Impedance Matching of Tag Antenna to Maximize RFID Read Ranges & Design Optimization

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Abstract: Radiofrequency Identification (RFID) tags are ever increasing in use, from the monitoring of components to the tracking of produce or livestock during processing & production. They are also widely used in the touch-less technologies seen today in store and payment cards and banking services. With this there has been the ever increasing need to reduce the power required to activate the RFID tag, while maximizing the read range. In addition there is a need to reduce the size of the RFID tags, which are typically embedded in labels and/or cards, in order to make them discreet. In order to maximize read ranges, one needs to ideally match the impedance of the RFID tag antenna to the chip utilized in the tag & ensure that for a particular reader that a minimum threshold power is achieved to activate the tag chip at the required operating frequencies. In this work, we look at the modelling of a physical RFID tag used in a store card and its read ranges obtained from literature, and make comparisons of the model simulations to physical test data. In addition, we take the validated model and find an optimal tag antenna design for a particular application with both size and manufacturing constraints.

Keywords: RFID, Antenna, Optimization, Read Range, Impedance Matching, Power Transmission Coefficient.

1. Introduction

RFID involves the wireless non-contact use of radio-frequency electromagnetic fields to transfer information, identify and track objects with the use of a RFID transponder, or tag. A reader is then used to interrogate the tag through electromagnetic fields as illustrated in Figure 1(i). As RFID uses electromagnetic fields, they do not need to be in the line of sight of the reader to operate, thus the tags can be embedded in objects or material, making them a desirable discreet technology.

Some tags are powered by electromagnetic induction from the interrogating electromagnetic field, while others use local power sources to operate. Tags with local power sources, such as batteries can operate at several meters, however, those powered by the readers interrogating field, typically have a very limited operational range.

In this paper we look at how to determine the operating range of RFID tags powered by the reader interrogating fields by making use of a validated RFID COMSOL model. Additionally, we look at maximizing the operating range by optimizing the antenna design to ideally match that of the RFID chip.

2. Theory & Equations

RFID tags essentially consist of an antenna and a chip which have complex input impedances as illustrated in Figure 1(ii). The chips are typically located at the terminals of the antenna, and the voltage (V_a) developed at the antenna terminals, from the readers interrogating field, powers the chip. Thus, in order to maximize the read range of a RFID system, where the tag is powered by electromagnetic induction it is important to ideally match the impedance of the tag's antenna with the chip [1-5].

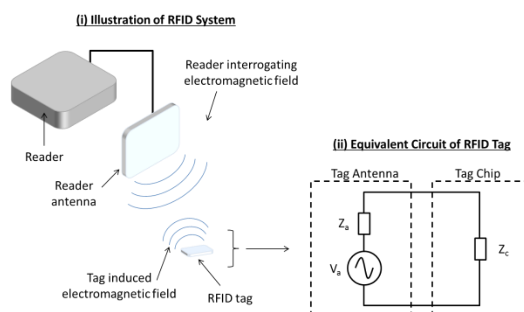

Figure 1: (i) Illustration of RFID System & (ii) Equivalent Circuit of RFID Tag.

2.1. Impedance Matching

From the work by Rao *et al*. (2005), and the equivalent lumped circuit illustrated in Figure 1(ii), the chip impedance (Z_c) and antenna impedance (Z_a), which are frequency dependent, and can be expressed as follows:

$$Z_c = R_c + jX_c \qquad (1)$$

$$Z_a = R_a + jX_a \qquad (2)$$

Where, R_c & R_a are the chip and antenna resistances respectively, and X_c & X_a are the chip and antenna reactance, respectively. The chip The voltage supply (V_a) is an open circuit radiofrequency (RF) voltage developed on the terminals of the tag antenna from the reader antenna's interrogating electromagnetic field. The chip's impedance (Z_c), can vary with the power absorbed by the chip (P_c) and includes energy sapping effects. P_c can be expressed in terms of the maximum available power from the antenna (P_a) and the power transmission coefficient (τ), as follows.

$$P_c = P_a\tau \qquad (3)$$

The maximum available power from the antenna (P_a) is achieved when $Z_c = Z_a$, and the power transmission coefficient (τ), describes the degree of impedance match between the tag chip and antenna, and is given by:

$$\tau = \frac{4R_cR_a}{|Z_c+Z_a|^2} \qquad (4)$$

The closer τ tends to unity, the better the impedance match between the tag chip and antenna. When $\tau = 1$, then this is described as the perfect complex conjugate impedance match between the antenna and the chip. Thus, for a particular combined chip and tag antenna design, ideally you'd want $\tau = 1$, where $Z_c = Z_a$. In addition to this, the antenna is typically matched to minimum threshold power (P_{th}) point in order for the chip to activate.

2.2 Read Range

Impedance matching is a requirement of RFID tag design, however more importantly is the read range of the tag design in combination with the reader and the reader antenna as illustrated in Figure 1(i). The read range of a combined tag and reader system is defined as the smaller of; (i) the maximum distance at which the tag receives the minimum threshold power (P_{th}) required to turn on and scatter a signal back, and (ii) the maximum distance at which the reader can detect this return signal.

Generally, the maximum distance at which the reader can detect a return signal high is far greater than the maximum distance the tag can receive P_{th} to turn on and scatter back. Additionally, it is easy to adjust the power settings or the antenna of the reader system to ensure that this is always the case. Thus, for this work the read range will be considered the maximum distance at which the tag can receive the minimum threshold power (P_{th}) required to turn on and scatter a signal back.

In free-space, the power received by a tag antenna (P_a) can be calculated using the Friis free-space equation, where:

$$\boldsymbol{P_a = P_rG_rG_a\left(\frac{\lambda}{4\pi d}\right)^2} \qquad (5)$$

Where, P_r is the power transmitted by the reader, G_r is the reader antenna gain, G_a is the gain of the receiving tag antenna, λ is the wavelength, and d the distance between the tag and reader.

Substituting in Equation (3) and the read range (r) is the distance at which the tag receives the minimum threshold power (P_{th}), gives the read range as follows:

$$\boldsymbol{r = \frac{\lambda}{4\pi}\sqrt{\frac{P_rG_rG_a\tau}{P_{th}}}} \qquad (6)$$

The peak read range (r), across a frequency range can be referred to as the tags resonance and coincides with the maximum power transmission coefficient (τ). Thus to obtain the maximum read range, one can optimise for the maximum power transmission coefficient (τ) for the tag and then determine the read range based on the Equation (6) in combination with the reader system.

3. Numerical Model

A COMSOL Multiphysics® model which made use of the RF Module, was developed for the analysis of a general RFID tag, including substrate, antenna and chip geometry and material properties. The reader system details included values for the power transmitted by the reader (P_r) the reader antenna gain (G_r) and operating frequency.

The model was developed to perform the electromagnetic field and frequency domain analysis of the combined chip and antenna design, to determine the components of the antenna's complex impedance (Z_a), the power transmission coefficient (τ) using equation (4), the gain of the tag antenna (G_a), and the read range (r) of the combined reader and tag system using Equation (6).

The model also included the optimization module, which implemented to find the optimal geometric design of a tag's antenna to maximize the read range for a particular reader system and tag chip.

The model was fully parameterized and driven completely from the parameters section of the model. Parameters included; antenna and substrate optimisation geometric relations and constraints, material properties, reader power & antenna gain, as well as tag chip impedance, operating frequency, & threshold power ratings.

Figure 2 below shows the features of the RFID Tag model, including air domains, perfectly matched layer (PML) regions, tag substrate, antenna and chip geometries.

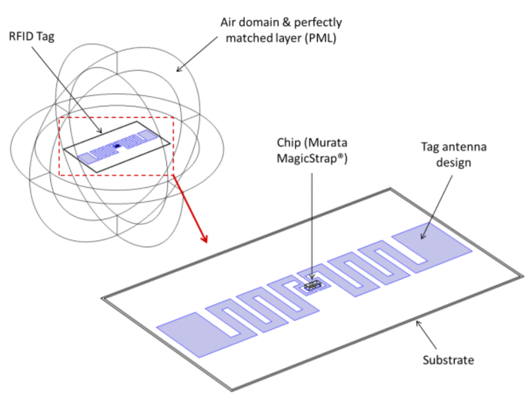

Figure 2: COMSOL model of RFID Tag, including substrate, antenna and chip.

4. Model Validation

In order to have confidence in the analysis results of the COMSOL model before optimization, validation of the developed model is essential. Due to the time and budgetary constraints, it was decided that physical test data of a reader-tag combination would be obtained from literature to validate the model. A literature review was done on various studies relating to RFID tags, antenna design & optimization [1-5]. The work by Rao *et al.* (2005)[5] provides enough physical test data, including read range (r) and power transmission coefficients (τ) at various frequencies for validation purposes. Figure 3, summaries the physical test data of read range (r) and power transmission coefficients (τ) vs. frequency obtained from Rao *et al.* (2005)[5].

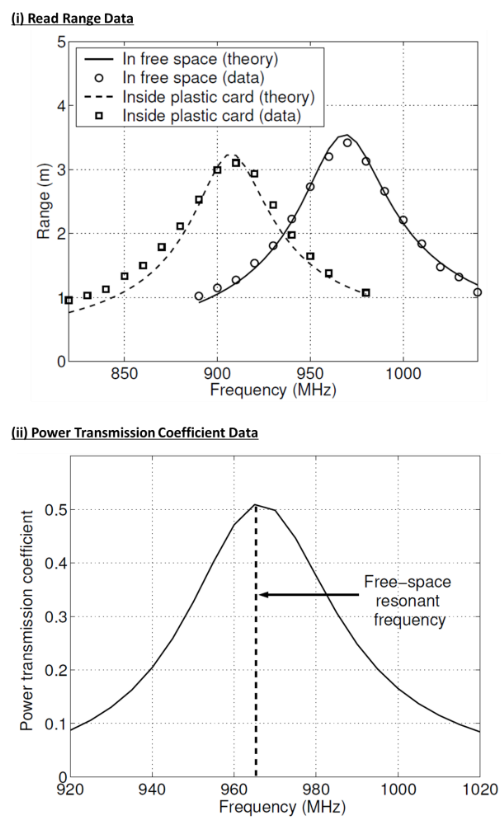

Figure 3: Physical test data (i) read range & (ii) power transmission coefficient obtained from the work by Rao *et al.* [5].

The geometric details of the tag antenna design were not provided by Rao *et al.* (2005) [5], however an image of the antenna design and the external dimensions were provided. Thus, the geometric dimensions of the antenna design were extracted and implemented the equivalent model by scaling the measurements off the image provided. Figure 4 below, compares the antenna image provided by Rao *et al.* [5] and the tag antenna geometry built in the equivalent model.

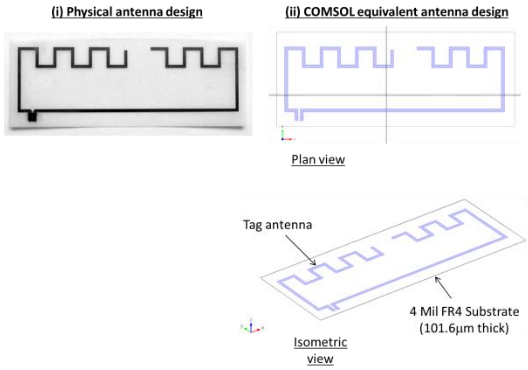

Figure 4: Equivalent tag antenna model compared to physical sample from the work by Rao *et al*. [5].

A frequency sweep of the equivalent model was run and the results of read range and power transmission coefficient were compared with the physical test data provided by Rao *et al*. (2005). Figure 5 below graphically compares the solution obtained from the model compared to the physical test data.

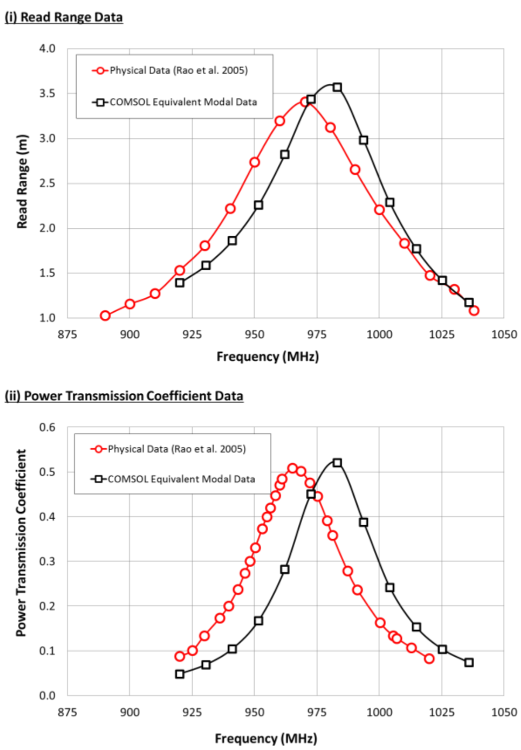

Figure 5: Comparisons of (i) read range & (ii) power transmission coefficient obtained from model vs. physical test data from R**a**o *et al*. [**5**].

As can be seen from the graphs in Figure 5 the results obtained from the model are in line with physical test data for both read range and power transmission coefficient. The model trends gave reasonable and realistic results, and follow those observed in the physical tests. However the model predicts marginally higher values for the tag's resonance, and the read range and power transmission coefficient at resonance. Where, the marginal percentage increases in tag's resonance, read range and power transmission coefficient at resonance were found to be 1.34%, 2.43% and 4.77% above the physical test data, respectively.

These small variations could be due to the possible variations in extracting geometric data from the antenna image, or variations in the modelled substrate material vs the physical samples used by Rao *et al*. (2005). In addition to this, a single constant value for the chips impedance ($Z_c = 15 - j\ 420\Omega$) was given in the paper, where it would be expected that the chips impedance would vary slightly with change in frequency. However, regardless of these issues, the small percentage variations were deemed minor and the results acceptable where the modelling method accurately predicts the read range.

5. Optimisation of RFID Tag Design

The validated RFID tag read range model was then used to optimise the tag antenna design for an office card security system, with a maximum footprint size of 75×45mm. The system is to use the LRU1002 OBID® UHF long range reader (FEIG Electronic GmbH, Germany) [6], coupled with a OBID® i-scan® UHF reader antenna (FEIG Electronic GmbH, Germany) [7]. In addition to these, the tag was to use the Murata Magicstrap® (Murata Manufacturing Co., Ltd., Japan) [8].

For the optimisation work the following reader, reader antenna, chip and tag substrate properties were used in the model:

- Chip frequency: 866.5 MHz
- Chip Impedance: 15-45j Ω
- Tag Substrate: 250µm FR4
- Reader Power: 1W (mid range value)
- Reader Antenna: ID ISC.ANT.U.270/270
- Reader Antenna Gain: 9dBi

5.1 Antenna Design Starting Point

In order help the optimisation process it is important to have a good starting point for the geometric design of the tag antenna. Based on the Murata Magicstrap® documentation [8], specifically their “Murata-A3” inlay antenna design for a durable tag, it was decided to use a similar scaled down version of the “Murata-A3” antenna design as the starting point for the optimisation process. Figure 6 below, illustrates the initial start tag antenna design for optimisation (71.2×45mm), which is similar to the “Murata-A3” (95×15mm) antenna.

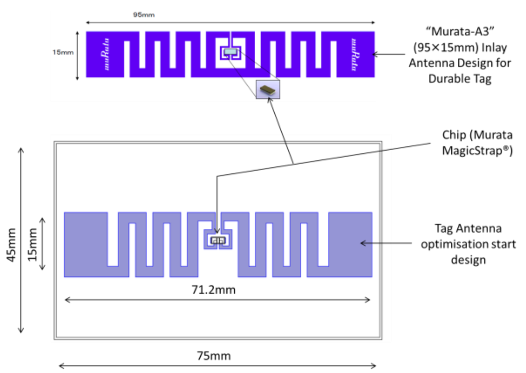

Figure 6: Initial tag antenna design (71.2×15mm) for optimisation compared to Murata-A3 (95×15mm) inlay antenna design for a durable tag [8].

5.2 Variables & Objective Function

The objective function for optimization was set up to maximize the power transmission coefficient (τ) and thus the read range for the chips operating frequency of 866.5MHz. 34 antenna section geometric variables of length and width were adjusted to find the maximum objective value for the RFID system. Additionally, the antenna design was constrained to remain within a 75×45mm footprint area, and within the manufacturing scales and tolerances available at the manufacturing subcontractor, Newbury Electronics Ltd. (Berkshire UK) [10]. Finally, the Murata Magicstrap® chip was to be centrally located on the card, and the chip’s antenna mounting pattern as required for manufacture was enforced to prevent spurious non-feasible solutions being evaluated. The objective function, variables and constraints are listed below:

- Objective Function: maximize the power transmission coefficient (τ)
- Lengths: l1 to 117
  - Length values can be +ve or –ve.
  - Maximum & minimum lengths constrained to half the card length of 37.5mm.
- Widths: t1 to t17
  - Width values can only be +ve
  - Maximum width constrained to half the card width of 22.5mm.
  - Maximum width constrained to minimum manufacture width of 125µm.
- Antenna design footprint constrained to remain within a 75×45mm footprint area.
- Murata Magicstrap® chip to remain centrally located on the card.
- Regional antenna constraints around the chip mounting pattern to prevent spurious non-feasible solutions being evaluated.
- Fixed antenna mounting pattern as required for Murata Magicstrap® chip.

The Figure 7 below illustrates graphically the 34 geometric variables of length (*l*) and width (*t*) considered for the optimization of the antenna design.

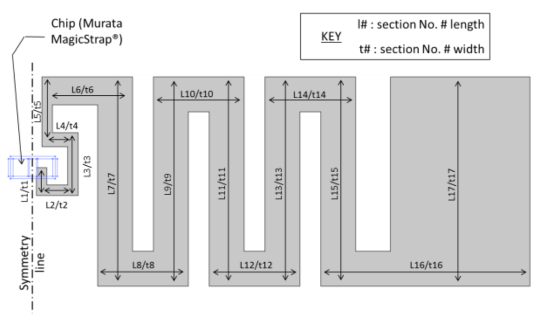

Figure 7: Schematic illustrating the tag antenna design (one side only) optimisation variables.

5.3 Optimization Solvers

Two gradient-free optimisation methods were looked at in the work, namely the bound optimization by quadratic approximation (BOBYQA) method and the Monte Carlo method [9]. These were chosen as the objective function does not need to be differentiable with respect to the control variables, and the definition of the problem and the geometric relations and constraints will be discontinuous, making traditional ‘hill climbing’ optimisation methods unsuitable [11].

Initially, the BOBYQA optimisation solver was used, however solutions found were localized and were highly dependent on the initial start geometric design. This, method, although it did improve the designs the power transmission coefficient, they only sought localized maxima for the objective function. Thus, the Monte Carlo method was favored initially, as this looked at the complete design space and introduced random variations in the design variables assessed, similar to how mutations are introduced in optimisation using genetic algorithms [11], thus allowing for a global maxima to be sought. The drawback for this method is the time taken to find a solution. However this drawback was deemed small compared to the benefits of a finding a global maxima, in addition, by making use of parallel computing and solving multiple models simultaneously in the COMSOL solvers greatly reduced the computational analysis run times for the Monte Carlo method.

Following the optimization solution from the Monte Carlo method, a final analysis run was performed using the BOBYQA optimisation solver, where the starting point was the optimised solution found from the Monte Carlo method, thus ensuring a refined local maxima for the objective function was found based on the global maxima.

6. Optimized Solution & Results

Overall it took a total of 42h 23m simulation runtime to find the optimised antenna design, using both the BOBYQA and the Monte Carlo methods in series, with the use of a PC with two E5649 (2.53GHz) Zeon® processors and 32 GB RAM. Table 1, summarizes the run times for each section of the optimization process and the objective (τ) values obtained at the end.

Table 1: Optimisation runs and changes in Power Transmission Coefficient (τ).

Stage #	Optimisation Solver	Design Start Point	Run time	Objective Value
1	BOBYQA	Initial design	2h 13m	0.498
2	Monte Carlo	Solution from Stage 1	36h 28m	0.644
3	BOBYQA	Solution from Stage 2	3h 42m	0.675
Initial (start) antenna design objective value				0.303

As can be seen from stage 3, the final optimised solution has a power transmission coefficient (τ) of 0.676, a vast improvement on the initial 0.303, and a read range of 2.38m when used in combination with the OBID® LRU1002 UHF long range reader and the i-scan® UHF reader antenna. The geometric characteristics of the optimised tag antenna design are detailed in Figure 8 below, and as can be seen in this figure the antenna design is vastly different from the initial starting design illustrated in Figure 6, where the final solution fills a large percentage of the space available and has a dramatically different design scheme.

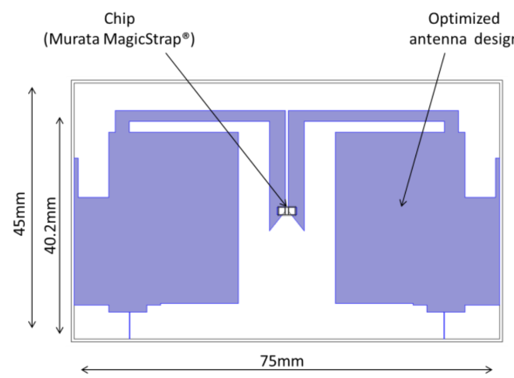

Figure 8: Optimized tag antenna design obtained

Table 2, below gives the changes in the read ranges when the tag is used with changes in the reader power settings & the type of reader antenna used. As can be seen by boosting the reader to 2W and using the larger 600/270 reader antenna, the read range increased to 4.23m.

Table 2: Read range for optimised tag antenna design, for different reader power settings & antenna options.

Description		Units	Value			
Reader Power		W	1	2	1	2
Reader Antenna	Type	#	270/ 270	270/ 270	600/ 270	600/ 270
	Gain	dBi	9	9	11	11
Read Range		m	2.38	3.36	2.99	4.23

A frequency sweep was performed on the optimised antenna design to assess the tag response over different chip operating frequencies, namely 865 to 965MHz. The results of power transmission coefficient (τ), read range & antenna Gain (G_a) are presented graphically in Figure 9 below. As can be seen from the graphs, the antenna design's peak response is at 876MHz, which corresponds closely with the chip frequency used for the optimisation work. The tags response over the chips operating frequency range does not fair well, where at the chips higher operating frequency of 965MHz the read range drops dramatically to 0.45m.

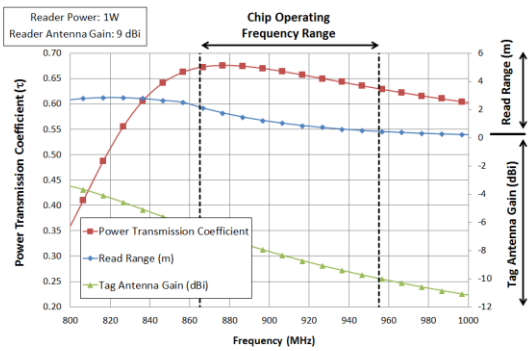

Figure 9: Frequency response of optimised antenna design.

A simple omnidirectional far-field radiation pattern was observed for the antenna design as illustrated in Figure 10. This was expected due to the symmetric antenna design.

7. Discussion & Conclusions

In this paper we have presented a COMSOL model which models a tags RFID response, and calculates the power transmission coefficient (τ) and read range (r), in combination with a reader system. The RFID tag model was validated for a particular antenna design against physical test data obtained from literature, where the model was found to marginally over-estimate the tag's response 1.34%, 2.43% and 4.77% for the tag's resonance, read range and power transmission coefficient at resonance, respectively. These small percentage deviations from the physical test data were minor and the modelling method was deemed to accurately predict the observed read range.

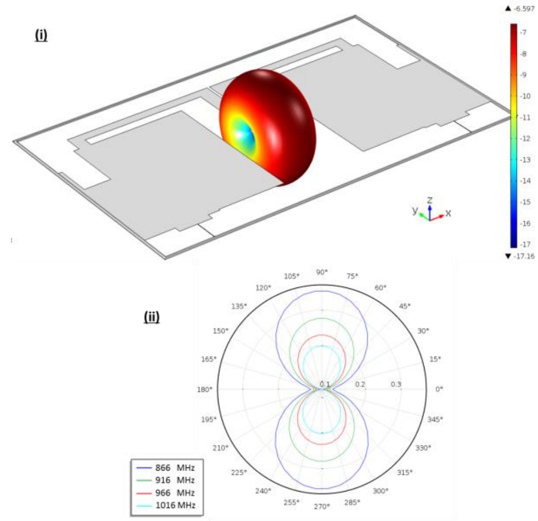

Figure 10: (i) Simple omnidirectional far-field pattern response of optimized antenna design at 866.5MHz, & (ii) Polar plots of far-field response at different frequencies.

The model was then used to find an optimal antenna design for a particular chip and reader set, where the antenna's footprint was constrained to remain within a 75×45mm region. A solution was found and the tag's response curves and read ranges presented. Two optimization solver methods were used in the work, namely the BOBYQA and the Monte Carlo methods. The Monte Carlo method was used to find the global maxima across the complete search space, while the BOBYQA solver method was run to refine the solution around the global maxima.

The optimization of the antenna design, also included known manufacturing constraints for RFID antenna, including minimum feature constraints and the requirements for the mounting pattern as stipulated by the chip manufacturer. These manufacturing constraints were implemented to prevent spurious non-feasible solutions being evaluated.

Production of a final optimized antenna tag design is now being completed at Newbury Electronics Ltd. (Berkshire UK) [10]. These antenna's and the respective chip, reader and reader antenna will then be tested to assess and validate the COMSOL model further against a second antenna design, with variations the substrate properties and chip utilized.

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