2.

THEORETICAL BACKGROUND AND IMPEDANCE MEASUREMENT METHODS OF RFID TAG ANTENNAS

2.1 Introduction

In the previous chapter basics of RFID systems along with literature review is presented. In the present chapter, theoretical background and performance parameters such as input impedance, power reflection coefficient, differential RCS, and read range of the RFID tag antenna are presented. Furthermore, input impedance measurement techniques which are available in the literature are discussed. Out of these methods, differential probe technique is discussed in details, which is used in the measurement of input impedance of the RFID tag antennas in the entire thesis.

2.2 Theoretical background of RFID Tag Antenna

In RFID systems, proper impedance matching between the antenna and the tag chip is very important. It directly influences the performance characteristics of the RFID system such as the read range of a tag which is the maximum distance at which a reader can either read or write information to the tag.

In RFID tags, the antenna is generally directly connected to the tag chip as shown in figure 2.1, where the antenna is represented with its Thevenin's equivalent. In figure 2.1, $Z_a = R_a + jX_a$ is the complex antenna impedance and $Z_L = R_L + jX_L$ is the complex chip (load) impedance. Antenna impedance is typically matched to the high impedance state of the chip in order to maximize the collected power.

An RFID chip is a nonlinear load whose complex impedance in each state varies with the frequency and the input power. The passive chip circuitry needs certain minimum voltage or power to turn on. This threshold and the impedance dependence on the input power are determined by the details of the chip RF front end and the power consumption of the specific chip [Vita and Iannaccone (2005)]. The variation of the chip impedance with power and frequency can drastically affect the performance of the tag. Usually, to maximize the read range, the antenna impedance is matched to the complex conjugate of the chip impedance at the minimum power level required for the chip to work.

Figure 2.2 shows the schematic of conventional and dual antenna structure (DAS) for RFID tag. The whole communication between reader and the tag involves two steps [Chen *et al.* (2011)a]. In first step, the reader radiates commands and continuous wave (CW) to the tag. After receiving sufficient power from the CW radiated by reader, tag wake up and respond to command by reader. Secondly, in process to send signal to reader, the tag antenna is alternatively connected to two different load impedances as per the data stored in the tag chip. The CW is modulated by this process and scattered back to the reader. When the difference between the low and high levels of the backscattered wave is sufficient, the reader can demodulate the back scattered signal properly. Therefore, a proper tag design should continuously provide sufficient power for tag chip while exhibiting maximum level difference in the backscattered fields.

A conventional passive RFID tag typically uses a single antenna for both reception and scattering. When the tag is in response, the tag chip alternatively switches between two different impedance states. Therefore, conventional tags cannot have simultaneously maximum power reception and maximum level difference in the backscattered signal because there is no power supply for the

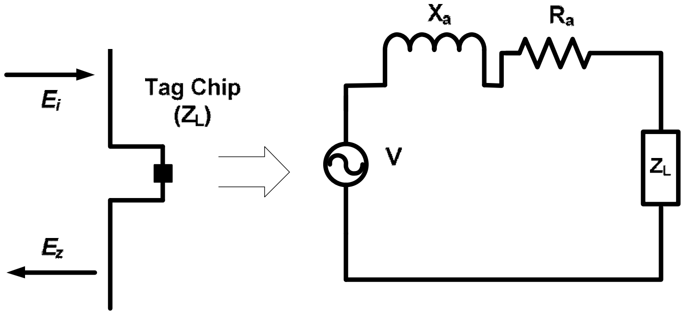
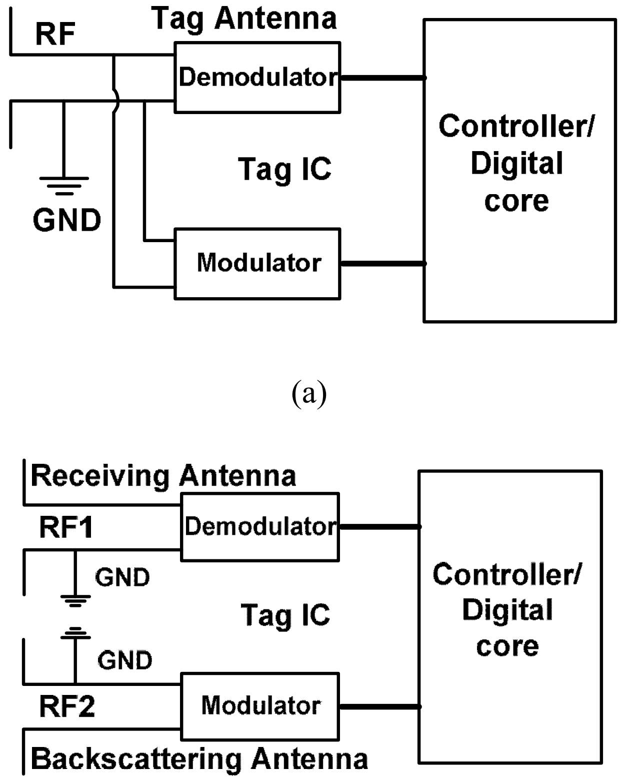


Figure 2.1: Configuration and equivalent circuit of a passive RFID tag.



(a)

(b)

Figure 2.2: Schematic of (a) conventional tag and (b) proposed dual antenna tag.

chip. In contrast, one of the impedance states is chosen to be conjugate matched to the input impedance of the tag antenna regarding the power supply for the tag chip, which is the case in conventional passive RFID tags, the level difference thus obtained is obviously not the optimum.

To simultaneously maximize the power supply for the chip and the level difference in the backscattered signals, dual-antenna structure for passive RFID tags as shown in Figure 2.2. The two ports of the tag chip are formed by three terminals namely RF1, RF2, and common Ground. Each port is connected to an independent antenna. One antenna, denoted as the receiving antenna, is constantly used for reception, while the other, denoted as the backscattering antenna, is used for signal backscattering and modulation. The control circuit within the chip is responsible for switching the impedance states according to the data stored.

In passive RFID tags, the chip is power up by a plane wave E_i, so that the total received power by the chip (P_L) is given as [Chen *et al.* (2011)a] and [Balanis (2005)],

$$P_L = (1 - |\Gamma(Z_L)|^2) * P_a \tag{2.1}$$

where P_a is the power collected by the antenna, and $\Gamma(Z_L)$ is the complex power reflection coefficient given as [Nikitin *et al.* (2005)],

$$\Gamma(Z_L) = \frac{(Z_L - Z_a^*)}{(Z_L + Z_a)} \tag{2.2}$$

where Z_L is the impedance of chip, Z_a is the input impedance of antenna and Z_a^* is complex conjugate of antenna's impedance. The backscattered electric field of an antenna is a function of load impedance which can be defined as [Green (1963)],

$$E_Z = E_Z^* - \Gamma(Z_L) I_{(Z^*)} E_r \tag{2.3}$$

where E_Z^* is the electric field that scatters when the impedance of the tag antenna is complex conjugate; $\Gamma(Z_L)$ is complex power reflection coefficient; $I(z^*)$ is the terminal current of tag antenna when the impedance of the antenna is complex conjugate and E_r is the radiated electric field of an antenna when it is excited by a unit current source.

In backscattering mode, the Z_L switches between two impedance states that are short (Z_L=0) and open (Z_L= ∞) circuits. So we have two different amounts of backscattered electric field that can be written as [Chen *et al.* (2011)a],

$$\Delta = |(E_{Z=0})| - |E_{Z=\infty}| = |\Gamma(Z_{L=0}) - \Gamma(Z_{L=\infty})| |I_{(Z^*)} E_r| \tag{2.4}$$

The stored data in microchip should modulate in such a way that the reader detects the difference between these two levels, so that the maximum value of differential radar cross section (RCS) (Δ) is needed. In equation (2.4), the term

$I_{(Z^*)}E_r$ is constant and the term $|\Gamma(Z_{L=0}) - \Gamma(Z_{L=\infty})|$ could be positive and between [0, 2], therefore for having maximum of Δ,

$$\Gamma(Z_{L=0}) = -\Gamma(Z_{L=\infty}) \tag{2.5}$$

Using equation (2.2), for having $\Gamma(Z_{L=\infty}) = 1$ and $\Gamma(Z_{L=0}) = -1$, the input impedance of backscattering antenna should be purely resistive i.e., reactance X_{bsant} should be zero.

Finally, we have one condition for receiving antenna and one condition for backscattering antenna that is,

$$Z_{recant} = Z^*_{chip} \quad \text{and} \quad X_{bsant} = 0 \tag{2.6}$$

where Z_{recant} and Z^*_{chip} are the impedance of receiving antenna and complex conjugate of chip impedance, respectively.

Considering these two conditions to achieve the maximum Δ and read range. The read-range of the tag antenna is given as, [Chen *et al.* (2011)a], [Aleksieieva *et al.* (2010)],

$$d_{\max} = \left(\frac{P_t G_t^2 \lambda^2}{(4\pi)^3 S_R} \Delta\sigma\right)^{1/4} \tag{2.7}$$

where, λ is free space wavelength at operating frequency, P_t is power radiated by reader, G_t is Gain of the reader antenna, S_R is sensitivity of reader circuitry, and $\Delta\sigma$ is the differential RCS between two loading states of backscattering antenna. RCS can be calculated as [Nikitin and Rao (2006), Harrington (1963)],

$$\sigma = \frac{R_a^2 G_r^2 \lambda^2}{\pi |Z_a + Z_L|^2} \tag{2.8}$$

where, $Z_a = R_a + j X_a$ and Z_L is impedance of chip.

The realized gain G_r of the antenna can be defined as [Virtanen *et al.* (2010)]

$$G_r = \eta_r \eta_{cd} D = (1 - |\Gamma|^2) \eta_{cd} D \qquad (2.9)$$

where $\acute{\eta}_r$ is the efficiency due to impedance mismatches, $\acute{\eta}_{cd}$ is the efficiency due to conductor and dielectric losses (i.e., radiation efficiency) and, D is the directivity of the antenna.

2.3 Measurement of RFID Tag Antenna

Several measurement techniques are reported in the literature [Kuo *et al.* (2008)]. Input impedance measurement of RFID tag antenna with the desired accuracy has been a troublesome issue for years. Before the emergence of RFID, small antenna measurement was based on a 50Ω system, which could not be applied directly to RFID tag antenna due to the incompatible nature of the feed. A RFID strap shown in figure 2.3 has two identical pads which transmit energy into tag antenna. As the feed structure is symmetrical and electrically small, the virtual ground plane established is a mid-way plane. Therefore, a RFID strap is served as a balanced feed.

Following four measurement techniques which utilize for measurement of input impedance of RFID tag antennas are reviewed in this section [Qing *et al.* (2009)a].

(i) Measurement using on-wafer-prober
(ii) Single-ended probe
(iii) Balun probe
(iv) Differential probe

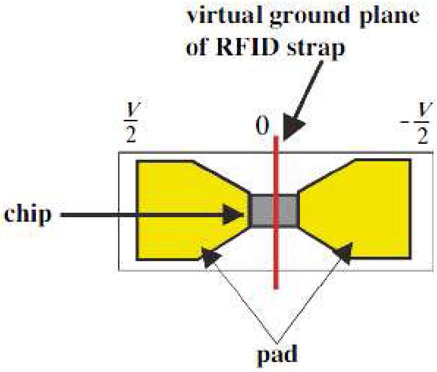


Figure 2.3: An RFID trap and its virtual ground surface.

2.3.1 Measurement using on-wafer-prober

Camp *et al.* demonstrated the measurement setup for the determination of the input impedance of the RFID tag antenna using on-wafer prober [Camp *et al.* (2007)]. To perform the measurement, he has modified the on-wafer-prober (PA 200 HS) and combined with a network analyzer (PNA E8361A). Figure 2.4 shows the measurement setup for the determination of RFID tag antenna impedances with on-wafer prober PA 200 HS and network analyzer PNA E8361A (Agilent). Initially, the probe level of the on-wafer prober is elevated by means of mechanical spacers over the Chuck. The Chuck is then covered with the type C RAM FLX 900 absorber material and is fixed by negative pressure. A Styrofoam layer and the antenna substrate is placed on the absorber material with the tag antenna to be measured. In this way, the input impedance of a RFID tag antenna can be measured approximately under free space conditions.

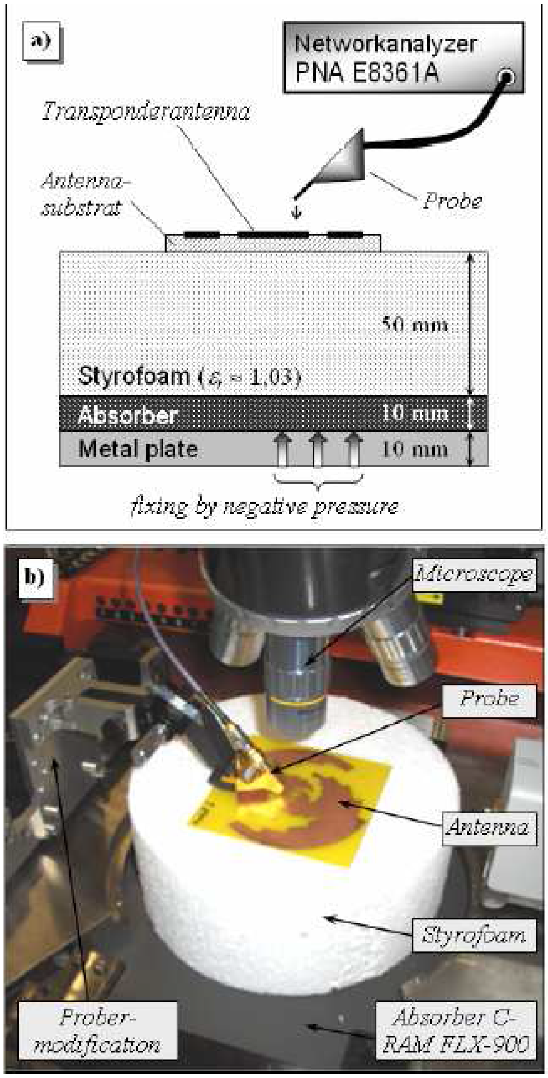


Figure 2.4: Measurement setup for the determination of RFID tag antenna impedances with on-wafer prober

2.3.2 Single-ended Probe

A single-ended probe is consists of connecting an extension to a coaxial cable. The extension can be an SMA connector [Eunni (2004)] and [Leong *et al*. (2007)], a wafer probe [Camp *et al*. (2007)]. Figure 2.5 shows a commercially available probe extension. Since the single-ended probe is an unbalanced feed due to which measurement of tag antenna is inappropriate.

Figure 2.5: Single ended probe

The virtual ground surface is very close to a three-dimensional cylindrical surface. When connecting a single-ended probe to a balanced tag antenna, the unbalanced nature of the probe changes the electromagnetic field distribution around the feed area. The situation might become worse when probing an unbalanced antenna. Therefore, this method cannot provide accurate measurement results.

2.3.3 Balun probe

Another technique to measure RFID tag antenna is balun. A balun is recognized as a balance-unbalance converter that can provide differential current at its output port [Yang *et al.* (2007)]. A wire balun has a larger bandwidth than a microstrip balun, and hence has been used for tag antenna measurement [Dobkin, and Weigand (2005), Leong *et al.* (2007)]. Figure 2.6 shows a probe which is formed by connecting a wire balun in front of an SMA connector.

Two probe tips attached to the other side of the balun are used for probing the antenna. The commercially available wire balun has a 2.5 turns coil-wound around a ferrite core, offering a bandwidth around 3.3 GHz. Because the balun is inherently a transformer, it exerts equal and opposite currents at both tips. Therefore, the way it distributes the electromagnetic field is identical to a RFID strap.

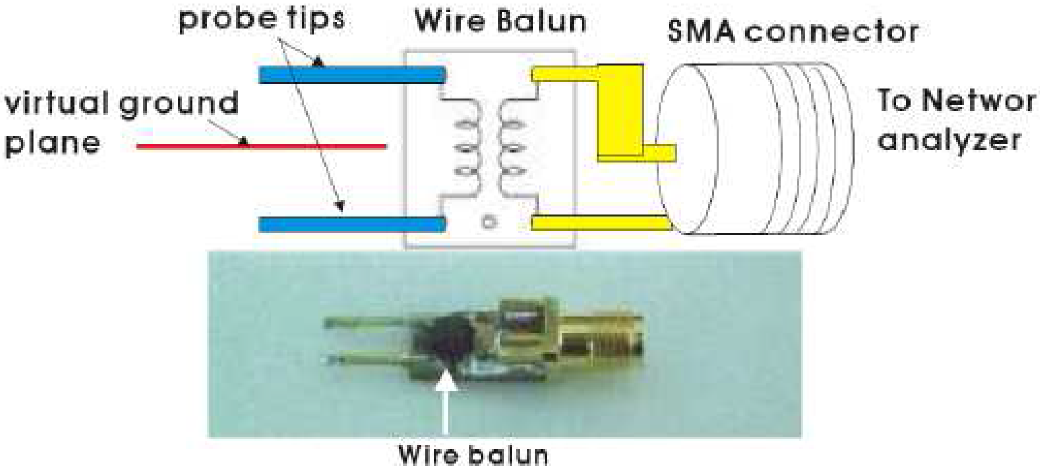


Figure 2.6: Balun

2.3.4 Differential Probe

As mentioned in the previous Section, the majority of the RFID tag antennas are balanced designs. The impedance of a balanced antenna cannot be measured directly by most measurement instruments which are terminated with unbalanced ports such as coaxial ports. The impedance of a symmetrically balanced antenna can also be measured using imaging method, i.e., mounting half part of the radiators of the antenna on a ground plane, which provides a mirror imaging to configure the other part of radiators. The impedance of the antenna can be obtained by multiplying a factor of 2 of the measured impedance of the equivalent monopole. However, the accuracy of the measurement results is much dependent on the size of the ground plane used, and this method is valid only for symmetrically balanced antennas [Meier and Summers (1949)]. Meys and Janssens in [Meys and Janssens (1998)] carried out a parameter-based method for measuring the impedance of a symmetrically balanced antenna by using a two-port vector network analyzer (VNA). Two 50 Ω microstrip lines, which were etched onto a printed circuit board (PCB) and mounted back to back, were used as a test fixture to connect the antenna under test to a two-port VNA. The measurement system was calibrated at the end of the microstrip lines by using a set of special-purpose standards. It has been proven to be able to characterize the impedance of a symmetrical dipole antenna up to 1 GHz.

Later, Palmer *et al.* [Palmer *et al.* (2006)] developed the technique by replacing the microstrip lines with coaxial cables and using the standard calibration. This technique had overcome the frequency limitation of the nonstandard calibration kits and made the measurement more convenient. However, using this method, the antenna impedance could not be extracted from the measured S –parameters directly. Another measurement must be carried out to find the network parameters of the coaxial cables. The de-embedding of the influence of the cables from the measured S-parameters is complicated and tedious, including multiple parameter conversion of S-parameters, ABCD-parameters, and Y-parameters, as well as pre- and post-multiplication of s-parameters. The methodology presented can able to characterize the asymmetrical/symmetrical balanced antenna impedance precisely. Together with the coaxial fixture and the port-extension technique, the impedance of the antennas can be extracted directly from the measured S-parameters over broad frequency band.

Figure 2.7(a) shows a typical asymmetrical balanced dipole antenna, which is with two arms of different lengths and excited differentially. The positive and negative ports of the source with a voltage of V are connected to the input terminals of the radiators of the antenna, respectively. As shown in Figure 2.7(b), the driven voltage can be split as V_1 and V_2 with a virtual ground plane without any disturbance of the current distribution on the antenna. Therefore, each terminal of the antenna radiators and the ground plane can be considered as a "port," as shown in Figure 2.7(c). The antenna can be equivalent to a "two-port" network, as shown in Figure 2.8. The impedance of the antenna is thus related to the network parameters of the equivalent two-port network, and can be characterized by measuring the network parameters such as S-parameters. From Figure 2.8, the normalized impedance of the antenna can be expressed as:

$$\tilde{Z}_d = \frac{V_d}{I_0} = \frac{V_1 - V_2}{I_0} \tag{2.10}$$

Based on the definition of Z-parameters, the port voltages and currents are related as [Pozar (2002)]

$$V_1 = Z_{11}I_1 + Z_{12}I_2 \tag{2.11}$$

$$V_2 = Z_{21}I_1 + Z_{22}I_2 \tag{2.12}$$

Considering $I_1 = I_0$ and $I_2 = -I_0$, the differential voltage V_d is given by

$$V_d = V_1 - V_2 = (Z_{11} - Z_{21} - Z_{12} + Z_{22})I \tag{2.13}$$

and the impedance is

$$\tilde{Z}_d = \frac{V_d}{I_0} = \frac{V_1 - V_2}{I_0} = (Z_{11} - Z_{21} - Z_{12} + Z_{22}) \tag{2.14}$$

And after converting the Z-parameters to S-parameters and considering $Z_d = Z_0 \bullet \tilde{Z}_d$ and Z_d can be expressed as [Frickey (1994)]:

$$Z_d = \frac{2Z_0(1 - S_{11}S_{22} + S_{12}S_{21} - S_{12} - S_{21})}{(1 - S_{11})(1 - S_{22}) - S_{12}S_{21}} \tag{2.15}$$

Where Z_0 is the characteristic impedance of the connected transmission lines, which is 50 ohm for most of measurement systems.

For the symmetrical balanced antenna, $S_{11} = S_{22}$, and $S_{12} = S_{21}$ Eqn. (2.15) van be simplified as [Qing *et al.* (2009), Koskinen *et al.* (2009), and Chen *et al.* (2010)]

$$Z_d = \frac{2Z_0(1 - S_{11}{}^2 + S_{12}{}^2 - 2S_{12})}{(1 - S_{11})^2 - S_{12}{}^2} \tag{2.16}$$

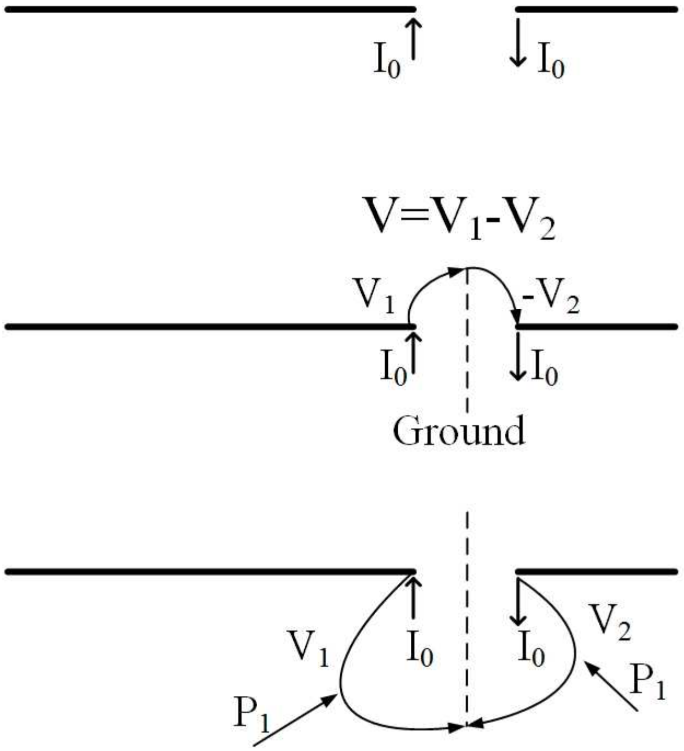


Figure 2.7: Excitation and port definition of the asymmetrical balanced dipole antenna. (a) Excitation. (b) Virtual ground. (c) Ports definition.

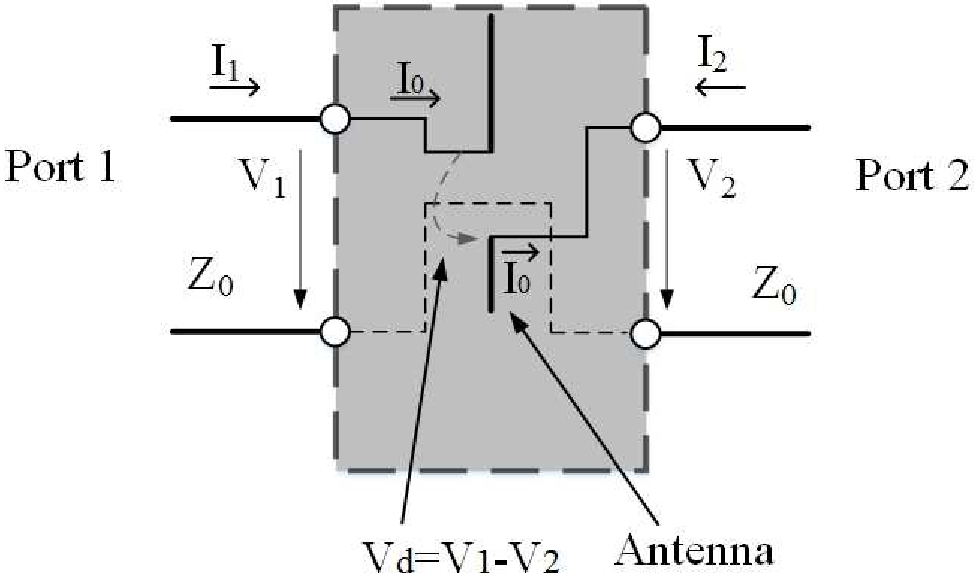


Figure 2.8: Network representation of the asymmetrical dipole antenna [Qing *et al.* (2009)a]

2.3.4.1. Measurement Setup

Xianming *et al.* presented configuration of the measurement system is illustrated in Figure 2.9 [Qing *et al.* (2009)]. The measurement can be conducted by using a two-port VNA and a test fixture. The test fixture is constructed by using two semi-rigid coaxial cables. The coaxial cables are soldered together on their outer conductors. One end of the fixture is with two subminiature A (SMA) connectors and connected to the VNA through the test cables. The other end of the fixture is open with the small extensions of inner conductors to form the tips to connect the antenna under test.

2.3.4.2. Measurement Procedures

Following procedure is adopted for the input impedance measurement of RFID tag antennas.

a) Setting and calibration of standard VNA parameters.

b) Port extension techniques: Shift the calibration plane through the port-extension technique provided in the manual of the VNA used for measurements. For port tension, connect the test fixture to the test cables and carry out the port extension to shift the calibration plane to the tips of the fixture. The fixture is required to be open or short circuited when performing the port extension. Short-circuited configuration (solder the tips of the fixture and outer conductors of the coaxial cables together) is recommended since perfect “open” condition is very difficult to achieve, especially at higher frequencies.

c) Connect the antenna to the fixture and measure the S-parameters.

d) Calculate the impedance of the antenna using equations (2.15) or (2.16).

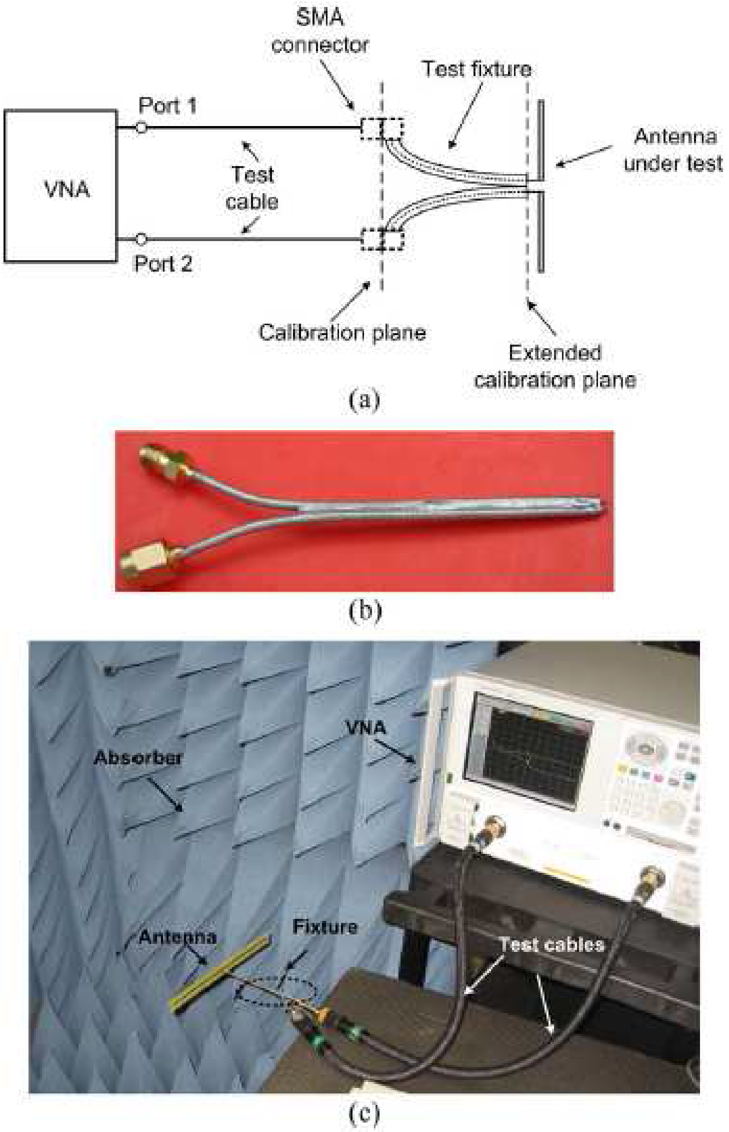


Figure 2.9: Measurement setup. (a) Schematic configuration. (b) Fixture prototype. (c) Measurement setup using network analyzer.

2.4 Summary

In this Chapter, the theoretical background about the working of RFID tag antenna has been present in detail. Further, the concept of dual antenna structure to mitigate the limitation of conventional antenna is reported. The different methods of input impedance measurement of RFID tag antenna ars also presented. The theoretical background about one of the impedance measurement technique is discussed in detail.