 3-dB axial ratio bandwidth of 0.97%. This design is suitable for RFID systems in the Taiwan operational band, demonstrating efficient CP performance and reliable operational frequency.

In **2022**, Ping Wang e*t al.* proposed a circularly-polarized (CP) metal-tolerant UHF RFID tag antenna designed for long reading distances [34]. The antenna features a cross slot on the top patch for two orthogonal polarizations and a meandered strip for a 90° phase difference. An equivalent circuit model (ECM) was developed to understand its impedance characteristics. The prototype, mounted on a 200×200 mm metal plate, showed an 8 MHz impedance bandwidth (918–926 MHz), a 1.3 MHz axial ratio bandwidth (921.6–922.9 MHz), a maximum gain of 2 dBi at 922 MHz, and a reading distance of about 22.4 meters, demonstrating its suitability for metal objects.

In **2023**, A. Sharif *et al.* introduced a bio-inspired circularly polarized (CP) UHF RFID tag antenna optimized for metallic and low-permittivity substances [35]. The design, featuring a leaf-shaped radiator with shorting stubs and etched slots on an F4B substrate, employs characteristic mode analysis (CMA) for tuning. The antenna achieves a 7-4.5 m read range on a 100×100 mm metal plate and low-permittivity substrates in the 902–928 MHz band. Tunable to the European RFID band (866–868 MHz), it offers a read range of 5.7-3.5 m. Its advantages include cost efficiency, CP functionality, and ease of fabrication without vias or matching circuits, making it suitable for IoT applications, industrial conveyer belts, and baggage handling systems.

In **2024**, Casula *et al.* introduced a compact AMC structure for wearable UHF RFID tags aimed at on-body applications. The design features a small footprint of 41.4 × 82.8 mm^2 and utilizes a high-permittivity silicone-doped dielectric substrate [24]. The AMC structure significantly enhances tag antenna gain and reading range by isolating the antenna from the human body. This platform-tolerant and biocompatible device allows for skin transpiration through apertures in the substrate and ground plane. Tested at around 900 MHz, the antenna's performance shows good agreement with simulations, making it suitable for on-skin health monitoring, including body temperature and skin impedance.

A. Hamidi *et al.* proposed a passive UHF RFID tag featuring a metallic reflector to enhance performance [36]. The design includes a metallic square loop and T-match structure for impedance matching, with a reflector placed at a quarter wavelength distance to maximize gain. The antenna achieves a 25 MHz impedance bandwidth (907-932 MHz) and a broadside CP radiation with a gain of 7.72 dBi. Notably, it provides a long reading range of up to 22.56 meters at 915 MHz. This simple, cost-effective design is suitable for high-gain RFID applications.

The literature review has identified several gaps in the current research on UHF RFID tag antennas. While various antenna parameters have been optimized using impedance matching techniques, there is a lack of studies that focus on optimizing more relevant parameters within a single antenna structure. This suggests that the potential for overall performance improvement has not been fully explored. Additionally, many antennas achieve good performance after impedance matching, but the specific techniques used are often not detailed or elaborated upon, limiting the ability to replicate or enhance these methods. Furthermore, earlier RFID tag antennas for the UHF band tend to be large and bulky, making them incompatible with the compact nature of modern wireless devices. Only a few reported designs are both compact and use cost-effective, durable materials, indicating a need for further research in this area.

Given these gaps, there is a clear opportunity to design a miniaturized planar RFID tag antenna that offers a greater read range and utilizes RFID chips with lower sensitivity while maintaining high efficiency. Such a design should also focus on using less costly and more durable materials, making the antenna both effective and accessible for future wireless technology applications.

In Chapter 2, components and characteristics of UHF RFID systems have been explored, establishing the basis for understanding antenna behavior at frequencies between 860 MHz and 960 MHz, a range where UHF RFID applications commonly operate. This foundation leads us to Chapter 3, where we apply matching techniques like the Nested Slot and T-Match Network, specifically designed to achieve efficient impedance matching. These methods are chosen to counteract power loss and ensure that the antenna resonates effectively within the UHF frequency range (859 MHz to 871 MHz), thereby enhancing overall tag readability and detection range.