The impact of three-dimensional electromagnetic modelling and experiential work on the design and performance of RFID coupled antennas

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To ensure maximum power transfer between the reader and tag coils in an RFID system it is important that they are tuned correctly. The tuning also has an impact on the modulation index and the ability of the system to recover data. Traditionally the reader and the tag circuits are resonant; series and parallel respectively. In order to achieve resonance, tuning capacitors are used to resonate the coil reactance. Resonance is necessary in order to provide the appropriate drive (power) tag side, which also increase the inter-coil separation and to maximise the loading effects of the tag on the reader.

In practice maximum power transfer and maximum modulation index is found experimentally whereby the tag and reader antenna reactances are compensated (by use of a capacitance) to account for mutual reactive effects of the coils when in proximity to each other. Usually maximum power transfer is found using a trial and error method. This is done by placing the two coils in close proximity, attaching an oscilloscope probe to the tag voltage rail and tuning a variable capacitor on both the reader and tag to maximise the voltage. This method requires probe capacitances to be considered. The tune can also be determined with the use of a network analyser. The variable capacitors are tuned on both reader and tag until the reader and tag reactances cancel out.

A body of work was undertaken to correlate the results achieved from the modelling and practical performance of antenna structures. One aspect of the work identified a trend in the measurements which suggested that the compensatory capacitance required to bring two coils a fixed distance apart, into tune (as distinct from measuring resonance in isolation) could be calculated. This paper reports on this and ongoing work to establish a method to simply obtain the value of the compensatory capacitor through calculation. Were such a method available it would: -

1. Remove trial and error,
2. Ensure consistency in terms of setting up systems,
3. Simplify design,
4. Remove experimental error and probe capacitances from the tuning procedure

Introduction

Figure 1 depicts a typical inductively coupled (RFID) system.

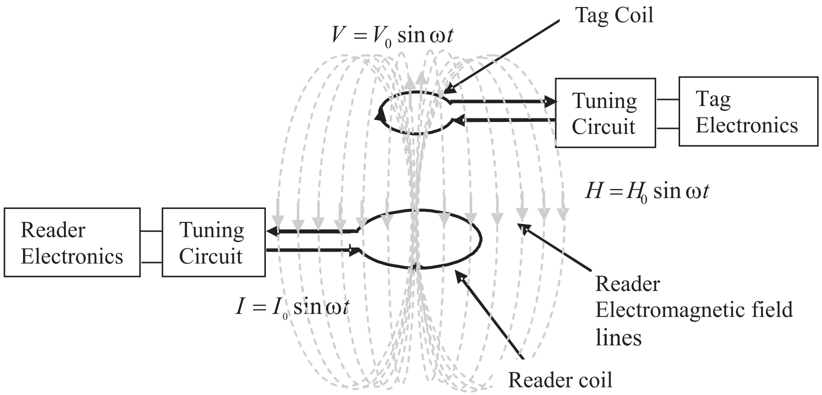

Figure 1: A basic configuration of reader & tag antennae in a typical RFID application

The reader electronics comprise a power source and signal generator. When coupled to the tuned circuit they produce an Electromagnetic (EM) field, which induces a current and associated voltage in the tag. This coupling exists only when the tag is within the EM field. Evidently the reader and tag both require an antenna and this is usually in the form of a planar or three dimensional coil. In most cases the antenna coil provides the inductive reactance to the tuning circuit. Normally the reader comprises a series resonant circuit and the tag a parallel resonant circuit; this is to maximise current and induced voltage in the reader and tag respectively. Often the reader and tag circuits need to be optimised to provide maximum power to the tag and ensure maximum loading of the reader by the tag for data transfer. These metrics influence the 'read-range' of the tag i.e. the maximum inter-coil separation over which data may be relayed from the tag to the reader. Instrumentel tags have the ability to actuate a lock and/or sense parameters such as temperature and pressure. To enable this it is essential to obtain maximum power on the tag.

In practice maximum power transfer is found experimentally whereby the tag and reader antenna reactances are compensated (by use of a capacitance) to account for mutual reactive effects of the coils when in proximity to each other. Usually maximum power transfer is found using a trial and error method. This is done by placing the two coils in close proximity, attaching an oscilloscope probe to the tag voltage rail and tuning a variable capacitor on both the reader and tag to maximise the voltage. This method introduces inaccuracies, takes time and requires probe capacitances to be considered.

At 13.56MHz the inductor values are usually of the order of μH, thus capacitors in the pF range are required to make such components resonate. However, the smaller the capacitor value the more difficult it is to tune. This is due to:-

- Inherent capacitances associated with a physical design; for example a piece of FR4 circuit board could have a capacitance of 4-5 pF at 13.56MHz.
- Probes of typically 16pF being used to take measurements.
- The range and tolerances of variable tuning capacitors

As a result significant errors in circuit resonance can result.

Some of these problems can be overcome:-

- The inductor can be fabricated to have an appropriate inductance to allow a suitable resonant capacitor value.
- The probe capacitances are static and can be deducted from the final capacitance required.

However the problems relating to using a variable capacitor can only be eliminated by using a static capacitor.

The tune can also be determined with the use of a network analyser . The variable capacitors are tuned on both reader and tag until the reactances cancel out; leaving a purely real tune and therefore maximising current through the coils. The problem with this method is the drive conditions created by the network analyser will almost certainly differ from those produced by conventional reader boxes. Both the methods offer advantages and disadvantages however they both require time and a certain skill level due to the fact that the 'compensatory' capacitance needed varies with each coil pair.

If we consider a single coil the calculation for resonance is trivial since we only have to balance the capacitive reactance. Evidently the circuit could be tuned more accurately but the calculation is simplified due to the absence of the mutual effects of the second coil. It would be beneficial if another formula or method could be found which would allow two coils to be tuned at set distances apart; the complexity and trial and error process could then be minimised. Such a method would require the calculation of the 'compensatory' capacitance required at all inter-coil separations.

The original aim of the work is to correlate physical system performance with theory from an Electromagnetic model (EM). The experimental data was obtained to validate my theoretical model. A corollary to that is that if the EM model works, the EM solutions can be used accurately in the middle ground of the spectrum. However all EM software only look at the EM solution for the resonant structure, this is inadequate for a full system model as once the driving circuit and the tag circuitry is added the 'compensatory' capacitance may change as these systems communicate using load modulation. Therefore a task has been set to combine the EM model to a circuit simulator in order to accurately model a full inductively coupled system. The draw back to this model is that it becomes very complex and computationally intense; thus a theoretical formula would be preferable. This paper looks at the results (from validation experiments)to find a simpler way of modelling overall system performance. The observations are trends and should be taken at face value more data points are required in order to be categoric.

Observations

All of the observations were made using the following experimental set up. A Network analyser (Model: PNA E8358A) was used to take all of the measurements. The inter-coil separation was varied from 1-10cm for all coil pairs in both the X and Y planes. This was done using a height gauge accurate to $10\mu m$ (LNR-31300L) and an experimental rig custom built. This enabled the two coils to be moved very accurately in any direction. The parameters chosen to vary were those that would have large effects on the performance of the coils. The parameters that were varied were; coil diameter, number of turns and wire thickness. *The experimental rig is shown in figure 2(do I show a picture??).*

As there are currently no RFID software packages available to perform full 3D electromagnetic (EM) simulations on such coils, a 3D electromagnetic solver is used to clarify the experimental work. The 3D EM package used is Ansoft's High Frequency Structure Simulator (HFSS). A model has been drawn into this package taking into account all of the variables along with such parameters as board capacitance. Therefore the model should produce results that are comparable to the experimental work. This model can be seen in figure 2. The results from the simulations will be displayed on the graphs along with the experimental data. These results will have more data points between them. *GREG - should I bother with including simulations or leave it as observations made purely from experimental data.*

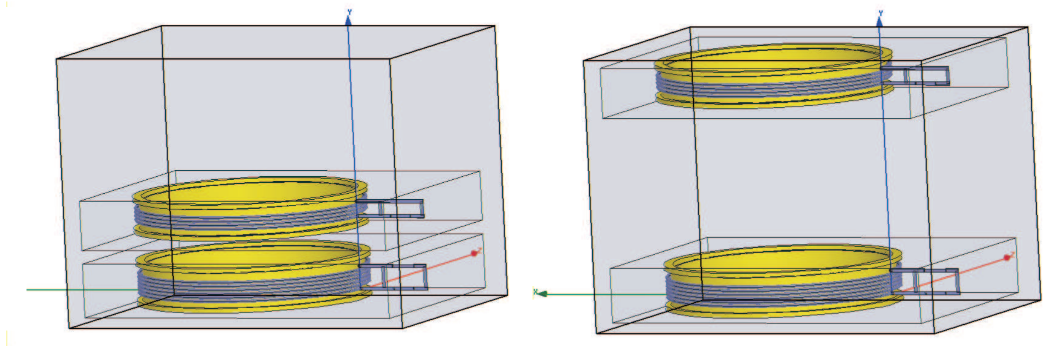

Figure 2: Coil pairs at different inter-coil separation using HFSS

Three main observations were drawn from the experimental data. The first relates to the wire thickness of the coil and turned out to be a little counter intuitive. It was found that as the reader wire thickness was increased the 'compensatory' capacitance required on the reader was reduced. The same was true that if the wire thickness of the tag coil was increased the 'compensatory' capacitance required on the reader was reduced. This can be viewed as, when the combined inductance of the reader tag pair decreases (i.e. wire thickness increasing) the capacitance required to tune the pair to maximum voltage on the tag also decreases. This can be seen in figure 3. This is counter intuitive as for a single coil its the opposite; as inductance increases the 'compensatory' capacitance required decreases. However, this point was reinforced when the diameter of tag coil was analysed. As the tag diameter increases the reader 'compensatory' capacitance increases. Thus as combined inductance increases the 'compensatory' capacitance increases figure 4.

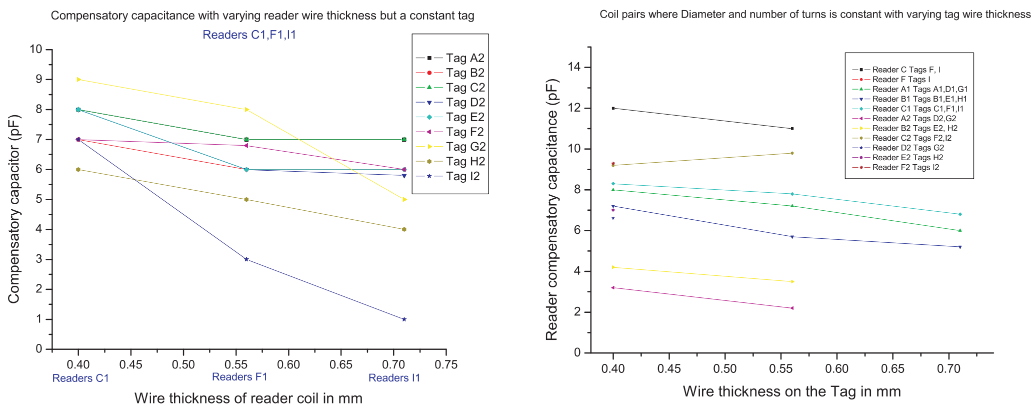

Figure 3: The effects of changing wire thickness on 'compensatory' capacitance

GREG - Is it ok to leave these graphs as lines as all I wish to show is the general trend i.e. they decrease or should they be points as I do not know what happens between the points?

The trends shown in figure 3 and figure 4 can clearly be seen for a variety of reader tag combinations; although more data points are required to be conclusive.

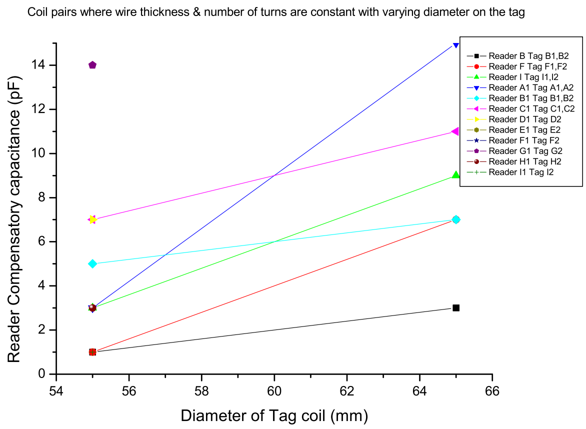

Figure 4: The effects of changing tag diameter on ‘compensatory’ capacitance

The second observation was pertaining to increasing the power transfer on a reader tag combination already tuned at 1cm inter-coil separation. If the maximum voltage on the tag at an inter-coil separation of 1cm has been found and deemed insufficient, the traditional thing to do is increase the number of turns on the antennae. This possibility will certainly achieve increased power transfer, although this will also greatly increase the inductance of the antenna and change its performance and thus the ‘compensatory’ capacitance required. There is a far more subtle way of achieving the increased magnetic flux density (B) and thus the power coupled from reader to tag. This is to increase the wire thickness of the reader antenna increasing B and thus the power transfer, this will lower the resistance of the coil therefore increasing the current that is passed through it. This will then set up a larger current in the tag antenna giving more power. However this will NOT increase the inductance of the reader coil by a massive amount and therefore has a smaller effect on the ‘compensatory’ capacitance required. This is best explained by the use of an example. The magnetic flux density produced by a circular loop antenna is given by Formula 2.

Formula 2

$$B = \frac{\mu_0 I N a^2}{2(a^2+r^2)^3/2}$$

where

I	=	current
N	=	number of turns
r	=	distance from centre of loop
μ_0	=	permeability of free space and given as $4\pi \times 10^{-7}$ (Henry/meter)

If the wire thickness is increased then in turn the current will increase. It can be seen from Formula 2 that this will mean more B produced and more power on the tag. Table 1 shows three coils with the same number of turns but different wire thickness; it can be seen that the inductance of the coils changes slightly. It can also be seen that the B produced by coil C is greater than A or B.

When the reader wire thickness is increased to give more power on the tag, conventionally the resonant circuits will need retuning. This is not the case for the tag, it was found that if the reader wire thickness was increased it was only the reader ‘compensatory’ capacitance which needed to be altered the tag ‘compensatory’ capacitance only varied by $1pF$ from coil A - C. This is especially true for the case where the reader inductance is far greater than that of the tag. This will enable the designer to adjust the amount of power on the tag by changing the wire thickness but only

Coil name	A	B	C
Diameter (mm)	66	66	66
Number of Turns	6	6	6
Wire thickness (mm)	0.4	0.56	0.71
Inductance (μH)	10.2	9.4	9.2
ISO capacitance @13.56MHz (pF)	13	14.5	15
Current used (mA)	80	90	100
Magnetic flux density (Wb/m^2)	$96e^{-9}$	$108e^{-9}$	$120e^{-9}$

Table 1: Wire thickness effects on Magnetic Flux density

have one variable capacitor to change instead of two. *GREG I don't like the order of the second observation it sounds too complicated and I'm not sure my use of examples work that well - any ideas are welcomed*

This paper has stated throughout the importance of transferring maximum power to the tag. It has primarily looked at a 'compensatory' capacitance used to tune out the additional mutual reactance. A third observation was made whilst looking at the amounts of 'compensatory' capacitance required on both reader and tag. The value of 'compensatory' capacitance required to tune both reader and tag back to resonance at 1cm inter-coil separation is generally more than 20% of the capacitance required to tune the antenna in isolation.

Discussion

The observations made in short were as follows: -

1. As reader or tag wire thickness increases so does the reader 'compensatory' capacitance required. This was backed up by the fact that as the tag diameter is increased so is the 'compensatory' capacitance required.
2. If a Reader and tag combination are tuned at 1cm inter-coil separation but provide insufficient power. The reader wire thickness can be increased to provide more power; with only a re-tune on the reader required.
3. The 'compensatory' capacitance required is generally more than 20% of that of the capacitance required to resonate the coil in isolation.

A unified model for EM and circuit simulation has been undertaken, data for parametrised antennae and circuits have been collected. The two of these have been correlated and some preliminary observations have been made. These observations have limited data points due to the fact that the experiments were taken to validate a software model. However the majority of the results are reinforced by the theoretical formulas available at present. Extra data will be generated in order to improve these results and hopefully lead to categoric statements and possibly a formula.

The reason for this work is to design and implement a simplified model to allow inductively coupled system performance to be assessed before being built. The model should be capable of returning important parameters such as read-range, voltage, current, power, modulation index, optimum coil geometry and more importantly 'compensatory' capacitance.