Localization of Compact Circularly Polarized RFID Tag Using ToA Technique

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Abstract. *A compact, flexible crossed-dipole circularly polarized antenna using commercially available paper substrate is presented which caters North American frequency band. The crossed-dipoles have meandered lines for reduction of size as well as increased inductivity in the antenna. Dipoles have asymmetric T-shaped rectangular endings to provide the required compactness. Two semicircles are induced between the orthogonal dipoles and meandering matching structure to accomplish circular polarization excitation. Good impedance matching with the chip is achieved through a modified meander line matching structure. The proposed design dimensions are 32×32×0.4 mm^3. Systematic analysis revealed the results comprising circular polarization 3dB-AR bandwidth of 12 MHz (908–920 MHz) and power transmission coefficient bandwidth of 36 MHz (900–936 MHz). Time delay between interrogating signal and backscattered signal is measured and relative distance is calculated. Linear Least Square (LLS) method is applied to approximate the position of tag in interrogation area. The proposed tag is placed at known locations and its position is measured to analyze accuracy of the method by simulating the positioning algorithm code in MATLAB. Six valid tag positions 0.5–2 m read range and 0°–150° angular resolution has been investigated.*

Keywords

Circular polarized antenna, paper substrate, impedance matching, RFID, RFIC, time of arrival

1. Introduction

The deployment of passive Radio Frequency Identification (RFID) tags operating in the UHF band have shown an enormous increase recently, particularly in the fast moving consumer goods and logistics industry [1]. This staggering growth has lead to the replacement of barcodes with RFID tags, primarily due to their lower read time, better read-range, and the provision for multiple tags to be detected simultaneously. Passive RFID tag is one of the most significant components of the RFID system because the tag antenna parameters heavily influence the overall performance of the system, such as the overall size of the tag, its read-range, and its operability with the tagged object. At present, the majority of the RFID tags used commercially consist of linearly polarized antennas, mostly derived from dipole and microstrip patch antennas. Furthermore, RFID reader antennas are commonly designed as circularly polarized antennas to achieve minimum polarization loss and increased orientation diversity. On the contrary, linearly polarized antenna absorbs only half power of the transmitted signal due to the polarization mismatch, resulting in a considerable amount of reduction in the read range. Compared to linear polarization, circularly polarized tag antennas are theoretically proven to increase the read range of the tag by 41% [2]. Several circularly polarized tag antennas have been proposed based on planar dipole antennas [3], circular microstrip patch antennas [4], square patch antennas [2], and loop antennas [5]. However, these designs are large in size and incorporate multi-layered substrates that have a high dielectric value resulting in a bulky antenna.

RFID reader antenna transmits the interrogation signal towards the tag and the tag reflects it back in the form of backscattered signal. By some mathematical manipulation on the backscattered signal tag's locality in the reader area could be estimated. It opens vast applications for RFID technology to be used in daily life environment such as identifying and locating medicines in pharmacy, products in markets, books in the library, injured in a calamity, health care in hospitals, in cancer treatment [6], in the chipless RFID sensors localization [7], [8]. Different matrices such as Received Signal Strength (RSS), Angle of Arrival (AoA) and Time of Arrival (ToA) of the backscattered signal are used to locate the tags accurately. RSS is a low cost, less complex technique and that utilizes the attenuation in the strength of transmitted radio signal to estimate the location of the tag from the reader.

However, in practical scenarios, apart from distance, multipath effects and interference also cause attenuation. Several unpredicted points might lead to major estimation errors by recording of the similar RSS value [9]. More reference tags at static, and known positions are suggested to enhance the RSSI-based algorithms accuracy [10–13]. AoA based localization measures the angle with which the backscattered signal is received at the reader antennas and by applying triangulation method the position of the tag is estimated [14]. The limitations of AoA based techniques are line-of-sight and customized units required for modulation/demodulation of RF signal. In ToA-based localization technique, the time taken by the signal to travel from reader to tag is used to find out the distance between tag and reader [15], [16]. For this scheme to work well, all readers and tags are required to be strictly synchronized.

In this paper, a compact, planar circularly polarized antenna based on a flexible substrate is presented, and ToA based technique is applied to estimate its location in the interrogation area. The antenna design comprises of perpendicularly crossed dipoles with meandered arms, and T-shaped tip endings. Furthermore, a modified meandered T-match network is utilized to match the impedance of Radio Frequency Integrated Circuit (RFIC) to that of the antenna. To achieve circular polarization, a pair of semi-circles has been introduced between the dipole arms. Section 2 elaborates the antenna design whereas Sec. 3 describes the ToA localization technique. Finally, Sec. 4 presents a conclusion of the research study.

2. Antenna Design

The detailed geometric design of the proposed passive RFID tag, exhibiting circular polarization is shown in Fig. 1. A systematic approach is used to design the proposed antenna that elaborates in the flow chart as shown in Fig. 2. The tag antenna is designed for UHF North American (902–928 MHz) frequency band.

In Fig. 1, ‘r’ is the radius of the inner circle, ‘w_{sc}’ is the width of the semi-circle,‘L_m’ is the length of the meandering lines, ‘g_m’ is the gap between the meandering lines, ‘L_{r1}’ is the length of the outer rectangular end-tip loading, ‘W_{r1}’ is the width of the outer rectangular end-tip loading,‘L_{r2}’ is the length of the inner rectangular end-tip loading and ‘W_{r2}’ is the width of the inner rectangular end-tip loading.

The antenna consists of two perpendicularly-crossed dipole antennas with T-shaped endings introduced along the boundaries of the substrate. The arms of the dipole are meandered at the center to make the antenna more inductive as well as compact. A modified meandering T-match network is attached to the meandered arms of the dipole to achieve maximum power transfer between RFIC and the antenna. NXP IC with an impedance of 14 – j145 Ω at 915 MHz is used in the proposed design. The RFIC requires -15 dBm of wake-up power to activate itself. The input impedance of the

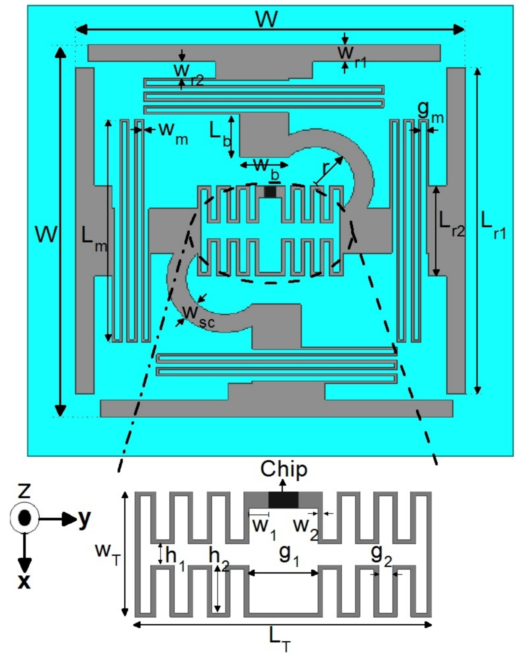

Fig. 1. Geometry of RFID CP tag antenna.

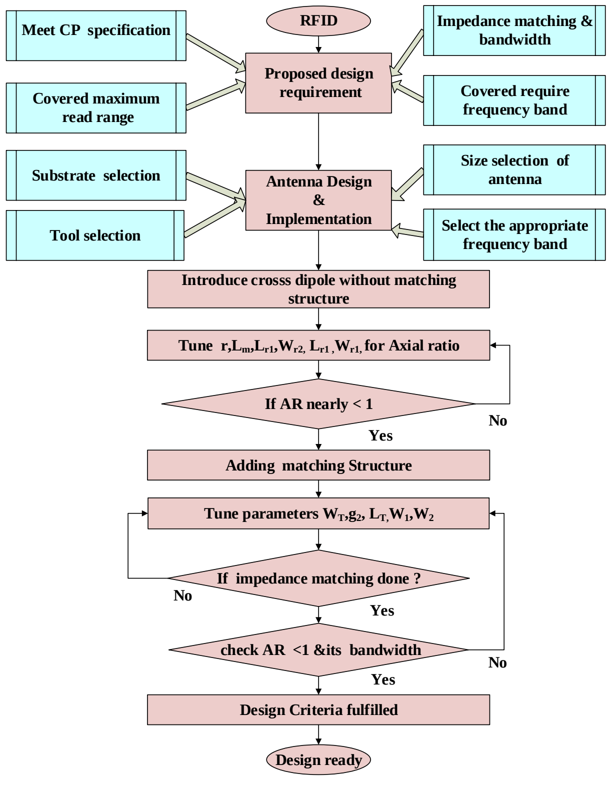

Fig. 2. Geometry of RFID CP tag antenna.

proposed antenna is chosen to be an exact conjugate to that of the chip impedance, i.e. 14 + j145 Ω. A pair of semi-circles is introduced between the perpendicularly-crossed dipoles to generate a 90° phase difference between the two equal field components. The development and investigation of the proposed antenna design is carried out using full-wave EM simulation tool HFSS. The optimized design parameters of the CP RFID antenna is given in Tab. 1.

Parameters	W	L_m	w_m	g_m	w_{sc}	r	L_{r1}
(mm)	32	19.8	0.2	0.4	1.6	3.2	29
Parameters	L_{r2}	w_{r1}	w_{r2}	L_b	w_b	L_T	W_T
(mm)	8	1.5	1.3	3.8	4	12	8
Parameters	h_1	h_2	w_1	w_2	g_1	g_2	
(mm)	1.4	3	0.4	0.3	1.8	0.5	

Tab. 1. Antenna structure dimension.

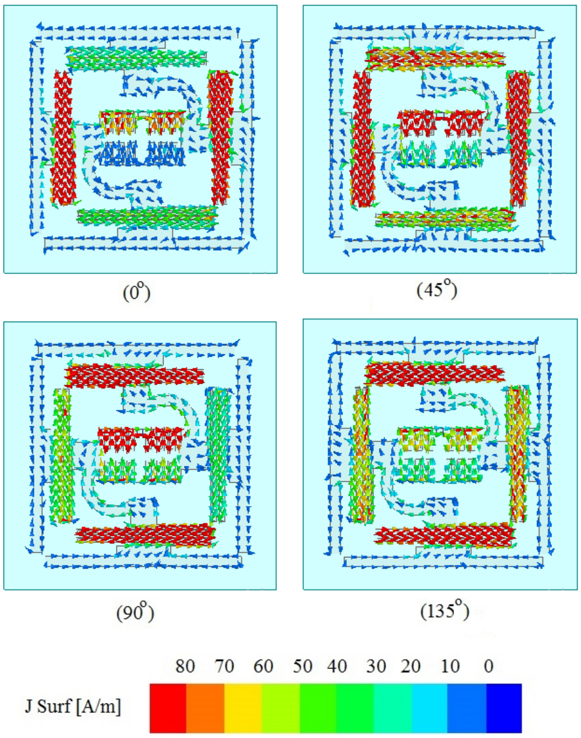

Fig. 3. Simulated current distribution of RFID tag at 915 MHz for two phases.

In order to achieve circularly polarized characteristics, aforementioned pair of semi-circles between perpendicularly-crossed dipole arms are used to tune the asymmetric dipoles. The tuning is configured at 915 MHz in such a way that the overlapping resonances having a phase difference of 90° are obtained. The simulated current distribution at 915 MHz is shown in Fig. 3, which illustrates the circularly polarized excitation of the antenna at phase angles of 0°, 45°, 90° and 135°. The figure shows a relatively high current density at a phase of 0° and 45° on the horizontal dipole. Similar trends of current distribution are also observed on the vertical dipole at a phase of 90° 135°. The asymmetric geometry of the antenna causes the current through T-match network to flow differently at 0° and 90° phases. Particularly, the currents flow from left to right in the horizontal dipole at 0° and 45° phase. The currents passing through the modified meandering T-match network get distributed into two paths with comparable phases and amplitudes. The currents flow from top to bottom in the vertical dipole at 90° and 135° phase. High amount of current flows through the top meandered line of T-match network. Whereas, a significant amount of current can also be observed in the bottom path of meandered line T-match, flowing in the opposite direction. Therefore, at phase 90°, the meandering line of T-match has a higher amount of current distribution than at phase 0°. Moreover, it can be seen that the current flow in the clockwise direction from phase 0°, 45°, 90° and 135° which implies that the tag antenna is left hand circularly polarized.

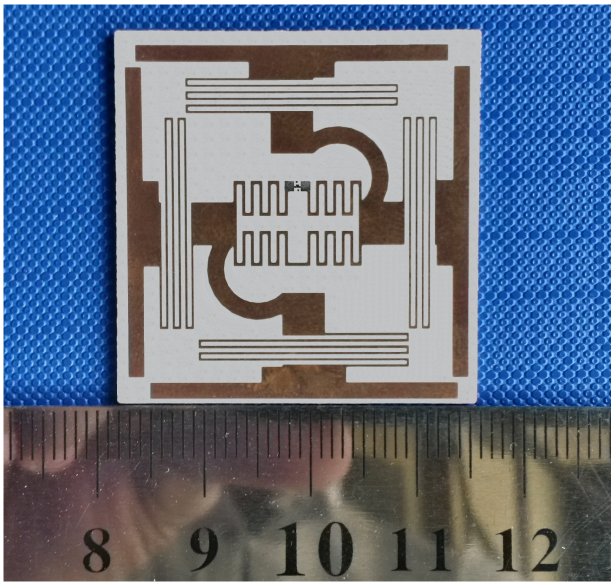

Fig. 4. Fabricated CP RFID tag antenna.

2.1 Characteristics of Antenna

The proposed circularly polarized RFID tag is printed on a commercially available HP photopaper using Fujifilm Dimatix DMP2800 with silver nano ink (Cabot CCI-330) as shown in Fig. 4. NXP chip is connected using CW4200 silver conductive epoxy and then cured for 4 hours to achieve maximum conductivity and adhesion. Soft soldering is avoided because it can damage the printed traces on the paper substrate. The characterization of the paper substrate and ink are also carried out [17].

The input impedance of the fabricated antenna is measured by two-port differential probe method as in [18]. The computed and measured input impedances of the proposed antenna are shown in Fig. 5 and Fig. 6. As it can be observed, the measured results are in good agreement with the computed results. Good conjugate matching between the input impedances of the antenna and the chip is achieved. The resistance and reactance components of the antenna were fairly close to those of the chip in the 900–930 MHz range.

These results also indicate that the antenna has a good impedance-matching bandwidth. This is validated in Fig. 7, which shows the computed and measured power transmission coefficients that were derived from computed and measured input impedances of the proposed antenna. The values are determined by using the following basic formulas as in [19]. The computed results yielded a power transmission coefficient bandwidth of 36 MHz (899–935 MHz) and measured results are 36 MHz from (900–936 MHz). Figure 8 depicts the plot of the axial ratio (AR) of the proposed tag. It can

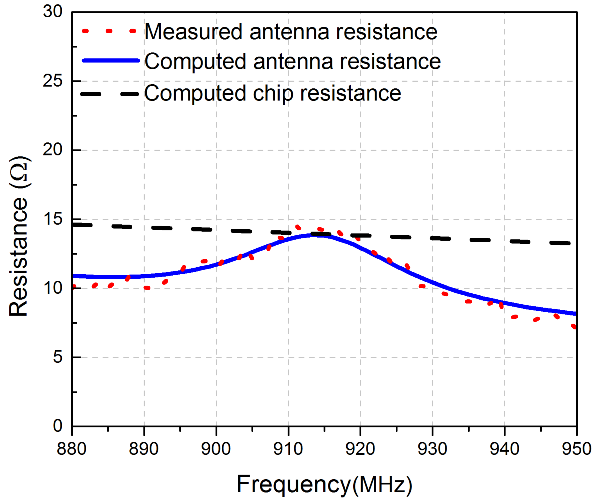

Fig. 5. Computed and measured resistance of the tag antenna.

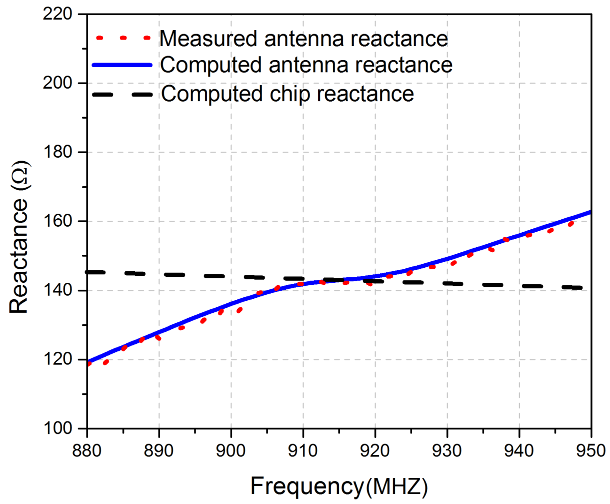

Fig. 6. Computed and measured reactance of the tag antenna.

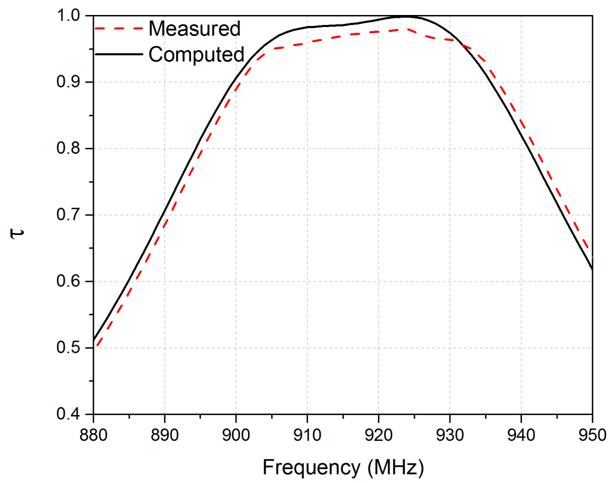

Fig. 7. Computed and measured power transmission coefficient of the tag antenna.

be observed that an axial ratio bandwidth of 12 MHz (908–920 MHz) has been successfully achieved in the proposed design [20].

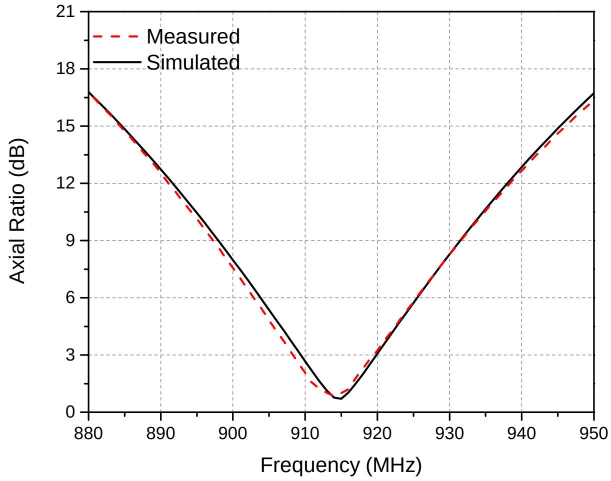

Fig. 8. Simulated and measured axial ratio of CP tag antenna.

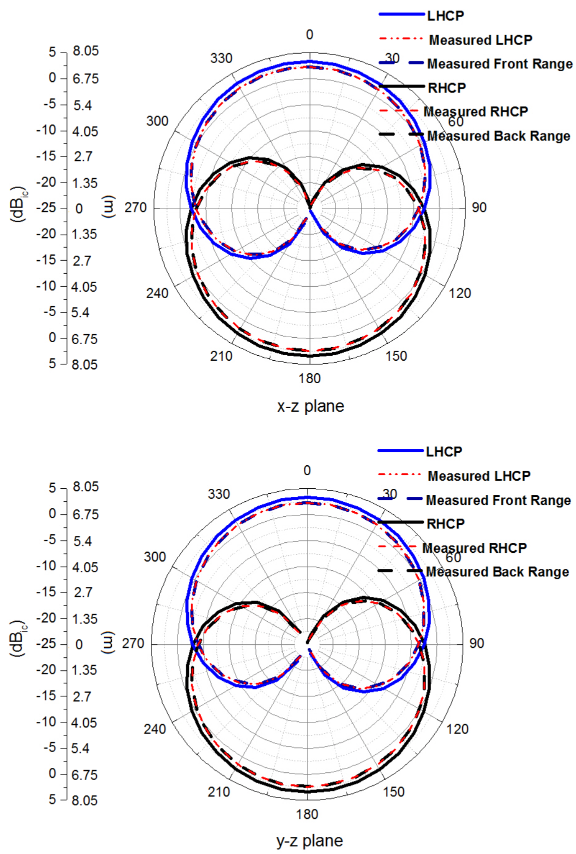

Fig. 9. Simulated and measured radiation pattern along with measured range.

Figure 9 shows the simulated and measured radiation pattern along with measured readrange that shows the proposed antenna has very good ciruclarly polarized radiation characteristics [21]. As the proposed antenna is not matched to 50 Ω therefore measurements of radiation characteristic can not be done using conventional anechoic chamber. The read range is verified using Impinj RFID reader Laird S9028PCL. The bore sight read range of the proposed circularly polarized tag antenna is 6.7 meters.

Antenna Size (mm^2)	Substrate	AR BW (MHz)	Band Coverage (MHz)	Range (m)
32×32 [pro.]	Paper	11	900-936	6.7
36.5×36.5 [22]	RO4003	11.4	892-929	7.6
60×60 [23]	FR4	20	897-934	1.52
80×80 [24]	FR4	6	896-927	3.13

Tab. 2. Comparison of different antenna parameters.

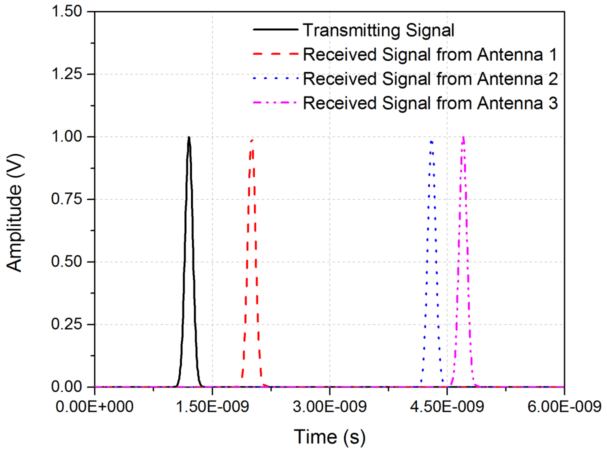

Fig. 10. Transmitted and received signals in time domain.

From Tab. 2, it is apparent that the proposed circularly polarized RFID tag antenna offers a smaller size as compared to CP antennas presented in [22–24]. The decrease in size has not effected the axial ratio bandwidth, north american band coverage and the read range. The additive advantage of the proposed design lies in the flexible substrate and the low cost printing of the tag.

3. Localization

In this section, a ToA based localization method for RFID tags has been described. This method extracts the Return Time Of Flight (RTOF) information by analyzing the backscattered signal in the time domain for localization. Three reader antennas are necessary for precise localization in a specified area. So, as the tag comes into the interrogation region, three signals are received at the reader. These signals are analyzed in the time domain for relative read range calculation. Once the relative read range calculation is done at the reader end, Linear Least Square (LLS) method is applied to estimate tag's location. This is done by the difference of locations estimated through proposed method. The whole procedure of localization mainly involves determining relative distance by extracting the RTOF information of the received signal and using these distance to estimate the location $P(r_t, \theta_t)$ of the tag in the interrogation area.

In ToA based localization technique, the delay between the transmitting and received signal are used to to find out the unknown location of the RFID tag in the interrogation region. A single case scenario is presented in Fig. 10, where the interrogation and three received signals are presented in the time domain. The interrogation signal is positioned at 1.18 ns, whereas the three received signals are placed at 2.13 ns, 4.25 ns and 4.75 ns according to the time stamped

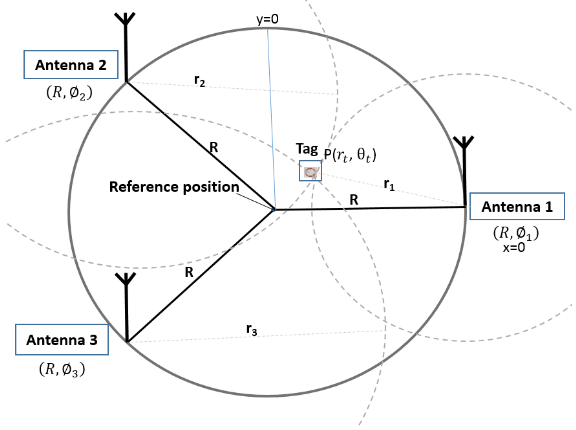

Fig. 11. Reader antenna's and tag positions in the interrogation region.

at the reader end. Three non-linear equations are applied to calculated the readrange of the tag and then LLS method is used to estimate the tag location. The relative distance between the reader and the tag is expressed by the following equations:

$$r_{xi} = \sqrt{(r_t \cos\theta_t - R\cos\phi_{xi})^2 + (r_t \sin\theta_t - R\sin\phi_{xi})^2}, \quad (1)$$

$$r_{xi}^2 = (r_t \cos\theta_t - R\cos\phi_{xi})^2 + (r_t \sin\theta_t - R\sin\phi_{xi})^2, \quad (2)$$

$$b_{xi,yj} = r_t \cos\theta_t(\cos\phi_{yj} - \cos\phi_{xi}) + r_t \sin\theta_t(\sin\phi_{yj} - \sin\phi_{xi}) \quad (3)$$

where

$$b_{xi,yj} = (1/2D)(r_{xi}^2 - r_{yj}^2) \quad (4)$$

Thus the linearized system of equations for 'n' number of receivers are

$$b_{n,yj} = (\cos\phi_{yj} - \cos\phi_n) r_t \cos\theta_t + (\sin\phi_{yj} - \sin\phi_n) r_t \sin\theta_t. \quad (5)$$

The matrix notation of these system equations are as follows [25]

$$\vec{b} = L\vec{r} \quad (6)$$

where

$$L = \begin{bmatrix} (\cos\phi_{yj} - \cos\phi_1) & (\sin\phi_{yj} - \sin\phi_1) \\ (\cos\phi_{yj} - \cos\phi_2) & (\sin\phi_{yj} - \sin\phi_2) \\ \vdots & \vdots \\ \vdots & \vdots \\ (\cos\phi_{yj} - \cos\phi_n) & (\sin\phi_{yj} - \sin\phi_n) \end{bmatrix}_{n\times 2}, \quad (7)$$

$$\vec{b} = \begin{bmatrix} b_{1yj} \\ b_{2yj} \\ \vdots \\ b_{nyj} \end{bmatrix}_{n\times 1}, \quad (8)$$

$$\vec{r} = \begin{bmatrix} r_t \cos\theta_t \\ r_t \sin\theta_t \end{bmatrix}_{n\times 1}. \quad (9)$$

θ_t	0°	40°	60°	100°	120°	150°
% error	7.3	8.1	8.7	9.3	7.9	8.4
r_t **(m)**	2	1.6	1.2	1.0	0.8	0.5
% error	10	10.4	11.3	12.5	13.0	12.7

Tab. 3. Position of the tag at different distances.

Here, **L** denotes already known readers static positions, $\overrightarrow{\mathbf{b}}$ can be calculated from (6) using r_{xi} and r_{yj} achieved, and the required tag position is obtained from $\overrightarrow{\mathbf{r}}$.

3.1 Localization Procedure

The test equipment is setup using three RFID Laird reader antennas at 120 degree apart from each other as shown in Fig. 11. The Impinj reader is used to communicate with the proposed tag present in interrogation area. From the tag response RTOF is extracted to approximate the distance between tag and reader antennas. To estimate tag's position $P(r_t, \theta_t)$, non-linear equations are solved and then LLS is applied to estimate the tag location. All mathematical formulation for tag localization is done in MATLAB. The tags are first placed at known positions and then tag position is estimated using localization method. The results of some of the tag's position and the percentage error are given in Tab. 3.

4. Conclusion

A compact cross-dipole RFID tag antenna has been designed, fabricated and tested. The formulated design offers a minuscule footprint of 32×32 mm^2 on a commercially available paper based substrate. A bandwidth of 36 MHz ranges from (900–936 MHz) is achieved with an axial ratio bandwidth of 12 MHz within the range of (908–920 MHz). A method for localization of the designed tag using ToA technique is also proposed. The proposed tag is a prime candidate for deployment in consumer goods, retail and logistic applications.

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