AN11276

NTAG Antenna Design Guide

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242115 **COMPANY PUBLIC**

Document information

Info	Content
Keywords	NTAG, NTAG I²C, NTAG I²C *plus*, RFID Tag, Antenna Theory, Antenna Design, Measurement Methods, Antenna Design Procedure
Abstract	NTAG ICs need to be connected to an antenna to turn them into an operational RFID tag. This application note provides guidance for designing such antenna.

Revision history

Rev	Date	Description
1.5	20160427	Security status changed into COMPANY PUBLIC
1.4	20160201	NTAG I²C and NTAG I²C *plus* added
1.3	20130408	NTAG210 and NTAG212 added
1.1	20121106	Small text correction
1.0	20121012	First release

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1. Introduction

NXP Semiconductors´ NTAG ICs provide a platform for the design of NFC Forum Type 2 Tag compliant tags and are designed to be used with NFC Forum´s ISO/IEC 14443A enabled devices.

The RF interface complies with part 2 and 3 of the ISO/IEC 14443A standard [4] and [6].

Communication with the NTAG IC can only be established when the IC is connected to an antenna. This document provides all necessary information to design antennas for NXP NTAG ICs that are compatible with NFC compliant read / write devices.

Note: in RFID terminology an antenna is sometimes referred to as a coil.

1.1 Structure of the document

This document is subdivided into several parts.

Section 2 provides an overview of the theory of an antenna design.

Section 3 contains a description of various measurement methods to measure and calculate the equivalent circuits of an antenna. This section also provides a list of applicable instruments.

Section 4 provides a practical procedure for the development of rectangular, square or round (circular) antennas with cupper wire, etched or printed antenna material.

Section 5 contains a link to the ISO/IEC 14443 standard that defines six antenna classes. NXP Semiconductors offers reference designs for “Class 4”, “Class 5” and “Class 6” antennas that can be used to design an NFC tag based on the NTAG. This section also contains the Gerber files for the reference designs.

Some NTAG ICs, like the NTAG203F, NTAG213F, NTAG216F offer a so-called “Field detect” pin that can be used to activate an electronic device. (See AN11141 and AN11383 for description). On top NTAG I²C, NTAG I²C *plus* features an I²C interface to be connected to e.g. a microcontroller. NXP Semiconductors offers demo boards for the NTAG203F, NTAG216F, NTAG I²C and NTAG I²C *plus* that can be used to experience the functionality of the NTAG. Section 6 contains a description of the demo boards and also contains the Gerber files for the reference antenna designs.

Section 7 contains a list of abbreviations that are used throughout the document.

Customers that are familiar with antenna design can go straight to section 4 for the design of their antenna.

Note: Section 2, 3 and 4 are written for an antenna design on a label base, but are also applicable for PCB antennas. It is recommended to carry out read/ write tests with the tags and all different read / write devices that will be used with the tags.

2. Antenna theory

2.1 NTAG IC connections

The NTAG IC needs to be connected to the antenna with the pads L_A and L_B

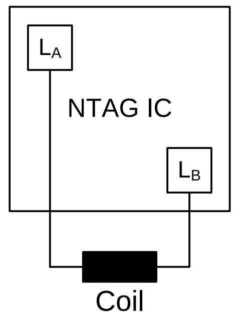

Fig 1. NTAG IC

2.1.1 NTAG IC equivalent circuit

The following simple equivalent circuit describes the properties of the NTAG IC which are relevant for the antenna design.

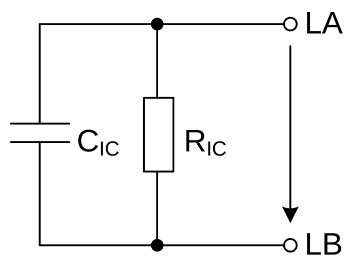

Fig 2. Equivalent circuit of the NTAG IC

2.1.2 NTAG IC input capacitance C_{IC}

This electrical parameter of the NTAG IC is the most important factor for the antenna design. The form factor and the parameters of the antenna are affected by the input capacitance

The input capacitance depends on the applied chip voltage.

The following table specifies the value of this capacitance for the given type of NTAG IC.

Table 1. Capacitance value of NTAG IC

Type		C_{IC}	Measurement conditions
NT2L1011G0DUx	NTAG210	17 pF	V_{LA-LB} = 2 Vrms, f = 13.56 MHz[1]
NT2L1211G0DUx	NTAG212	17 pF	V_{LA-LB} = 2 Vrms, f = 13.56 MHz[1]
NT2H0301F0DTx	NTAG203F	50 pF	V_{LA-LB} = 2 Vrms, f = 13.56 MHz[1]
NT2H1311G0DUx	NTAG213	50pF	V_{LA-LB} = 1.5 Vrms, f = 13.56 MHz
NT2H1511G0DUx	NTAG215	50pF	V_{LA-LB} = 1.5 Vrms, f = 13.56 MHz
NT2H1611G0DUx	NTAG216	50pF	V_{LA-LB} = 1.5 Vrms, f = 13.56 MHz
NT2H1301F0DTL	NTAG213F	50pF	V_{LA-LB} = 1.5 Vrms, f = 13.56 MHz
NT2H1601F0DTL	NTAG216F	50pF	V_{LA-LB} = 1.5 Vrms, f = 13.56 MHz
NT3H1x01W0x	NTAG I²C 1k / 2k	50pF	V_{LA-LB} = 2.4 Vrms, f = 13.56 MHz
NT3H2x11W0x	NTAG I²C *plus* 1k / 2k	50pF	V_{LA-LB} = 2.4 Vrms, f = 13.56 MHz

[1] Measured with HP4285A LCR meter

2.2 Series and parallel equivalent circuits

2.2.1 Series equivalent circuit of the antenna

The antenna can be described by an inductance L_{sc} in series to a loss resistance R_{sc}. The antenna capacitance C_c is in parallel to this series circuit. This capacitance consists of the inter-turn capacitance and a possibly designed tag capacitance. The design of such a tag capacitance is not considered in this application note.

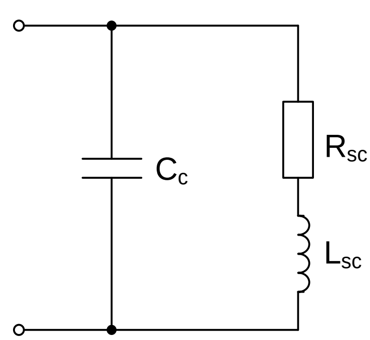

Fig 3. Series equivalent circuit of the antenna

The antenna quality factor is calculated by

$$Q_{sc} = \frac{2 \cdot \pi \cdot f_{op} \cdot L_{sc}}{R_{sc}}$$

with operating frequency f_{op} = 13.56 MHz.

2.2.2 Parallel equivalent circuit of the antenna

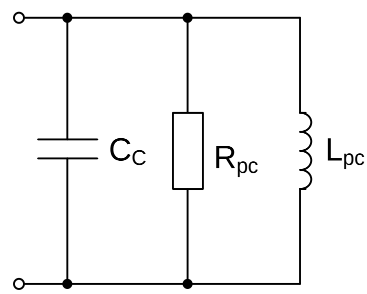

Fig 4. Parallel equivalent circuit of the antenna

The following applies:

$$L_{pc} = \frac{R_{sc}^2 + (2 \cdot \pi \cdot f_{op} \cdot L_{sc})^2}{(2 \cdot \pi \cdot f_{op})^2 \cdot L_{sc}} = L_{sc} \cdot \frac{1 + Q_{sc}^2}{Q_{sc}^2}$$

$$R_{pc} = \frac{R_{sc}^2 + (2 \cdot \pi \cdot f_{op} \cdot L_{sc})^2}{R_{sc}} = R_{sc} \cdot (1 + Q_{sc}^2)$$

$$Q_{pc} = \frac{R_{pc}}{2 \cdot \pi \cdot f_{op} \cdot L_{pc}} = Q_{sc}$$

For the further calculations the parallel equivalent circuit was chosen to simplify the resonance circuit. This makes calculation easier.

2.2.3 Equivalent circuit of the tag

The following figure shows the equivalent circuit of the whole tag.

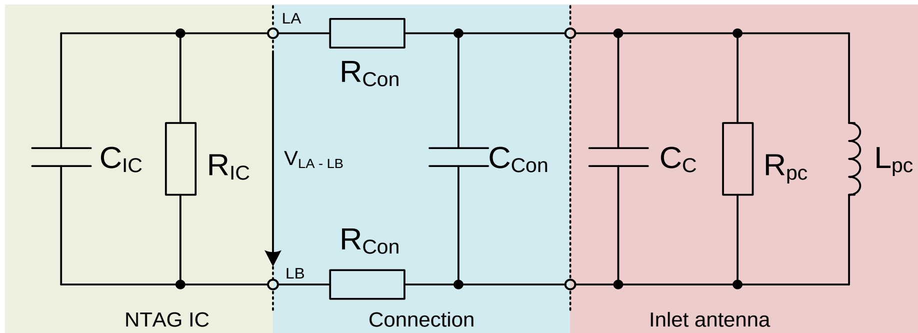

Fig 5. Equivalent circuit of the tag

The NTAG IC capacitance C_{IC} together with the antenna capacitance and the parasitic connection capacitance forms a resonance circuit with the inductance of the antenna.

The NTAG IC input resistance R_{IC} together with the loss resistance of the antenna and the connection resistance defines the quality factor of the tag. This quality factor has an effect on the threshold field strength of the tag and will be explained in the following sections.

R_{Con} should be kept as low as possible in order not to influence the total parallel equivalent resistance of the tag R_{pl}. A relatively high connection resistance will decrease the total parallel quality factor of the tag and therefore decrease the transmission range.

C_{Con} describes the increase of the total tag capacitance due to dielectric changes (under filler, adhesive …) in the connection area when the chip is applied to the antenna.

For $R_{Con} << 1\Omega$ the following simplified circuit can be used for the tag:

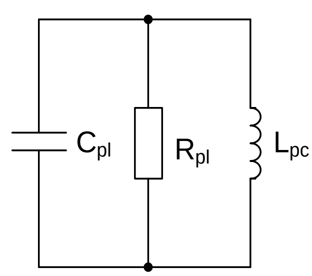

Fig 6. Simplified equivalent circuit of the tag

Parallel equivalent capacitance of the tag

$$C_{pl} = C_{IC} + C_{Con} + C_c$$

Parallel equivalent resistance of the tag

$$R_{pl} = \frac{R_{IC} \cdot R_{pc}}{R_{IC} + R_{pc}}$$

2.3 Resonance frequency and qualification factor of the tag

Based on the simplified equivalent circuit the resonance frequency f_R of the tag can be calculated with:

$$f_R = \frac{1}{2 \cdot \pi \cdot \sqrt{L_{pc} \cdot C_{pl}}}$$

The value of the NTAG IC input capacitance C_{IC} depends on the chip input voltage V_{LA-LB}. Therefore the resonance frequency of the tag changes with the IC input voltage.

Based on the simplified equivalent circuit (Fig 6) the quality factor Q of the tag at the operating frequency can be calculated with:

$$Q = \frac{R_{pl}}{2 \cdot \pi \cdot f_{op} \cdot L_{pc}}$$

The value of the NTAG IC input resistance R_{IC} depends on the chip input voltage V_{LA-LB}. Therefore also the quality factor of the tag changes with the IC input voltage.

2.3.1 Threshold resonance frequency f_{RT} and threshold quality factor Q_T

The threshold resonance frequency f_{RT} is the resulting resonance frequency for the minimum operating input voltage of the IC.

V_{LA-LB} Minimal voltage level for NTAG IC operation

$$C_{plT} = C_{ICT} + C_{Con} + C_c$$

C_{ICT} NTAG IC input capacitance for threshold condition

C_{plT} Parallel equivalent capacitance of the tag for threshold condition

C_{ICT} represents the NTAG IC input capacitance for minimal operating conditions and corresponds to the specified typical value.

$$f_{RT} = \frac{1}{2 \cdot \pi \cdot \sqrt{L_{pc} \cdot C_{plT}}}$$

$$R_{plT} = \frac{R_{ICT} \cdot R_{pc}}{R_{ICT} + R_{pc}}$$

R_{ICT} NTAG IC input resistance for threshold condition

R_{plT} Parallel equivalent resistance of the tag for threshold condition

R_{ICT} represents the NTAG IC input resistance for the minimal operating conditions and corresponds to the shown typical value.

$$Q_T = \frac{R_{plT}}{2 \cdot \pi \cdot f_{RT} \cdot L_{pc}}$$

2.4 Threshold field strength H_T

This section gives formulas to calculate the threshold field strength H_T which is significant for the transmission range. The influence of the threshold resonance frequency f_{RT} and the antenna quality factor Q_{pc} on this field strength is figured out.

The voltage on the IC generated by the magnetic field of the reader with antenna current I_1 is given by:

$$V_{LA-LB} = \frac{2\cdot\pi\cdot f\cdot M}{\left(\left(1-\left(\frac{f}{f_R}\right)^2\right)^2+\left(\frac{2\cdot\pi\cdot f\cdot L_{pc}}{R_{pl}}\right)^2\right)^{1/2}}\cdot I_1$$

With the assumption that the turns of the tag antenna are concentrated on the average antenna dimensions, the threshold field strength for NTAG IC operation can be calculated with:

$$H_T = \frac{\left(\left(1-\left(\frac{f}{f_{RT}}\right)^2\right)^2+\left(\frac{2\cdot\pi\cdot f\cdot L_{pc}}{R_{plT}}\right)^2\right)^{1/2}}{2\cdot\pi\cdot f\cdot\mu_0\cdot N_c\cdot A_c}\cdot V_{LA-LB\min}$$

The following figure shows the behavior of threshold field strength H_T versus the frequency f of the inducing magnetic field for a tag with the threshold resonance frequency f_{RT}.

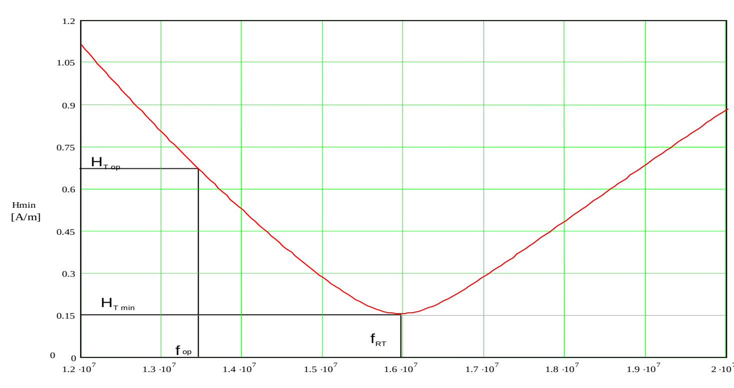

Fig 7. Threshold field strength vs. frequency

The curve of the threshold field strength reaches its minimum at the threshold resonance frequency f_{RT} of the tag. For $f=f_{RT}$ the minimal threshold field strength H_{Tmin} results in:

$$H_{T\min} = \frac{L_{pc}}{\mu_0 \cdot N_c \cdot A_c \cdot R_{plT}} \cdot V_{LA-LB\min}$$

At the operating frequency f_{op} the threshold field strength results in:

$$H_{Top} = \frac{\left(\left(1 - \left(\frac{f_{op}}{f_{RT}}\right)^2\right)^2 + \left(\frac{2 \cdot \pi \cdot f_{op} \cdot L_{pc}}{R_{plT}}\right)^2\right)^{1/2}}{2 \cdot \pi \cdot \mu_0 \cdot f_{op} \cdot N_c \cdot A_c} \cdot V_{LA-LB\min}$$

Lowest operating field strength is reached if $f_{RT} = f_{op} = 13.56$ MHz resulting in $H_T = H_{T\min}$.

3. Antenna measurement methods

3.1 Antenna characterization

The equivalent circuit of the antenna (without IC) can be determined by using the following measuring instruments with associated measuring principals.

3.1.1 Impedance analyzer with equivalent circuit calculation

The following instruments are examples of equipment that can be used to determine the value of the parameter of a serial or parallel equivalent circuit by measuring the magnitude and the phase of the impedance of the connected antenna.

Instruments: HP 4194A – Impedance analyzer

HP 4294A – LCR impedance analyzer

HP 4195A – Network/ Spectrum analyzer

HP 4295A – LCR meter

The antenna under test must be connected to the analyzer by using an appropriate test fixture that does not influence the antenna parameters (no metal parts near the antenna etc.).

Before each measurement the analyzer must be calibrated (open, short and load compensation at the calibration plane) and the test fixture compensated (open, short compensation at the connection points) according to the instruments manual.

Settings: $|Z|$, Θ

Center frequency: 13.56MHz

Span: ± 4 MHz

Parallel equivalent circuit is used for measurement. The values can then be used for the antenna design procedure.

3.1.2 Method for ISO/IEC 7810 ID-1 sized card

For ID-1 sized cards a measurement method is available.

Measurement principle:

A measurement (or calibration) antenna has to be connected to the instrument. A short-calibration has to be performed with this measurement antenna connected to the terminals of the instrument.

The measuring antenna itself is described in section 6.1 of [1] and meets the following requirements.

- Roughly the same dimensions as the calibration antenna
- 1 turn
- Low parasitic capacitance
- High quality factor; *Q* ~ 40

The measurement of the bare short-compensated measuring antenna (no tag antenna next to it) shows very low impedance. For tag characterization it has to be positioned without any distance and covering the measuring antenna completely. The measurement of R and X shows a well-defined maximum of the resistance. The resonance frequency of the tag is found at the maximum of R.

Resonance frequency: f_R @ / R = maximum

Measurement preparations:

- The measuring antenna has to be connected to the test fixture of the instrument
- A short correction of the measuring antenna has to be performed and switched on
- Settings: R, X, frequency sweep (if using LCR meter this has to be done manually or by software)
- Output power has to be set to 15mA.

3.1.3 Impedance analyzer or LCR meter

Measurement principle:

A measurement antenna has to be connected to the instrument. A short-calibration has to be performed with this measurement antenna connected to the terminals of the instrument.

The measuring antenna has to meet the following requirements:

- Roughly the same dimension as the card antenna
- 1 turn
- Low parasitic capacitance
- High quality factor; Q~40

The measurement of the bare compensated measuring antenna (no tag antenna next to it) shows very low impedance. For tag characterization it has to be positioned close to the measuring antenna (approx. 1cm distance). The measurement (R, X) of the measuring antenna shows a well-defined maximum of the resistance. The resonance frequency is found at this maximum of R.

Resonance frequency: f_R @ / R = maximum

Measurement preparations:

- The measuring antenna has to be connected to the test fixture of the instrument
- A short correction of the measuring antenna has to be performed and switched on
- Settings: R, X, frequency sweep (for LCR meter this has to be done manually or by software)
- Use highest possible output power of the measurement equipment

3.1.4 Reference measurement using capacitor

This measurement generally only verifies the antenna, because there is no IC connected. It can be used to verify the tuning of a tag.

Measurement principle:

Instead of a tag consisting of antenna with NTAG IC, now a dummy tag consisting of antenna with reference capacitor is used.

The reference capacitor should meet to following requirements:

- Value of reference capacitor optimal is the nominal capacitance of the used NTAG IC
- High quality capacitors have to be used; capacitors with a low tolerance

A measuring antenna has to be connected to the instrument. A short-calibration has to be performed with this measuring antenna connected to the terminals of the instrument.

The measuring antenna has to meet the following requirements:

- Roughly the same dimension as the card antenna
- 1 turn
- Low parasitic capacitance
- High quality factor; Q~40

The measurement of the bare compensated measuring antenna (no tag antenna next to it) shows very low impedance. The tag has to be positioned close to the measuring antenna (approx. 1cm distance). The measurement (R, X) of the measuring antenna shows a well-defined maximum of the resistance. The resonance frequency is found at this maximum of R.

Resonance frequency: f_R @ / R = maximum

Measurement preparations:

- The measuring antenna has to be connected to the test fixture of the instrument
- A short correction of the measuring antenna has to be performed and switched on

Settings: R, X, frequency sweep

3.1.5 Minimum field strength measurement

With this measurement the frequency is determined where the tag can be operated with the lowest field strength. This frequency is called resonance frequency.

This measurement is performed with the measurement configuration as it is used in [1].

4. Antenna design procedure

4.1 Design flow

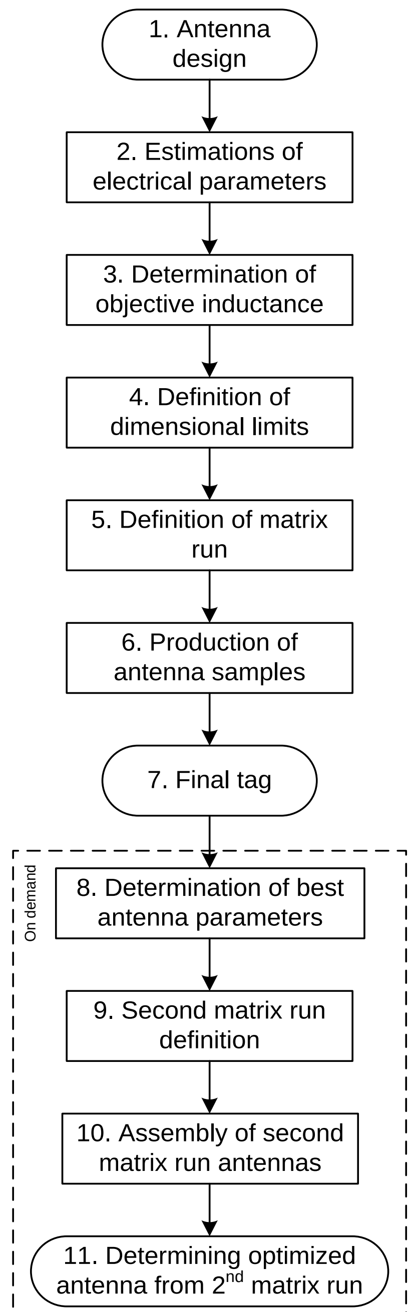

Fig 8. Design flow

4.2 Estimation of electrical parameters

4.2.1 Ideal threshold frequency f_{IDEAL} determination

Based on the application it is necessary to determine what resonance frequency the inlet should be tuned to.

For single tag operation a tuning slightly above 13.56 MHz would lead to maximum read-/write distance. Due to manufacturing tolerances a nominal frequency of 14.5 MHz for single tag operation is recommended.

4.2.2 Estimation of the antenna capacitance C_c

In order to be able to calculate the approximate objective inductance L_o of the antenna, it is necessary to estimate the capacitance C_c of the antenna. This capacitance can be split up into the always existing antenna inter turn capacitance C_{it}, the additional capacitance due to possibly realized bridge C_{br} and a possibly designed on tag capacitance C_{in}.

The antenna inter turn capacitance C_{it} is dependent upon the technology used for the antenna manufacturing. The following table shows the estimated values for some often used technologies.

Table 2. Antenna inter turn capacitance

Antenna manufacturing technology	C_{it} [pF]
Wired	5 – 7
Etched	2 – 4
Printed	2 – 4

The capacitance of a possibly realized bridge C_{br} depends on the bridge length and bridge width.

Estimated value: C_{br} = 1 – 5 pF

An additional capacitance realized on the tag C_{in} depends on the capacitor area. This capacitance is difficult to estimate, so it is recommended to make a measurement of this tag capacitor.

$$C_c = C_{it} + C_{br} + C_{in}$$

4.2.3 Estimation of the connection capacitance C_{Con}

The connection capacitance can be estimated by choosing a value out of the following range:

C_{Con} = 0.5 – 2 pF

4.2.4 Calculation of objective antenna inductance L_o based on an estimated tag capacitance C_{plT}

$$C_{plT} = C_{ICT} + C_{Con} + C_c$$

With C_{ICT} = 50 pF

$$L_o = \frac{1}{(2 \cdot \pi \cdot f_{RT})^2 \cdot C_{plT}}$$

With $f_{RT} = f_{ideal}$

4.3 Determination of objective inductance L_o

4.3.1 Rectangular (square) antennas

4.3.1.1 Calculation of inductance

The inductance of the antenna based on geometrical parameters estimates to:

$$L_{calc} = \frac{\mu_0}{\pi} \cdot [x_1 + x_2 - x_3 + x_4] \cdot N_c^p$$

with:

$$d = \frac{2 \cdot (t + w)}{\pi}$$

$$a_{avg} = a_o - N_c \cdot (g + w)$$

$$b_{avg} = b_o - N_c \cdot (g + w)$$

$$x_1 = a_{avg} \cdot \ln\left[\frac{2 \cdot a_{avg} \cdot b_{avg}}{d \cdot \left(a_{avg} + \sqrt{a_{avg}^2 + b_{avg}^2}\right)}\right]$$

$$x_2 = b_{avg} \cdot \ln\left[\frac{2 \cdot a_{avg} \cdot b_{avg}}{d \cdot \left(b_{avg} + \sqrt{a_{avg}^2 + b_{avg}^2}\right)}\right]$$

$$x_3 = 2 \cdot \left[a_{avg} + b_{avg} - \sqrt{a_{avg}^2 + b_{avg}^2}\right]$$

$$x_4 = \frac{a_{avg} + b_{avg}}{4}$$

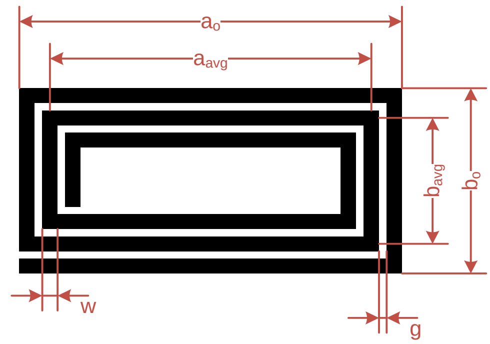

Fig 9. Rectangular antenna design

Table 3. Rectangular antenna parameter

Parameters	Description
a_o, b_o	Overall dimensions of the antenna
a_{avg}, b_{avg}	Average dimensions of the antenna
t	Track thickness
w	Track width
g	Gap between the tracks
N_c	Number of turns
d	Equivalent diameter of the track
p	Turn exponent

4.3.2 Round antennas

The inductance of the antenna based on geometrical parameters estimates to:

$$L_{calc}[nH] = 2 \cdot l \cdot \left[\ln \frac{l}{d} - 1{,}07 \right] \cdot N^{p}$$

$$l = D_{avg} \cdot \pi$$

$$D_{avg} = D_{o} - N \cdot (g + w)$$

$$d = \frac{2 \cdot (w + g)}{\pi}$$

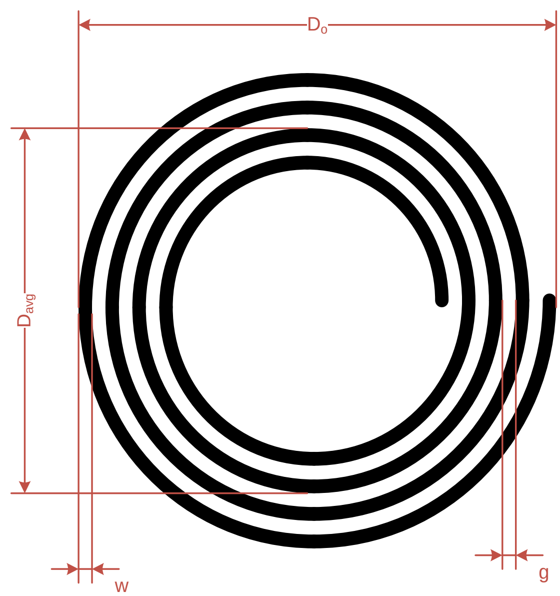

Fig 10. Round antenna design

Table 4. Round antenna parameters

Parameter	Description
D_o	Antenna diameter [cm]
t	Track thickness
w	Track width
g	Gap between the tracks
N_c	Number of turns
d	Equivalent diameter of the track
p	Turn exponent
D_{avg}	Average antenna diameter [cm]
l	Average antenna circumference

4.4 Determination of dimensional limits

4.4.1 Rectangular (square) antennas

4.4.1.1 Maximum antenna dimensions a_{max}, b_{max}

The maximum dimensions of the antenna a_{max} and b_{max} are determined by the application which the tag is designed for.

Therefore the starting point for the calculations is always:

$a_o = a_{max}$

$b_o = b_{max}$

The actual overall dimension of the antenna a_o and b_o can also be smaller than a_{max} and b_{max} in some cases (large tags) but the product $A_c \cdot N_c$ should kept always as high as possible (see "minimal threshold field strength" in section 2.4)!

$$A_c = a_{avg} \cdot b_{avg}$$

The active antenna A_{active} area is the product of average antenna area A_c and the number of turns N_c.

$$A_{active} = A_c \cdot N_c$$

4.4.1.2 Gap between the tracks *g*

The minimal gap between the tracks g_{min} is defined by the antenna production process. To get the highest possible antenna area:

$$g = g_{\min}$$

4.4.1.3 Track thickness *t* and track width *w*

For aluminum and copper antennas a track thickness of $t \geq 30\mu m$ should give a sufficient quality factor even for a small track width *w.*

For printed antennas the track thickness should be chosen as high as possible to get highest possible quality factors.

The track width *w* remains as fit-parameter for the calculation of the inductance L_{calc}. It is recommended to choose the track width *w* not to small as it influences the quality factor Q_{pc} and a variation of the track width *w* is needed for the second matrix run as well.

4.4.1.4 Estimation of turn exponent *p*

Under the assumption that all turns are concentrated on the outline of the antenna, so all magnetic flux passes the enclosed area of all turns (no stray field) and the magnetic coupling between the turns is 100%, the inductance is proportional to N_c^2.

As this is not possible to realize the following table gives estimated values for the turn exponent *p* for different antenna manufacturing technologies.

Table 5. Turn exponent *p*

Antenna manufacturing technology	p
Wired	1.8 – 1.9
Etched	1.75 – 1.85
Printed	1.7 – 1.8

4.4.2 Round antennas

4.4.2.1 Maximum antenna dimension D_{max}

The maximum dimension of the antenna D_{max} is determined by the application the tag is designed for.

Therefore the starting point for the calculation is always:

$$D_o = D_{\max}$$

The actual overall dimension of the antenna D_o can also be smaller than D_{max} in some cases (large tags) but the product $A_c \cdot N_c$ should kept always as high as possible.

$$A_c = D_{avg}^2 \cdot \frac{\pi}{4}$$

4.4.2.2 Gap between tracks *g*

The minimal gap between the tracks g_{min} is defined by the antenna production process.

To get the highest possible average antenna area:

$$g = g_{\min}$$

4.4.2.3 Track thickness t and track width *w*

For aluminum and copper antenna a track thickness of $t \geq 30\mu m$ should give a sufficient quality factor even for a small track width *w*.

For printed antennas the track thickness should be chosen as high as possible to get the highest possible quality factor.

The track width w remains as fit-parameter for the calculation of the inductance L_{calc}. It is recommended to choose the track width *w* not to small as it influences the quality factor Q_{pc} and a variation of the track width *w* is needed for the second matrix run as well.

4.4.2.4 Estimation of turn exponent *p*

Under the assumption that all turns are concentrated on the outline of the antenna, so all magnetic flux passes the enclosed area of all turns (no stray field) and the magnetic coupling between the turns is 100%, the inductance is proportional to N_c^2.

As this is not possible to realize the following table gives estimated values for the turn exponent p for different antenna manufacturing technologies.

Table 6. Turn exponent *p*

Antenna manufacturing technology	p
Wired	1.8 – 1.9
Etched	1.75 – 1.85
Printed	1.7 – 1.8

4.5 Definition of matrix run

4.5.1 Rectangular (square) antennas

4.5.1.1 Matrix run definition

The following values have to be fixed before starting the matrix run calculations:

L_o, p, a_{max}, b_{max}, t, g

The calculation of the inductance L_o is based on estimated values and also the calculation of the antenna parameters at this time can only be made approximately. Therefore the inductance of the matrix run antennas should be varied within ± 20% of the estimated objective inductance L_o.

i … first matrix run antenna number

Table 7. First matrix run

i	1	2	3	4	5
$L_{calc,\,i}$	0.8 L_o	0.9 L_o	L_o	1.1 L_o	1.2 L_o
$a_{o,\,i}$					
$b_{o,\,i}$					
$N_{c,\,i}$					
w_i					

The antenna parameters $a_{o,\,i}$, $b_{o,\,i}$, $N_{c,\,i}$ and w_i must be experimentally varied until $L_{calc,\,i}$ is equal to the given percentage of the estimated objective inductance L_o. During this antenna parameter determination it must be always attempted to keep the product $A_{c,i} \cdot N_{c,i}$ as high as possible!

4.5.2 Round antennas

4.5.2.1 Matrix run definition

The following values have to be fixed before starting the matrix run calculations:

L_o, p, D_{max}, t, g

The calculation of the inductance L_o is based on estimated values and also the calculation of the antenna parameters at this time can only be made approximately.

Therefore the inductance of the matrix run antennas should be varied within ± 20% of the estimated objective inductance L_o.

i … first matrix run antenna number

Table 8. First matrix run

i	1	2	3	4	5
$L_{calc, i}$	0.8 L_o	0.9 L_o	L_o	1.1 L_o	1.2 L_o
$D_{o, i}$					
$N_{c, i}$					
w_i					

The antenna parameters $D_{o, i}$, $N_{c, i}$ and w_i must be experimentally varied until $L_{calc, i}$ is equal to the given percentage of the estimated objective inductance L_o. During this antenna parameter determination it must be always attempted to keep the product $A_{c,i} \cdot N_{c,i}$ as high as possible!

4.6 Final antenna/ tag

To decide which antenna fits the requirements of resonance frequency best, it is recommended to measure the tag resonance frequency and compare with the targets defined at the beginning (f_{Ideal}).

For this measurement the ISO setup or a measurement as described in 3.1.3 or 3.1.4 is recommended.

Table 9. Result table

k	1	2	3	4	5
f_R					

4.6.1 Choosing the best antenna

Calculate the difference between the measured resonance frequency f_R and the ideal resonance frequency f_{Ideal}

$$\Delta f_{Ideal-R,j} = \left| f_{Ideal} - f_{R,j} \right|$$

Table 10. Optimum antenna

j	1	2	3	4	5
$f_{Ideal\text{-}R,j}$					

The optimum antenna is the antenna that´s nearest to f_{Ideal}.

$$\Delta f_{Ideal-R,j} = Minimum$$

Table 11. Summary table of parameters of antenna *j* (rectangular)

Parameter	Value
J	
$L_{pc,j}$	
$C_{c,j}$	
$a_{o,j}$	
$b_{o,j}$	
$N_{c,j}$	
w_j	

Table 12. Summary table of parameters of antenna *j* (round)

Parameter	Value
J	
$L_{pc,j}$	
$C_{c,j}$	
$D_{o,j}$	
$N_{c,j}$	
w_j	

4.7 Determination of best antenna parameters

If there is no antenna fitting to your requirements up to here, it is possible to do a second optimization step – a second matrix run.

4.7.1 Rectangular antennas

4.7.1.1 Equivalent circuit measurement and evaluation of antennas

The parallel equivalent circuit of the matrix run antennas must be determined (see also section 3).

Table 13. Measurement results

i	1	2	3	4	5
$C_{c,i}$					
$L_{pc,i}$					

i	1	2	3	4	5
$R_{pc,i}$					
$Q_{pc,i}$					

4.7.1.2 Calculation of objective antenna inductance $L_{o,i}$

The value of the antenna capacitance $C_{c,i}$ is determined for all antennas now. These values are used to calculate the objective antenna inductance $L_{o,i}$ for all antennas.

$$C_{plT,i} = C_{ICT} + C_{Con} + C_{c,i}$$

$$L_{o,i} = \frac{1}{(2 \cdot \pi \cdot f_{RT})^2 \cdot C_{plT,i}}$$

with $f_{RT} = f_{Ideal}$

4.7.1.3 Minimal difference between $L_{pc,i}$ and $L_{o,i}$

The optimum antenna of the matrix run is the one where the difference of measured inductance $L_{pc,i}$ and objective inductance $L_{o,i}$ is a minimum.

$$\Delta L_i = \left| L_{pc,i} - L_{o,i} \right|$$

Table 14. Inductance comparison

i	1	2	3	4	5
$L_{pc,i}$					
$L_{o,i}$					
ΔL_i					

The antenna number I with minimum ΔL_i: $j=i$

j … Antenna number with minimum ΔL_j

Table 15. Parameter summary

Parameter	Value
j	
$L_{pc,j}$	
$C_{c,j}$	

Parameter	Value
$a_{o,j}$	
$b_{o,j}$	
$N_{c,j}$	
w_j	

Usually the antenna chosen here is the final antenna design for NTAG designs. If more exact tuning is necessary for the application, this antenna is the starting point for the second matrix calculation.

4.7.1.4 Determination of turn exponent *p*

For the chosen antenna *j* the precise turn exponent *p* can be calculated now.

$$a_o = a_{o,j}$$

$$b_o = b_{o,j}$$

$$L_{pc,j} = L_{calc} = \frac{\mu_0}{\pi} \cdot \left[x_1 + x_2 + x_3 + x_4\right] \cdot N_{c,j}^{p}$$

$$p = \frac{\ln\left(\dfrac{L_{pc,j} \cdot \pi}{\mu_0 \cdot \left[x_1 + x_2 + x_3 + x_4\right]}\right)}{\ln N_{c,j}}$$

4.7.2 Round antennas

4.7.2.1 Equivalent circuit measurement and evaluation of antennas

The parallel equivalent circuit of the matrix run antennas must be determined (see also section 3).

Table 16. Measurement results

i	1	2	3	4	5
$C_{c,i}$					
$L_{pc,i}$					
$R_{pc,i}$					
$Q_{pc,i}$					

4.7.2.2 Calculation of the objective antenna inductance $L_{o,i}$

The value of the antenna capacitance $C_{c,i}$ is determined for all antennas now. These values are used to calculate objective antenna inductance $L_{o,i}$ for all antennas.

$$C_{plT,i} = C_{ICT} + C_{Con} + C_{c,i}$$

$$L_{o,i} = \frac{1}{(2 \cdot \pi \cdot f_{RT})^2 \cdot C_{plT,i}}$$

with $f_{RT} = f_{Ideal}$

4.7.2.3 Minimal difference between $L_{pc,i}$ and $L_{o,i}$

The optimum antenna of the matrix run is the one where the difference of measured inductance $L_{pc,i}$ and objective inductance $L_{o,i}$ is a minimum.

$$\Delta L_i = \left| L_{pc,i} - L_{o,i} \right|$$

Table 17. Inductance comparison

i	1	2	3	4	5
$L_{pc,i}$					
$L_{o,i}$					
ΔL_i					

The antenna number i with minimum ΔL_i: $j = i$

j … Antenna number with minimum ΔL_j

Table 18. Parameter summary

Parameter	Value
j	
$L_{pc,j}$	
$C_{c,j}$	
$D_{o,j}$	
$N_{c,j}$	
w_j	

Usually the antenna chosen here is the final antenna design for NTAG designs. If more exact tuning is necessary for the application, this antenna is the starting point for the second matrix calculation.

4.7.2.4 Determination of turn exponent *p*

For the chosen antenna *j* the precise turn exponent *p* can be calculated now.

$$D_o = D_{o,j}$$

$$p = \frac{\ln\left(\dfrac{L_{pc,j}}{2 \cdot l_j \cdot \left\{\ln\left({l_j}/{d_j} \right) \cdot 1{,}07 \right\}}\right)}{\ln N_{c,j}}$$

4.8 Second matrix run definition

4.8.1 Rectangular antennas

$$a_o = a_{o,j}$$

$$b_o = b_{o.j}$$

$$L_{calc} = \frac{\mu_0}{\pi} \cdot \left[x_1 + x_2 + x_3 + x_4\right] \cdot N_{c,j}^{p}$$

4.8.2 Circular antennas

$$D_o = D_{o,j}$$

$$L_{calc}\left[nH\right] = 2 \cdot l \cdot \left[\ln \frac{l_j}{d_j} - 1{,}07\right] \cdot N_{c,j}^{p}$$

4.8.3 Table for optimized antennas

The calculation of the inductance $L_{o,j}$ is still based on an estimated connection capacitance C_{Con} and also the antenna parameters have an influence on each other giving a nonlinear system. Therefore the inductance of the second matrix run antennas should be varied within ± 8% of the objective inductance $L_{o,j}$.

k … second matrix run antenna number

Table 19. Second matrix run

k	1	2	3	4	5
$L_{calc,k}$	0.92 $L_{o,j}$	0.96 $L_{o,j}$	$L_{o,j}$	1.04 $L_{o,j}$	1.08 $L_{o,j}$
w_k					

Only the antenna parameter track width w_k should be varied until $L_{calc,k}$ is equal the given percentage of objective inductance $L_{o,j}$. In order to keep the accuracy of the calculation on a high level the overall dimension a_o, b_o, D_o and the gap between the tracks *g* as well as the track thickness *t* should not be varied anymore.

4.9 Determining optimized antenna from second matrix run

4.9.1 Tag with IC

The unloaded resonance frequency f_R of the second matrix run tags should be characterized (see section 3).

A tag must be determined where the value of the measured threshold resonance frequency $f_{RT,k}$ is closest to the optimal value. The used track width w_k of this tag defines the optimum track width for the antenna.

Table 20. Result table

k	1	2	3	4	5
f_R					

4.9.2 Choosing the best antenna

Calculate the difference between the measured resonance frequency f_{RT}, and the ideal resonance frequency f_{ideal}:

$$\Delta f_{ideal-R,k} = \left| f_{ideal} - f_{R,k} \right|$$

Table 21. Optimum antenna

k	1	2	3	4	5
$f_{ideal\text{-}RTnom,k}$					

The optimum antenna is the antenna that´s nearest to f_{ideal}.

$$\Delta f_{ideal-R,k} = Minimum \qquad (1)$$

Table 22. Summary table of parameters of antenna *k*

Parameter	Value
k	
$L_{pc,k}$	
$C_{c,k}$	
$a_{o,k}$	
$b_{o,k}$	
$N_{c,k}$	

Parameter	Value
w_K	

4.10 Antenna calculation tools

NXP provides their customers an excel-based calculation tool for rectangular and round antennas, to make the antenna design easier.

The rectangular antenna calculation tool is described in NTAG_CDG_SQUARE_V1.xlsx

Round antenna calculation is described in NTAG_CDG_ROUND_V1.xlsx

5. Antenna classes

5.1 Class definition

In [3] and [5] six antenna classes are defined (Class1 – Class6). All six classes describe different form factors and sizes.

For a NFC tag, NXP recommend to use “Class 3”, “Class 4”, “Class 5” or “Class 6” antennas.

5.1.1 “Class 3” antenna

A “Class 3” antenna shall fulfill the following requirements.

The antenna shall be located within a zone defined either:

- External rectangle: 50 x 40mm
- Internal rectangle: 35 x 24mm, centered in the external rectangle, with 3mm corner radii

or

- external circle with diameter 50mm
- internal circle with diameter 32mm, concentric with the external circle

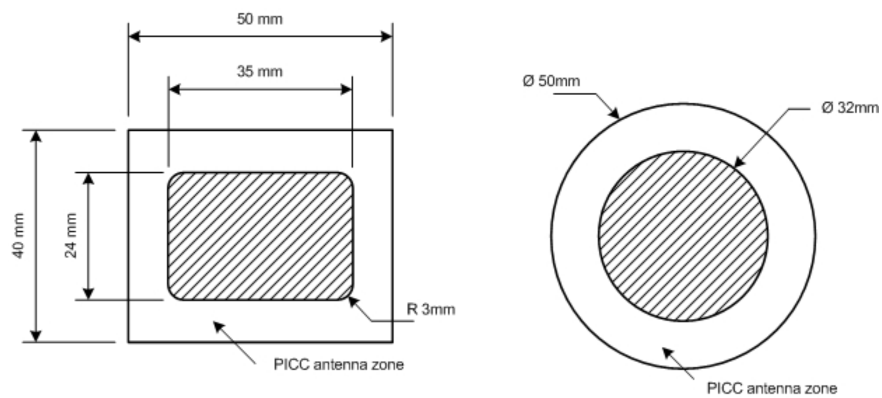

Fig 11. “Class 3” antenna

5.1.2 “Class 4” antenna

A “Class 4” antenna shall fulfill the following requirements.

The antenna shall be located within a zone defined either:

- External rectangle: 50 x 27mm
- Internal rectangle: 35 x 13mm, centered in the external rectangle, with 3mm corner radii

or

- external circle with diameter 41mm
- internal circle with diameter 24mm, concentric with the external circle

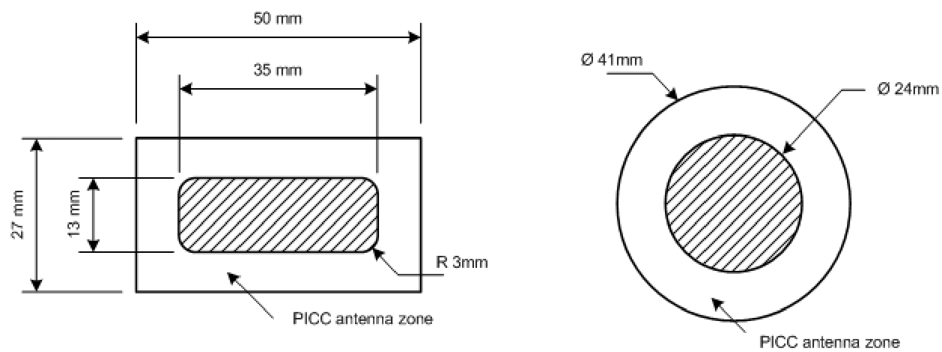

Fig 12. "Class 4" antenna

5.1.3 "Class 5" antenna

A "Class 5" antenna shall fulfill the following requirements.

The antenna shall be located within a zone defined either:

- External rectangle: 40,5 x 24,5mm
- Internal rectangle: 25 x 10mm, centered in the external rectangle, with 3mm corner radii

or

- external circle with diameter 35mm
- internal circle with diameter 18mm, concentric with the external circle

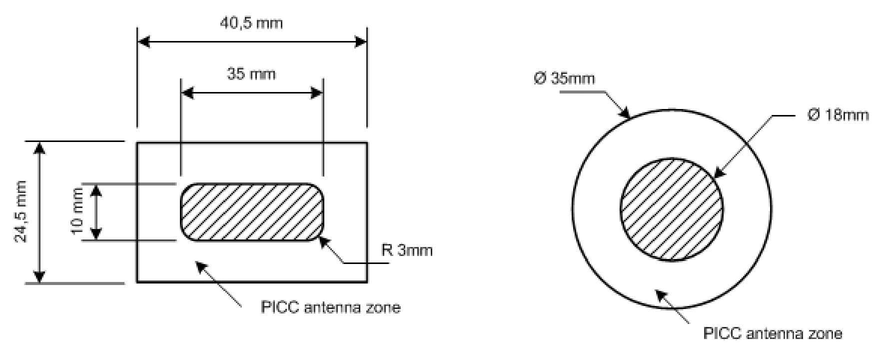

Fig 13. "Class 5" antenna

5.1.4 “Class 6” antenna

The antenna of a “Class 6” design shall be located within a zone defined by either a rectangle of dimensions 25 x 20mm or a circle of 25mm diameter.

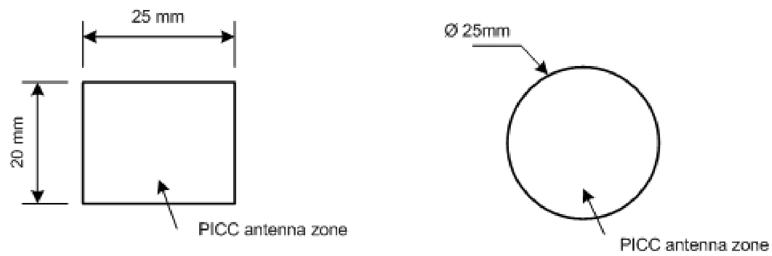

Fig 14. “Class 6” antenna

5.2 Reference antennas for NFC tags on PCBs

NXP also offers reference designs for the “Class4”, “Class5” and “Class6” antennas as a NFC tag.

5.2.1 “Class 4” reference antenna

Fig 15. “Class 4” antenna

The Gerber file for the reference design: Class_4.zip

5.2.2 “Class 5” reference antenna

Fig 16. “Class 5” antenna

The Gerber file for the reference design: Class_5.zip

5.2.3 “Class 6” reference antenna

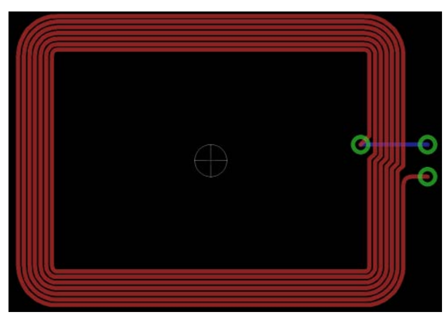

Fig 17. “Class 6” antenna

The Gerber file for the reference design: Class_6.zip

6. NTAG demo boards and reference designs

NXP offers demo boards and reference designs for the NTAG203F with “Class 5” and “Class6” antennas.

6.1 NTAG 203F demo and reference board “Class 5” antenna

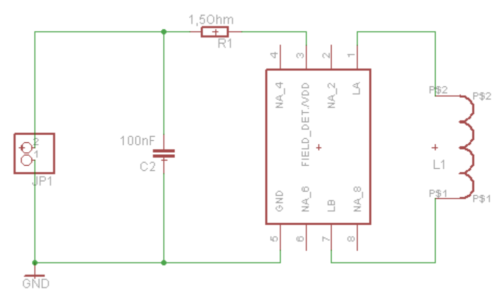

Fig 18. Circuitry of the NTAG203F “Class 5” demo board

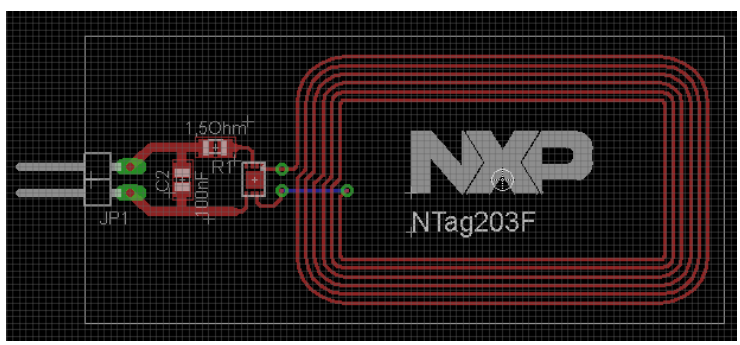

Fig 19. NTAG203F “Class 5” demo board

The Eagle files for the reference design: Class_5-NTAG203F.zip

6.2 NTAG 203F demo and reference board “Class 6” antenna

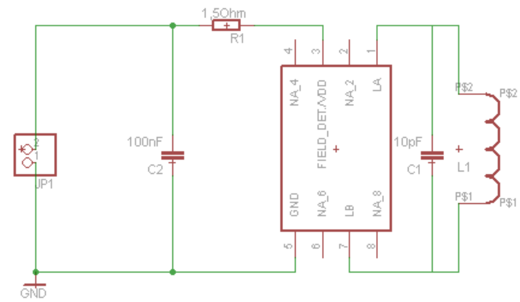

Fig 20. Circuitry of the NTAG203F “Class 6” demo board

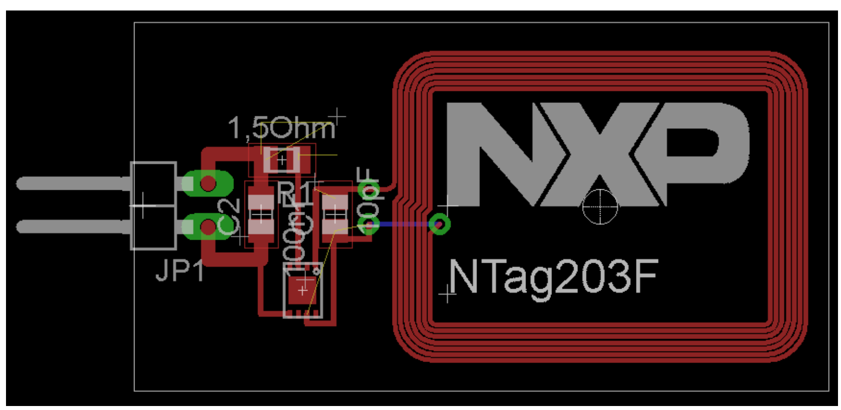

Fig 21. NTAG203F “Class 6” demo board

The Eagle files for the reference design: Class_6-NTAG203F.zip

The “Class 6” antenna is designed with a ferrite foil to use in a metal environment. More detailed information about HF antenna design with ferrite can be found in the document: “Design of 13.56 MHz Smartcard Stickers with ferrite for payment and Authentication.pdf”.

6.3 NTAG I²C *plus* Explorer board antenna

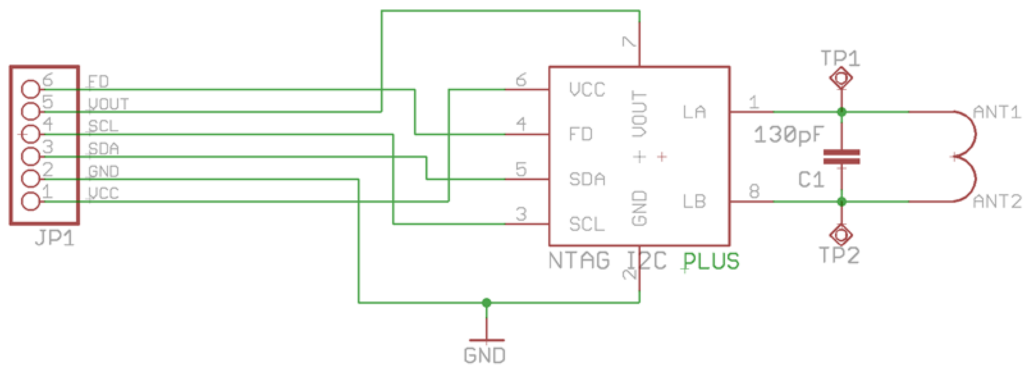

Fig 22. Circuitry of the NTAG I²C *plus* Antenna board

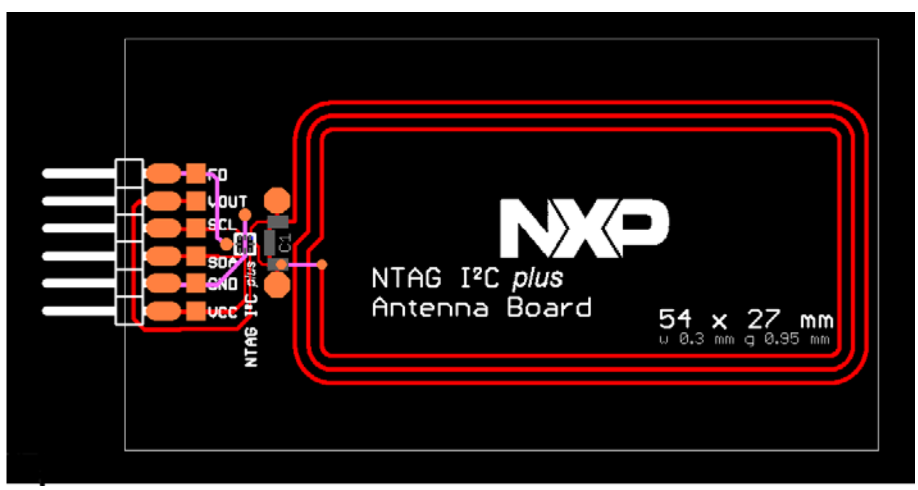

Fig 23. NTAG I²C *plus* Antenna board

The Eagle files for the reference design:
http://www.nxp.com/documents/software/SW3639.zip

7. List of abbreviations

This document uses the following list of abbreviations:

A_c	Average antenna area
A_{Active}	Active antenna area
A_i	Area of antenna winding i
a_{avg}, b_{avg}	Average dimensions of the antenna
a_{max}, b_{max}	Maximum dimensions of the antenna
a_o, b_o	Overall dimensions of the antenna
C_c	Antenna capacitance
C_{br}	Bridge capacitance
C_{Con}	Capacitance due the connection NTAG IC – antenna
C_{IC}	NTAG IC input capacitance
C_{ICT}	NTAG IC input capacitance for threshold condition
C_{in}	Designed inlet capacitance
C_{it}	Inter turn capacitance of the antenna
C_{pl}	Parallel equivalent capacitance of the inlet
C_{plT}	Parallel equivalent capacitance of the inlet for threshold condition
d	Antenna wire diameter
f	Frequency
f_{op}	Operating frequency
f_R	Resonance frequency of the inlet
f_{RT}	Threshold resonance frequency of the inlet
g	Gap between the tracks
H_T	Threshold field strength
H_{Tmin}	Minimal threshold field strength
H_{Top}	Threshold field strength at operating frequency
I_1	Reader antenna current
L_{calc}	Inductance calculated out of the geometrical antenna parameters
L_o	Objective inductance of the antenna
L_{pc}	Parallel equivalent inductance of the antenna
L_{sc}	Serial equivalent inductance of the antenna

M	Mutual inductance between the inlet antenna and reader antenna
N_c	Number of turns of the antenna
p	Turn exponent
Q	Quality factor of the inlet
Q_{pc}	Quality factor of the antenna for parallel equivalent circuit
Q_{sc}	Quality factor of the antenna for serial equivalent circuit
Q_T	Threshold quality factor of the inlet
R_{Con}	Resistance of the connection NTAG IC – antenna
R_{IC}	NTAG IC input resistance
R_{ICT}	NTAG IC input resistance for threshold condition
R_{pc}	Parallel equivalent resistance of the antenna
R_{pl}	Parallel equivalent resistance of the inlet
R_{plT}	Parallel equivalent resistance of the inlet at threshold condition
R_{sc}	Serial equivalent resistance of the antenna
t	Track thickness
$V_{LA\text{-}LB}$	NTAG IC input voltage
$V_{LA\text{-}LB\ min}$	Minimal voltage level for NTAG IC operation
w	Track width

8. Reference documentation

NXP provides several documents to support the development of customized antennas.

8.1 Datasheets

NXP provides the following datasheets:

- NTAG203F, NFC Forum Type 2 Tag compliant IC with 144 bytes user memory and field detection; http://www.nxp.com/restricted_documents/53420/NTAG203F.pdf
- NTAG210_212, NFC Forum Type 2 Tag compliant IC with 48/128 bytes user memory; http://www.nxp.com/documents/data_sheet/NTAG210_212.pdf
- NTAG213_215_216, NFC Forum Type 2 Tag compliant IC with 144/504/888 bytes user memory http://www.nxp.com/documents/data_sheet/NTAG213_215_216.pdf
- NTAG213F_216F, NFC Forum Type 2 Tag compliant IC with 144/888 bytes user memory and field detection http://www.nxp.com/documents/data_sheet/NTAG213F_216F.pdf
- NT3H1101/NT3H1201, NTAG I²C - Energy harvesting NFC Forum Type 2 Tag with field detection pin and I²C interface http://www.nxp.com/documents/data_sheet/NT3H1101_1201.pdf
- NT3H2111/NT3H2211, NTAG I²C *plus*, NFC Forum Type 2 Tag compliant IC with I²C interface http://www.nxp.com/documents/data_sheet/NT3H2111_2211.pdf

8.2 Application notes

NXP provides the following application notes:

- AN11141; NTAG203F, How to use the FD pin; http://www.nxp.com/documents/application_note/AN11141.pdf
- AN11383, NTAG21x Field Detection and sleep mode feature http://www.nxp.com/documents/application_note/AN11383.pdf
- AN11350; NTAG Originality Signature Validation; http://www.nxp.com/documents/application_note/AN11350.pdf

8.3 ISO/IEC standards

[1] ISO/IEC 10373-6:2011, *Identification cards — Test methods — Part 6: Proximity cards*

[2] ISO/IEC 14443-1:2008, *Identification cards — Contactless integrated circuit cards — Proximity cards — Part 1: Physical characteristics*

[3] ISO/IEC 14443-1:2008/Amd 1:2012, *Additional PICC classes*

[4] ISO/IEC 14443-2:2010, *Identification cards — Contactless integrated circuit cards — Proximity cards — Part 2: Radio frequency power and signal interface*

[5] ISO/IEC 14443-2:2010/Amd 2:2012*, Additional PICC classes*

[6] ISO/IEC 14443-3:2011, *Identification cards — Contactless integrated circuit cards — Proximity cards — Part 3: Initialization and anticollision*

[7] ISO/IEC 18092:2004, *Information technology — Telecommunications and information exchange between systems — Near Field Communication — Interface and Protocol (NFCIP-1)*

[8] ISO/IEC 21481:2012, *Information technology — Telecommunications and information exchange between systems — Near Field Communication Interface and Protocol -2 (NFCIP-2)*

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10. List of figures

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