# Optimal Design of a RFID Tag Antenna Based on Plane-Wave Incidence

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**Abstract — In order to increase the detection range and radar cross section (RCS), the patch shape of a UHF RFID tag antenna is optimized using continuum design sensitivity analysis. To maximize RCS and reflect the practical RFID tag operating condition, the design goal is set considering not only the matching characteristics of the antenna but also the induced voltage at the RFID chip terminal when the plane-wave is incident upon the antenna. The complex impedance of the RFID chip is taken into account by defining a lumped port at the chip location. The design results show that the induced voltage at the chip has increased more than 24 % after the optimization.**

## I. Introduction

With the increasing use in manufacturing companies, supply chains, and retail stores, the demand for high performance and cheap RFID tag remains high. The performance of the tag antenna is usually assessed by the detection range. However, different RFID system companies have different detection sensitivity, which inevitably introduces undesirable uncertainty when detection range is used as performance criterion. One of the alternative, independent performance criteria for tag antennas is the radar cross section (RCS). The RCS is a measure of how much the target reflects the incident wave from the radar, and defined by the following equation,

$$\sigma(\theta,\varphi,\theta^{\text{inc}},\varphi^{\text{inc}}) = \lim_{r\to\infty} 4\pi r^2 \frac{\left|\mathbf{E}^{\text{sc}}(r,\theta,\varphi)\right|^2}{\left|\mathbf{E}^{\text{inc}}(\theta^{\text{inc}},\varphi^{\text{inc}})\right|^2}, \qquad (1)$$

where $\mathbf{E}^{\text{sc}}$ denote the scattered field observed in the direction $(\theta,\varphi)$ and $\mathbf{E}^{\text{inc}}$ denote the incident field from the direction $(\theta^{\text{inc}},\varphi^{\text{inc}})$. Since the radar is far away from the target, plane-wave incidence is assumed when RCS is calculated. Fighter planes are designed to minimize RCS from all radar wave directions. On the contrary, RFID tag should be designed to maximize the monostatic (backscatter) RCS where $\theta=\theta^{\text{inc}}$ and $\varphi=\varphi^{\text{inc}}$ to increase the detection range.

Until now, many researches have been done on the analysis of the RCS of the RFID tag antenna [1]-[3]. However, most of these works focused on the measurement and assessment, and a few works have been done on the optimal design of the tag antenna to increase RCS. Some of the previous works on the design of the patch antenna used stochastic optimization method such as evolution strategy and genetic algorithm to change simple size variables. Recently, the authors have proposed a new design optimization algorithm applicable in the RF domain. This algorithm is characterized by the decreased total computation time compared to stochastic methods, and by employment of the continuum design sensitivity analysis (CDSA) [4]-[6], which enables the use of the commercial EM software as an analysis module. So far, this method has been applied for 3-D shape design of a dielectric resonator in a waveguide filter [4] and a conducting post shape in the waveguide T-junction [5]. In this paper, a practical design of a RFID tag antenna is performed to maximize the backscatter RCS using the optimization method based on CDSA. The numerical implementation for the construction of the adjoint equation and calculating sensitivity values is thoroughly investigated.

## II. RFID Model Definition

Fig. 1 shows the polarization of the incident plane-wave and the layout of the RFID tag antenna model to be optimized. The model is EPC Gen2 UHF inlay "propeller" type antenna, and should have good matching between 860 – 960 MHz. The frequency of the incident plane-wave is set to 900 MHz, and its magnitude is normalized to 1 V/m for electric field. The design goal is to maximize the induced voltage between the RFID chip terminals which is located at the center of the tag when plane-wave is incident on the RFID tag. It can be assumed that when the RFID chip is driven by the maximum voltage, the output power of the antenna, scattered field, and thus RCS will also be maximized.

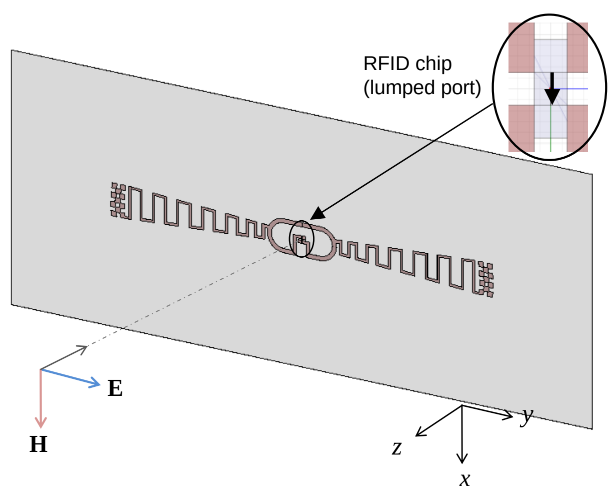


Fig. 1. Polarization of the incident plane-wave on the RFID tag antenna.

For the optimal design, CDSA and optimization modules were implemented by MS Excel spreadsheets with VB editor, and were combined with Ansoft HFSS analysis module [7]. Even though the plane-wave incidence is the only source of the primary system, a lumped port is defined at the location of the RFID chip for 2 reasons. First, complex impedance of the chip can be properly considered by setting the impedance of the lumped port. Second, for the adjoint system analysis required for CDSA, the adjoint source term is applied at the lumped port, which also defines an integration path for the electric field in the objective function. The optimization problem is mathematically defined as:

$$\text{maximize} \qquad F = \left| \int_{\Gamma_1} \mathbf{E} \cdot d\mathbf{\Gamma} \right|^2 \tag{2}$$

where $\Gamma_1$ is the integration path defined by the lumped port depicted in Fig. 1.

Fig. 2 shows the size design variables for the RFID antenna. Since the shape of the antenna wings should be symmetric, the design variables are defined in pairs on both wings of the antenna, and sensitivity for each pair is calculated by averaging the sensitivity values of both wings.

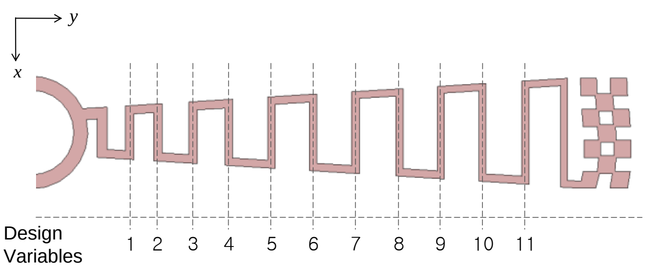


Fig. 2. Design variables for the RFID tag antenna.

## III. Sensitivity Analysis

Applying the CDSA procedure [4]-[6] to (2), the adjoint source term can be calculated from:

$$\frac{\partial F}{\partial \mathbf{E}_{real}} = 2l\left(\int_{\Gamma_1} \mathbf{E}_{real} \cdot d\mathbf{\Gamma}\right), \quad \frac{\partial F}{\partial \mathbf{E}_{imag}} = 2l\left(\int_{\Gamma_1} \mathbf{E}_{imag} \cdot d\mathbf{\Gamma}\right)$$

$$\frac{\partial F}{\partial \mathbf{E}} = \frac{1}{2}\left(\frac{\partial F}{\partial \mathbf{E}_{real}} - j\frac{\partial F}{\partial \mathbf{E}_{imag}}\right)$$

$$= l\left(\int_{\Gamma_1} \mathbf{E}_{real} \cdot d\mathbf{\Gamma} - j\int_{\Gamma_1} \mathbf{E}_{imag} \cdot d\mathbf{\Gamma}\right) = l\int_{\Gamma_1} \mathbf{E}^* \cdot d\mathbf{\Gamma} \tag{3}$$

where $l$ is the length of the lumped port $\Gamma_1$ and $\mathbf{E}^*$ denotes the complex conjugate of the electric field. Since the lumped port source in HFSS is normalized with respect to 1 W, the adjoint source given by (3) should also be normalized to 1 W.

The final sensitivity equation is given by [5],

$$\dot{F} = -\int_{\Gamma} (\gamma_e \mathrm{H}_t \lambda_t H) m_{\Gamma} d\Gamma \tag{4}$$

where $\gamma_e$ is a known parameter determined by the boundary condition on the patch conductor, $\mathrm{H}_t$ is the tangential component of the magnetic field from the primary (original) system, $\lambda_t$ is the tangential component of the magnetic field from the adjoint system, the function $m_{\Gamma}$ denotes parts of conductor patch boundary where the design variables are defined, and $H$ is the mean curvature of the boundaries defined by $m_{\Gamma}$.

## IV. Design Results and Discussion

Table I shows the change of the design variables and objective function before and after the optimization. For the design variables near the center (D1-D7), the changes are very small and can essentially be ignored. The meaningful change of the design variable happens near the outer part of the antenna (D8-D11), and the objective function has increased about 24.2 % after 19 iterations. Fig. 3 shows the modified shape of the tag antenna after the optimization.

TABLE I
Comparison of Design Variables and Objective Function

| Variables | D1 | D2 | D3 | D4 | D5 | D6 |
|---|---|---|---|---|---|---|
| Initial | 11.450 | 13.450 | 15.950 | 18.475 | 21.475 | 24.475 |
| Optimal | 11.448 | 13.448 | 15.946 | 18.469 | 21.471 | 24.449 |
| Variables | D7 | D8 | D9 | D10 | D11 | *F* |
| Initial | 27.475 | 30.500 | 33.500 | 36.500 | 39.500 | 0.98 |
| Optimal | 27.443 | 30.406 | 33.462 | 36.351 | 39.370 | 1.23 |

Design variables values (mm) are the *y* coordinate of the patch boundary shown in Fig. 2. *F* is the calculated value of the objective function defined in (2).

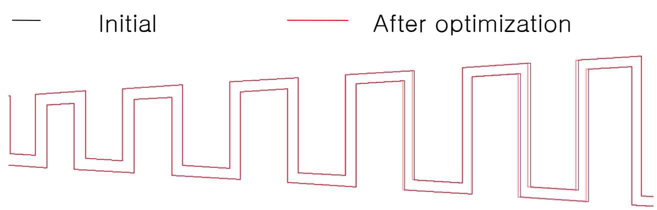


Fig. 3. The initial and optimized shape of the patch antenna.

In the extended paper, the objective function will be expanded to include the desired *S*-parameter profile, as well as the induced voltage at the lumped port, and multi-objective optimal design of the RFID tag antenna will be performed.

## V. References

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