Optimization of the Wheeler Cap Technique for Efficiency Measurement of RFID Antennas Matched to Complex Loads

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Abstract—This paper proposes an improved mathematical formulation of Johnston's approach to measure the radiation efficiency of an antenna, based on the Wheeler Cap (WC) technique. The proposed modifications allow the measurement of the radiation efficiency of small antennas matched to complex loads implemented on Radio Frequency IDentification (RFID) tags. The studied structure is a low-cost, silver-printed, differentially-fed RFID dipole antenna. The antenna is printed on a flexible PET (polyethylene terephthalate) paper that is conformable on various objects. Link budget measurements validate the accuracy of the formulation, which can be applied to any dipole antenna matched to an RFID chip with a complex input impedance.

1. INTRODUCTION

Inkjet printed antennas are those made up from conductive ink printed on substrates such as PET paper. Their practicality lies in their low cost, fast fabrication, and flexibility. Yet a major drawback is their efficiency. As conductive ink is printed from a printer ink nozzle in forms of drops, this yields a thin and nonuniform metallization layer and hinders the conductivity and efficiency. While the exact thickness and conductivity of the metallic layer can only be roughly estimated, the validity of the efficiency provided by electromagnetic simulators is uncertain. Therefore, it is crucial to develop a fast and accurate experimental method to estimate this efficiency.

On another note, inkjet antennas are used in RFID tags for many applications, especially in the medical field [1, 2]. In this case, tags are mounted on the human body, which has major dielectric losses. This significantly reduces the efficiency of the antennas and makes efficiency measurements noteworthy.

Several efficiency measurement techniques have been proposed in the literature for RFID antennas. For example, in [3], the authors use an array of electronically scanned probes in an anechoic chamber measurement system. Measurements of the realized gain, directivity, and power transmission coefficients are used to calculate the efficiency of an RFID tag dipole antenna in [4] while the extraction of the radiation efficiency from the measured actual gain, antenna gain, and tag read range is implemented in [5]. A reverberation chamber is used for efficiency measurements in [6]. The authors of [7] use the Wheeler Cap method as well as the loss method based on the method of moments. This proposed solution is tested theoretically and in simulation without practical measurements.

In this paper, we present an accurate procedure based on the Wheeler Cap method to specifically measure the efficiency of an inkjet printed antenna tailored for an RFID tag over a large frequency band. As RFID antennas are matched to complex chip impedances (and not to 50 Ω), adjustments of the original method are introduced for optimal results. In this context, two cases are presented, one calculating the efficiency by considering a real load and the other by including the load reactance into the antenna body and modifying its impedance.

The structure of the paper is organized as follows. Section 2 discusses different equations applied to the Wheeler Cap technique, followed by description of the antenna under study and the measurement procedure. Link budget measurements are then deliberated and compared to WC efficiency measurements. Efficiency simulations using Ansoft HFSS are finally presented.

2. REVIEW OF WC TECHNIQUES

In 1959, Wheeler described the radiansphere, whose radius is equal to $\lambda/2\pi$, as the boundary between the antenna's near field and far field [8]. A conducting cap at that radius prevents radiation without changing the near field and allows the efficiency calculation at the resonant frequency. Based on whether the antenna's impedance is modelled as a series or a parallel RLC circuit, the radiation efficiency can then be determined as follows [9]:

For a series RLC circuit:

$$\eta = \left(\frac{R_{\text{FS}} - R_{\text{WC}}}{R_{\text{FS}}} \right) \tag{1}$$

For a parallel RLC circuit:

$$\eta = \left(\frac{G_{\text{FS}} - G_{\text{WC}}}{G_{\text{FS}}} \right) \tag{2}$$

where R is the resistance; G is the conductance; FS and WC indicate whether the impedance measurement is performed in free-space or by adding the cap, respectively. Several modifications to the WC method are later presented to adjust for different antenna types and bandwidths [10, 11].

In [12], an improved WC method based on modeling the antenna as a high-order circuit model is introduced. The technique uses a genetic algorithm to find the values of the lumped elements comprising the circuit that includes transformers as well. After modeling, the circuit resistance is separated into loss resistance and radiation resistance to calculate the antenna's efficiency. The method uses Wheeler Cap method but requires more sophisticated modeling in order to be applied.

In [13], Schantz proposed an Ultra-Wide Band (UWB) WC to measure the radiation efficiency of UWB antennas. This method includes the mismatch reflected power as a loss term into the efficiency equation. By calculating the reflection coefficient Γ with or without WC, the radiation efficiency is deduced to be:

$$\eta = \sqrt{\left(1 - |\Gamma_{\text{FS}}|^2\right)\left(|\Gamma_{\text{WC}}|^2 - |\Gamma_{\text{FS}}|^2\right)} \tag{3}$$

In this UWB Wheeler Cap method, the antenna radiates freely and then receives its reflected signal. For that, the distance between the antenna tip and the cap walls should be much larger than $\lambda/2\pi$. This requires a much bigger cap size than Johnston's method (presented shortly), so this formulation will not be considered any further.

In [14], Johnston and McRory introduced the generalized Wheeler Cap method that makes it possible to calculate the efficiency of an antenna without assuming that it has a purely series equivalent circuit. Once the antenna reflection coefficients Γ_{FS} in free space and Γ_{WC} in the cap are measured, the efficiency can then be calculated as follows:

$$\eta = \frac{2}{(\Delta_{S,\max})^{-1} + (\Delta_{S,\min})^{-1}} \cdot \frac{1}{1 - |\Gamma_{\text{FS}}|^2} \tag{4}$$

where $\Delta_{S,\max} = \max\{|\Gamma_{11,\text{WC}} - \Gamma_{11,\text{FS}}|\}$ and $\Delta_{S,\min} = \min\{|\Gamma_{11,\text{WC}} - \Gamma_{11,\text{FS}}|\}$. In order to calculate these distances, the circle formed by Γ_{WC} in the complex plane range must be extrapolated from the measurements available in a limited frequency band.

3. RFID TAG ANTENNA DESIGN

A loop matched dipole, originally designed in [15], is realized using silver nanoparticle ink printed on a PET paper provided by [16]. The antenna is matched at 900 MHz to the Impinj Monza 5 [17] RFID chip whose input impedance is modelled as $1.8\,\text{k}\Omega//1.07\,\text{pF}$. Fig. 1 shows the antenna designed
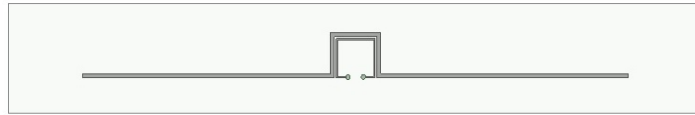
Figure 1. Inkjet printed antenna designed in HFSS.

in HFSS having dimensions $140\,\text{mm} * 15\,\text{mm}$. To measure the differential impedance of the antenna, it is connected to two ports of the network analyzer using two coaxial cables acting as a differential port [18]. The antenna impedance is then extracted from the S matrix, using the following differential probe equation [19]:

$$Z_{ant} = 2Z_0 \frac{(1 - S_{12})(1 - S_{21}) - S_{11}S_{22}}{(1 - S_{11})(1 - S_{22}) - S_{12}S_{21}} \tag{5}$$

with Z_0 being the characteristic impedance ($50\,\Omega$) of the feeding coaxial cables. Once Z_{ant} is obtained, the corresponding reflection coefficient normalized to the chip impedance is calculated and used in Eq. (3) or (4) to get the radiation efficiency.

4. DETERMINATION OF THE REFERENCE EFFICIENCY USING THE EXPERIMENTAL LINK BUDGET

The link budget measurements were performed in an anechoic chamber with a patch antenna acting as a receiver and a half-wavelength copper wire dipole or the inkjet printed antenna acting as transmitting antenna, one at a time. The difference between the power received by the patch antenna when the wire dipole transmits and the power received by the patch antenna when the inkjet printed antenna transmits reflects the gain difference ΔG between the two antennas. ΔG is also given by:

$$\Delta G = \eta_d + D_d + 10 * \log\left((1 - |\Gamma_d|^2)/(1 - |\Gamma_t|^2)\right) - \eta_t - D_t \tag{6}$$

where η_d, D_d, and Γ_d are the simulated efficiency ($\approx 100\%$ over the frequency band), simulated directivity, and measured reflection coefficient of the wire dipole. η_t, D_t and Γ_t are respectively the unknown efficiency, simulated directivity, and measured reflection coefficient of the inkjet printed antenna. After calculating ΔG, η_t is determined based on Eq. (6).

5. WC DIMENSIONS

While the shape of the cap can be altered according to the antenna's type and shape [20], the cap dimensions have to respect two conditions: 1/cap radius greater than $\lambda/2\pi$, and 2/lowest cut-off
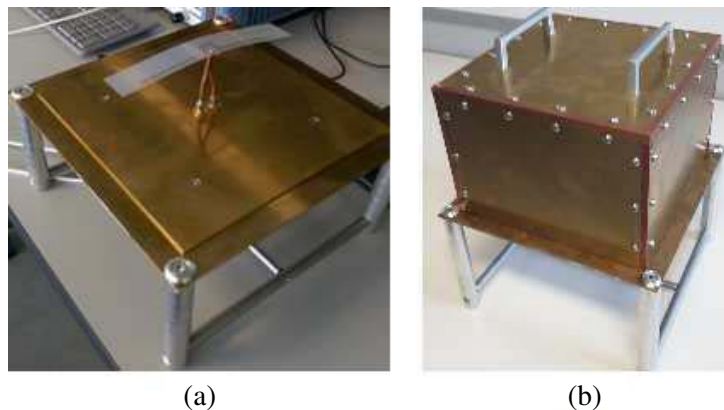

(a)   (b)

Figure 2. (a) Printed antenna with differential port, connected to the WC base, (b) WC with top cover.

frequency of the cavity modes greater than the antenna's resonant frequency. The WC designed for this work is rectangular, made of copper plates having dimensions of $220 * 220 * 150 \, \text{mm}^3$, with $150 \, \text{mm}$ being the caps height (Fig. 2). When being simulated in HFSS, the lowest cavity mode was at $963 \, \text{MHz}$, which is higher than the UHF RFID band (860–$960 \, \text{MHz}$), the working frequency $900 \, \text{MHz}$ being roughly in the middle of this band.

6. EXPERIMENTAL ESTIMATION OF THE RADIATION EFFICIENCY

The differential feeding port at the WC base is connected to the inkjet printed antenna as shown in Fig. 2(a). The base is then covered to form a rectangular box Fig. 2(b), and the S-parameters are measured in the WC. The measured antenna impedance $Z_{ant} = R_{ant} + jX_{ant}$, based on Eq. (5) is plotted in Fig. 3. For the resonant frequency $900 \, \text{MHz}$, $Z_{ant} = 57 \, \Omega + j182 \, \Omega$.
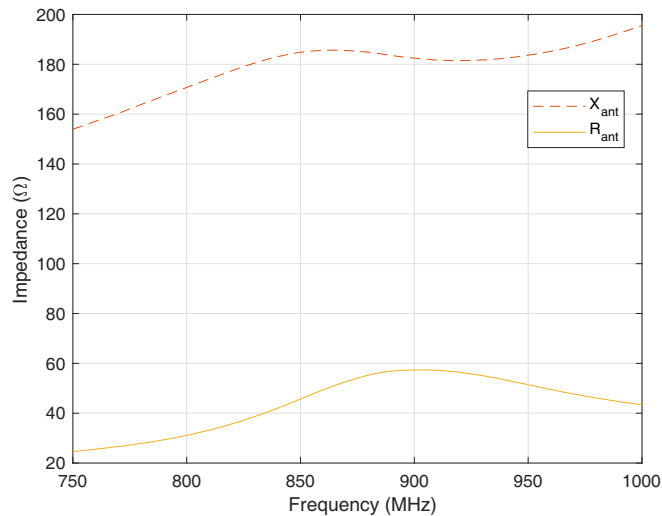

Figure 3. Measured differential impedance of the inkjet printed antenna.

A Matlab code is used to calculate the efficiency using Johnston's method as follows. First, the WC reflection coefficient points are plotted, and a curve fitting code is used to generate the circle shown in Fig. 4. The Γ_{FS} curve with respect to frequency is also plotted, and for every frequency point, the minimum and maximum distances to the circle are then measured. These distances are the $\Delta_{S,\text{min}}$ and $\Delta_{S,\text{max}}$ used to calculate the efficiency in Eq. (4).

Figure 4 shows Γ_{FS} and Γ_{WC} plots drawn for case 1, where the load impedance is chosen to be $Z_L = 50 \, \Omega$ which is the default coaxial cable impedance. It can be observed that the Γ_{FS} curve overlaps a portion of the Γ_{WC} circle.

In case 2, the RFID chip reactance jX_{chip} is included in the antenna body leading to a modified antenna impedance $Z'_{ant} = Z_{ant} + jX_{chip}$.

The chip reactance balances the antenna's reactance over the bandwidth. As observed in Fig. 5, it results in: 1/a rotation of the Γ_{FS} locus and 2/a clear separation between Γ_{FS} and Γ_{WC} curves. It is important to mention that when a pure reactance is added to an antenna, the efficiency of the original and modified antenna should be identical as no losses are added to the structure.

Efficiency calculated using Eq. (4) is plotted in Fig. 6 for case 1 and case 2. Efficiency measured using the link budget method is also illustrated as a reference. The three plots are in very good agreement over the frequency band of interest, showing the effectiveness of Johnston's method to find the efficiency of differentially-fed lossy antennas. However, the efficiency curve in case 2 shows much less ripples at lower frequencies than in case 1 and is closer to the link budget curve. This is due to the reactive part of the load added to the antenna impedance which prevents close to zero values of $\Delta_{S,\text{min}}$ in Eq. (4) and uncertainties on the numerical end result.
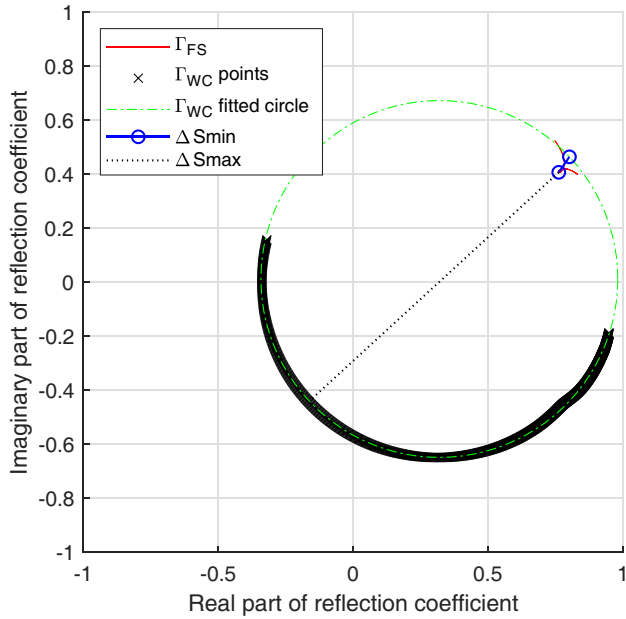
Figure 4. Reflection coefficient of the antenna in free space (Γ_{FS}) and Wheeler Cap (Γ_{WC}) with respect to $50\,\Omega$ reference (case 1).
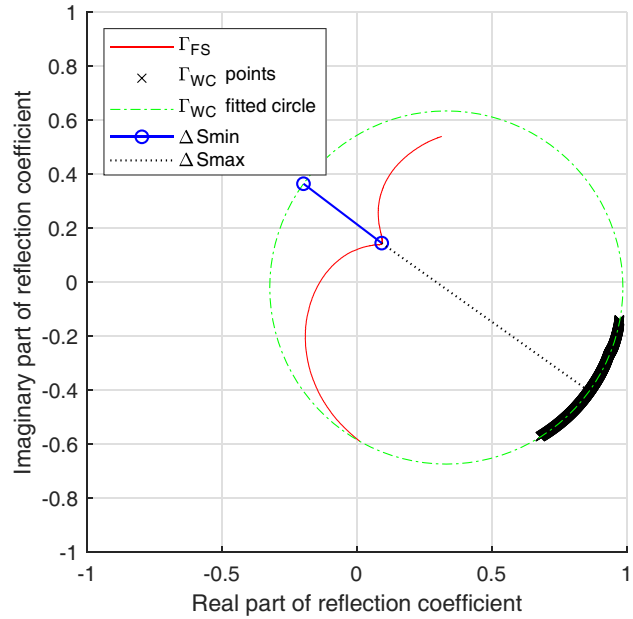

Figure 5. Reflection coefficient of the antenna in free space (Γ_{FS}) and Wheeler Cap (Γ_{WC}) with respect to complex load (case 2).
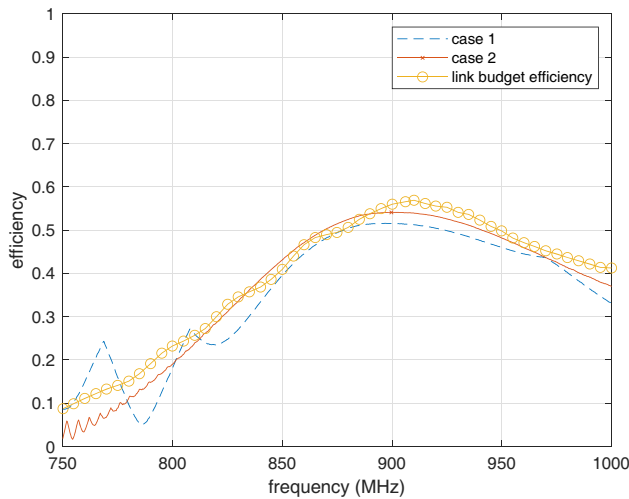

Figure 6. Measured efficiency of the inkjet printed antenna using link budget method and Johnston's equation for real load (case 1) and complex load (case 2).
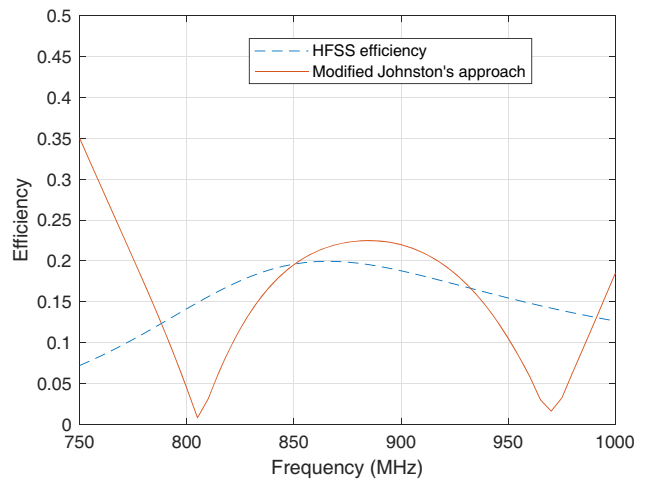

Figure 7. Simulated efficiency of the inkjet printed antenna using 1/the default method in HFSS and 2/the modified Johnston's equation using a numerical model of the Wheeler Cap.

7. SIMULATED RADIATION EFFICIENCY

For the sake of completeness of the work, the antenna's efficiency was simulated in HFSS. The silver ink was modeled as having a conductivity of 1.46×10^7 and a thickness of $0.2\,\mu$m. The PET paper was simulated with thickness of $0.135\,$mm and relative permittivity of 6.5 [15]. Initially, the antenna was simulated in free space to find S parameters and the efficiency calculated by HFSS, shown in Fig. 7. The antenna was then placed inside a Wheeler Cap model to extract the WC S parameters. Our proposed

modified Johnstons method was then applied to calculate the simulated radiation efficiency shown on the same graph. The plots show that the modified approach gave radiation efficiency values close to the values calculated by HFSS.

However, the measured maximum radiation efficiency is much higher than the simulated values (around 50% versus 23%) while the frequency variation is very similar. This difference results from the uncertainty in the estimation of the conductivity and thickness of the inks with the available manufacturing and measurement means. This result demonstrates the usefulness of effective methodologies for measuring radiation efficiency, when all design parameters are not perfectly known, and limits confidence in the simulation results.

8. CONCLUSION

Efficiency measurements using WC-based method are performed on a loop matched dipole antenna printed using low cost silver ink on PET paper. This antenna is canonical but representative of the diversity of UHF RFID tag antenna designs, which are matched to complex loads. Based on the comparison of measured (link budget) efficiencies, it is demonstrated that with some mathematical modifications, Johnston's equation is fully applicable to low efficiency differentially-fed antennas matched to complex impedances, i.e., most UHF RFID tags. This has also been verified in simulations.

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