AN5605
Application note

Design of a 13.56 MHz double-layer antenna

Introduction

This document describes a simplified method to design a double-layer antenna for the products listed in *Table 1*. This method is based on eDesignSuite, a free on-line tool (available on *www.st.com*) featuring a calculation module that helps customers to design single-layer, rectangular coil antennas for NFC applications.

Antenna tuning frequency adjustment and validation is required as part of the procedure. The maximum acceptable value for the external tuning capacitance is discussed regarding RF communication requirements.

Table 1. Applicable products

Type	Applicable products
NFC / RFID Tags	ST25TA, ST25TB, ST25TN and ST25TV series NFC tags
	ST25DV-I2C and ST25DV-PWM series Dynamic NFC Tags
	M24LR and M24SR series Dynamic NFC Tags

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1 Tag electrical model

Figure 1 shows a tag in a variable magnetic field: its electrical model is sketched in *Figure 2*, where Z_a represents the spiral antenna impedance, Z_c the RFID/NFC tag IC impedance and V_{oc} the open circuit voltage delivered by the antenna.

Figure 1. RFID tag physical model

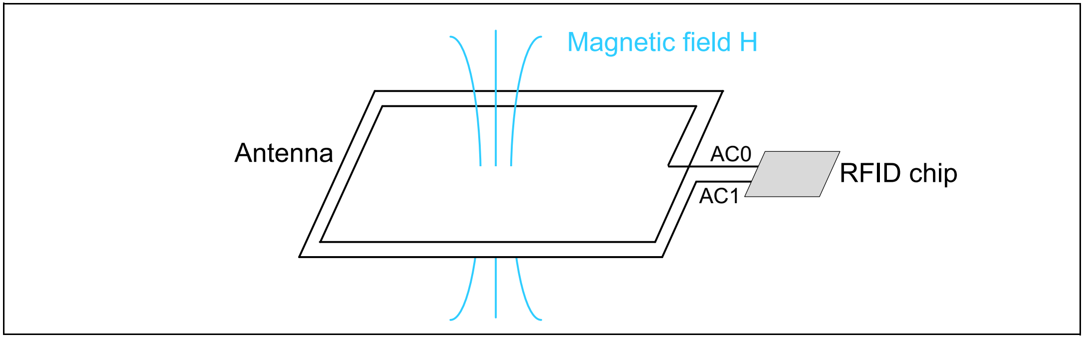
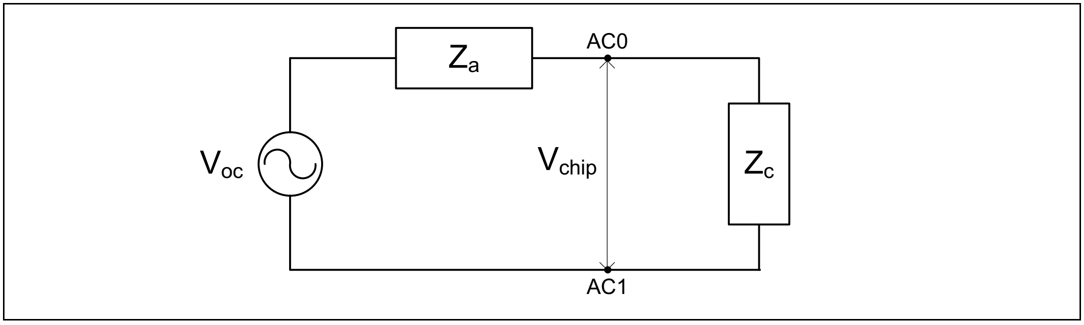


Figure 2. RFID tag electrical model



2 Tag antenna tuning

The optimization of the communication distance requires to maximize the power transfer between tag antenna and the RFID/NFC tag IC under minimum operating conditions. This occurs when

Equation 1: $Z_a^* = Z_c$ (Z_a^* is the complex conjugate of Z_a)

Expressing the impedances of tag antenna and tag IC as, respectively, $Z_a = R_a + j\,X_a$ and $Z_c = R_s + j\,X_s$, the condition leads to

Equation 2: $R_a = R_s$ and $X_a = -X_s$

At minimum operating condition, serial equivalent resistance of the tag IC and of the antenna are both in a range of few ohms, hence it is possible to consider that the first part of *Equation 2* is satisfied.

Regarding power reception, RFID/NFC tag IC can be modeled as a resistance (representing the current consumption) in parallel to a capacitor, hence its reactance X_s is capacitive: $X_s = -1 / (C_s * \omega)$, with $\omega = 2 \pi f$, where f is the desired tuning frequency and C_s represents the series equivalent capacitance of the chip.

For the antenna design the datasheets provide the value of tuning capacitance (C_{tune}), that is C_s at minimum operating power.

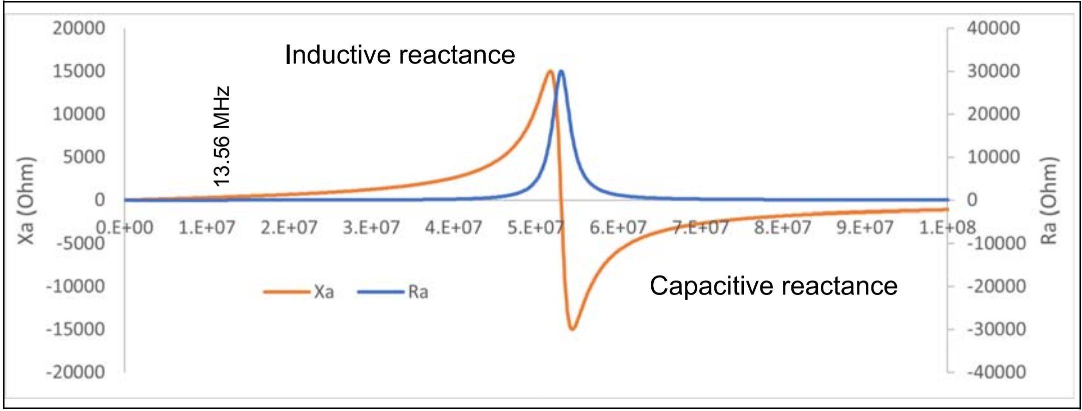
Then, following *Equation 2*, the design of a 13.56 MHz tag antenna consists in building a spiral coil with inductive reactance X_a satisfying $X_a = 1 / (C_{tune} * \omega)$ for the desired tuning frequency f_{tune}.

3 Tag antenna equivalent model

Figure 3 shows the typical impedance of a spiral coil as a function of frequency: the impedance varies according to frequency and shows a self-resonant frequency f_{self_res}:

- $f > f_{self\_res}$: $X_a < 0$ and the spiral coil impedance is capacitive
- $f < f_{self\_res}$: $X_a > 0$ and the spiral coil impedance is inductive

Figure 3. Spiral coil typical impedance vs. frequency



NFC/RFID antennas must have a self-resonant frequency higher than 13.56 MHz to have a small serial equivalent resistance and operate in the inductive range.

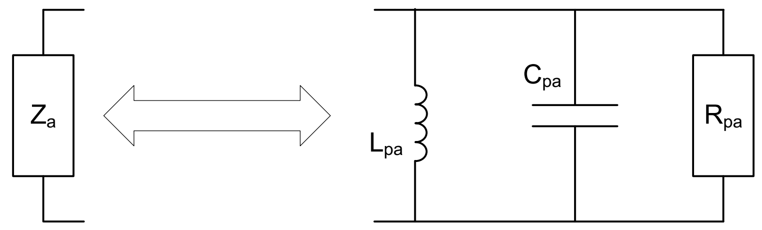
A simplified equivalent model of antenna impedance based on frequency independent components is shown in *Figure 4*:

- L_{pa} correspond to the self-inductance of antenna, measured at very low frequency
- C_{pa} is a stray capacitance that can be calculated from L_{pa} and the antenna self-resonant frequency using

Equation 3: $$L_{pa} * C_{pa} * (2 \pi f_{self\_res})^2 = 1$$

- R_{pa} corresponds to the serial equivalent resistance measured at self-resonant frequency.

Figure 4. Simplified antenna equivalent model



3.1 eDesignSuite NFC antenna calculation module features

The self-inductance of a spiral coil can be approximated using well-known formulas. However, the lower the self-resonant frequency (high number of turns, small spacing), the higher is the C_{pa} impact on antenna impedance, and antenna reactance X_a cannot be approximated by the formula $X_a = L_{pa} * 2 \pi f$.

As described in application notes AN2866 and AN2972 (available on *www.st.com*), tag antenna can be designed based on antenna self-inductance, neglecting in a first step the stray capacitance. This process requires to produce antenna variants, finding the right design by successive approximations. For antennas etched on application PCBs, this trial-and-error process is not efficient.

STMicroelectronics eDesignSuite NFC antenna module provides an accurate value of coil antenna reactance X_a by calculating the self-inductance and combining it with the effects of the stray capacitance. eDesignSuite antenna module displays as a result the serial equivalent inductance obtained from the formula L_a (in H) = $X_a / (2 \pi * 13.56$ MHz).

The expected precision is in the 5% range. For antennas whose self-resonant frequency is too low to guarantee this precision, a specific message warns the user.

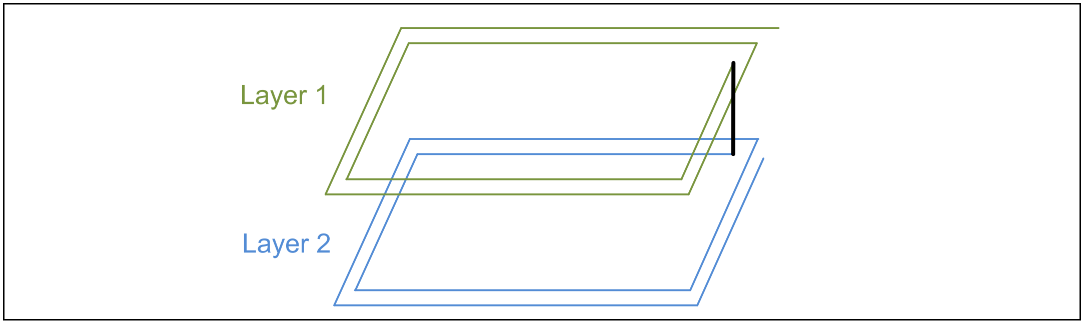
4 Designing double layer antennas with eDesignSuite

To guarantee a good precision, eDesignSuite NFC antenna module is limited to one-layer antennas. However, it is possible to use it to design a double-layer antenna.

4.1 Simplified equivalent electrical model of a double layer antenna

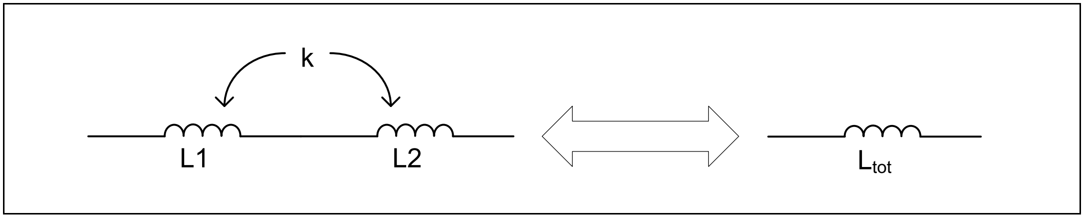
Figure 5 shows the diagram a double layer antenna. Turn rotation is the same on both layers. L1 is the inductance of layer 1 spiral, and L2 the inductance of spiral on layer 2.

Figure 5. Diagram form of a double layer antenna



L1 and L2 are connected in series and coupled magnetically by a coupling factor k, as shown in *Figure 6*.

Figure 6. Double layer antenna simple electrical model



The total equivalent self-inductance is $L_{tot} = L1 + L2 + k\,(L1 * L2)^{1/2} + k\,(L1 * L2)^{1/2}$.

If the two coils have an equal number of turns, the same dimensions, track width and spacing, then L1 = L2 = L. In the ideal case where the two coils are perfectly coupled, k = 1 and the total self-inductance is:

Equation 4: $L_{tot} = L + L + L + L = 4\,L$

Coupling factor between the two identical spiral coil depends upon the distance between layers and the size of coils, usually is lower than 1. The total antenna inductance becomes:

Equation 5: $L_{tot} = L + L + kL + kL = 2\,L(1 + k)$

This simplified model does not take into account the effect of the parasitic capacitance between the two coils.

4.2 Practical study

When performing electromagnetic simulation of double layer antennas and their single layer counterparts, it comes that for layer spacings between 0.1 and 0.8 mm the k factor from *Equation 5* varies roughly from 0.9 to 0.5.

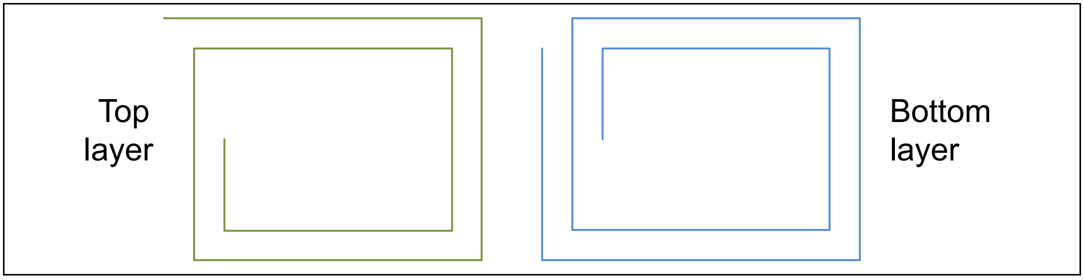
In other words, L_{tot} varies from 3 to 3.8 L, where L is the equivalent inductance of the single layer part of the antenna.

4.3 Double layer antenna design methodology with eDesignSuite

Based on the data presented before the following methodology can be used to design a double layer antenna using the NFC antenna design module of eDesignSuite.

1. Define the desired antenna equivalent inductance L_{tot} (see AN2866 and AN2972 for more details about antenna inductance choice and tuning frequency validation).
2. Compute the single layer spiral coil with $L = L_{tot} / 4$ equivalent inductance using eDesignSuite.
3. Layout the double layer antenna on PCB using the dimensions calculated in 2, keeping the same turn orientation on both layers. *Figure 7* shows an example of good spiral coil implementation (clockwise turning spirals): top layer spiral turns from outside to inside, bottom layer spiral turns from inside to outside.

Figure 7. Top view of top and bottom antenna layers



4. Add the footprint for an external tuning capacitance, needed to compensate the difference between the real antenna tuning frequency and the desired one.
5. On prototype, measure the actual tag tuning frequency f_1 with the NFC/RFID tag IC mounted.
6. Compute the additional tuning capacitance C_{add} from the NFC/RFID tag IC tuning capacitance C_{tune}, the desired tuning frequency f_{tune} and the actual tuning frequency f_1 (previously measured) using the formula $C_{add} = [(f_1 / f_{tune})^2 - 1] * C_{tune}$.Note that the additional tuning capacitance increases the tag intrinsic Q factor proportionately: an ideal external tuning capacitance with 30% of the tag IC internal tuning capacitance leads to a 30% increase of the tag Q factor, resulting in a 30% increase of the rising and falling times of reader modulation envelop received by the tag IC. The tag IC may not be able to decode reader command properly in low power conditions and system performance may be impacted. Impact of additional tuning capacitance depends on its

own Q factor and tag IC Q factor. As a consequence, a tag performance validation is necessary in addition to tag tuning frequency validation.

7. Tag performance validation: with the additional tuning capacitance mounted, measure the communication distance, and compare it to the expected one. In parallel, measure the tag IC RF input differential voltage at maximum operating distance: if it is much larger than the minimum operating voltage documented in NFC/RFID tag IC datasheet, total Q factor is too high.
8. Design adjustment: if an excessive tag Q factor is suspected, decrease the additional tuning capacitance value: a combination of frequency change and Q factor decrease may restore a good performance level.
9. Decreasing the Q factor of the tag without changing the additional tuning capacitance value can be achieved using an extra parallel resistor, but is not recommended due to the impact on cost (bill of materials). Antenna design modification is preferred (go back to step *1*) with a new antenna inductance to compensate the additional capacitance value.
10. Validate tag performance and fine-tune the tuning frequency.

5 Revision history

Table 2. Document revision history

Date	Revision	Changes
01-Feb-2021	1	Initial release.

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