Impedance Measurement for Balanced UHF RFID Tag Antennas

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Abstract — **Dipole antennas in UHF RFID tags are driven by differential signals; it is difficult to measure the antenna input impedance accurately using single-ended probes. Furthermore, the testing fixture used in the antenna measurement process also induces additional parasitic effects; accurate measurement cannot be achieved without taking the fixture impact into consideration. In this paper, we propose to characterize the dipole antenna's input impedance using mixed mode S-parameters, the testing fixture impact can also be quantified with port extension and de-embedding techniques. Experiments demonstrate that the proposed measurement method achieves very consistent results over UHF frequency band with very high accuracy.**

Index Terms — **Impedance measurement, radio frequency identification (RFID), balanced antenna, network analyzer, de-embedding, mixed-mode S-parameter.**

I. Introduction

Ultra-high frequency (UHF) RFID system has prevailed in logistic and supply-chain industry in recent years. Compared with other RFID technologies using low frequency (LF) and high frequency (HF) band, UHF RFID offers higher dada rate, longer reading range and lower material cost for tags. Based on different application requirements, UHF RFID tag antennas can take different forms, such as dipole antenna, loop antenna, or patch antenna with a ground plane [1]. Regardless of these different antenna designs, to achieve the best performance, impedance of tag antenna must be conjugate-matched with the tag chip impedance in order to achieve maximum power transfer [2].

Antenna simulation software, such as High Frequency Structure Simulator (HFSS) and IE3D are the most commonly used tools for antenna design. The antenna design cycle is a trial-and-error practice, i.e. the antenna is first simulated by the tools based on some specific design requirements, then a prototype is built, field measurement is performance to characterize the performance, if the performance does not meet the expectation, the design has to be revised. Typically, this design cycle needs to go through several iterations until a good antenna design can be achieved.

Accurate impedance measurement plays a crucial role in RFID antenna designs. However, most of the UHF RFID tag antennas use balanced structures [1], such as symmetrical dipole, and loop. These antennas are fed by differential input signals without a real ground. The antenna's input impedance cannot be easily and accurately characterized using a normal single-ended, two-port vector network analyzer (VNA) [3].

In this paper, a new measurement method based on mixed-mode S-parameters is presented, which had been demonstrated to have a higher accuracy than other methods. The proposed measurement is performed using an AGILENT E5071C VNA, which is equipped with a built-in fixture simulator and capable to characterize a differential device with mixed-mode S-parameters directly. Because of the special physical structure of RFID tag antennas, an external test fixture must be developed to connect the testing probes to the tag antennas and reduce the ambient interference. Impacts of this test fixture can be calibrated using port extension or de-embedding methods. Simulation results from HFSS agree nicely with the measurement results using the proposed method throughout the whole frequency span of UHF band.

II. Impedance Measurement of Differential Devices

There are several methods to measure the input impedance of a balanced device with differential inputs. Each method has its limitations, such as:

1) Using external baluns. Measurement accuracy relies on the accuracy of the baluns itself [4]
2) Forming a big ground plane and using the mirror theory. Measurement accuracy relies on the size of the ground plane as compared to the antenna, and connection between measurement cable and tag antenna [4].
3) Forming a virtual ground in the middle of differential antenna ports to calculate input impedance from conventional single-ended S-parameters [5]. Measurement accuracy relies on the port extension and needs complicated post-processing of measurement data.
4) Using equivalent two ports scattering matrix to calculate impedance of tag antenna. Measurement accuracy relies strongly on the setup and environment. It also needs post-processing [6].

As most VNAs are equipped with only single-ended ports, to characterize a balanced device, special procedure and method must be designed.

The circuit model for balanced RFID tag antenna measurement is shown in Fig. 1. Port extension and equivalent characteristic elements of test fixture are also modeled to quantify their impact for the antenna measurement.

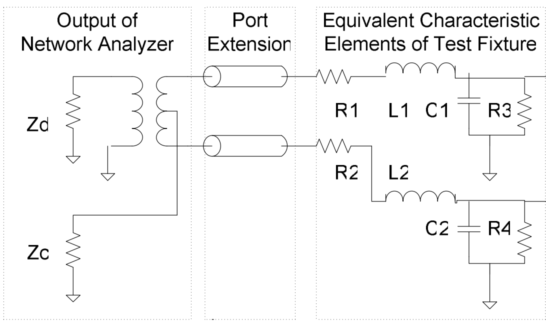

Fig. 1. Circuit model for balanced antenna measurement

A. Mixed-Mode S-parameter

To characterize balanced devices with differential inputs, such as RFID antennas, mixed-mode S-parameters are generally used, which can be regarded as a differential transformation of conventional S-parameters [7-8], as show in Fig. 2.

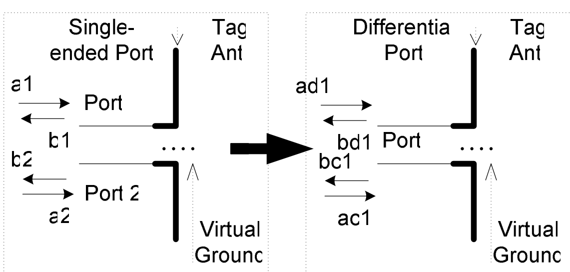

Fig. 2. Single-ended port to differential port transformation

Conventional S-parameters of Fig. 2 are formulated as

$$\begin{bmatrix} b_1 \\ b_2 \end{bmatrix} = \begin{bmatrix} S_{11} & S_{12} \\ S_{21} & S_{22} \end{bmatrix} \begin{bmatrix} a_1 \\ a_2 \end{bmatrix} = [S_{std}] \begin{bmatrix} a_1 \\ a_2 \end{bmatrix}. \tag{1}$$

Where a1 and a2 represent the input signals of port1 and port2, b1 and b2 represent the reflected signals of port1 and port2. $[S_{std}]$ represents the S-parameters matrix.

In comparison, mixed-mode S-parameters of Fig. 2 can be described by

$$\begin{bmatrix} b_{d1} \\ b_{c1} \end{bmatrix} = \begin{bmatrix} S_{dd11} & S_{dc12} \\ S_{cd21} & S_{cc22} \end{bmatrix} \begin{bmatrix} a_{d1} \\ a_{c1} \end{bmatrix} = [S_{mm}] \begin{bmatrix} a_{d1} \\ a_{c1} \end{bmatrix}. \tag{2}$$

Where a_{d1} and a_{c1} are differential mode and common mode input signals, b_{d1} and b_{c1} are differential mode and common mode reflected signals, $[S_{mm}]$ represents the matrix of mixed mode S-parameters. a_{d1} and a_{c1} , b_{d1} and b_{c1} can be derived from a1, a2, b1 and b2 respectively, as:

$$\begin{bmatrix} a_{d1} \\ a_{c1} \end{bmatrix} = \frac{1}{\sqrt{2}} \begin{bmatrix} 1 & -1 \\ 1 & 1 \end{bmatrix} \begin{bmatrix} a_1 \\ a_2 \end{bmatrix} = M \begin{bmatrix} a_1 \\ a_2 \end{bmatrix} \tag{3}$$

$$\begin{bmatrix} b_{d1} \\ b_{c1} \end{bmatrix} = \frac{1}{\sqrt{2}} \begin{bmatrix} 1 & -1 \\ 1 & 1 \end{bmatrix} \begin{bmatrix} b_1 \\ b_2 \end{bmatrix} = M \begin{bmatrix} b_1 \\ b_2 \end{bmatrix} \tag{4}$$

$$M^{-1} = \frac{M^*}{|M|} = \frac{1}{\sqrt{2}} \begin{bmatrix} 1 & 1 \\ -1 & 1 \end{bmatrix}. \tag{5}$$

Relation between $[S_{mm}]$ and $[S_{std}]$ can be derived from (1), (2), (3) and (4):

$$S_{mm} = MS_{std}M^{-1} = \frac{1}{\sqrt{2}} \begin{bmatrix} 1 & -1 \\ 1 & 1 \end{bmatrix} \begin{bmatrix} S_{11} & S_{12} \\ S_{21} & S_{22} \end{bmatrix} \frac{1}{\sqrt{2}} \begin{bmatrix} 1 & 1 \\ -1 & 1 \end{bmatrix} \tag{6}$$

$$\left. \begin{aligned} S_{dd11} &= \frac{1}{2}(S_{11} - S_{21} - S_{12} + S_{22}) \\ S_{dc12} &= \frac{1}{2}(S_{11} - S_{21} + S_{12} - S_{22}) \\ S_{cd11} &= \frac{1}{2}(S_{11} + S_{21} - S_{12} - S_{22}) \\ S_{cc11} &= \frac{1}{2}(S_{11} + S_{21} + S_{12} + S_{22}) \end{aligned} \right\}. \tag{7}$$

With a balanced RFID tag antenna, $S_{11} = S_{22}$, $S_{12} = S_{21}$, (7) can be further simplified to :

$$\left. \begin{aligned} S_{dd11} &= S_{11} - S_{12} \\ S_{dc12} &= 0 \\ S_{cd11} &= 0 \\ S_{cc11} &= S_{11} + S_{12} \end{aligned} \right\} \tag{8}$$

S_{std} can be derived from S_{mm} by the same approach:

$$S_{std} = M^{-1} S_{mm} M \tag{9}$$

The input impedance of a balanced antenna can be expressed as [3]-[5]:

$$Z_d = 2R_0 \frac{(1 - S_{11}^2 + S_{21}^2 - 2S_{21})}{(1 - S_{11})^2 - S_{21}^2} \tag{10}$$

Based on (7), (8), (9) and (10), network analyzer can derive the input impedance of balanced RFID tag antennas from the measured mixed-mode S-parameters. E5071C VNA has a built-in program to transform S_{dd11} to input impedance of balanced devices automatically.

The impact from external test fixture needs to be counted to achieve accurate impedance measurements. Two methods can be used to remove the effects of external test fixture, 1) Port extension and 2) De-embedding. Port extension method extends the calibration reference plane to compensate the insertion loss and phase shift. De-embedding method characterizes the test fixture with a 2-Ports S-parameters model and then removes its effect from the measured S-parameters.

B. Port Extension Method

Port extension method is commonly applied as a quick and simple way to compensate fixture effects. AGILENT E5071C has the capability to carry out auto-port extension in "port short" or "port open" mode calibration. The calibration plane will be extended to the end of the test probe after port extension. However, the geometries of port terminals (tips) are difficult to be accurately estimated. To ensure measurement accuracy, the cable length and tips have to be made identical.

C. De-Embedding Method

De-embedding can achieve a better accuracy to remove the test fixture effects. Test fixture can be characterized with short-open-load (SOL) modes in a full-1-port calibration. Assuming the transfer matrix of the test fixture can be denoted with $[T_{FIX}]$, the balanced antenna can be denoted with $[T_{ANT}]$. Conversion the measured S-parameters into T-parameters can be derived [9].

$$[T] = \begin{bmatrix} \frac{1}{S_{21}} & -\frac{S_{22}}{S_{21}} \\ \frac{S_{11}}{S_{21}} & S_{12} - \frac{S_{11}S_{22}}{S_{12}} \end{bmatrix}. \qquad (11)$$

Text fixture can be de-embedded using:

$$[T_{ANT}] = [T_{FIX}]^{-1}[T_{MEA}]. \qquad (12)$$

After de-embedding, we can convert the final T-parameters back to S-parameters [9]:

$$[S] = \begin{bmatrix} \frac{T_{21}}{T_{11}} & T_{22} - \frac{T_{12}T_{21}}{T_{11}} \\ \frac{1}{T_{11}} & -\frac{T_{12}}{T_{11}} \end{bmatrix}. \qquad (13)$$

Accurate impedance measurement can be achieved with the above procedures.

III. Measurement Setups

Dipole RFID antennas based on ALIEN H2 chip are used for simulation and measurements, as shown in figure 3. H2 chip's center working frequency is at 915MHz with input impedance of 13.9 - j143.6. The antenna is made of copper with thickness = 0.05mm on paper substrate (dielectric constant = 3.26, loss tangent = 0.27, thickness = 0.15mm).

The measurement is performed in an anechoic chamber, as shown in Fig.3. The probe table and bracket are made of thin wooden and plastics parts to minimize interference from the ambient environment. The test probe is made from two semi-rigid cables with ground shields soldered together. The other three cables shown in the figure are used for calibration of the test fixture in the open, short and load modes. The length of these cables, as well as the tips of these probes must be the same to reduce calibration error. Applying the AGILENT E5071C fixture simulator de-embedding function for each single-ended test port, the impact from the test fixture can be minimized.

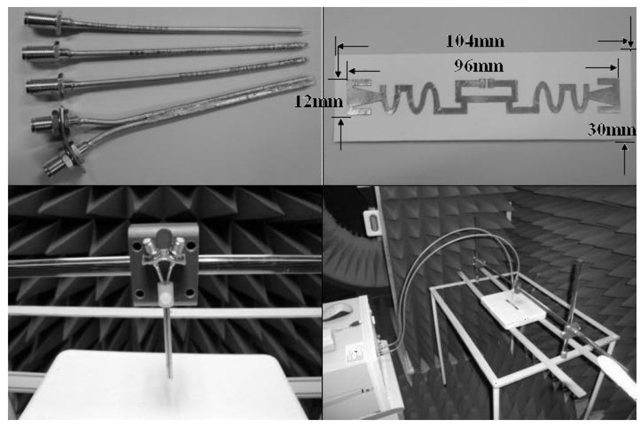

Fig. 3. Test fixture and measurement setup

IV. Simulation and Measured Results

Impedance measurements using the mixed S-parameters are performed. Both the port extension and test fixture de-embedding techniques are applied to remove the test fixture impact. The results are shown in Table 1. In order to demonstrate the measurement accuracy, HFSS simulation results are also listed in the table as references. Both the real and imaginary parts of the impedance are shown under five frequencies within the UHF band.

TABLE I
Measurement Deviation of Input Impedance

Frequency(GHz)	0.80	0.85	0.90	0.95	1.00
Simulation (Re)	2.808	5.571	13.25	36.16	60.25
Port Ext. (Re)	2.672	5.445	13.37	38.69	53.04
De-Emb. (Re)	2.139	5.396	13.87	39.63	53.89
Simulation (Im)	115.3	128.0	143.7	156.8	133.2
Port Ext. (Im)	118.3	130.0	144.0	152.9	124.1
De-Emb. (Im)	114.3	126.2	140.9	151.6	120.3

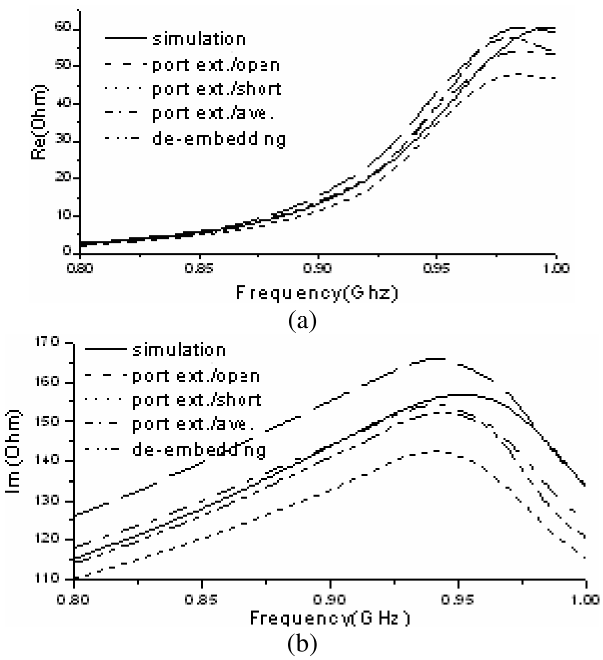

Fig. 4. Simulation and measured results. (a) Real part. (b) Imaginary part

V. Analysis and Discussion

As shown in table I and Fig. 4, impedance difference between the proposed method and HFSS simulation is smaller in the middle of the frequency span. It is because network analyzer has higher calibration accuracy in this range of frequency [10]. As shown in Fig. 1 and Fig. 2, the tips of probe terminal cause an equivalent shunt resistor and capacitor when the VNA carries out port extension in open mode. Effect of this equivalent shunt resistor and equivalent shunt capacitor can not be removed from measured result by port extension procedure. Similarly, an equivalent inductor and resistor in serial are formed when port extension is calibrated in short mode, and will cause deviations to measured results. A easy way to compensate the "tip effect" is to use the average of these two modes. The average results sometimes have higher accuracy than de-embedding method. Test fixture is characterized with SOL method. The tips of three separated probes shown in Fig. 3 are for open, shorted to ground modes respectively. They are all connected with two 100 Ohms SMD resistors to the ground. These modes are used to extract the S-parameters of the specific test fixture in the de-embedding process. Network analyzer itself may also induce additional measurement errors when it extracts a mixed mode S-parameters [11]. RFID dipole antennas are two-port symmetrical and differential network devices. The antennas are very sensitive to ambient environment, interferences and setups, etc. All these factors will contribute to the measurement errors.

VI. Conclusion

An accurate impedance measurement method for balanced RFID tag antennas is proposed and analyzed in this paper. The impedance is characterized based on mixed mode S-parameters. Impacts of the test fixture can be removed by port extension method or de-embedding method. Both techniques can achieve acceptable measured results. Relative differences compared with HFSS simulation, of both real part and imaginary part are lower than 5% in UHF frequency band. The proposed measurement techniques will expedite the design cycle for UHF RFID antennas.

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