Comparison of T-matched and Double T-matched Short Dipole Tag Antennas for UHF RFID Systems

Toni Björninen 1, Leena Ukkonen 1, Atef Z. Elsherbeni 2, and Lauri Sydänheimo 1

1 Department of Electronics, Rauma Research Unit
Tampere University of Technology, Rauma, FI-26100, Finland
toni.bjorninen@tut.fi, leena.ukkonen@tut.fi, lauri.sydanheimo@tut.fi

2 Department of Electrical Engineering
The University of Mississippi, University, MS 38677-1848, USA
atef@olemiss.edu

Abstract: The impact of impedance uncertainties to the power transfer between complex source and load impedances is investigated. An exact lower bound for the power transmission coefficient under given source and load uncertainties is derived. Presented analysis is applied in design verification of T- and double T-matched short dipole tag antennas for UHF RFID systems and the performance of these two tag antennas is compared.

Keywords: Passive UHF RFID, Tag Antenna, Impedance Matching, T-matching, Double T-matching

1. Introduction

In radio frequency identification (RFID) systems, electromagnetic interaction between a reader and electronic labels, designated as RFID tags, is employed to identify objects. In far field RFID systems, where the mechanism of the interaction is wave propagation within frequencies from 865 MHz to 955 MHz, depending on the local frequency regulations, the RFID tags are antennas loaded with a microchip. Passive RFID tags, which are studied in this article, scavenge energy for their operation from the incident electromagnetic wave sent by the reader. In addition to capturing energy with on-chip rectification, the tag chip stores a unique identification code to label the tagged object, demodulates commands from the reader and creates a response to the reader’s queries. A response from the tag is realized by switching the tag chip impedance between two values while the reader illuminates the tag with a single-frequency electromagnetic field. As a result the tag’s response is modulated in the scattered field of the tag antenna [1].

As the passive RFID tags are not equipped with an energy source, maximizing the power delivery from the tag antenna to the tag chip is often the principal goal in tag design. However, the boundary conditions for the design are stringent. For a globally operable tag, good conjugate matching is required over a broad 10% fractional bandwidth, while compact and low-profile structures are required for seamless integration to objects. As the tag antennas also need to be efficient radiators for successful communication with the reader, small antenna features need to be considered in the design as well. Most commonly the conjugate impedance matching between the tag antenna and the tag chip is arranged by designing the tag antenna geometry so that an appropriate input impedance is achieved together with the desired radiation characteristics. This results in cost savings, since additional discrete components are not needed for impedance matching and the tag manufacturing
process is simplified. Dipole antennas benefit from being structurally simple radiators with omnidirectional radiation pattern and clever size reduction and impedance matching techniques for them have been investigated in general context [2-3] as well as for RFID applications [4-5]. In the present study, power delivery from the tag antenna to the tag chip under given impedance uncertainties is investigated. The developed analysis is applied in tag antenna design verification and performance of two tag antennas with different impedance matching schemes is compared.

2. Tag Antenna Impedance Matching and Sensitivity of the Power Transfer to Impedance Uncertainties

Power delivery between the tag antenna and the tag chip can be analyzed by considering two complex impedances connected with a transmission line with negligible electrical length. In this case, the ratio of power available from the tag antenna \( P_{\text{tag}} \) and the power reflected back \( P_{\text{rfl}} \) from the antenna-chip interface due to impedance mismatch is given by [6]

\[
P_{\text{rfl}} = \frac{Z_{\text{ic}} - Z_a^*}{Z_{\text{ic}} + Z_a^*}
\]

where \( Z_a = R_a + jX_a \) and \( Z_{\text{ic}} = R_{\text{ic}} + jX_{\text{ic}} \) are the tag antenna and tag chip impedances, respectively and \((\cdot)^*\) denotes complex conjugation. The delivered power to the tag chip is the difference \( P_{\text{ic}} = P_{\text{tag}} - P_{\text{rfl}} \) and with the help of equation (1), the power transmission coefficient \( \tau \) between the tag antenna and tag chip can be written as

\[
\tau = \frac{P_{\text{ic}}}{P_{\text{tag}}} = 1 - \frac{P_{\text{rfl}}}{P_{\text{tag}}} = \frac{4R_a R_{\text{ic}}}{|Z_a + Z_{\text{ic}}|^2}.
\]

In practice neither the tag antenna nor the tag chip impedance is known exactly and therefore it is interesting to evaluate the minimum power transmission coefficient while assuming the tag antenna and the tag chip impedances to lie in the neighborhood of their nominal values \( Z_{a0} = R_{a0} + jX_{a0} \) and \( Z_{\text{ic0}} = R_{\text{ic0}} + jX_{\text{ic0}} \), respectively.

For the purposes of analysis, let \( D = \{(x, y) \in R^2 : x > 0, y \in R \} \)

\[
\Lambda_{pq} = \{(x, y) \in D : |R_{a0} - x| \leq pR_{a0}, |X_{a0} - y| \leq qX_{a0} \}
\]

and \( \Lambda_{rs} = \{(x, y) \in D : |R_{\text{ic0}} - x| \leq rR_{\text{ic0}}, |X_{\text{ic0}} - y| \leq sX_{\text{ic0}} \} \)

with \( 0 < r, p < 1 \) and \( 0 < q, s \). The set \( D \) defined in equation (3) is the positive half plane containing all impedance values with positive resistance. Sets \( \Lambda_{pq} \) and \( \Lambda_{rs} \) define uncertainty rectangles around the nominal tag chip and tag antenna impedances, respectively, according to the parameter pairs \((p, q)\) and \((r, s)\). The parameters \( r, p \) define the percentage tolerances for \( R_a \) and \( R_{\text{ic}} \), respectively and similarly the parameters \( s \) and \( q \) define the percentage tolerances for \( X_a \) and \( X_{\text{ic}} \), respectively.

Considering \( \tau \) as a function of the tag chip impedance and calculating the directional derivative \( D_u \tau \) at a point \((R_{\text{ic}}, X_{\text{ic}})\) along vector \( u \) pointing from \((R_{a0}, -X_{a0})\) to \((R_{\text{ic0}}, X_{\text{ic0}})\), one finds that

\[
D_u \tau = \frac{4R_a (R_a + R_{\text{ic}})(R_a - R_{\text{ic}})^2 + (X_a + X_{\text{ic}})^2}{(R_a + R_{\text{ic}})^2 + (X_a + X_{\text{ic}})^2}.
\]

which implies

\[
D_u \tau < 0, \quad \forall (R_{\text{ic}}, X_{\text{ic}}) \in D \setminus [(R_{a0}, -X_{a0})].
\]

Based on equation (5), as a function of the tag chip impedance, \( \tau \) is strictly decreasing at any point in \( D \) towards
the direction away from the point \((R_a, -X_a)\). The point \((R_a, -X_a)\) corresponds to perfect conjugate matching and at this point \(\tau\) attains its maximum value \(\tau = 1\). Equation (5) implies that, this maximum is also unique within \(D\), as expected.

Starting from equation (2), one can show that the load impedances corresponding to a constant \(\tau\) define a circle with center point \(P(\tau)\) and radius \(r(\tau)\) given by

\[
P(\tau) = \left( R_a, \frac{2 - \tau}{\tau}, -X_a \right) \quad \text{and} \quad r(\tau) = 2R_a \sqrt{1 - \tau}.
\]

This circle always encloses the point \((R_a, -X_a)\), where \(\tau\) is maximized. As known from the plane geometry, a rectangle can always be enclosed in a circle touching one of its corners and therefore, particularly the rectangle \(\Lambda_{pq}\) defined in equation (3) can always be enclosed in a constant-\(\tau\) circle touching one of its corners. Let \((R_{pq}, X_{pq})\) be the tag chip impedance corresponding to this corner. Since the point \((R_a, -X_a)\) is enclosed in all constant-\(\tau\) circles and at this point \(\tau\) attains its unique maximum within \(D\), equation (5) implies that at any point in \(\Lambda_{pq}\), except for \((R_{pq}, X_{pq})\), it holds that \(\tau > \tau(R_{pq}, X_{pq})\). Therefore, the minimum value of \(\tau\) in \(\Lambda_{pq}\) is always attained at a corner of the rectangle \(\Lambda_{pq}\) as illustrated in Fig. 1.

![Fig. 1. Constant power transmission coefficient circle enclosing the uncertainty rectangle \(\Lambda_{pq}\) in tag chip impedance plane.](image)

As seen from equation (2), the expression of \(\tau\) is symmetric with respect to pairs \((R_a, X_a)\) and \((R_{ic}, X_{ic})\). Therefore all the above conclusions about \(\tau\) as a function of the tag chip impedance are valid if \(\tau\) is considered as a function of the tag antenna impedance. From this observation it follows that in general, considering \(\tau\) simultaneous as a function of both tag antenna and tag chip impedances, in the hyper rectangle \(\Lambda_{pq} \times \Lambda_{rs}\) it holds that

\[
\tau(R_{pq}, X_{pq}) \geq \tau(R_{rs}, X_{rs}, R_{pq}, X_{pq}) \geq \tau(R_{rs}, X_{rs}, R_{pq}, X_{pq}),
\]

where \((R_{pq}, X_{pq})\) is a corner of \(\Lambda_{pq}\) and \((R_{rs}, X_{rs})\) is a corner of \(\Lambda_{rs}\). Obviously the lower bound of \(\tau\) from equation (7) is also attained at one of the corners of the hyper rectangle \(\Lambda_{pq} \times \Lambda_{rs}\) and thus it must be the minimum value of \(\tau\) in \(\Lambda_{pq} \times \Lambda_{rs}\). This allows calculation of the exact lower bound of the power transmission coefficient according to the expected uncertainties related to the tag antenna and tag chip impedances. Numerical value is obtained as the minimum of \(\tau\) evaluated at the 16 corners of the hyper rectangle, which is spanned by the uncertainty rectangles of the tag antenna and tag chip impedances. Compared with a direct numerical search through a four dimensional search grid, much less computations are needed.

### 3. Tag Designs and Simulation Results

The frontend circuitry of an RFID tag chip is composed of capacitors, diodes and semiconductor switches, making the input impedance of the IC capacitive, as well as frequency and power dependent [7-8]. On the other
hand, the input impedance of a short dipole tag antenna, operating below the fundamental resonance frequency of the antenna, is capacitive and needs to be transformed to inductive in order to conjugate match the tag antenna with the tag chip. This can be done using the embedded T-matching [4], which in practice is realized by shorting the antenna terminals near the tag chip. The input reactance of a fixed-length T-matched antenna is then controlled by the size of the shorting loop. An alternative to T-matching is double T-matching [5], which can be arranged by using two shorting loops instead of one. The main advantage of this approach is that it allows a small dip to be tailored in the antenna reactance versus frequency curve to reduce its total variation over a certain frequency range. Compared with the T-matching, significant increase in the operable bandwidth of the tag can be achieved by utilizing the local reactance dip in the tag antenna impedance to arrange a dual resonance type matching with the tag chip. This has also been reported in [5], where modified double T-matching is studied.

The experimental part of this study compares the performance of T-matched and double T-matched quarter wave dipole tag antennas with the same foot-print size and very similar radiating geometry. The structure of these tags is described in Fig. 2. Substrate material for the antenna designs is Rogers RT/duroid 5880 with thickness of 3.175 mm, relative permittivity 2.2 and loss tangent 0.0009. This material was chosen due to its well-known microwave properties, which reduces the design uncertainties. For tag antenna designs aimed for mass markets, thin low cost plastic films are preferred as substrate.

Ansoft high frequency structure simulator (HFSS) was employed in the antenna design. The design goal for the T-Tag was good matching at centre frequency of the US RFID band at 915 MHz. For the DT-Tag the design goal was good matching at the European and Japanese RFID bands, centered at 866.6 MHz and 954.2 MHz, respectively, while maintaining a reasonable 50% power transfer between the tag antenna and the tag chip in the US RFID frequencies.

The shape of the meandered dipole arms, described with parameters $H$, $T$, $q_1$ and $q_2$ and $u_1$ and $u_2$ was first chosen in such a way that the fundamental resonance of the tag antennas with lengths $L_1$ and $L_2$ set to 80 mm occurred slightly above 1 GHz. In this way, a gradual reactance slope favorable for the design was achieved over the frequencies of interest. After this initial step, DT-Tag was optimized according to the above-mentioned design goal, by varying the parameters $L_2$, $h_2$ and $s_2$. The parameter $L_1$ was then set equal to $L_2$, in order to achieve exactly the same antenna foot print size for both tags and thereby enable fair comparison between them. Finally, the parameters $h_2$ and $s_2$ were optimized according to the above-mentioned design goal. The built-in genetic optimizer of HFSS was used in the design.

The tag chip used in both tag designs is the Higgs-3 UHF RFID IC by Alien Technology with input impedance at the chip sensitivity level obtained in [9]. The optimized tag antenna impedances, the tag chip impedance and corresponding power transmission coefficient between the tag antenna and the tag chip are presented in Fig. 3. The exact lower bounds based on the analysis presented in Section 1 are included in Fig. 3, using one standard deviation uncertainty for the tag chip impedance, based on results reported in [9], together with 0%, 5%, and 10% uncertainties for the simulated antenna impedance. The gain of DT-Tag in the direction of positive z-axis in Fig. 2, which will be referred to as forward direction, was found to remain approximately constant; $G_{fwd} \approx 1.6$ dBi over the frequencies of interest and for T-Tag this value decreases linearly from $G_{fwd} \approx 1.5$ dBi at 860 MHz to $G_{fwd} \approx 0.7$ dBi at 960 MHz.
4. Measurement Results and Discussion

The transmitted threshold power, i.e. the minimum transmitted continuous wave power sufficient to enable the tag under test to send a valid response to EPC Gen 2 protocol’s query command, was measured in the forward direction in a compact anechoic cabinet with a linearly polarized transmitter antenna. The measurement was carried out with Tagformance measurement device [10], which is a measurement unit for RFID tag performance characterization. It allows power ramping at a defined frequency and thereby threshold power analysis. The core operations of the device are performed with a vector signal analyzer.

Using the measured transmitted threshold power ($P_{th}$), the theoretical read range ($d_{tag}$) in empty space was calculated assuming the European effective radiated power regulation ($P_{ERP} = 2\ W$). In the calculation, the measured path loss ($L_{fwd}$) from the output port of the transmitter to the tag’s location, provided by the calibration procedure of the measurement device, was used.

For comparison between the measurements and simulations, the theoretical read range can be calculated using the simulated power transmission coefficient, tag antenna gain in the forward direction ($G_{fwd}$), and the tag chip sensitivity ($P_{C,0} = -18\ \text{dBm}$) provided by the manufacturer. With these definitions, the measured and simulated theoretical read ranges are

\[
d_{\text{tag}}^m = \frac{\lambda}{4\pi} \sqrt{\frac{1.64 \cdot P_{ERP}}{L_{fwd}P_{th}}}
\]

and

\[
d_{\text{tag}}^s = \frac{\lambda}{4\pi} \sqrt{\frac{G_{fwd} \cdot 1.64 \cdot P_{ERP}}{P_{C,0}}},
\]

respectively. Comparison of these read ranges is shown in Fig. 4.

Fig. 4. Theoretical read range of T-Tag (left) and DT-Tag (right) in the forward direction.
Simulation results, in Fig. 3, predict good reactance matching for the DT-Tag at both ends of the studied frequency range while the tag antenna gain was observed to remain approximately constant. This agrees with the measured frequency response, shown in Fig. 4, with peak performance at the edges of the measured frequency range and slightly weaker performance in the middle. The simulated reactance of the T-Tag, shown in Fig. 3, increases monotonically through the studied frequencies and good conjugate impedance matching is achieved around 915 MHz. This agrees with the measured frequency response, shown in Fig. 4. Simulations also predict a decreasing slope in the tag antenna gain versus frequency, which agrees with the measured frequency response as well; the performance decays faster towards the higher end of the measured frequency range. In addition, both tag antenna designs are verified within 5% impedance tolerances through majority of the studied frequency points. This provides further assurance to the performance comparison between the designs.

5. Conclusions

The impact of impedance uncertainties to the power transfer between the tag antenna and tag chip impedances was investigated and an exact lower bound for the power transmission coefficient under given impedance uncertainties was obtained. The presented analysis was applied to estimate the worst case performance of T- and double T-matched tags. Comparison of the performance of these tags showed that with the same tag antenna foot-print size and with very similar radiating geometry, the double T-matching approach provided a significant bandwidth increase. The measured minimum read range of the double T-matched tag over the global UHF RFID frequencies in free space conditions is nine meters.

Future work includes investigation of impedance matching schemes for other types of tag antennas, such as slots and patches, to provide similar characteristics as the double T-matching with short dipole tag antennas.

Acknowledgment

This research work was funded by the Finnish Funding Agency for Technology and Innovation (TEKES), Academy of Finland, Centennial Foundation of Finnish Technology Industries, Tampere Doctoral Programme in Information Science and Engineering (TISE), HPY Research Foundation, and Nokia Foundation.

References