How to protect ST25 tags from wireless power charging

Introduction

This document describes a protection that may be added to tags with ST25 devices to prevent damage caused by wireless power chargers such as Qi or other inductive power transfer technology. It details the impact of the protection on tag antenna design, either when designing a new antenna, or when adapting an existing antenna.

1 Description of the issue

Wireless power charging consists of a power transmitter (PTx) which generates an electromagnetic field, and a power receiver (PRx) which converts this electromagnetic field to electrical power available for its load. A most widespread technology in this area is standardized as Qi, developed by the Wireless Power Consortium (WPC).

Figure 1. **Wireless power charging**

A RFID/NFC tag is designed according to standard specifications such as ISO/IEC 14443, ISO/IEC15693 and NFC Forum.

If a RFID/NFC tag is placed in the PTx operating volume, it may be exposed to a power level exceeding the limit value defined by the standard specifications, it has been designed for, resulting in its destruction.

Even if ST25-based tags demonstrated a better resistance in front of this effect than other tags in the market they may be destroyed when present inside a 15 W Qi charging system.

This is an issue in applications where a system with NFC (for communication) is known to be placed within an inductive charger. Some examples among others are:

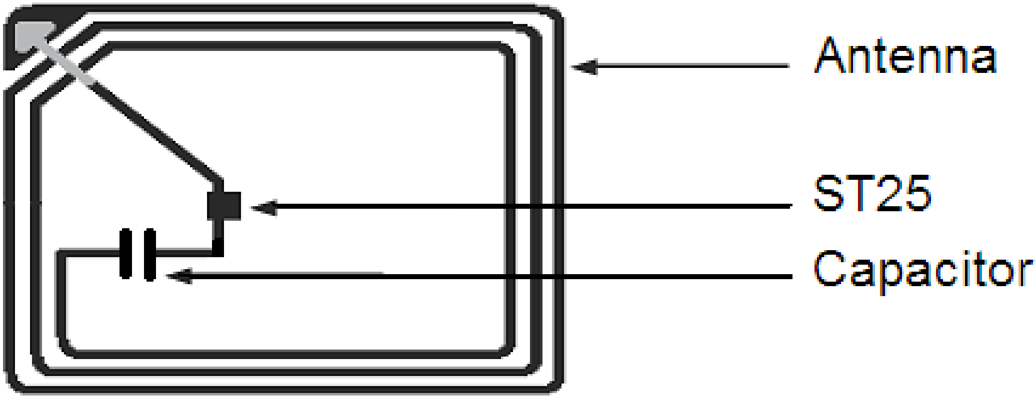
- A battery rechargeable by wireless charging embedding a dual interface NFC chip such as ST25DV to exchange information with its charger or a phone.
- A Bluetooth® headset rechargeable by wireless charging, embedding a NFC chip such as ST25TV for Bluetooth® pairing.

It is possible to protect the ST25 device with a simple and cost effective solution.

2 Description of the protection

The protection consists of adding a capacitance element in series between the tag antenna and the tag IC. On a PCB based design, the capacitance element is a discrete capacitor component. On an inlay, a capacitive pattern protects the device.

Figure 2. Tag with power transfer protection element



When a tag is in the operating volume of a power transfer, the following happens:

- An inductive PTx emits a low frequency signal, below 200 kHz and typically around 120 kHz, possibly with a high power.
- ST25 is designed to operate over a very large magnetic field strength range but at the fix frequency of 13.56 MHz. Its internal voltage regulation circuitry has negligible impact on the low frequency (LF) signals, resulting in high voltage reaching inside the chip.

This is the reason why the low frequency signal sent by PTx must be filtered-out. The capacitance element in series with the antenna acts as a high-pass filter with cut-off frequency chosen between the power transmitter frequency and ST25 operating frequency.

The value of the capacitance must be chosen to:

- Limit the voltage induced by PTx at ST25 AC0, AC1 pins within the maximum ratings of the chip
- Preserve the performance of RFID/NFC system

3 How to measure PTx danger on tag

The magnetic field generated by PTx is transformed into voltage by the tag antenna. Figure 3 illustrates the equivalent model of a NFC/RFID tag in presence of a magnetic field.

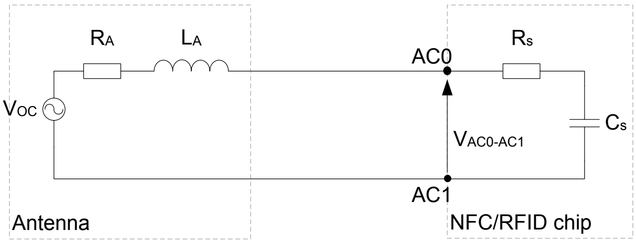
The loop antenna model includes:

- **V_{oc}**: open circuit voltage delivered by the antenna, depends upon the magnetic field strength, the antenna size and the number of turns
- **R_A**: equivalent antenna series resistance
- **L_A**: equivalent inductance defined by $L_A = X_a / \omega$, where X_A is the antenna reactance

The NFC / RFID chip model includes:

- **R_S**: series resistive component of the chip input stage
- **C_S**: series capacitive component of the chip input stage

Figure 3. Equivalent model of an NFC / RFID tag in presence of a magnetic field



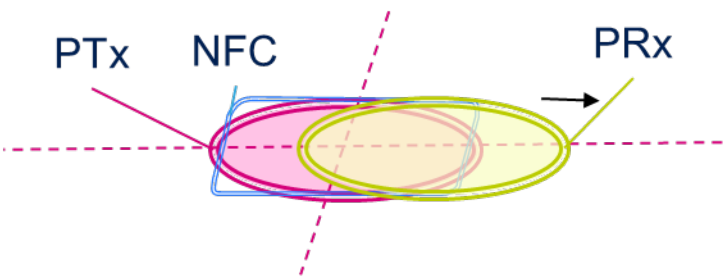
It is possible to measure the impact of PTx on tag by measuring the voltage at tag antenna pins without the RFID/NFC chip. Indeed, when there is no chip, the ciucuit is open and $V_{AC0-AC1} = V_{oc}$

To measure V_{OC}:

- Put tag antenna without the RFID chip inside the power transfer system, between the PTx and PRx
- Probe antenna pins with scope using a differential probe or by using two probes with the ground tips connected together and floating (not connected to any other point). Warning: antenna voltage may be as high as 100 Vpp, the user must ensure that the probes and the scope inputs can actually sustain this voltage.

The worst case has been observed to occur when the PRx load is minimum, the 15 W power transfer is setup and steady, and the PRx is slided very slowly away from the PTx on the antenna plane as shown on Figure 4.

Figure 4. Worst case of power charging for NFC tag



This is because the PRx receives less and less power and therefore requests the PTx to send more energy to compensate for this loss. As the PRx is moved away slowly, the magnetic field increases until tthe communication between PTx and PRx is broken or PTx exceeds its maximum power. This is why even a low load on PRx leads to a high magnetic field generated by PTx.

A value of V_{OC} = 100 V is used as a worst case observed.

If this voltage exceeds the maximum rating provided in following table, a protection measure must be taken to avoid tag damage.

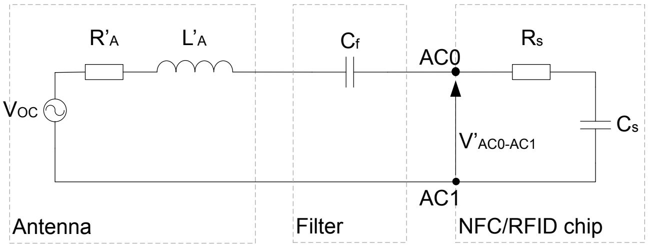
Table 1. Voltage limit in ST25 Series

ST25 Series	Maximum $V_{OC,\ peak\text{-}peak}$ (V)
ST25TV, ST25DV	5.5
ST25TA	4.0

4 How to choose the capacitance value for protection

Here is the equivalent model of the tag with additional capacitance connected in series to filter the low frequency signal.

Figure 5. Equivalent model of the tag with filter



A high C_f value is better to minimize impact on antenna design and quality factor while a lower C_f is better to minimize the risk of damage by power transmitter. This is summarized in following table.

Table 2. Impact of C_f value on tag system

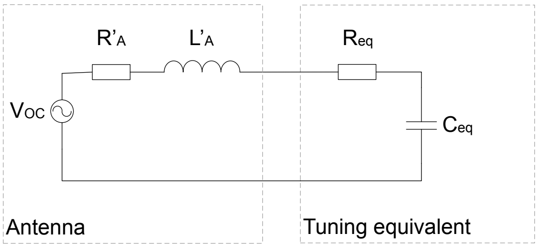
C_f value	Low	High
Antenna detuning	High	Low
LF protection	High	Low

4.1 Impact of C_f on NFC tag tuning

This section describes the impact of C_f on antenna tuning at 13.56 MHz.

The addition of C_f is a modification of the complex impedance to be considered for antenna tuning.

Figure 6. Equivalent model of the tag with filter (for antenna tuning)



The capacitance value C_{eq} is calculated according to the following equation:

$$C_{eq} = \frac{C_f C_s}{C_f + C_s}$$

The value of C_S is provided in ST25 datasheet as “internal tuning capacitance”. Values for various ST25 products are summarized in the following table.

Table 3. Internal tuning capacitance of ST25 device

Device	Internal tuning capacitance (pF)
ST25DV-xxx-xxxxx3 ST25TV64K-xxxx3	28.5
ST25TA02KB-xxxx5 ST25TA512B-xxxxx5	50
ST25TA16K-xxxx3 ST25TA64K-xxxx3	25
ST25TV02K-xxxx3	23.5
ST25TV02K-xxxx9	97

The following two graphs show the total equivalent series capacitance C_{eq} as a function of the filtering capacitance C_f for different ST25 chip internal tuning capacitance values C_{chip}.

Figure 7. Equivalent capacitance (low C_{chip})

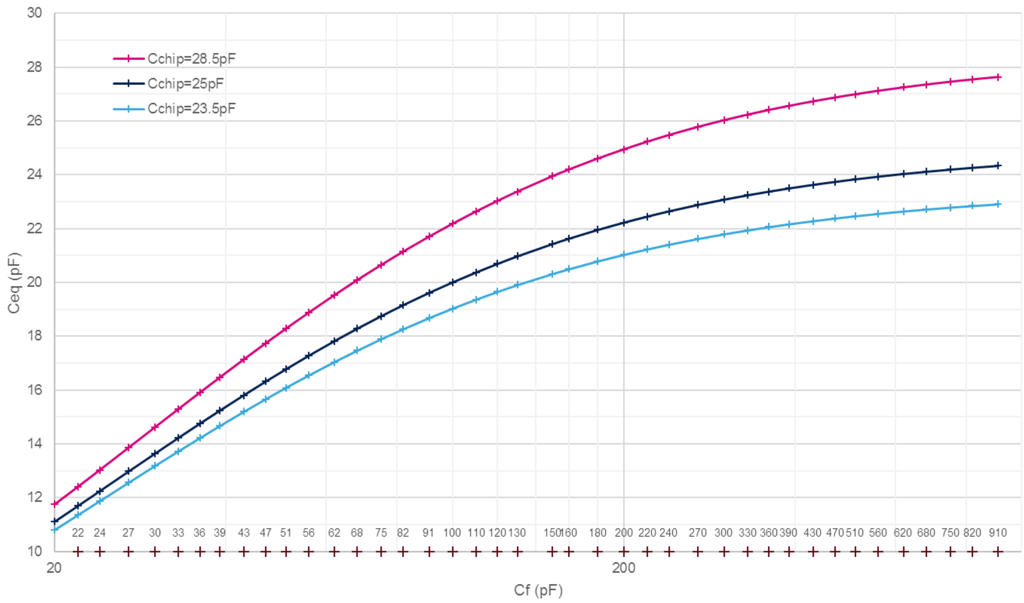
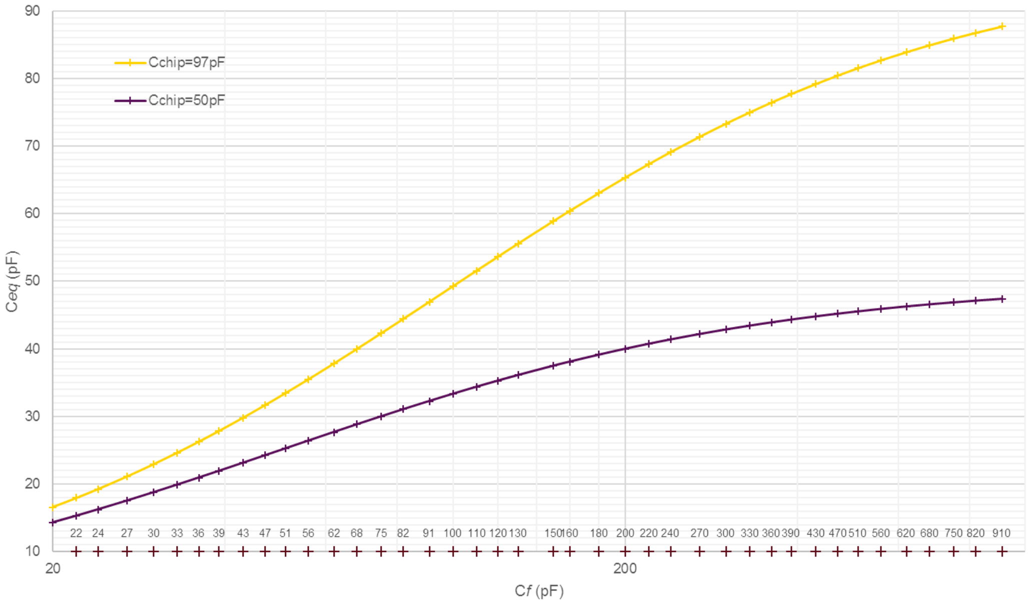


Figure 8. Equivalent capacitance (high C_{chip})



As summarized above, the plots show that a higher C_f has less impact on total equivalent serial capacitance and thus on the antenna tuning and tag characteristics.

4.2 Designing a new antenna taking into account the filter

Designing an antenna with the serial capacitance filter C_f follows the same procedure as for the tag IC alone but instead of considering the IC tuning capacitance C_s to compute the right antenna inductance L_a, the equivalent tuning capacitance C_{eq} must be considered to compute the right antenna inductance L_a'.

Refer to AN2866 “how to design a 13.56 MHz customized antenna for ST25 NFC/RFID tags” for details.

4.3 Modifying an existing antenna to take into account the filter

In case an existing tag with an antenna is modified to add the filter, it is important to know how the antenna must be modified to compensate the addition of the capacitance value C_f. The previous section showed that the lower is C_f, the more corrections are required on the antenna.

The following terminology is used hereafter:

L_a and R_a: the equivalent inductance and resistance of the antenna used in the tag without filter.

L_a' and R_a': the equivalent inductance and resistance of the antenna used in the tag with filter.

4.3.1 New antenna inductance

To maintain the tag tuning frequency when using the capacitance filter C_f, the antenna inductance must be modified to:

$$L'_a \approx \frac{C_f + C_s}{C_f} L_a$$

Regarding the antenna geometry, adding the serial capacitance C_f requires to add turns in order to compensate the decrease of the serial equivalent capacitance C_{eq}.

4.3.2 Impact on chip voltage

$V_{AC1\text{-}AC0}$ is used by the tag for tele-alimentation, so the critical operating point for performance is the value allowing a power-on-reset of the chip.

To evaluate the impact of the filter on the performance when the tag receives a weak RFID/NFC signal, the variation of performance, with and without filter, is expressed by the ratio between the voltage obtained at chip antenna in the system with filter and the voltage in the system without filter.

Assuming L_a' is chosen according to Section 4.3.1 New antenna inductance, and considering operation at resonance frequency, this gain is expressed as:

$$\frac{V'_{AC0-AC1}(\omega_0)}{V_{AC0-AC1}(\omega_0)} \approx \frac{R_S + R_a}{R_S + R'_a}$$

This expression shows that in case R_a' is equal or very close to R_a the reading distance is equivalent, while if R_a' increases significantly compared to R_s and R_a the reading distance is degraded.

As seen in Section 4.3 Modifying an existing antenna to take into account the filter, a value of C_f close to C_s requires adding many antenna turns which increases significantly the resistance of the antenna and consequently decreases the reading distance of the tag.

However applicative tests show that the impact is really relevant only for C_f value very close to C_S. That's why, unless the LF voltage to filter-out requires it, it is better to use a C_f value higher than $2 \times C_S$.

4.3.3 Impact on tag quality factor

The tag quality factor has an impact on the loading effect, also named “influence of the listener on the operating field” by NFC Forum specification. Since this value is bounded by RFID/NFC specifications, it is interesting to express how the tag quality factor behaves with new antenna.

If L'_a is chosen according to Section 4.3.1 New antenna inductance, the expression of the new quality factor of the tag is the following:

$$Q'_{tag} \approx Q_{tag}\frac{C_f + C_S}{C_f} \cdot \left(1 - \frac{\Delta R_a}{R'_a + R_S}\right)$$

Where:

$\Delta R_a = R'_a - R_a$

This expression shows that if $C_f \gg C_s$ and $R'_a \approx R_a$, the quality factor is equivalent, else, the quality factor is increased. So in case C_f is comparable to C_s and many antenna turns have been added, the loading effect increases significantly.

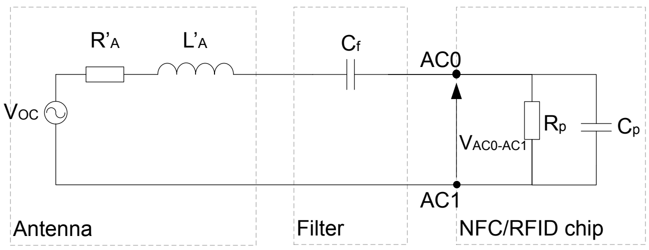
Note that the change in tag quality factor cannot be related to a change in reading distance performance because of the presence of the filter capacitor: the voltage increase with Q_{tag} is true before C_f and not at chip level

4.4 Impact of Cf on PTx protection

This section describes the impact of C_f value on the effectiveness of the protection against PTx low frequency signal.

The value of $V_{AC0\text{-}AC1}$ may be expressed as a function of induced voltage V_{OC}, filtering capacitor C_f and chip impedance with a parallel resistor R_p and parallel capacitor C_p as showed in following figure:

Figure 9. Equivalent model of tag with filter



$$V_{AC0} - AC1 = \frac{V_{OC}}{\left(1 - \omega^2 C_p L'_a + \frac{R'_a}{R_p} + \frac{C_p}{C_f}\right) + j\omega\left(\frac{L'_a}{R_p} + C_p R'_a - \frac{1}{R_p C_f \omega^2}\right)}$$

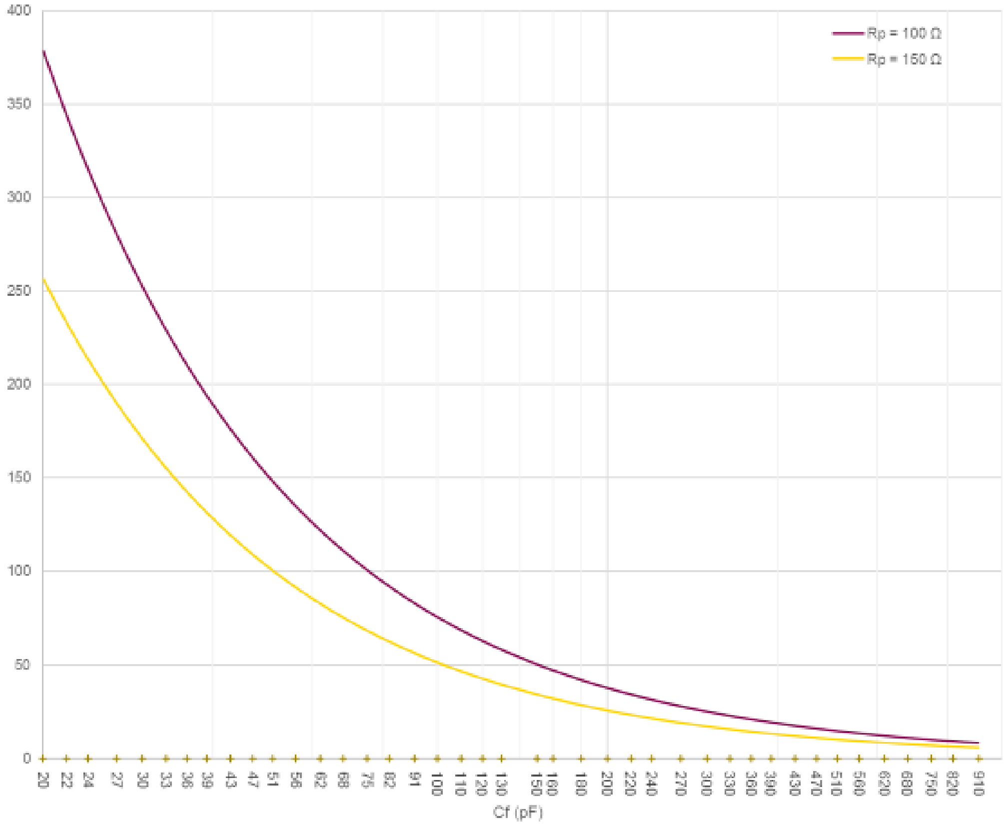
Knowing the maximum value $V_{AC0\text{-}AC1} = V_{MAX\_1}$ supported by the chip, its $R_p(V_{AC0\text{-}AC1})$ and C_p, it is possible to determine the values of C_f protecting the chip for a given induced voltage.

The following graph shows the voltage attenuation for various values of C_f: $\frac{V_{AC0} - AC1(C_f)}{V'_{AC0} - AC1(C_f)}$

It is a primary order approximation assuming a constant mutual between the reader and the tag (V_{OC} = V'_{OC}

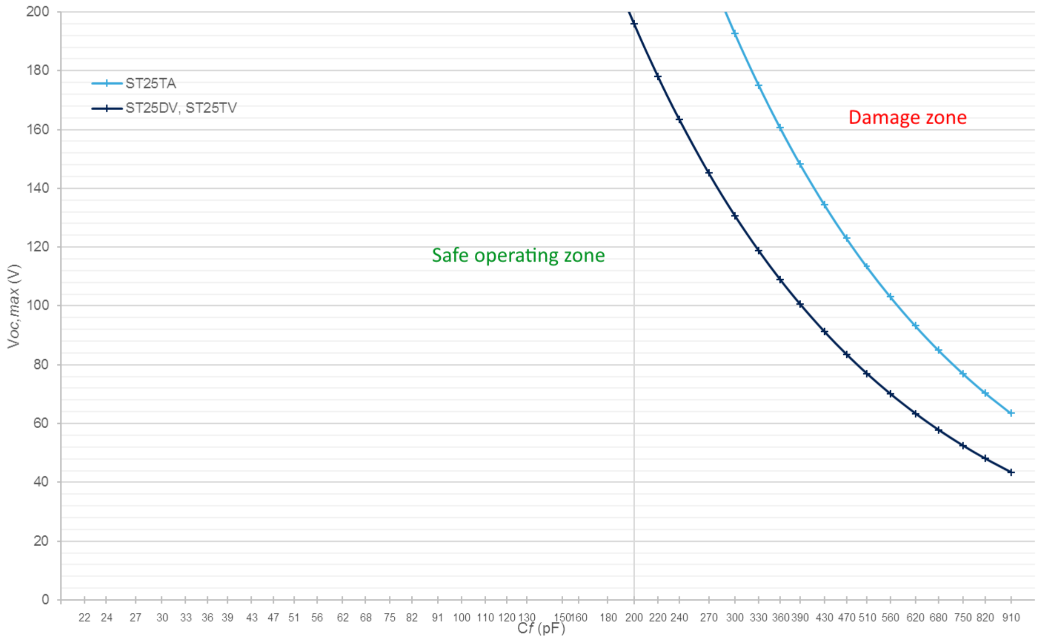
The same plot apply for all ST25 C_p values. R_p = 150 Ω must be considered for ST25 Series compliant with ISO/IEC 15693 standard while R_p = 100 Ω must be considered for ST25 Series compliant with ISO/IEC14434 standard.

Figure 10. Filter attenuation at 200 kHz



Going further, the following diagram represents directly the zone of safe operation for a given V_{OC}: the area below the curve is the V_{OC} values for which there is no damage risk for the chip.

Figure 11. **LF voltage filtered by capacitance value**



In this diagram:

- Computations have been done with f_{PTx} = 200 kHz which is the worst case of the range [80-200 kHz]
- C_p small variation has a negligible effect on result, that's why ST25DV and ST25TV share the same plot

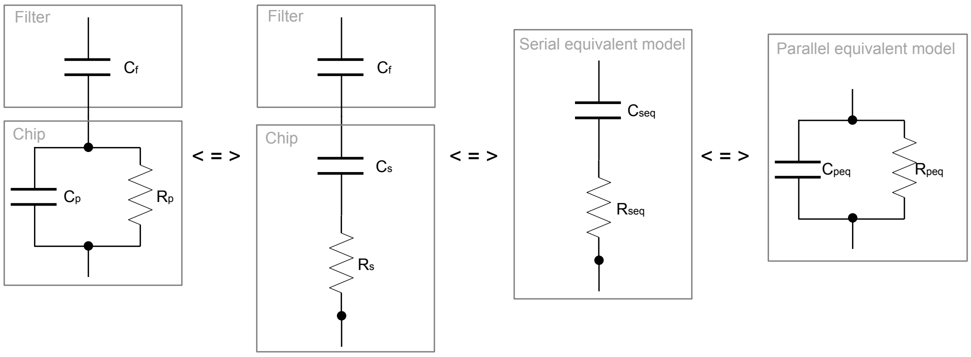
Appendix A Equations

This appendix details the calculations of the formulas used in the body of the document.

A.1 Conversion of tag with protection

Below are generic formulas used to convert the between various equivalent model topologies.

Figure 12. **Equivalent model conversions**



Conversion 1:

$$C_S = C_P \frac{1 + Q_{chip}^2}{Q_{chip}^2}$$

Where:

$$Q_{chip} = \omega C_P R_P = \frac{1}{\omega C_S R_S}$$

$$R_S = R_P \frac{1}{1 + Q_{chip}^2}$$

Conversion 2:

$$C_{seq} = \frac{C_f C_S}{C_f + C_S}$$

$$R_{seq} = R_S$$

Conversion 3:

$$C_{peq} = C_{seq} \frac{Q_{eq}^2}{1 + Q_{eq}^2}$$

Where:

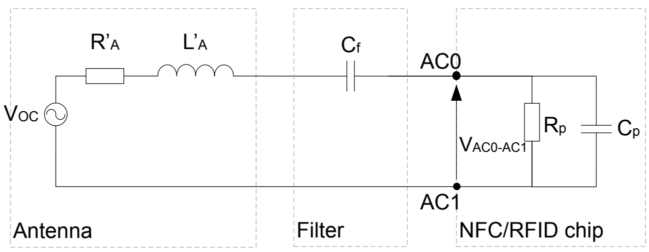
$$Q_{eq} = \frac{1}{\omega C_{seq} R_{seq}} = \frac{C_f + C_S}{\omega C_f C_S R_S} = Q_{chip} \frac{C_f + C_S}{C_f}$$

$$R_{peq} = R_{seq}\left(1 + Q_{eq}^2\right)$$

A.2 Expression of $L'_a = f(L_a)$

Below are the calculations corresponding to Section 4.3.1 New antenna inductance.

Figure 13. Equivalent model of tag with filter



System with filter:

$$V_{AC0-AC1} = \frac{V_{OC}}{\left(1 - \omega^2 C_p L'_a + \frac{R'_a}{R_p} + \frac{C_p}{C_f}\right) + j\omega\left(\frac{L'_a}{R_p} + C_p R'_a - \frac{1}{R_p C_f \omega^2}\right)}$$

Resonance occurs when the module is maximum: $1 + \omega^2 C_p L'_a + \frac{R'_a}{R_p} + \frac{C_p}{C_f} = 0$

Focusing at POR operating point where: $\frac{R'_a}{R_p} \ll 1$

$$L'_a = \frac{1 + \frac{C_p}{C_f}}{\omega_0^2 C_p} = \frac{C_f + C_p}{C_f} \cdot \frac{1}{\omega_0^2 C_p}$$

The goal is to keep the same resonant frequency (ω_0) than the system without filter for which it can be demonstrated that: $L_a \approx \frac{1}{\omega_0^2 C_p}$

So the expression becomes:

$$\mathbf{L'_a \approx \frac{C_f + C_p}{C_f} \cdot L_a}$$

A.3 Voltage attenuation introduced by the filtering capacitance

This is the calculation corresponding to Section 4.3.2 Impact on chip voltage using notation of the Figure 3. Equivalent model of an NFC / RFID tag in presence of a magnetic field and Figure 5. Equivalent model of the tag with filter.

$$\frac{V_{AC1-AC0}(\omega_0)}{V'_{AC1-AC0}(\omega_0)} = \frac{1}{G} = \frac{\frac{L'_a}{R_p} + C_p R'_a - \frac{1}{R_p C_f \omega_0^2}}{\frac{1}{R_p C_p \omega_0^2} + C_p R_a}$$

$$\frac{1}{G} = \frac{c_p \omega_0^2 L'_a + R_p R'_a C_p^2 \omega_0^2 = \frac{C_p}{C_f}}{1 + C_p^2 R_p R_a \omega_0^2}$$

Resonance occurs when: $1 - \omega_0^2 C_p L'_a + \frac{C_p}{C_f} = 0$ so $\omega_0^2 C_p L'_a - \frac{C_p}{C_f} = 1$

Since $R_p = R_s (1+Q^2)$

$$G = \frac{1 + \frac{Q_{chip}^2 R_a}{R_s\left(1 + Q_{chip}^2\right)}}{1 + \frac{Q_{chip}^2 R'_a}{R_s\left(1 + Q_{chip}^2\right)}} = \frac{1 + Q_{chip}^2 + \frac{Q_{chip}^2 R_a}{R_s}}{1 + Q_{chip}^2 + \frac{Q_{chip}^2 R'_a}{R_s}} = \frac{1 + Q_{chip}^2\left(1 + \frac{R_a}{R_s}\right)}{1 + Q_{chip}^2\left(1 + \frac{R'_a}{R_s}\right)}$$

$$\mathbf{G = \frac{A}{A + Q_{chip}^2 \frac{\Delta R_a}{R_s}}}$$

Numerical application: $Q_{chip}>10$, so $Q_{chip}^2\left(1 + \frac{R_a}{R_s}\right) \gg 1$ and the expression may be simplified:

$$G = \frac{1 + Q_{chip}^2\left(1 + \frac{R_a}{R_s}\right)}{1 + Q_{chip}^2\left(1 + \frac{R'_a}{R_s}\right)} \approx \frac{1 + \frac{R_a}{R_s}}{1 + \frac{R'_a}{R_s}}$$

$$\mathbf{G \approx \frac{R_s + R_a}{R_s + R'_a}}$$

A.4 Quality factor of the tag

This section shows calculations corresponding to Section 4.3.3 Impact on tag quality factor.

$$Q_{tag} = \frac{R_S}{R_a + R_S} Q_{chip}$$

$$Q'_{tag} = \frac{R_S}{R'_a + R_S} Q_{eq}$$

where $Q_{chip} = \frac{1}{\omega_0 C_S R_S}$

and $Q_{eq} = \frac{1}{\omega_0 C_{seq} R_{seq}}$

so:

$$Q'_{tag} = \frac{R_S}{R'_a + R_S} \cdot \frac{1}{\frac{\omega_0 C_f C_S R_S}{C_f + C_S}} = \frac{R_S}{R'_a + R_S} \cdot \frac{C_f + C_S}{\omega_0 C_f C_S R_S}$$

To simplify, decomposing $\frac{R_S}{R'_a + R_S} = \frac{R_S}{R_a + \Delta R_a + R_S}$ using following formula:

$$\frac{a}{b+c} = \frac{a}{b} + x \Rightarrow x = \frac{a}{b+c} - \frac{a}{b} = \frac{ab - a(b+c)}{(b+c)b} = \frac{a}{b} \cdot \frac{b - b - c}{b+c} = \frac{ac}{b(b+c)}$$

Introducing it with $b = R_a + R_S$ and $c = \Delta R_a$:

$$Q'_{tag} = \frac{R_S}{R'_a + R_S} \cdot \frac{C_f + C_S}{\omega_0 C_f C_S R_S} - \frac{R_S \Delta R_a}{(R_a + R_S)(R'_a + R_S)} \frac{C_f + C_S}{\omega_0 C_f C_S R_S} = Q_{tag} \frac{C_f + C_S}{C_f} - Q_{tag} \frac{C_f + C_S}{C_f} \frac{\Delta R_a}{(R'_a + R_S)}$$

$$Q'_{tag} = Q_{tag} \frac{C_f + C_S}{C_f} \left(1 - \frac{\Delta R_a}{(R'_a + R_S)}\right)$$

Revision history

Table 4. **Document revision history**

Date	Version	Changes
04-Sep-2019	1	Initial release.
13-Sep-2019	2	Changed confidentiality level

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