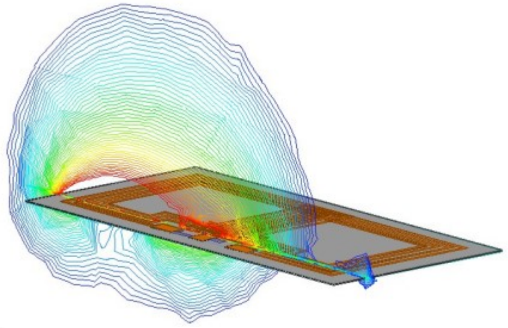

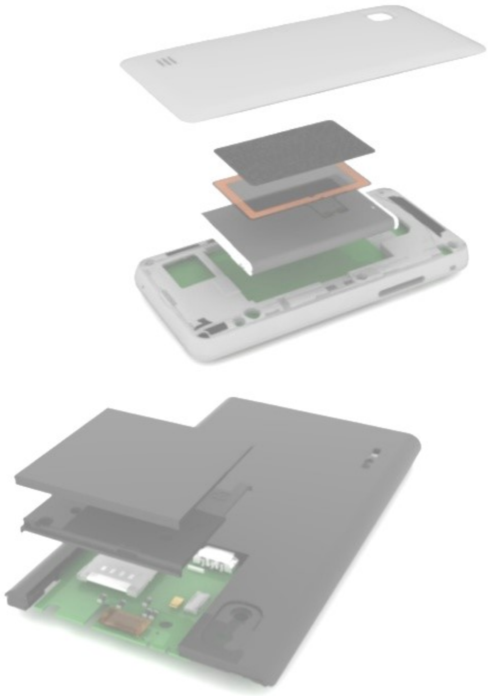

06 Contactless Transponders

6th unit in course 451.417, RFID Systems, TU Graz

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SS 2023, March 06st

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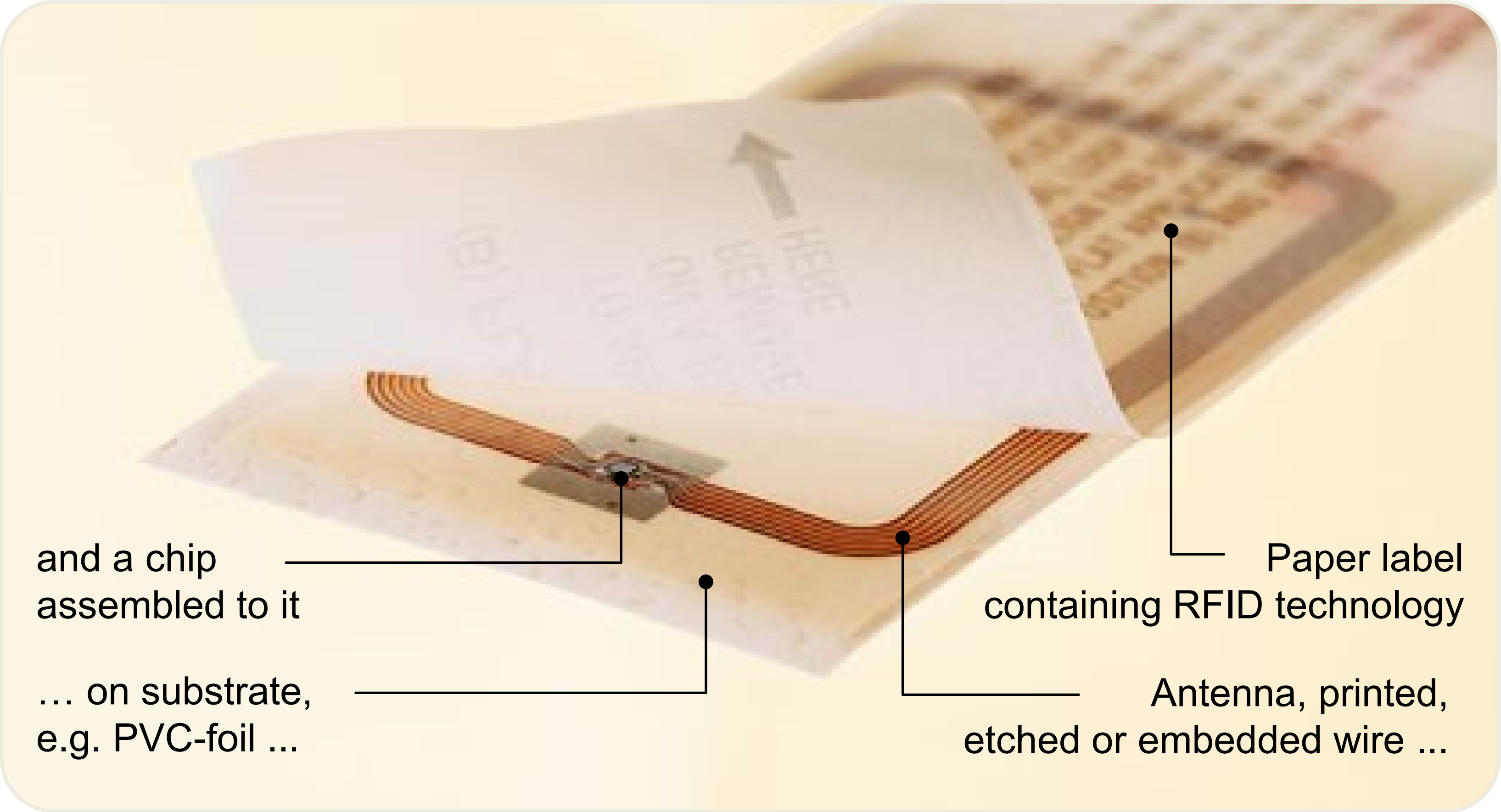
Advancing Technology

Content

- What is a contactless transponder?
  - Relevant standards for a contactless card
  - Functional blocks
  - Main circuits (simplified)
- Transponder chip impedance measurement
  - Setup
  - Typical traces for equivalent R_P, C_P over RF voltage
  - Relation to H_{MIN} based on a linear equivalent circuit model
- Simulation of 3 operational states in communication
- Stationary “Card Loading” effect
- Transponder load modulation estimation
- Examples

What is a “Smart Label”?

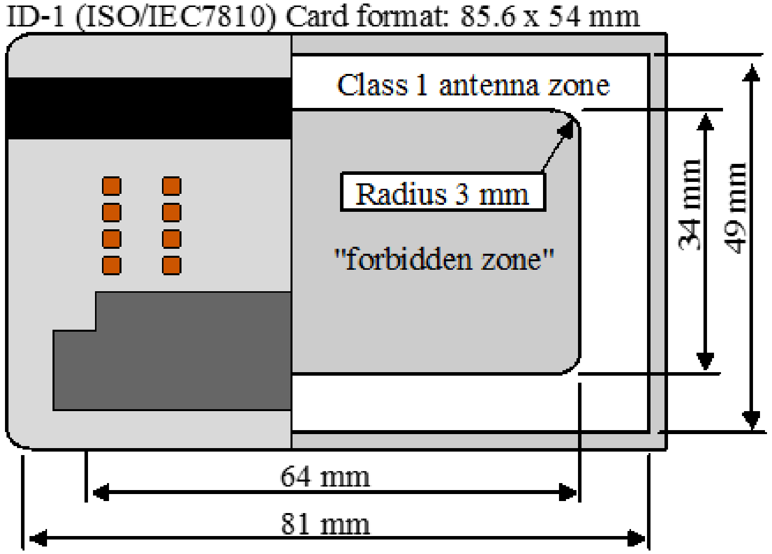
- The **contactless transponder** is the **electrically functional part**.
- “Label” refers to object-oriented tagging (e.g. logistics).



What is a “Smart Card”?

- **ISO/IEC14443**.........The **Contactless Proximity Air Interface** for **person-related applications** was standardized 2 decades ago.
- Applications in **Government** (e-Passports, driver license, health card...), **Payment** (Contactless Credit Cards), **Public Transport** (Ticketing), **Secure Access Control**, etc. are successfully deployed.
- The **battery-less**, field-proven secure chip technology did migrate into objects e.g. SD-Cards, watches, USB-Sticks, which require small antennas. This requires **more accurate characterization and production tolerance consideration**.

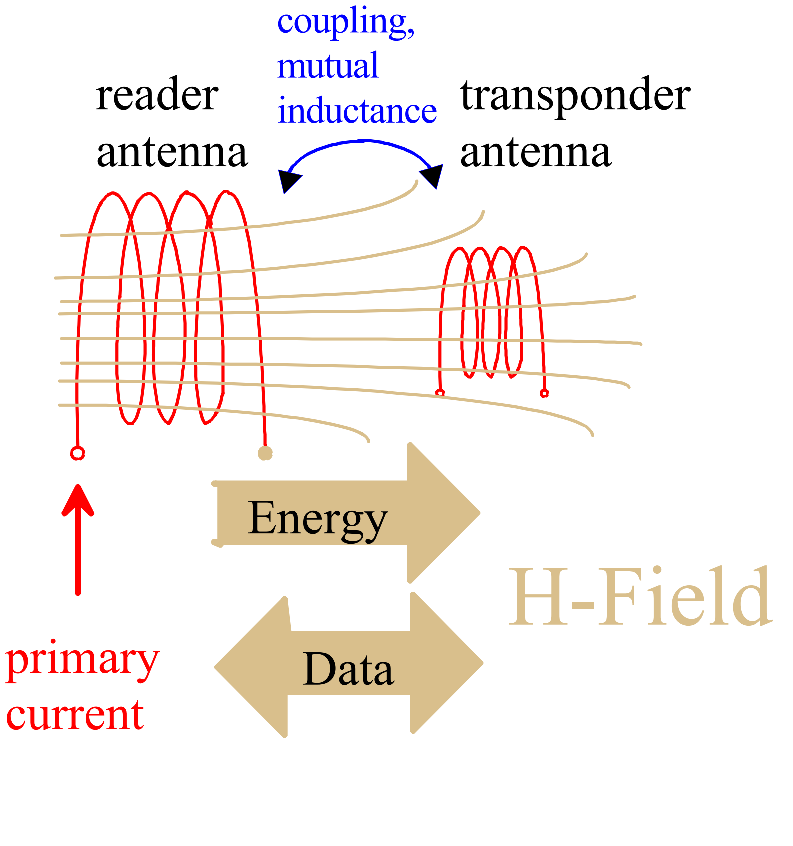
- **Related ISO/IEC Standards**
  - 7810...........Card geometry (e.g. ID-1 format) and physical properties
  - 7811-3/-3...Embossing (letters raised in relief)
  - 7811...........magnetic stripe cards
  - 7812...........optical character recognition cards
  - 7813...........bank cards
  - 7816...........contact cards with ICs
  - 10373.........test methods



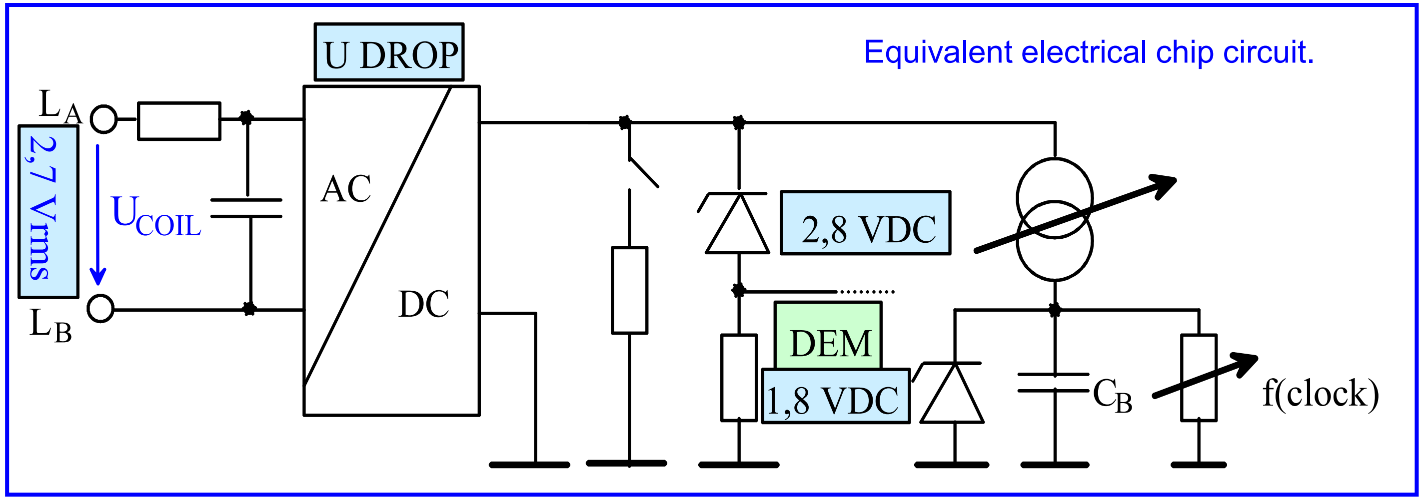
Card geometry specifications.

Introducing Contactless Proximity systems

- The Proximity coupling system operates in the 13,56 MHz world-wide license-free band in the near field (~ 10 cm range). Contactless supply power and communication interface are provided by a reader to a transponder.



Proximity (near field) communication system

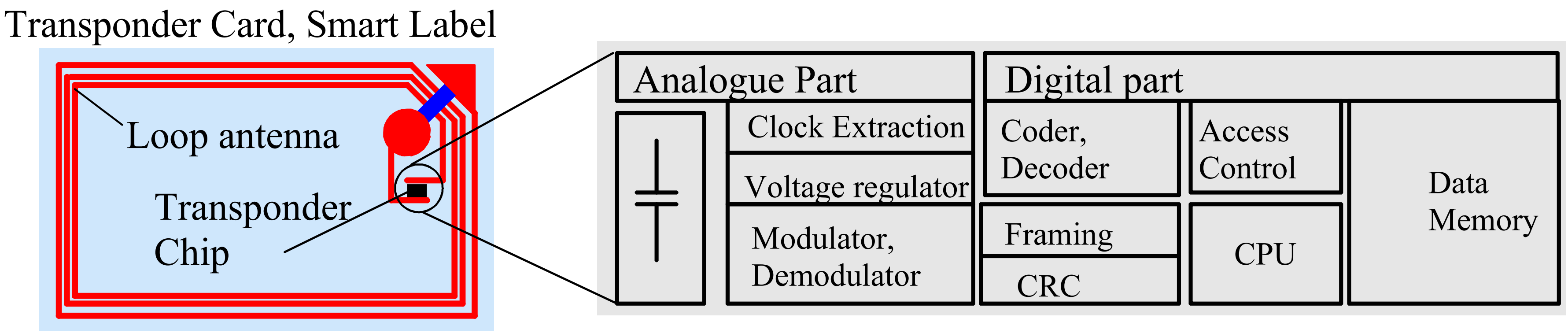


Equivalent electrical chip circuit.

- These systems „live“ from intentional de-tuning and are not 50 Ohm impedance matched between antenna and chip!

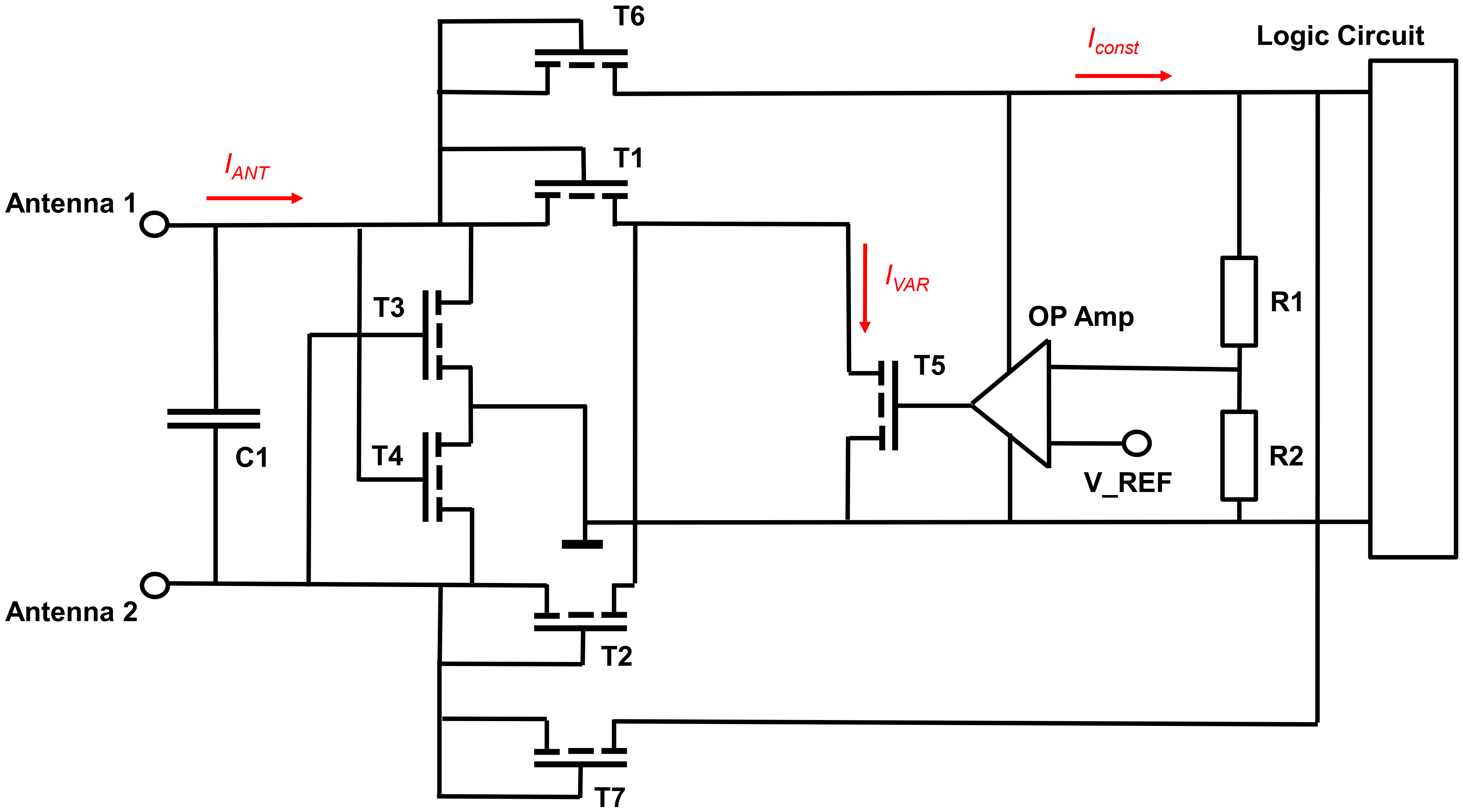
Introducing Contactless Proximity systems

- We can differentiate analog part and digital part.
- The analog part is relevant for the air interface and offers required operating conditions to the digital part.



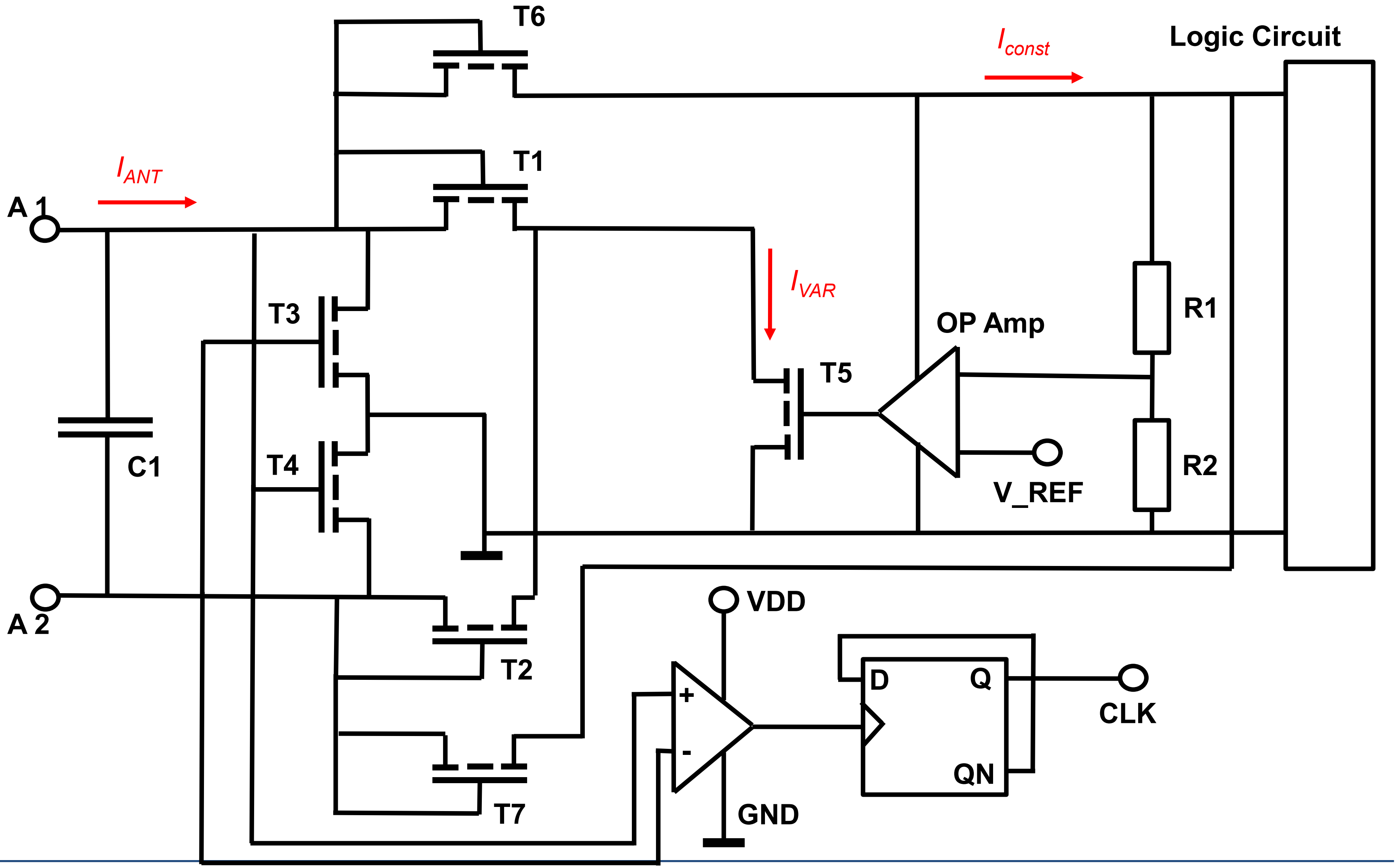
- Analog Part:
  - Over-voltage protection
  - Capacitance for resonant antenna circuit
  - Clock generation (from 13,56 MHz carrier)
  - Voltage regulator (limiter)
  - Demodulator for reader commands
  - Modulator for load modulation
- Digital Part:
  - Decoder (recognizes reader commands),
  - Encoder (for data transfer transponder ➔ reader),
  - Framing for data transmission (buffer...),
  - Error detection / protection (depends on protocol, e.g. CRC),
  - Access control (also rights, encryption,...),
  - Program and / or data memory

Typical Frontend – Supply voltage control (for the digital part)



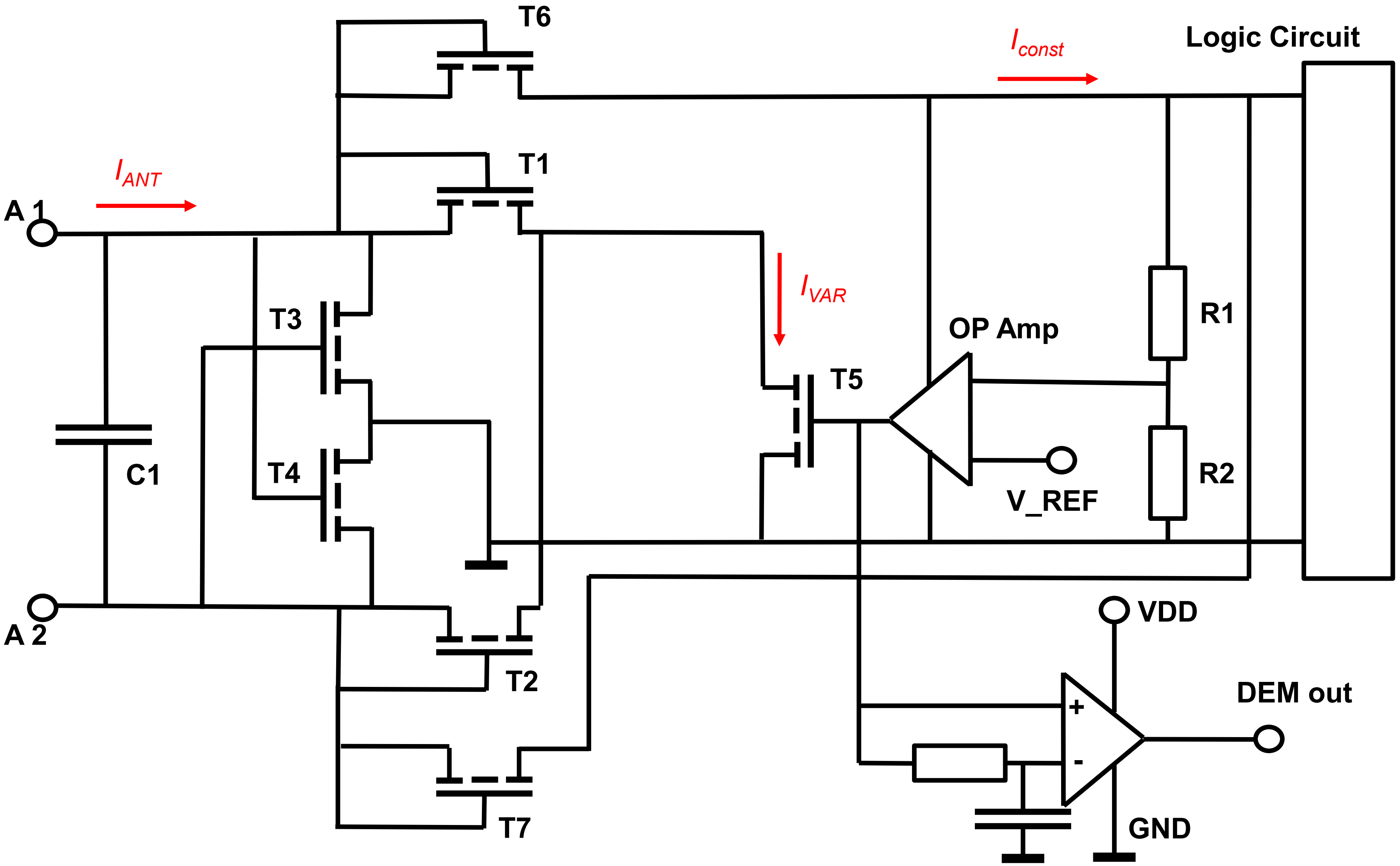
Typical Frontend –
Clock generation

- The reader carrier period is the time reference of communication.
- So the clock can be directly extracted from the RF carrier frequency.
- For lower clock frequencies (< 13,6 MHz) only a **comparator and divisor stages** are required. For higher clock frequencies e.g. a PLL may be used.



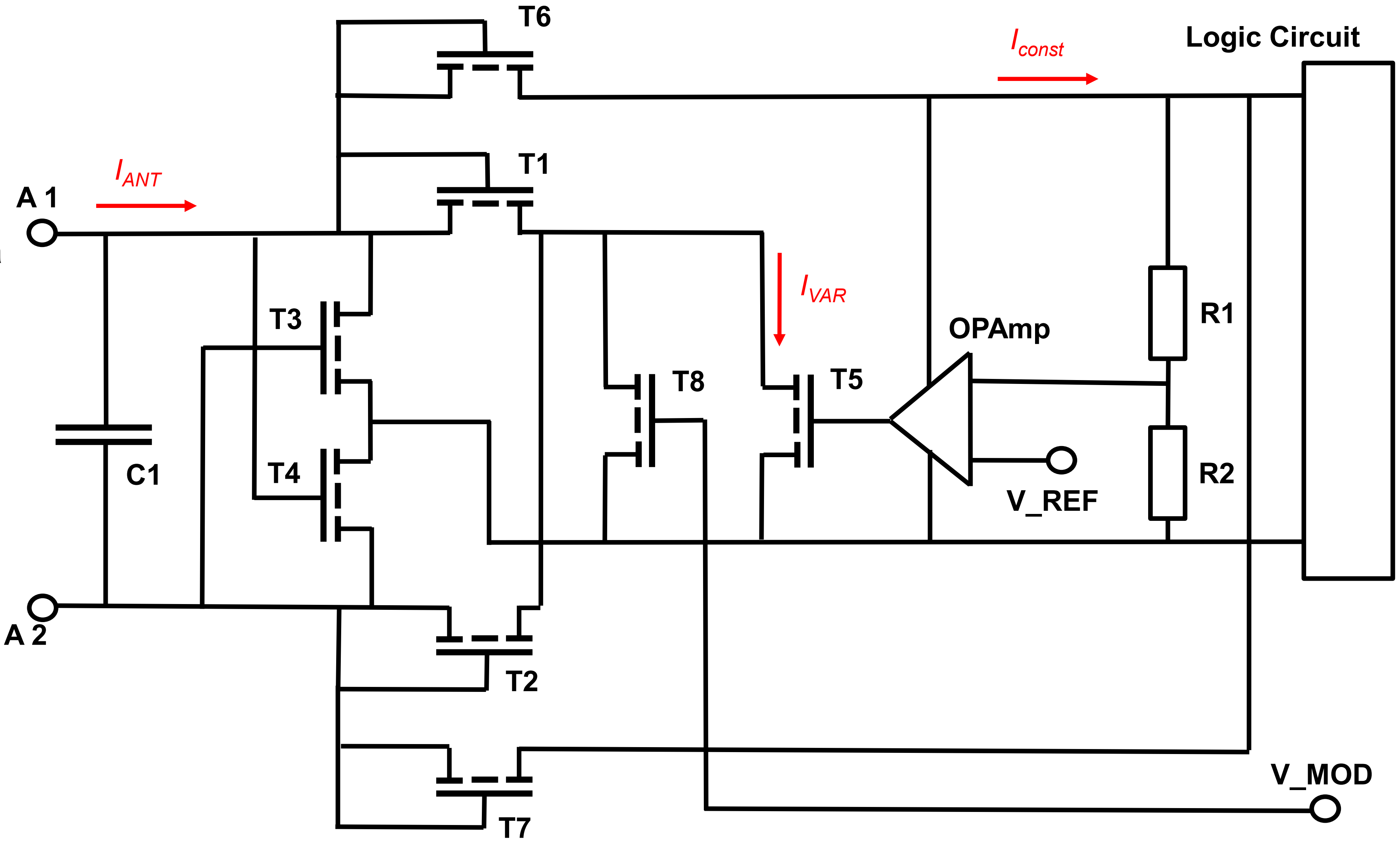
Typical Frontend – Demodulator

- The reader carrier period is the time reference of communication.
- So the clock can be directly extracted from the RF carrier frequency.
- For lower clock frequencies (< 13,6 MHz) only a **comparator and divisor stages** are required. For higher clock frequencies e.g. a PLL may be used.



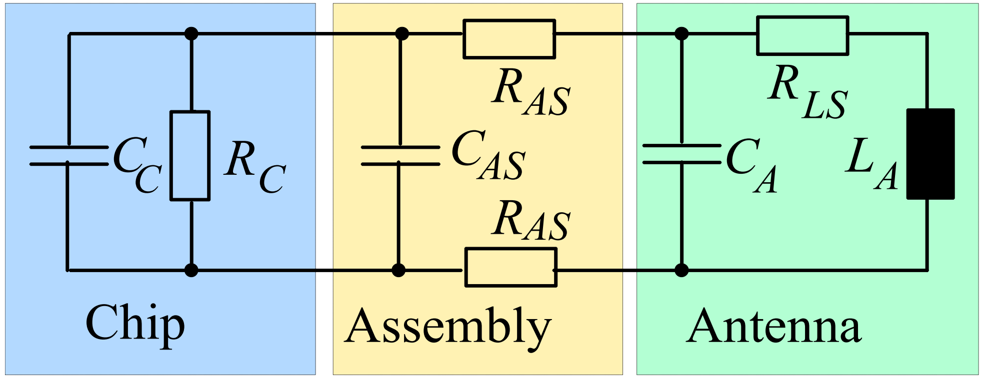
Typical Frontend – Modulator

- Modulator can be a shunt resistor (*Q*-shift) or a capacitor (f_{RES} shift).
- Resistor can short antenna voltage (➔ clock extraction difficult) or draw more current behind the rectifier (our example).

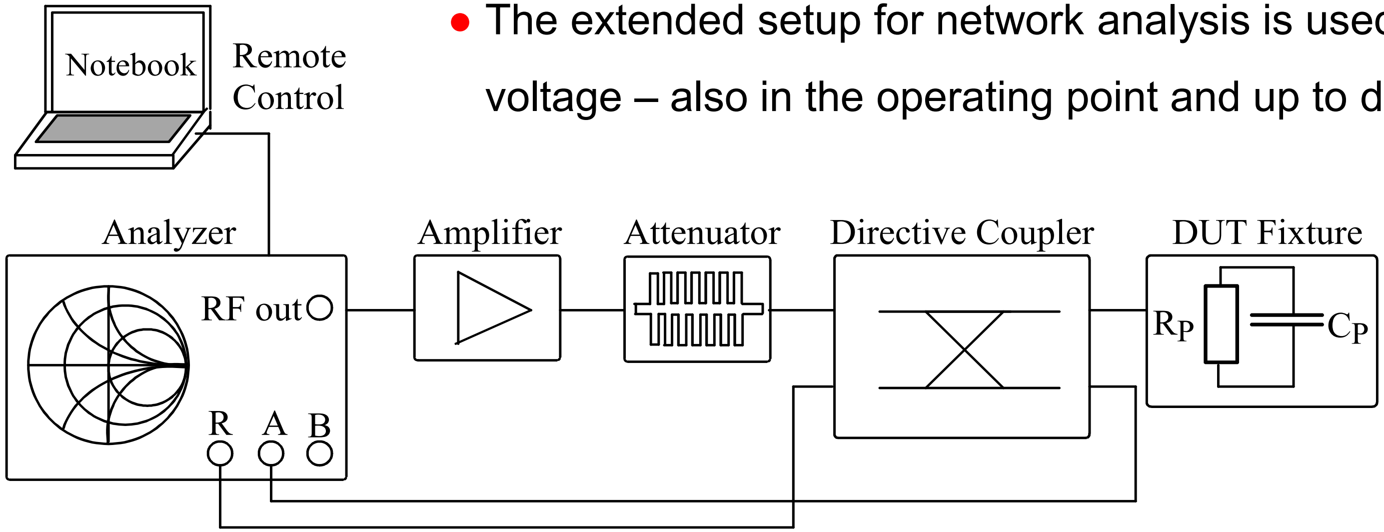


Transponder equivalent electrical circuit

- From system perspective, analogue RF performance of a transponder can be considered using a simplified EQC:
- **Chip**
  - C_C.....(equivalent) chip capacitance, voltage (& state) dependent!
  - R_C.....(equivalent) chip resistance, voltage (& state) dependent!
- **Assembly**
  - C_{AS}....assembly capacitance
  - R_{AS}....assembly serial resistance
- **Antenna**
  - L_A......(equivalent) antenna inductance
  - R_A.....(equivalent) parallel antenna resistance (losses)
  - C_A....(equivalent) parallel antenna capacitance
- RF system requirements for a transponder are mainly….
  - Minimum *H*-field for card operation, H_{MIN}
  - Load modulation side band amplitude, *LMA*



Chip input impedance characterization @ 13,56 MHz



- The extended setup for network analysis is used to characterize impedance over frequency and voltage – also in the operating point and up to destruction levels.

$$\underline{Z}_C = \frac{1+\underline{\Gamma}_C}{1-\underline{\Gamma}_C} Z_0 = \frac{1}{\underline{Y}_C}$$

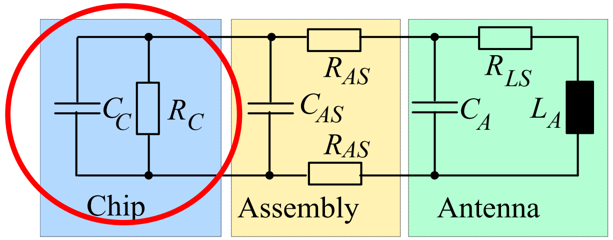
$$R_P = \mathrm{Re}\{\underline{Z}_C\} = \mathrm{Re}\left\{\frac{1}{\underline{Y}_C}\right\} = \mathrm{Re}\left\{\frac{1}{G_P + jB_P}\right\} = \frac{1}{G_P}$$

$$C_P = \mathrm{Im}\left\{\frac{1}{\underline{Y}_C}\right\} = -\mathrm{Im}\left\{\frac{1}{2\pi f_{MEAS}\underline{Z}_C}\right\} = \frac{B}{\omega}$$

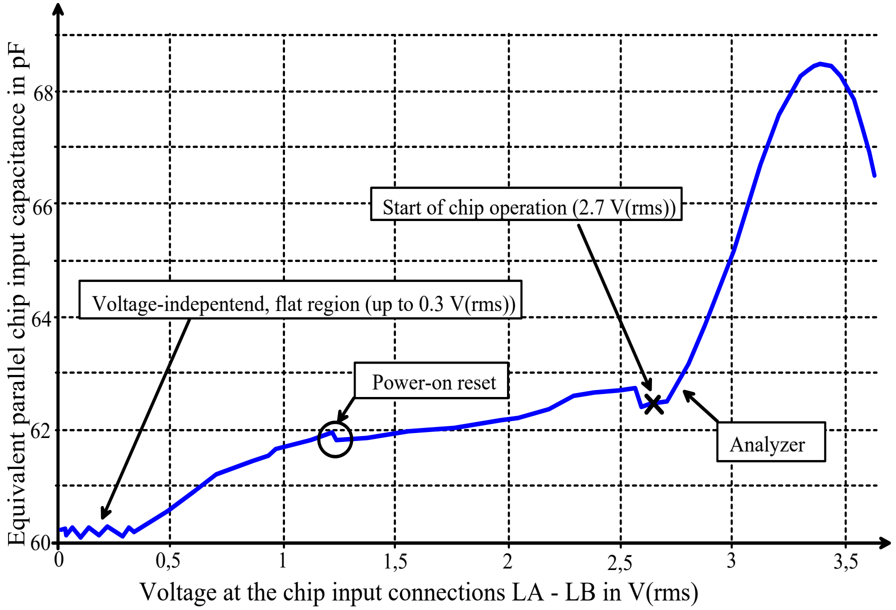
- The voltage on the DUT is calculated with a voltage divider (50 Ohm source and measured load impedance), from a previously measured output voltage to 50 Ohms.

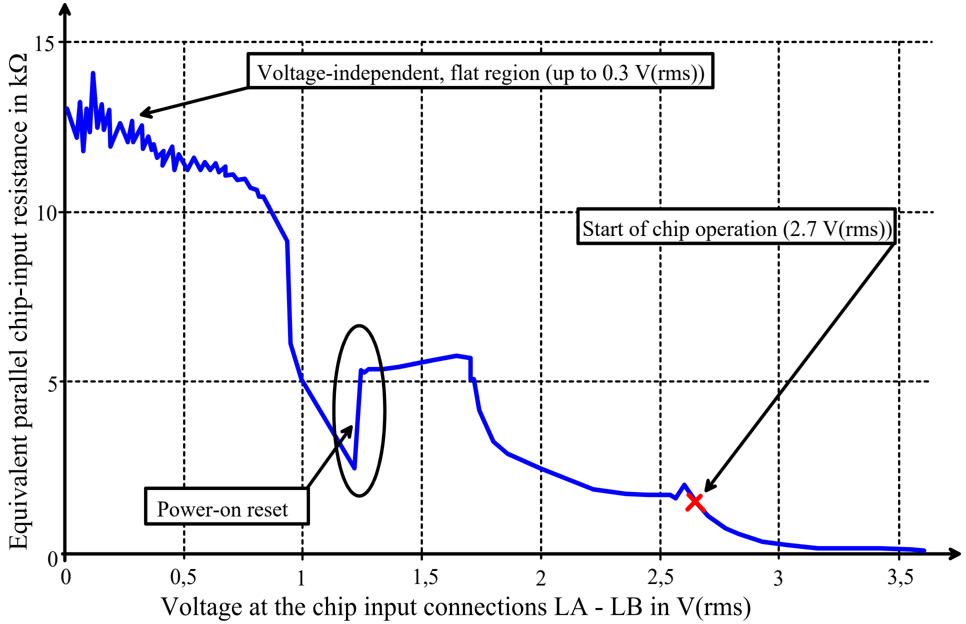
$$U_{DUT} = U_S \frac{R_P}{\sqrt{(R_P + R_S)^2 + (\omega R_P R_S C_P)^2}}$$

Equivalent Chip admittance measurement



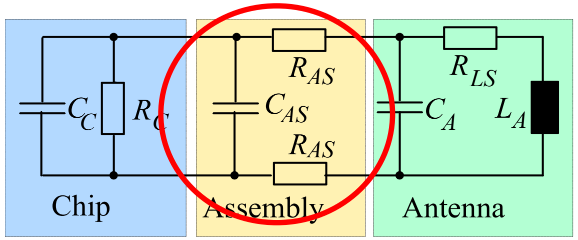
- Equivalent circuit values for a simple, linear model can be extracted.
- We measure the real part (parallel resistance, R_C) and imaginary part (C_C).





- This allows to verify some main points (e.g. power-on reset, start of chip operation, dependency on chip settings like clock / current source setting…)
- Note: It does not include any state transition or chip operation! (obverse and reverse voltage sweep can be done)

Antenna and assembly technology overview



Antenna Technologies

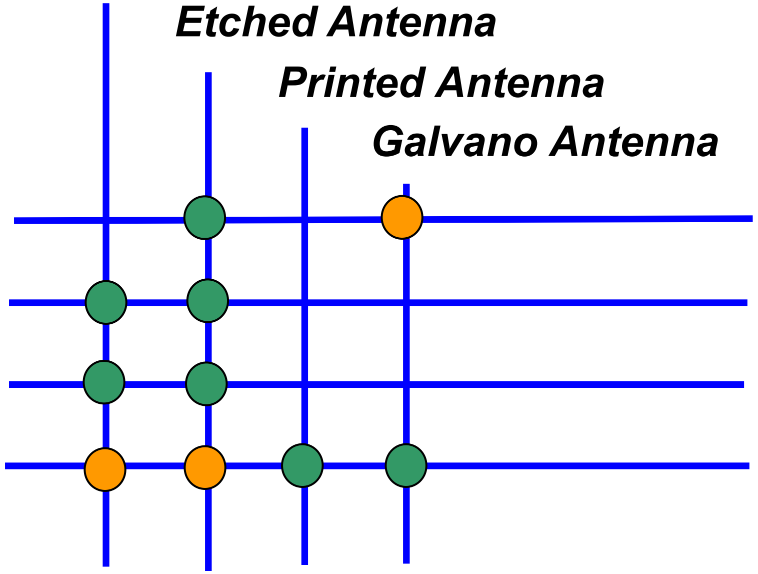
Embedded Wire Antenna

Etched Antenna

Printed Antenna

Galvano Antenna

Assembly Technology



Crimping

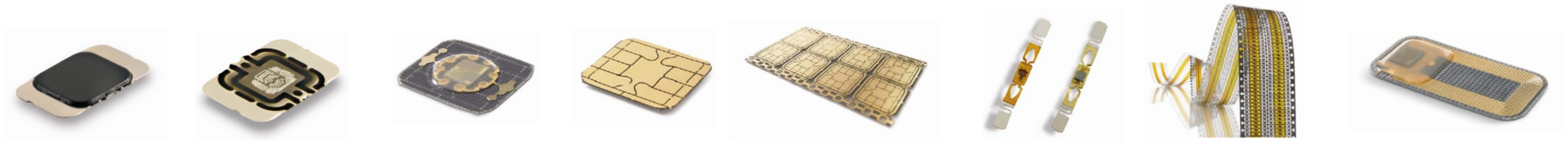
Welding

Soldering (not Alu)

Conductive Glueing

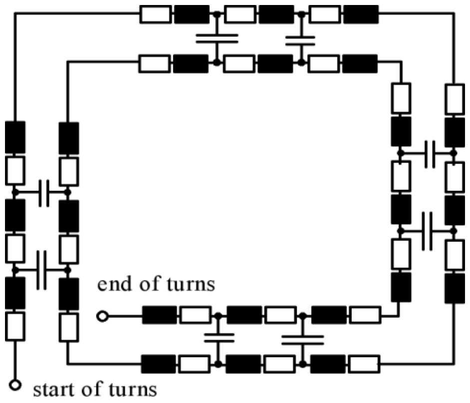
Conductor materials: *Copper, aluminum, conductive paste (e.g. silver ink)*

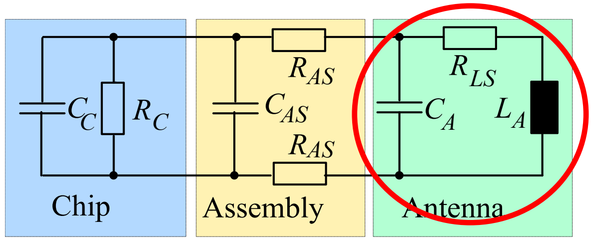
Chip packages: *Module (8 x 5 mm), Flip-Chip, Strap, bumped wafer*

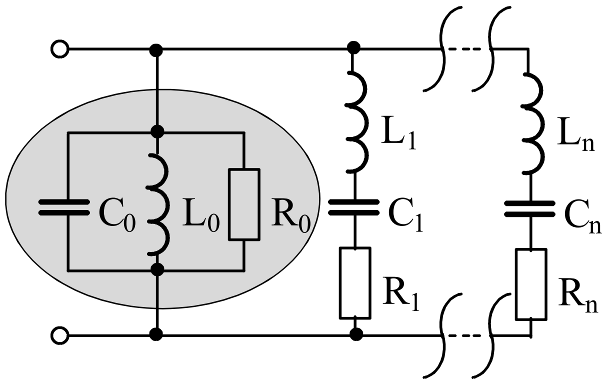


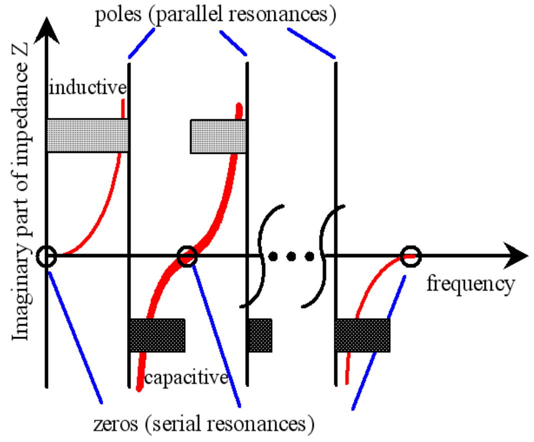
Loop antenna

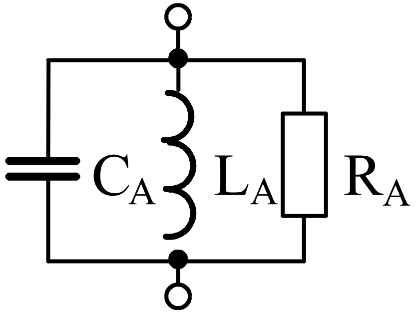
- The loop antenna is a **distributed component** with inductance (L) as main element and capacitance (C) and resistance (R) as parasitic network elements.
- For simulation it must be represented by an **equivalent circuit** network of **lumped elements**. Over a wide frequency range this can be a loose coupled reactive ladder network of resonance circuits - it has several resonances in frequency domain.
- At 13,56 MHz carrier frequency we use the fundamental (lowest) resonance. So we can simplify the equivalent circuit e.g. to a parallel resonance circuit (since losses are mainly determined by chip current consumption in Proximity Systems).
  - Note: This is a narrow-band approximation only!









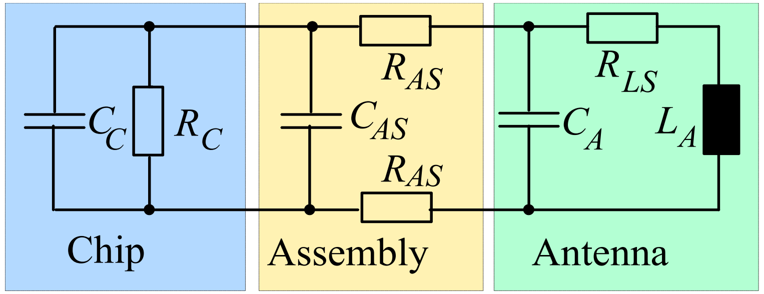


RF System aspects of a contactless transponder

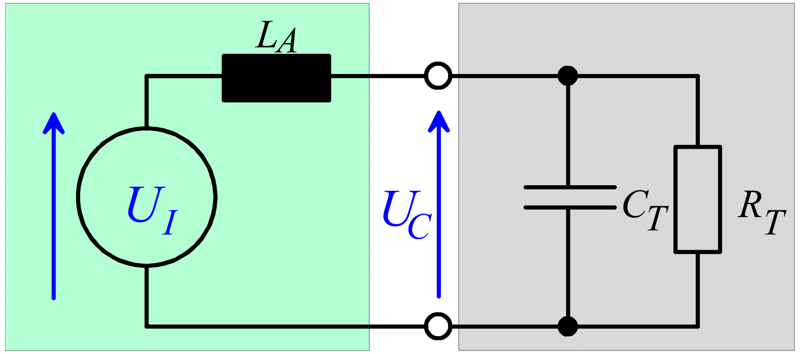
- This simplified linear analytical model can be used to consider some aspects of contactless transponder behaviour at the RF air interface:
  - **Energy** perspective, H_{MIN}
  - Energy perspective, H_{MAX}
  - „**Card loading**“ to the reader
  - Transponder **load modulation** (*LMA*) and ISO/IEC side band amplitudes
- This can be used to relate contact-based chip & antenna properties to the RF system behaviour, which is required by the standard.

- Note: Considerations in this context relate to the Proximity base standard, ISO/IEC14443, and the Proximity test standard, ISO/IEC10373-6.

Transponder properties – Energy (H_{MIN})



- The simple time-independent equivalent circuit model allows to consider the *H*-field



- The transmission function is given by

$$U_C = U_I \cdot \frac{\frac{R_T}{sR_T C_T + 1}}{sL_A + \frac{R_T}{sR_T C_T + 1}} = U_I \cdot \frac{1}{1 + j\omega \frac{L_A}{R_T} - \omega^2 L_A C_T}$$

- Where the resonance frequency is given by...

$$\omega_R = \frac{1}{\sqrt{L_A C_T}}, \quad f_R = \frac{1}{2\pi\sqrt{L_A C_T}}$$

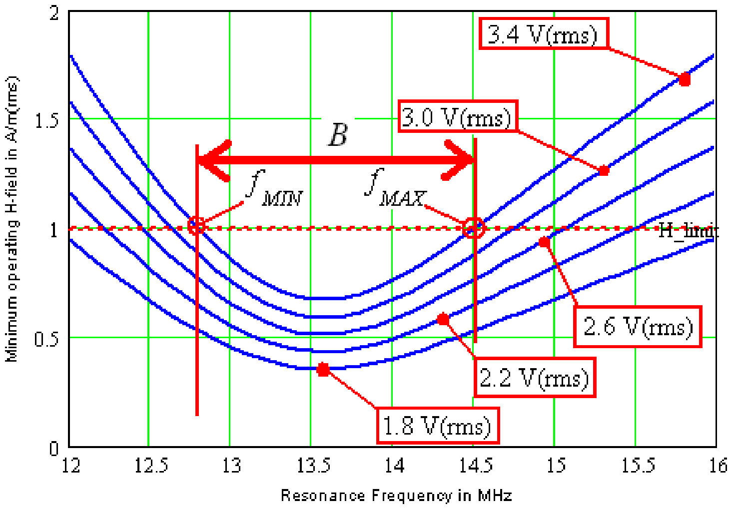
- and the transponder quality factor is...

$$Q_T = \frac{R_T}{\omega_R L_A} = \omega_R C_T R_T$$

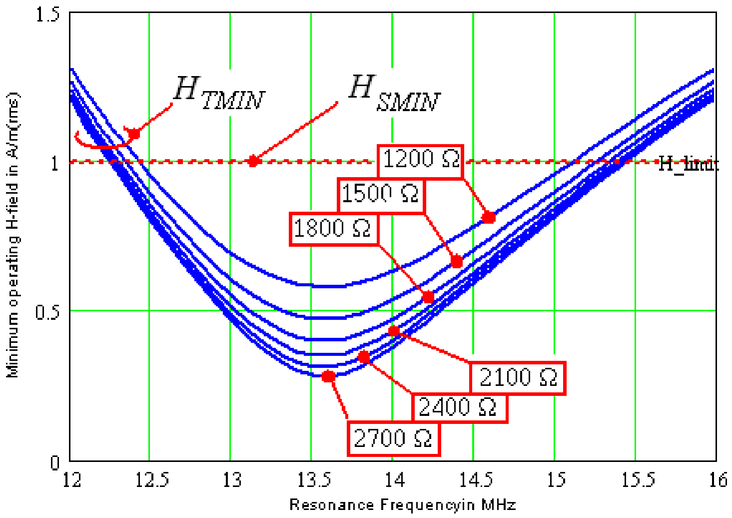
- Finally, we substitute U_I and re-arrange the function to express the required *H*-field by chip, antenna and system parameters:

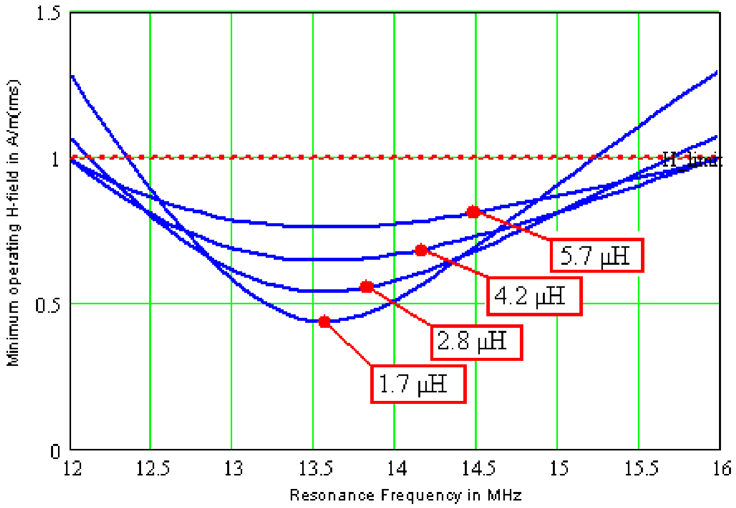
$$H = \frac{\sqrt{\left[\left(1 - \left(\frac{\omega}{\omega_R}\right)^2\right)^2 + \left(\frac{\omega L_A}{R_T}\right)^2\right]}}{\omega \mu_0 N A} \cdot U_C$$

H_{MIN} as function of chip and antenna properties

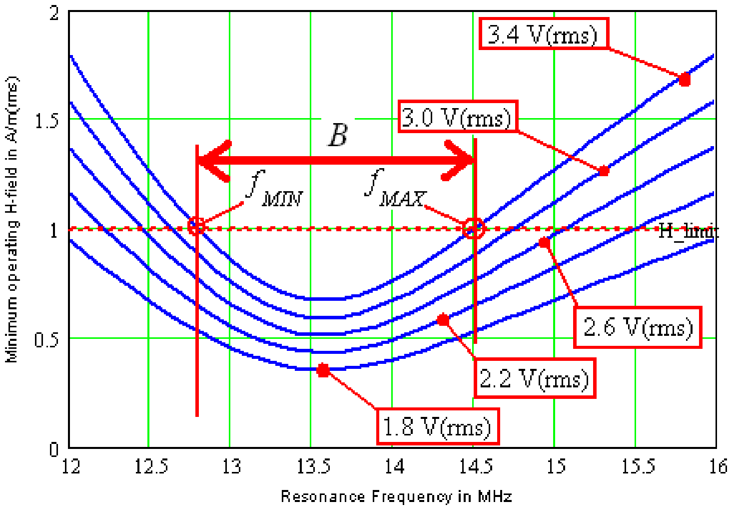


- Evaluating the analytical equation for H_{MIN} allows to consider how chip and antenna properties influence contactless transponder RF performance.
- As there are production tolerances, performance over resonance frequency is important.
- As standard compliance requires all samples to achieve an H_{MIN}, the allowable resonance frequency range can be determined.



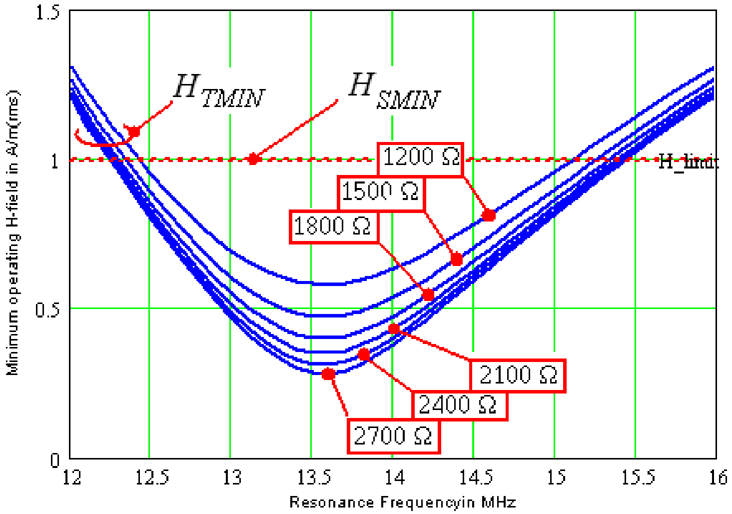


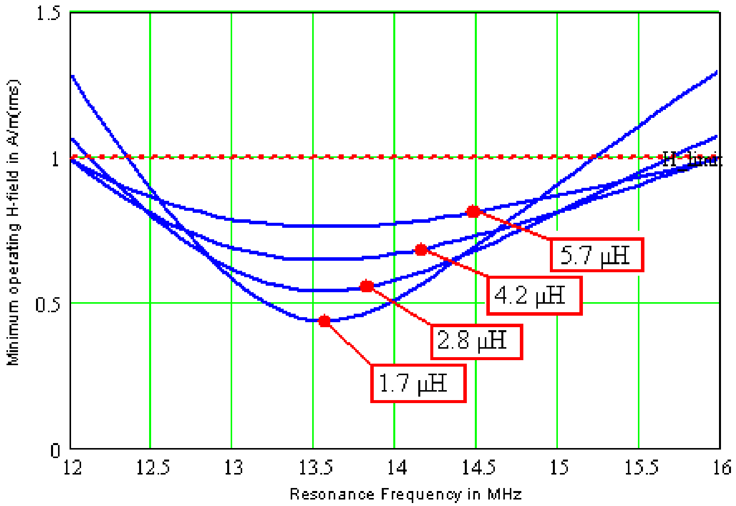
H_{MIN} as function of chip and antenna properties



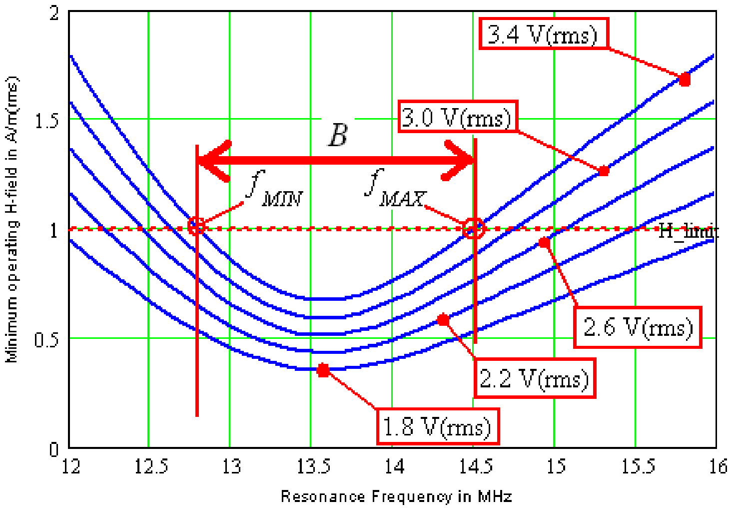
– Evaluating the analytical equation for H_{MIN} allows to consider how chip and antenna properties influence contactless transponder RF performance.

$$f_{LIM} = \frac{f_C}{\sqrt{1 \pm \sqrt{\left(\frac{H_{SMIN} 2\pi f_C \mu_0 NA}{U_{CMIN}}\right)^2 - \left(\frac{2\pi f_C L_A}{R_T}\right)^2}}}$$





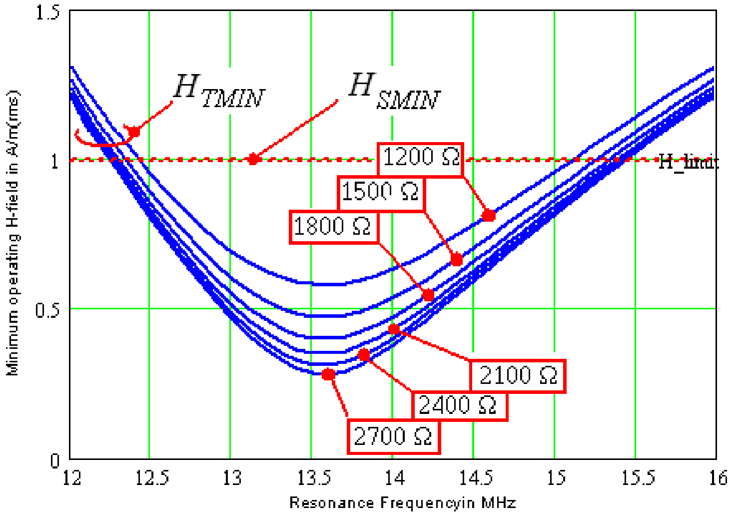
H_{MIN} as function of chip and antenna properties

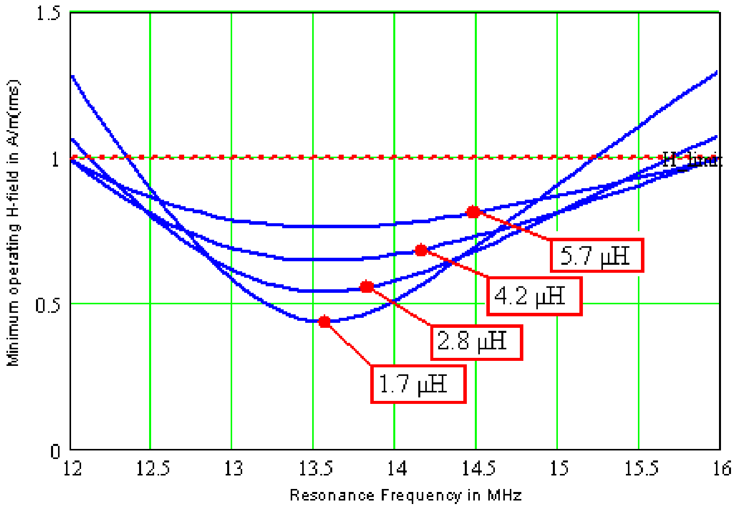


$$f_{RES} = \frac{1}{2\pi\sqrt{LC}}$$

$$Q_T = R_P\sqrt{\frac{C}{L}}$$

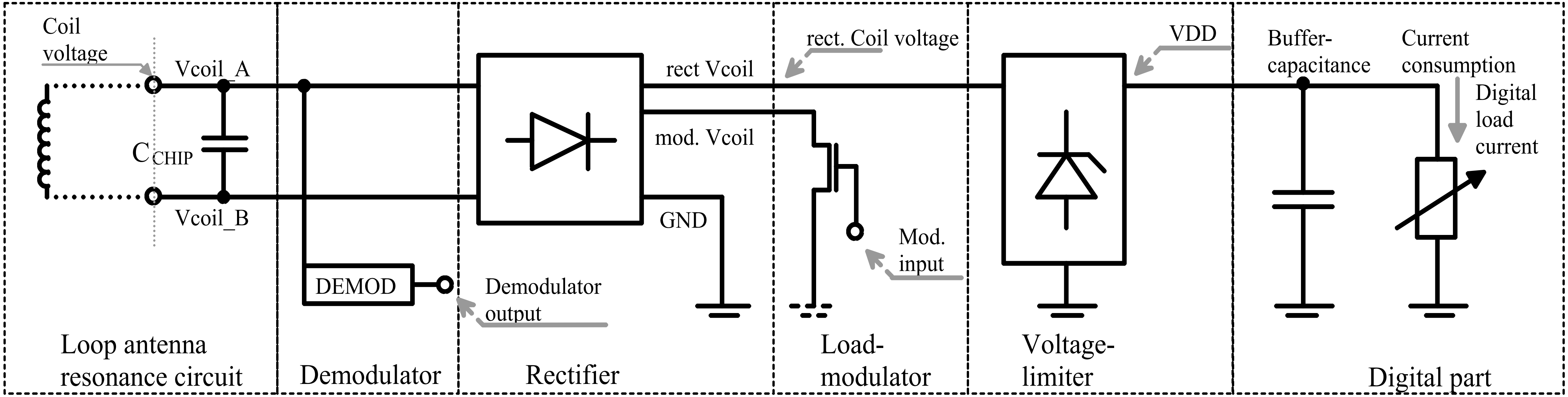
$$H_{MIN} \approx \frac{\sqrt{\left[1-\left(\frac{f_{CAR}}{f_{RES}}\right)^2\right]^2 + \left(\frac{2\pi f_{CAR} L_A}{R_P}\right)^2}}{2\pi f_{CAR}\,\mu_0\,N\,A_{EFF}} \cdot U_{CHIP,MIN}$$



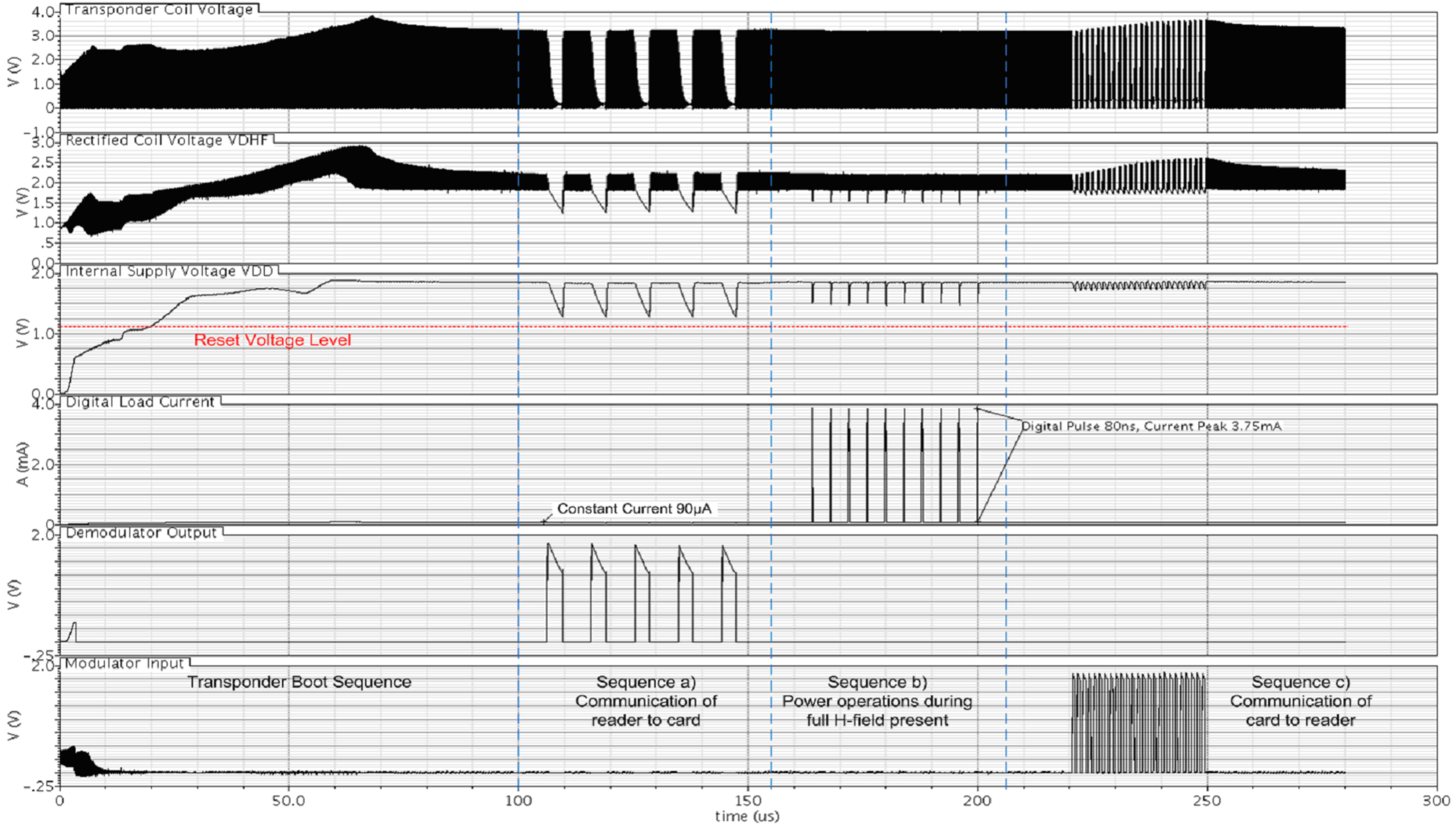


Transponder analog front-end

- Analogue Design simulation environment (e.g. CADENCE) is used to simulate functional blocks of a Proximity transponder chip analogue front-end.
- Hierarchical simulation model, based on semiconductor process component models (includes parasitics & dependencies).
- As power supply and communication share one common interface, the resonant antenna circuit, 3 functional states are mainly investigated, for the power requirement (H_{MIN}) analysis:
  - *Command reception - operation (e.g. r/w memory access) - load modulation*



3 functional states for the transponder



Thermal consideration and H_{MAX}

- To provide constant supply to the digital part in chip, a shunt regulator usually limits the chip voltage for an *H*-field > H_{MIN}.
- The antenna basically acts as a current source then, and it is possible to give a simple conversion ratio between *H*-field at transponder, and the (effective) current provided to the chip.
- In the analytical formula, this is expressed by R_T, which is voltage dependent. So we can re-arrange our formula, to calculate R_T out of the frame conditions.

$$R_T = \frac{\omega_C L_A}{\sqrt{\left(\frac{\omega_C \mu_0 N A H}{U_{CLIM}}\right)^2 - \left[1 - \left(\frac{\omega_C}{\omega_R}\right)^2\right]^2}}$$

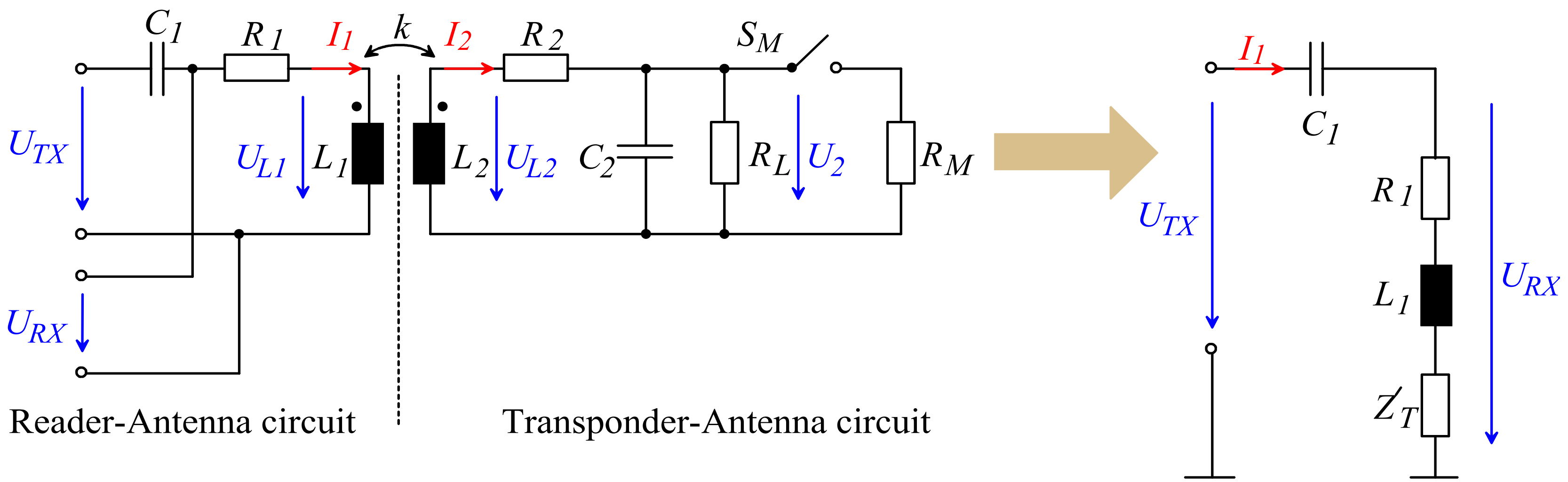
$$I_A = \frac{U_{CLIM}}{R_T(@\,\omega_{RES} \equiv \omega_{CAR})}$$

- This is useful to estimate, how much current will be available for the chip, and it also allows to calculate the maximum thermal power dissipation for a card.

$$P_{TH} = U_{CLIM} \cdot I_A(@\,H \equiv H_{MAX})$$

Transponder properties – „Card Loading“

- The inductive coupling of the transponder to the reader resonant antenna circuit (both loop antennas carry currents) have an impact:
  - mutual inductance – reader antenna resonance is shifted
  - transponder draws current – reader antenna *Q*-factor is decreased
  - a 2nd resonance may be introduced in the transmission function...
- To consider effects, the contactless transformer model can be modified into a galvanically connected equivalent circuit, which includes the „transformed transponder impedance“ Z_T'.



Transponder properties – „Card Loading“

- The Proximity standard defines „card loading“ just over the aspect of reduction of the reader *H*-field:

$$CLF = \frac{(H - \text{field with transponder}) - (H - \text{field without transponder})}{H - \text{field without transponder}}$$

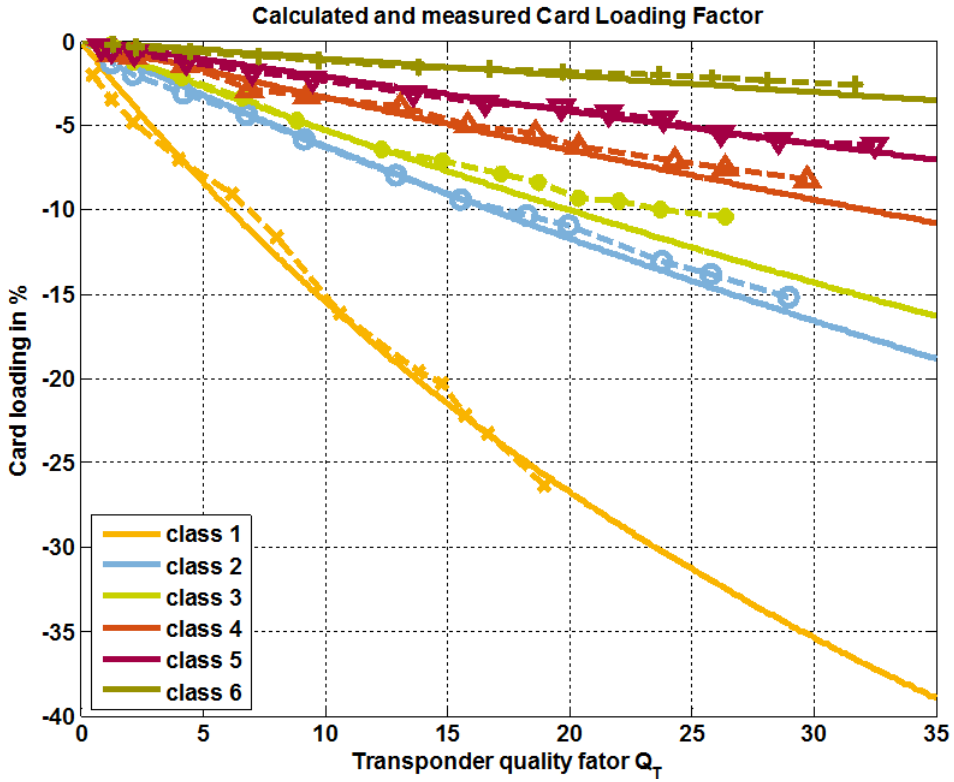
- The transformed transponder impedance is given by...

$$Z_T' \approx \frac{1 + j\frac{f_{CAR}}{f_{RES}} Q_T}{\left(\frac{f_{RES}}{f_{CAR}} - \frac{f_{CAR}}{f_{RES}}\right) Q_T + j} k^2 2\pi f_{CAR} L_{READER}$$

$$\Big| for\ f_{RES} \equiv f_{CAR} \quad \rightarrow \quad Z_T' \approx k^2 2\pi f_{CAR} L_{READER} (Q_T - 1)$$

- So the „card loading factor“ is given by

$$CLF \approx \frac{1}{abs\left(1 + \frac{Z_T'}{Z_{READER}}\right)} - 1$$



Maximum allowable Card Loading

- Card loading refers to a decrease of emitted *H*-field strength due to proximity coupling of the resonant reader antenna to a transponder card. The reader minimum *H*-field emission is tested under certain loaded conditions.
- So the test standard specifies a test case for cards, the maximum allowable card loading. It is specified relative to a so-called Reference PICC, for resonance at carrier frequency and a high Q_T-factor, specified as 6 VDC @ H_{MIN}, for antenna size class 1.
- This means, transponder cards will pass, if Q_T is below the value for the Ref. PICC at H_{SMIN}, considering similar antenna size (this is general and allows to vary L/C).

REFERENCE PICC MEASUREMENT FOR TRANSPONDER SIZE CLASSES

Class*	PCD*	H_{SMIN}*	L_A**	U_{DC}*	$R_2 typ$**	ΔH**	Q_{TLIM}***
		A/m(rms)	µH	V_{DC}	Ω	%	
1	1	1.5	2.29	6.0	975	6.9	3.0
2	1	1.5	2.38	4.5	1191	3.1	3.3
3	1	1.5	2.38	4.5	1308	3.2	3.6
4	2	2.0	2.36	4.5	1074	7.2	3.0
5	2	2.5	2.36	4.5	1092	4.7	3.1
6	2	4.5	2.25	4.5	839	2.1	2.5

*) defined, **) measured, ***) calculated from measurement

- for $f_{RES} = f_{CAR}$ *we get*

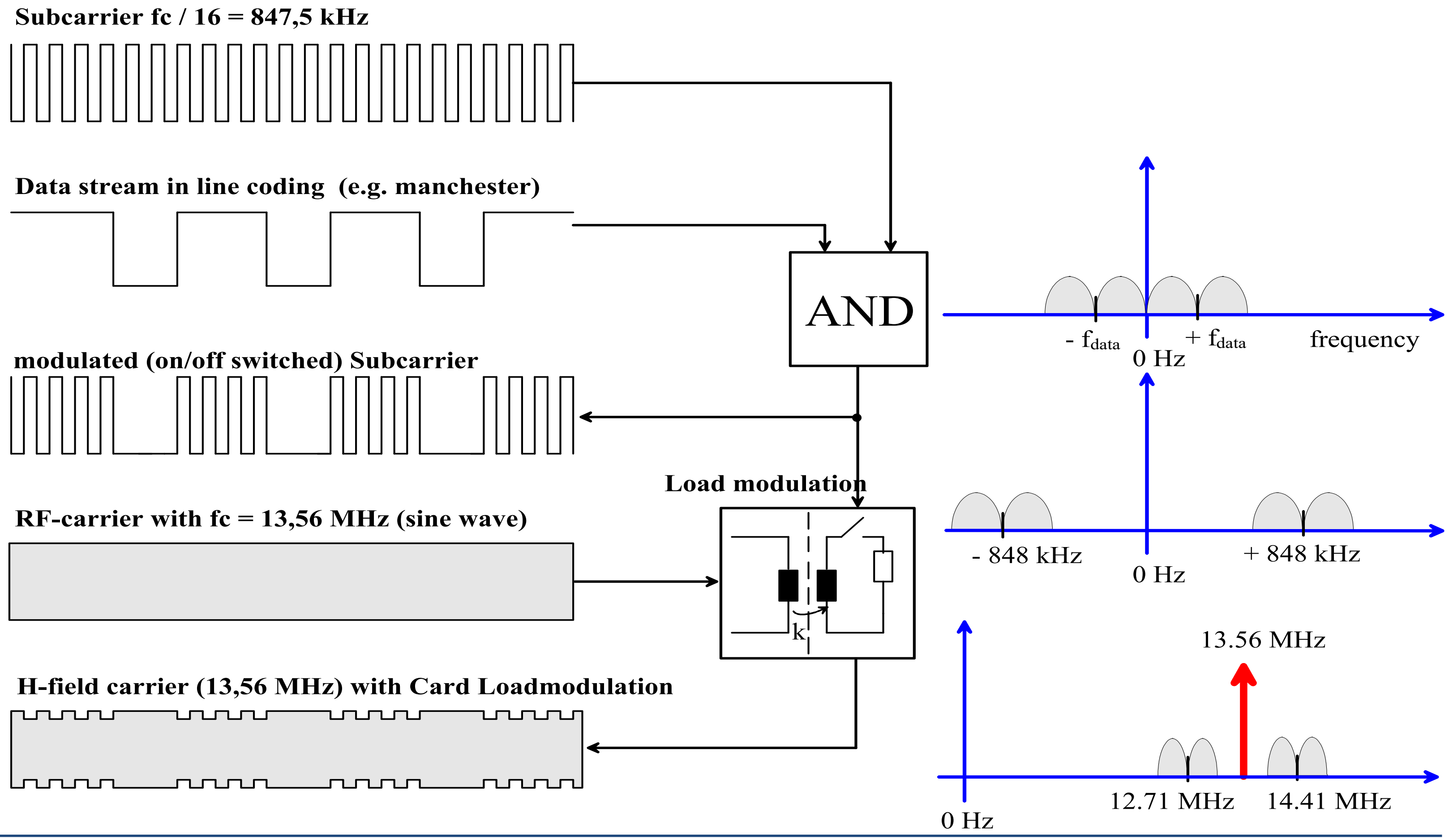
$$R_T(@\,\omega_R \equiv \omega_C) = \frac{U_C\, L_A}{\mu_0\, N A\, H}$$

- which means for Q_T

$$Q_{TLIM} = \frac{U_{CR}}{2\pi\, f_C\, \mu_0 N A H_{SMIN}}$$

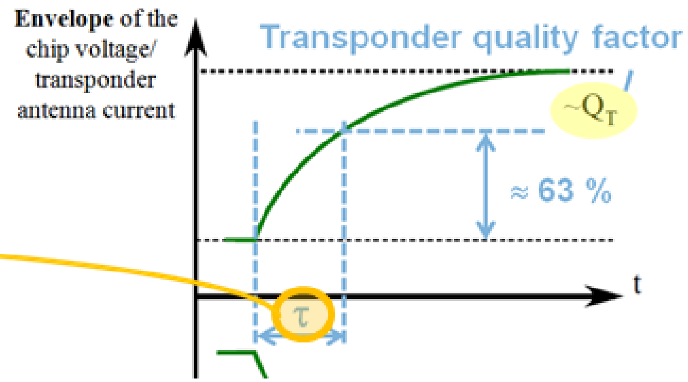
Transponder properties – Load Modulation

- The Transponder transmits data via impedance change / load modulation
- This can be seen as dynamic switch of the „Loading“ (f_{RES} or Q_T can be varied)



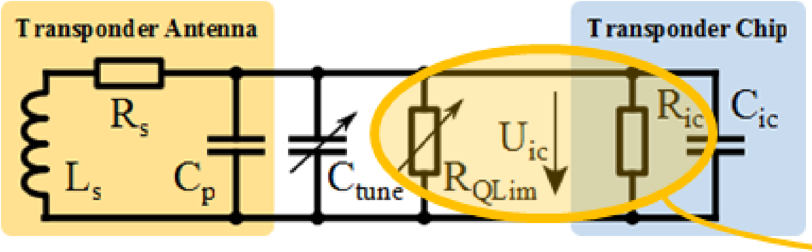
Transponder quality factor Q_T

- 3 ways to extract the quality factor:
  - Measurement of the **time constant** τ of the rising slope & calculate Q_T using



$$Q_T = \frac{\tau \omega_R}{2}$$ ➔ we name this Q_T here "$\boldsymbol{Q_{MEAS}}$"

  - Calculation based on EQC, measuring the parallel resistance Ric // RQLim



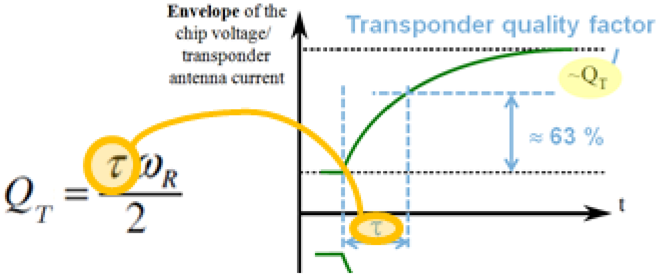
$$Q_T = \frac{1}{\frac{R_s}{\omega_{res} L_s} + \frac{\omega_{res} L_s}{R_{ic}}}$$

R_{IC} // R_{QLim} is measured with Impedance analyzer (chip impedance measurement) ➔ this Q_T is named "$\boldsymbol{Q_{NWA}}$"

- Alternative: Calculate R_{IC} of transponder chip measuring the time constant τ without R_{QLim} and calculate Q_T with component values of R_{QLim} ➔ "$\boldsymbol{Q_{CALC}}$"

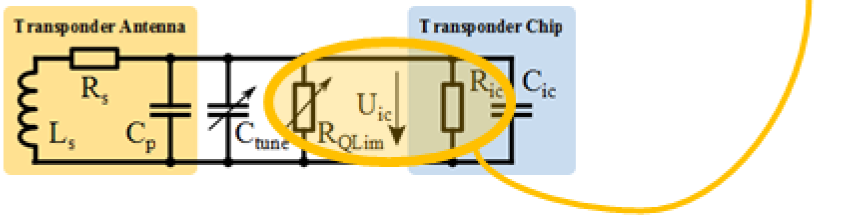
Consistency Check: Determination of $Q_{T,}$ 3 ways

- Q_{MEAS}



- Q_{NWA}

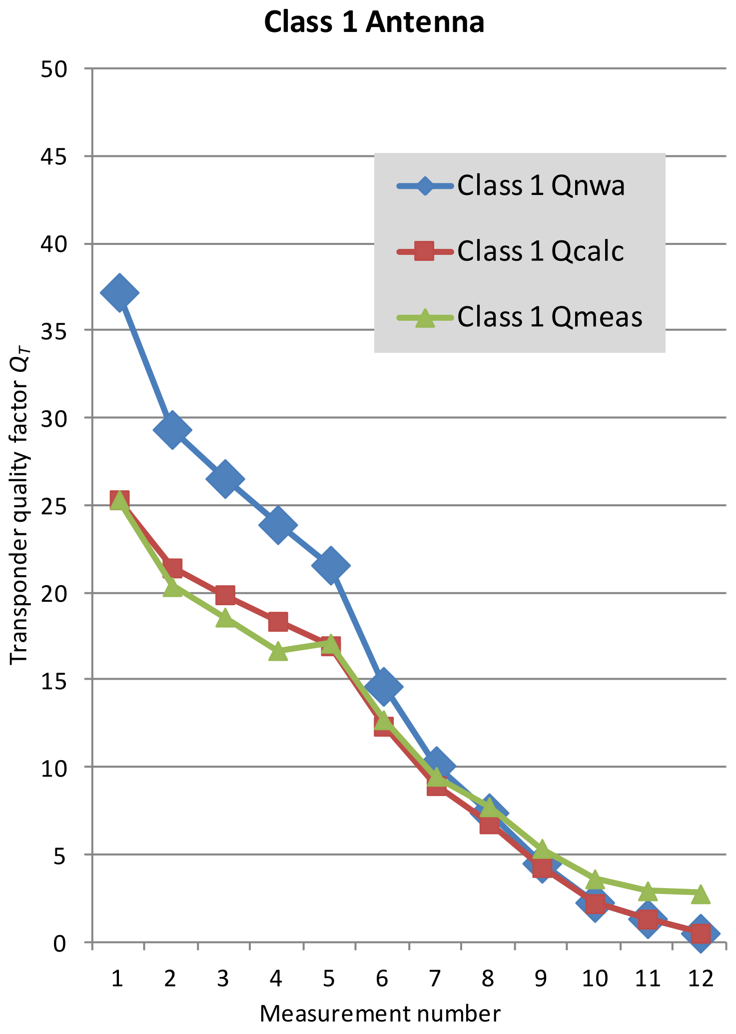
$$Q_T = \frac{1}{\frac{R_s}{\omega_{res} L_s} + \frac{\omega_{res} L_s}{R_{ic}}}$$



- Q_{CALC}

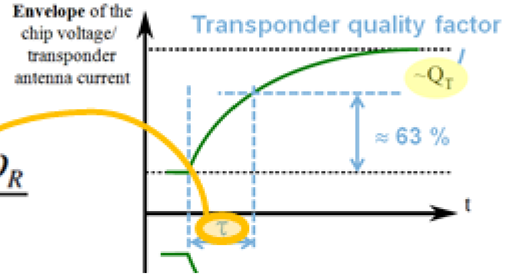
(i) calculate R_{IC} by measuring τ without R_{QLim}

(ii) calculate Q_T with component value of R_{QLim}



Consistency Check: Determination of Q_T, 3 ways

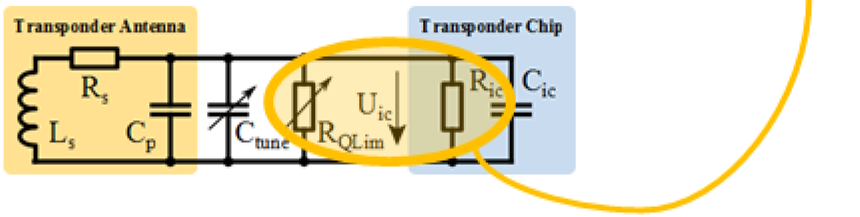
- Q_{MEAS}



$$Q_T = \frac{\tau \, \omega_R}{2}$$

- Q_{NWA}

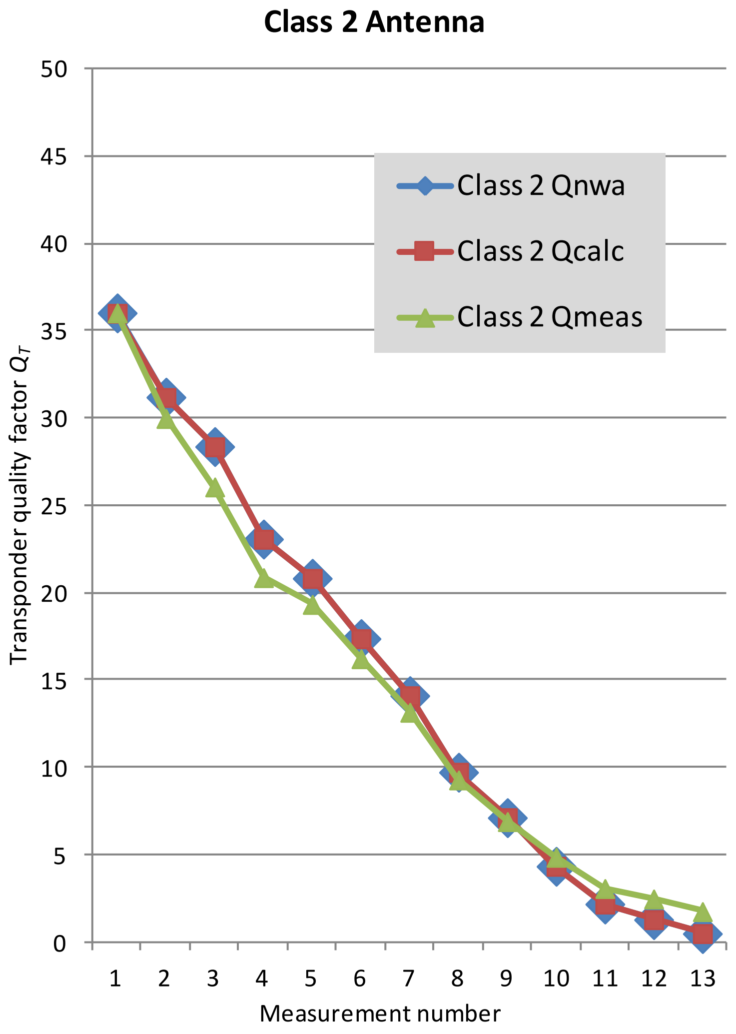
$$Q_T = \frac{1}{\frac{R_s}{\omega_{res} L_s} + \frac{\omega_{res} L_s}{R_{ic}}}$$



- Q_{CALC}

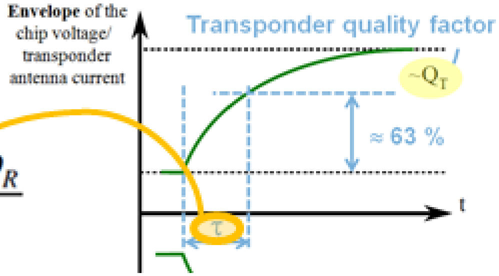
(i) calculate R_{IC} by measuring τ without R_{QLim}

(ii) calculate Q_T with component value of R_{QLim}



Consistency Check: Determination of Q_T, 3 ways

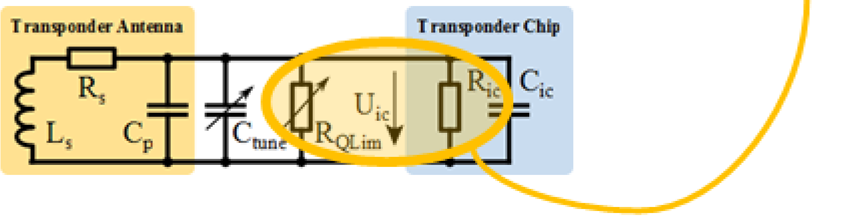
- Q_{MEAS}



$$Q_T = \frac{\tau\, \omega_R}{2}$$

- Q_{NWA}

$$Q_T = \frac{1}{\frac{R_s}{\omega_{res} L_s} + \frac{\omega_{res} L_s}{R_{ic}}}$$



- Q_{CALC}

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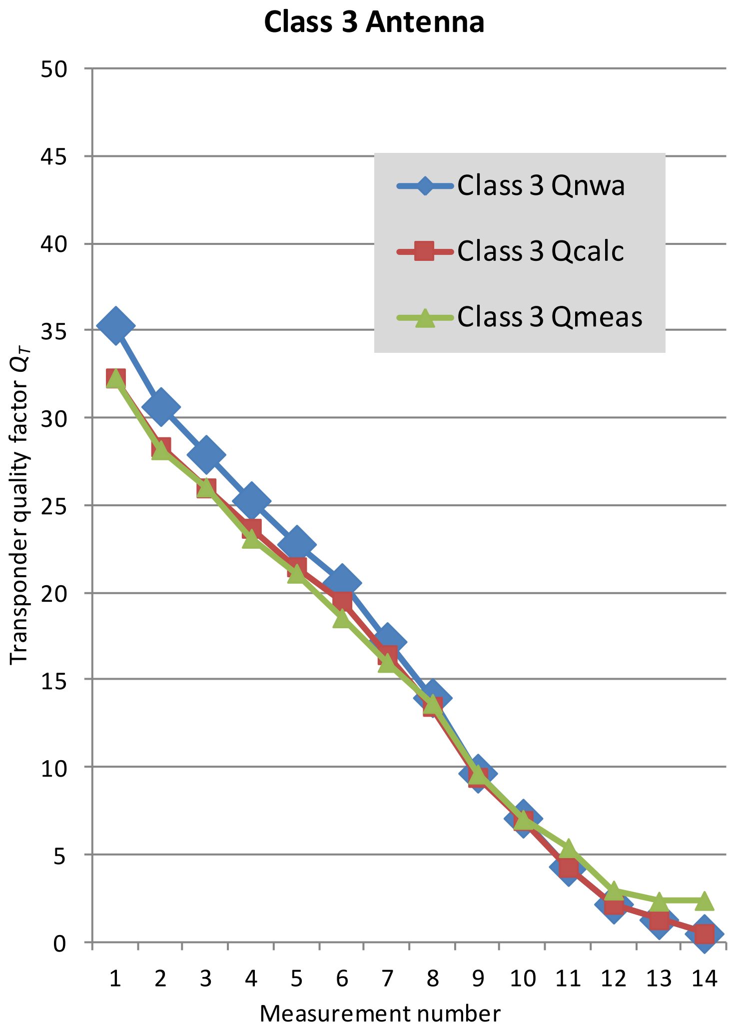
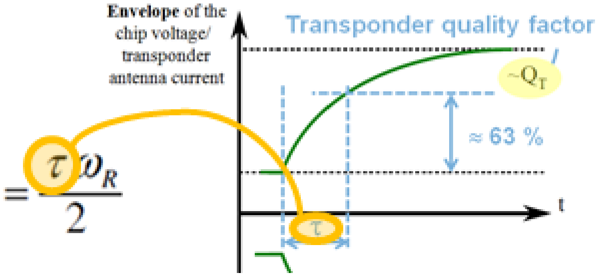
(ii) calculate Q_T with component value of R_{QLim}



Consistency Check: Determination of Q_T, 3 ways

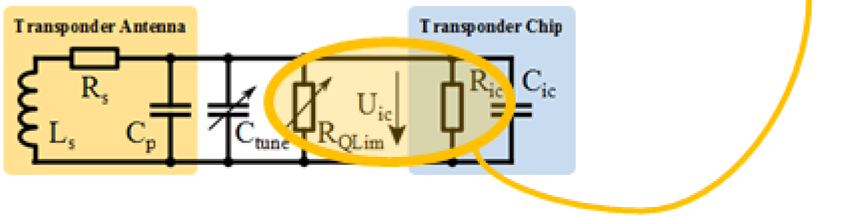
- Q_{MEAS}

$$Q_T = \frac{\tau \omega_R}{2}$$



- Q_{NWA}

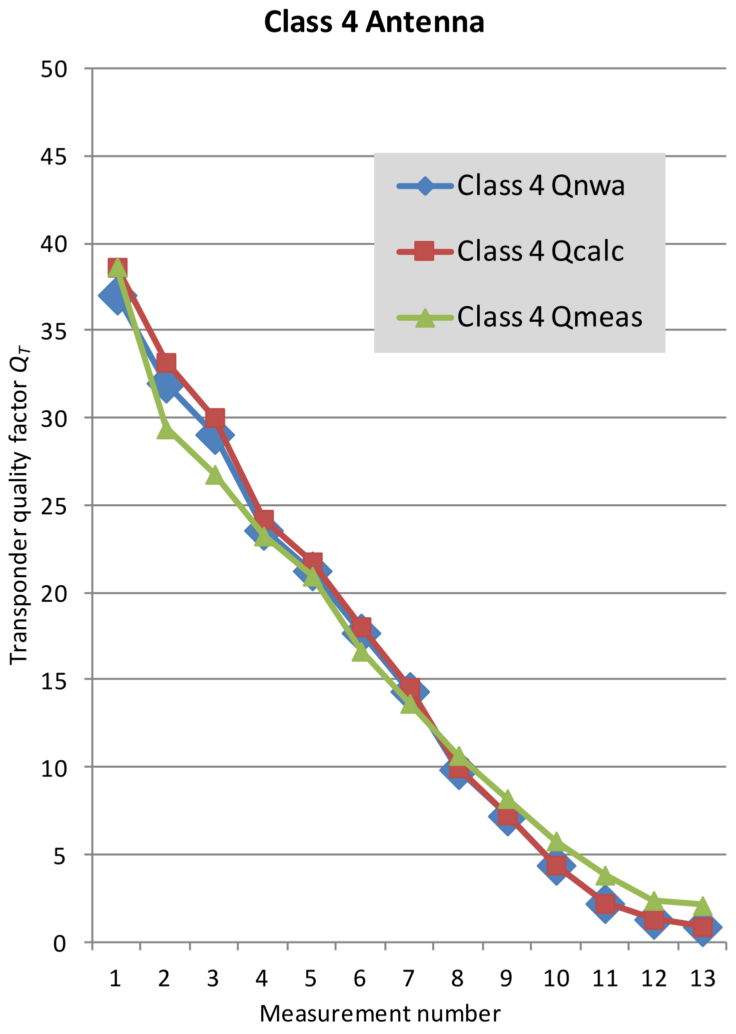
$$Q_T = \frac{1}{\frac{R_s}{\omega_{res} L_s} + \frac{\omega_{res} L_s}{R_{ic}}}$$



- Q_{CALC}

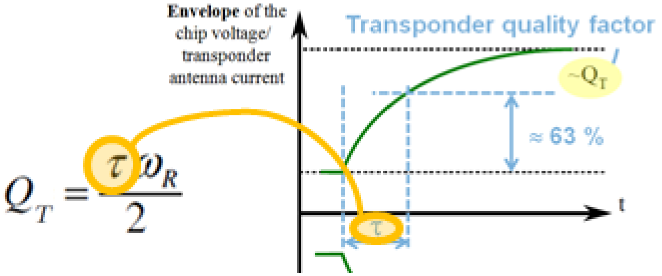
(i) calculate R_{IC} by measuring τ without R_{QLim}

(ii) calculate Q_T with component value of R_{QLim}



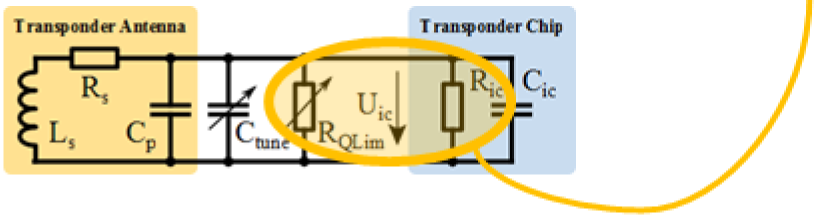
Consistency Check: Determination of Q_T, 3 ways

- Q_{MEAS}



- Q_{NWA}

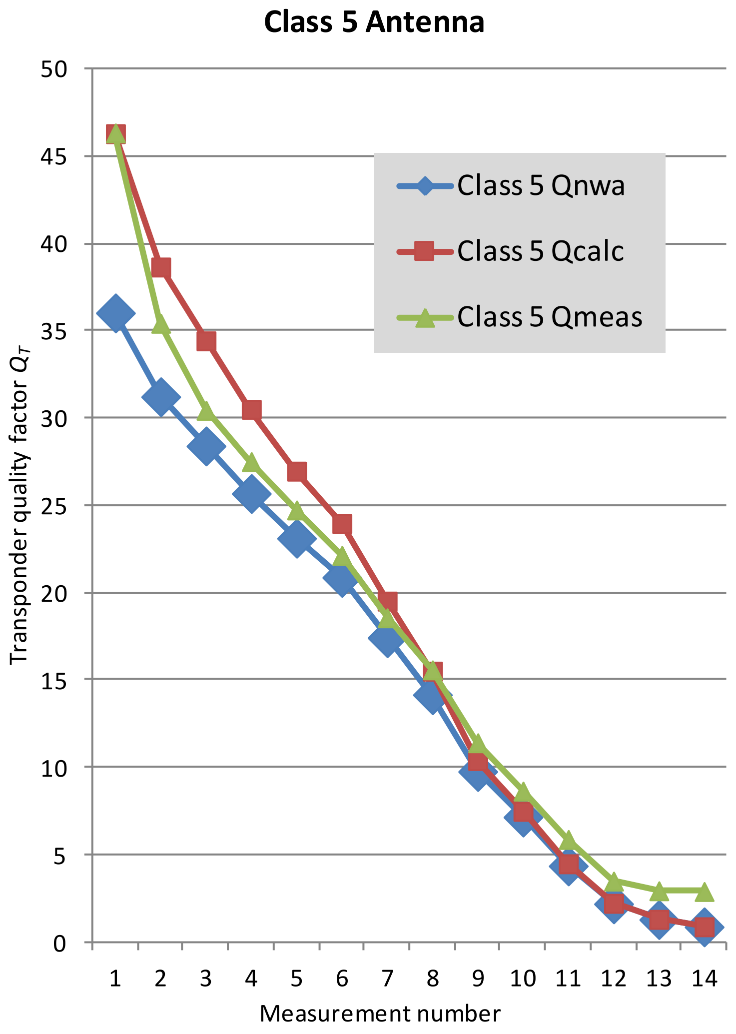
$$Q_T = \frac{1}{\frac{R_s}{\omega_{res} L_s} + \frac{\omega_{res} L_s}{R_{ic}}}$$



- Q_{CALC}

  (i) calculate R_{IC} by measuring τ without R_{QLim}

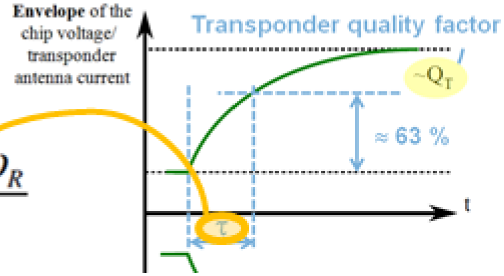
  (ii) calculate Q_T with component value of R_{QLim}



Consistency Check: Determination of Q_T, 3 ways

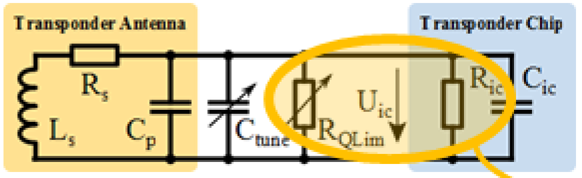
- Q_{MEAS}

$$Q_T = \frac{\tau \omega_R}{2}$$



- Q_{NWA}

$$Q_T = \frac{1}{\frac{R_s}{\omega_{res}L_s} + \frac{\omega_{res}L_s}{R_{ic}}}$$



- Q_{CALC}

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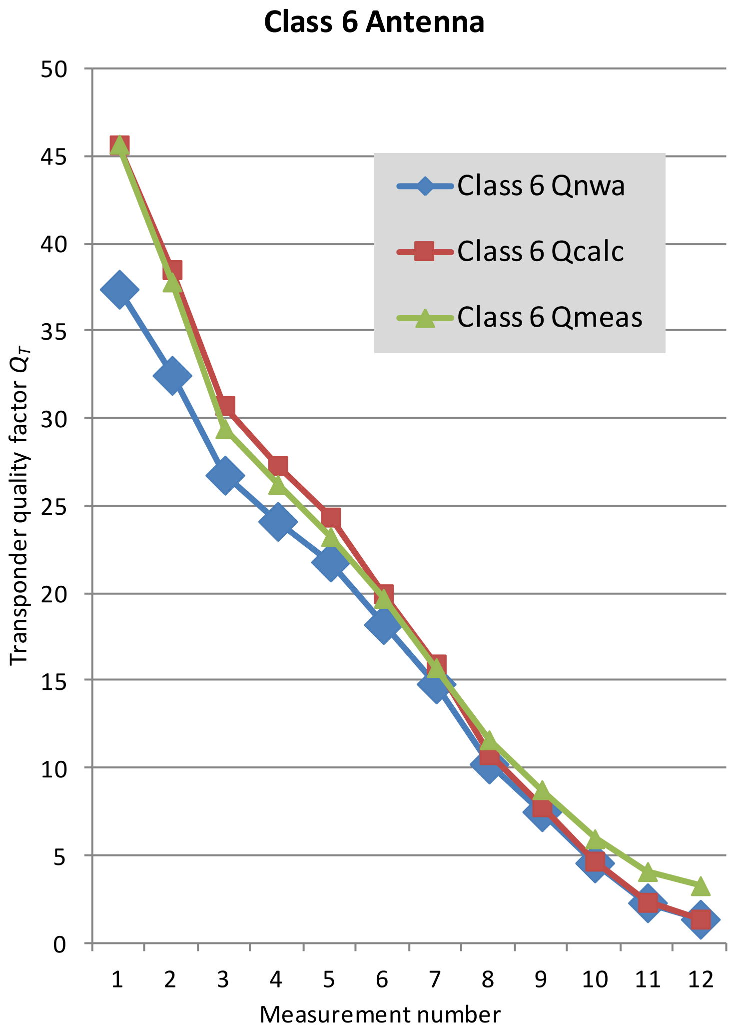
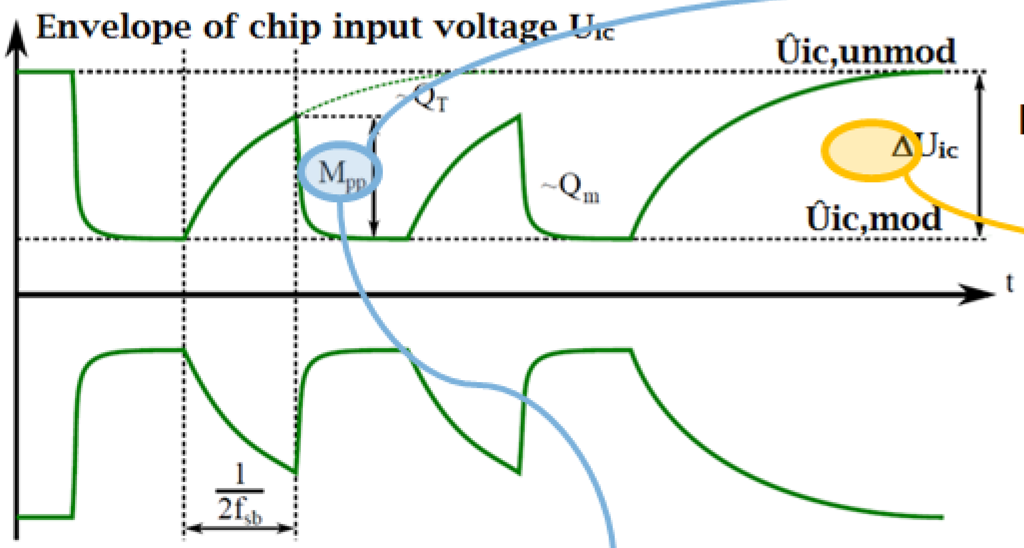
(ii) calculate Q_T with component value of R_{QLim}



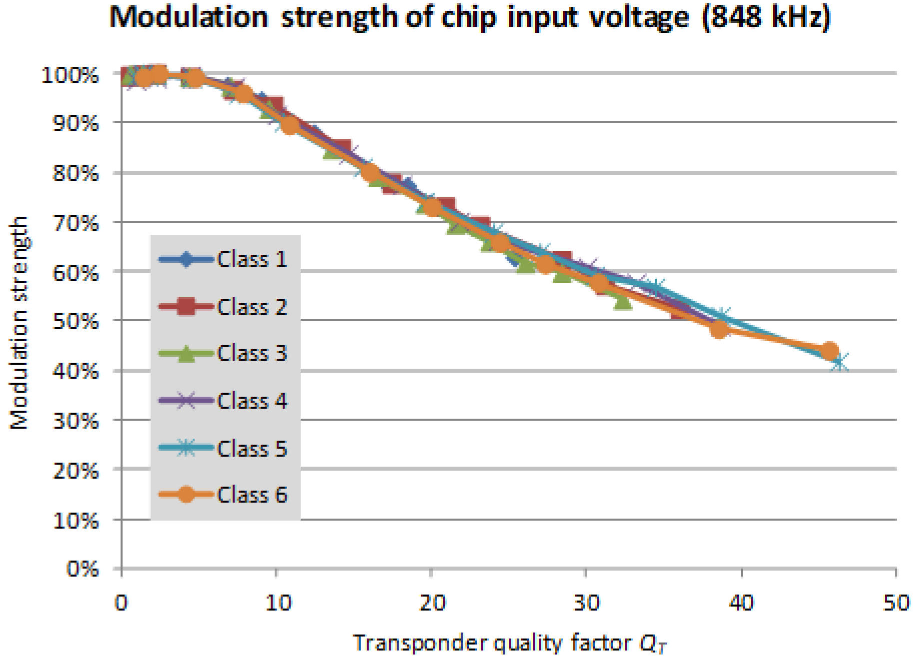
Modulation “Strength”

- 2 effects reduce the ideally achievable load modulation:



Modulation strength = $\frac{M_{pp}}{\Delta U_{ic}}$

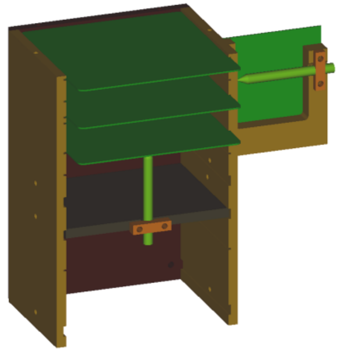
Modulation Amplitude $M_{pp} \rightarrow U_{ic,lma}$



- if antenna voltage ≠ 0 for closed shunt (➔ $Q_T = Q_M \neq 0$)
- if signal time constant < resonance time constant.

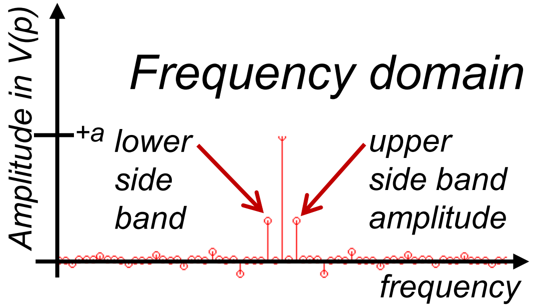
Estimation of the load modulation

based on empirical measurement data analysis



- Empirical formula for ISO/ IEC 14443-2 side band amplitude estimation (ideal case)

$$SBA \approx \frac{2}{3} k^2 H \Delta Q_T \frac{1}{\sqrt[4]{1 + Q_T^{\,2}\left(\frac{\omega_{RES}}{\omega_{CAR}} - \frac{\omega_{CAR}}{\omega_{RES}}\right)}}$$

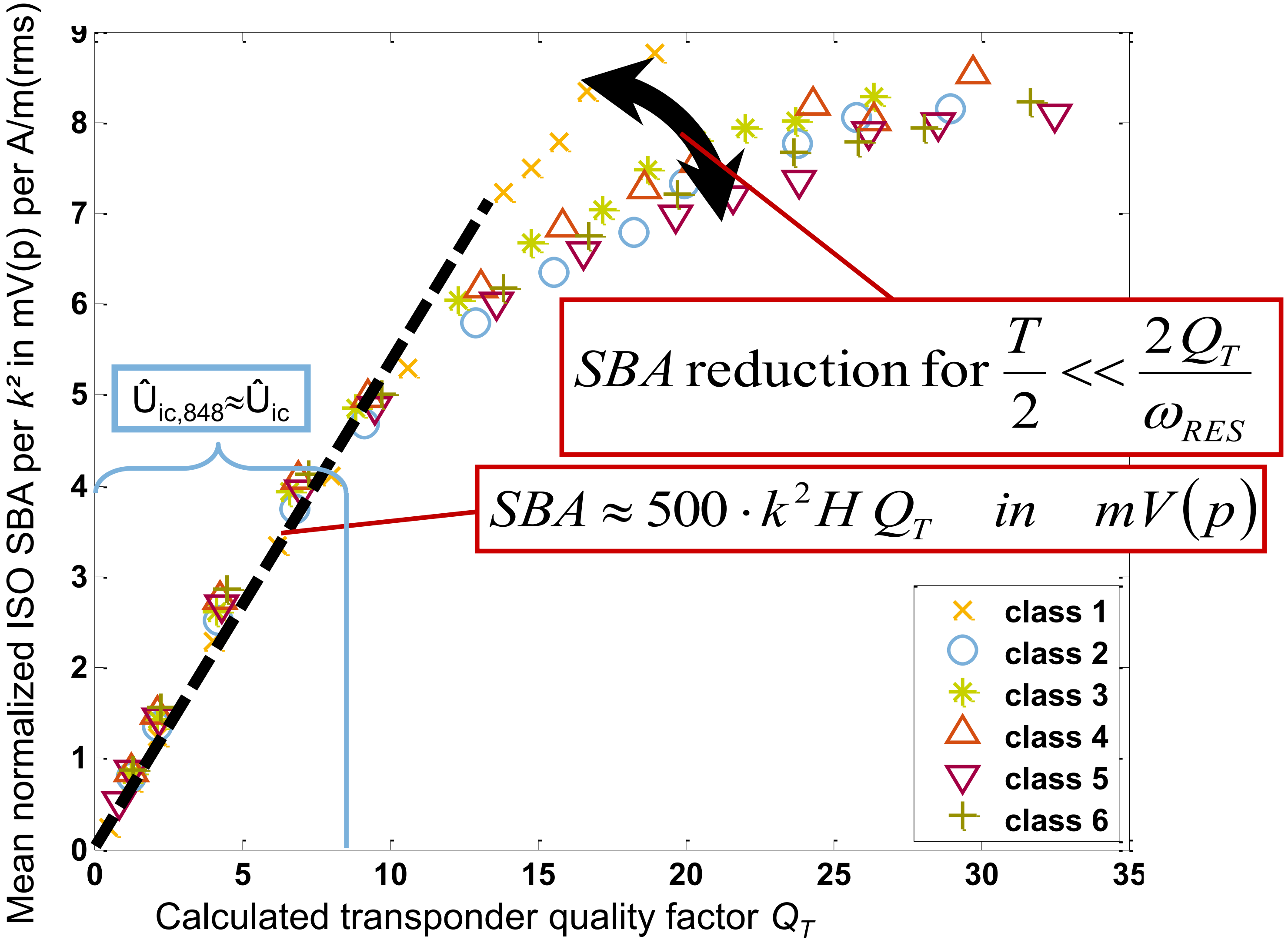


$SBA_{V(p)}$	ISO/IEC antenna arrangement sideband amplitudes in V(peak)
k	Coupling coefficient between sense coil A and transponder antenna
H	Magnetic field strength in DUT position in A/m (rms)
Q_T	Quality factor of the transponder (includes antenna and chip)
ΔQ_T	Difference between the modulated and the unmodulated Q_T
ω_{RES}	Angular resonance frequency of the transponder in s^{-1}
ω_{CAR}	Angular Frequency of the modulated sideband in s^{-1}, e.g. 2π(13,56 MHz ± 847,5 kHz)

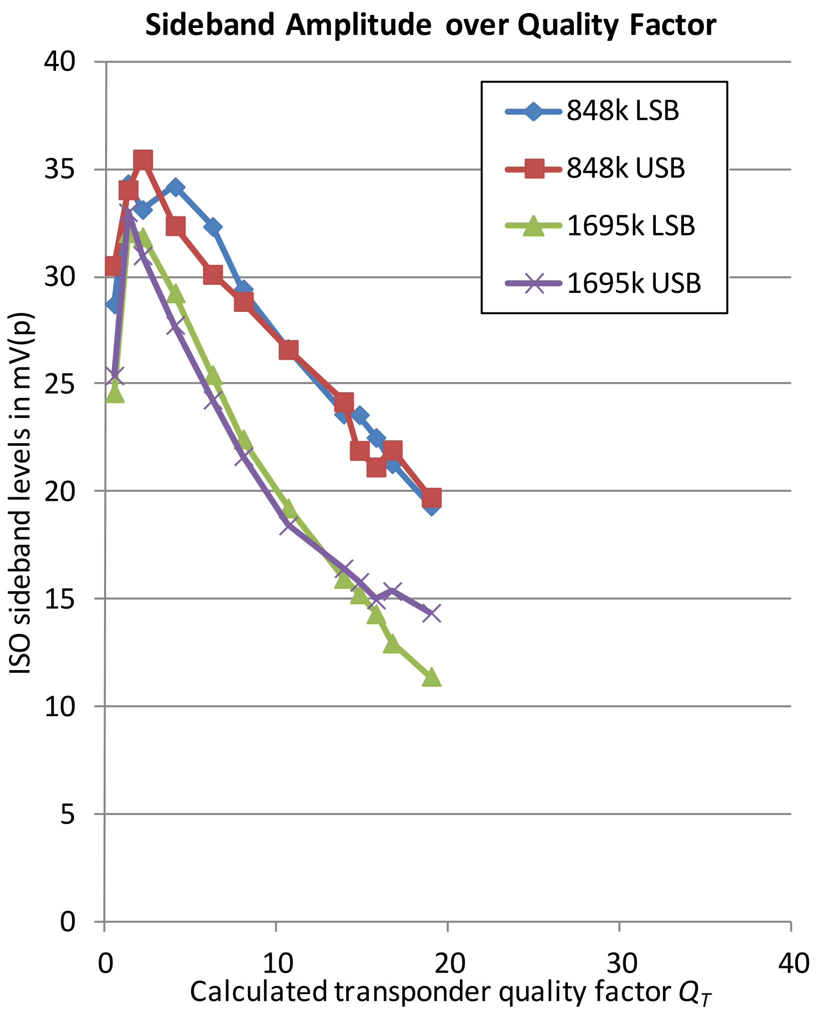
Note: This empirical model is most accurate for $Q_T < 25$, and $\Delta Q = Q_T$ if modulation is ideal ($Q_M = 0$)

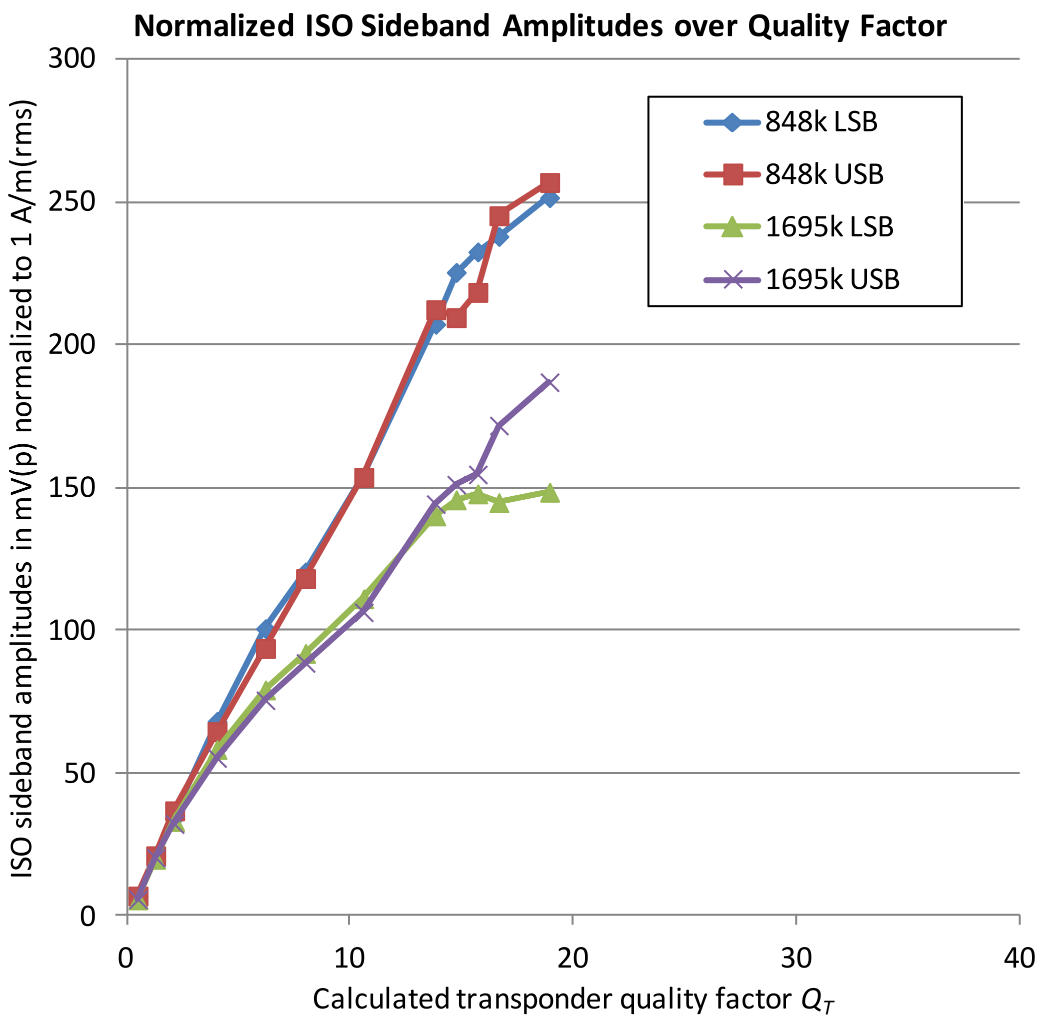
ISO/IEC sideband amplitudes over transponder Q_T

- So, it is a valid approach, to estimate transponder load modulation based on the equivalent transponder Q-factor!
- There is an empirical formula to estimate the side band amplitudes for the ISO/IEC test environment.
- Load modulation is proportional to Q_T, up to a certain limit.

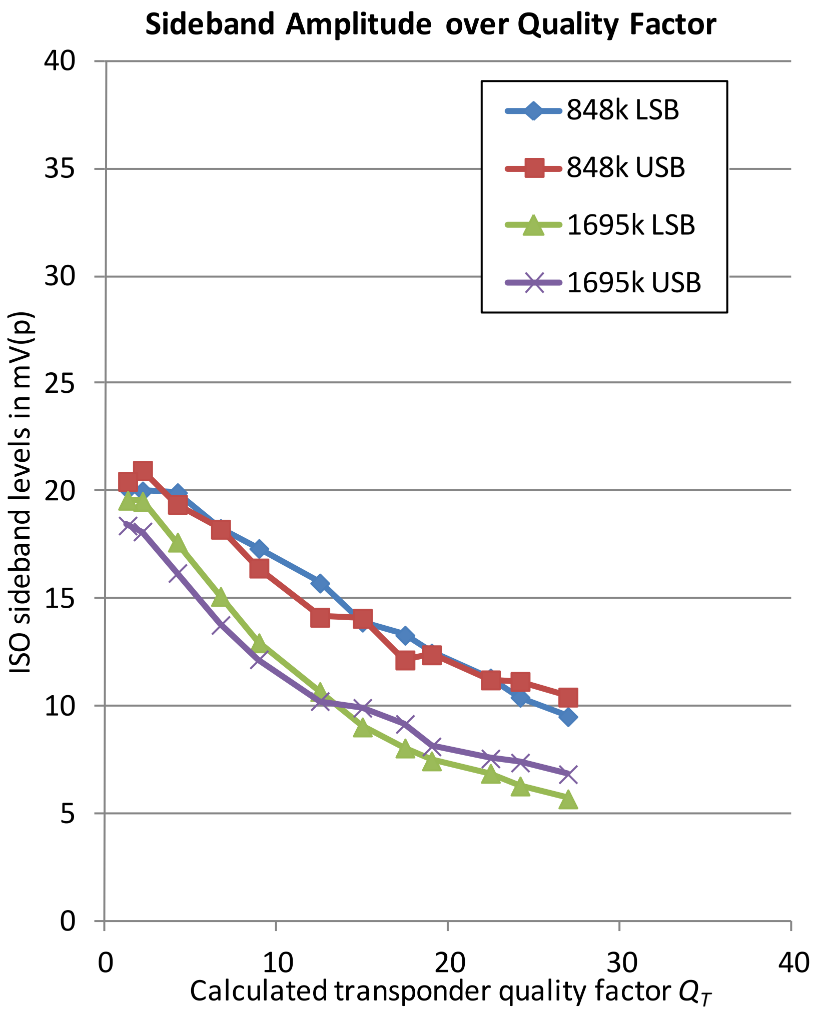


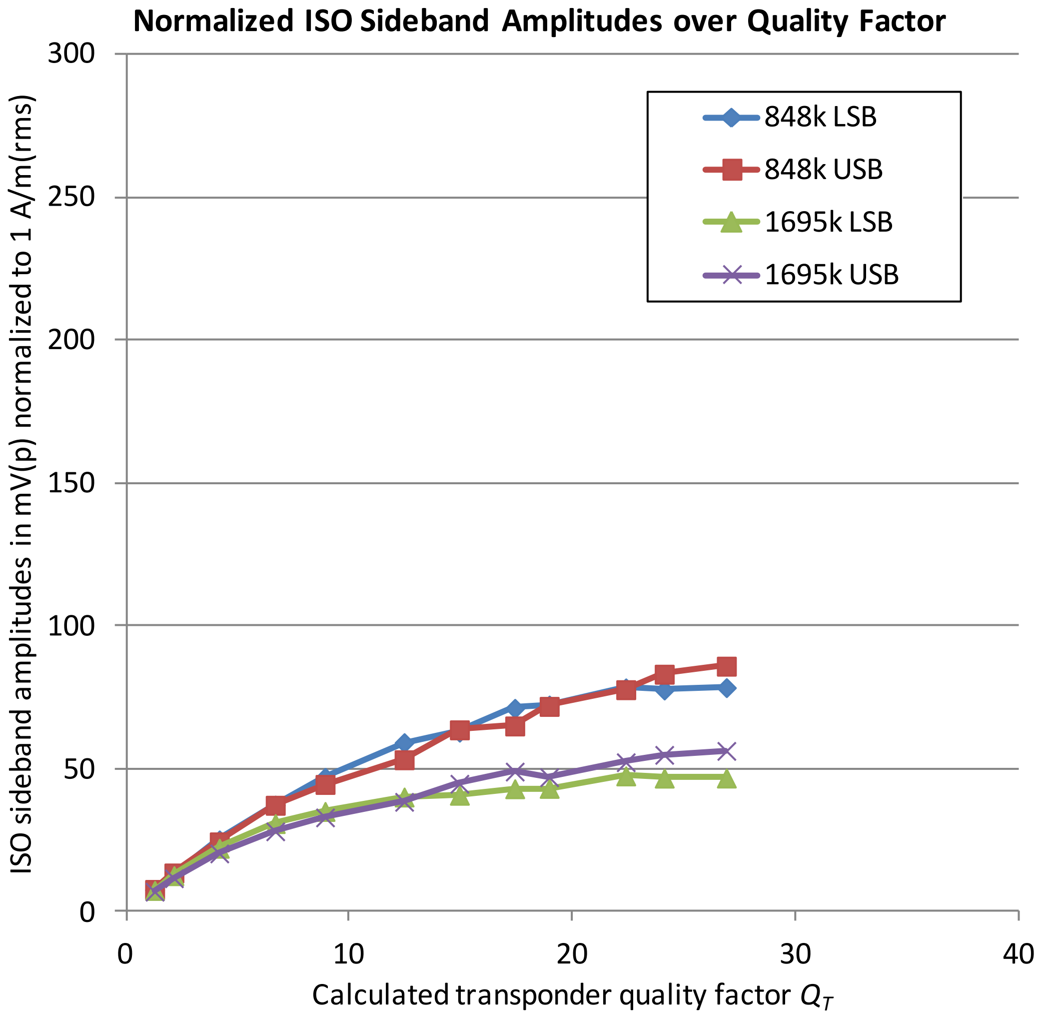
ISO/IEC SBA measurement for Class 1 antenna



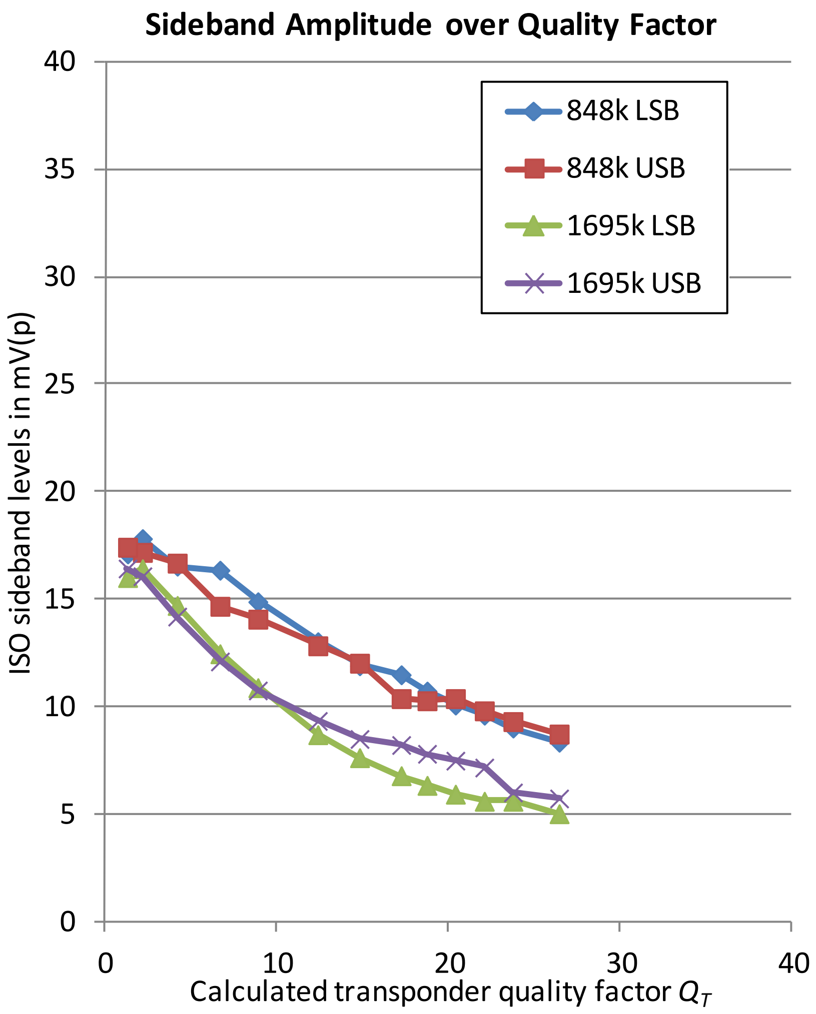


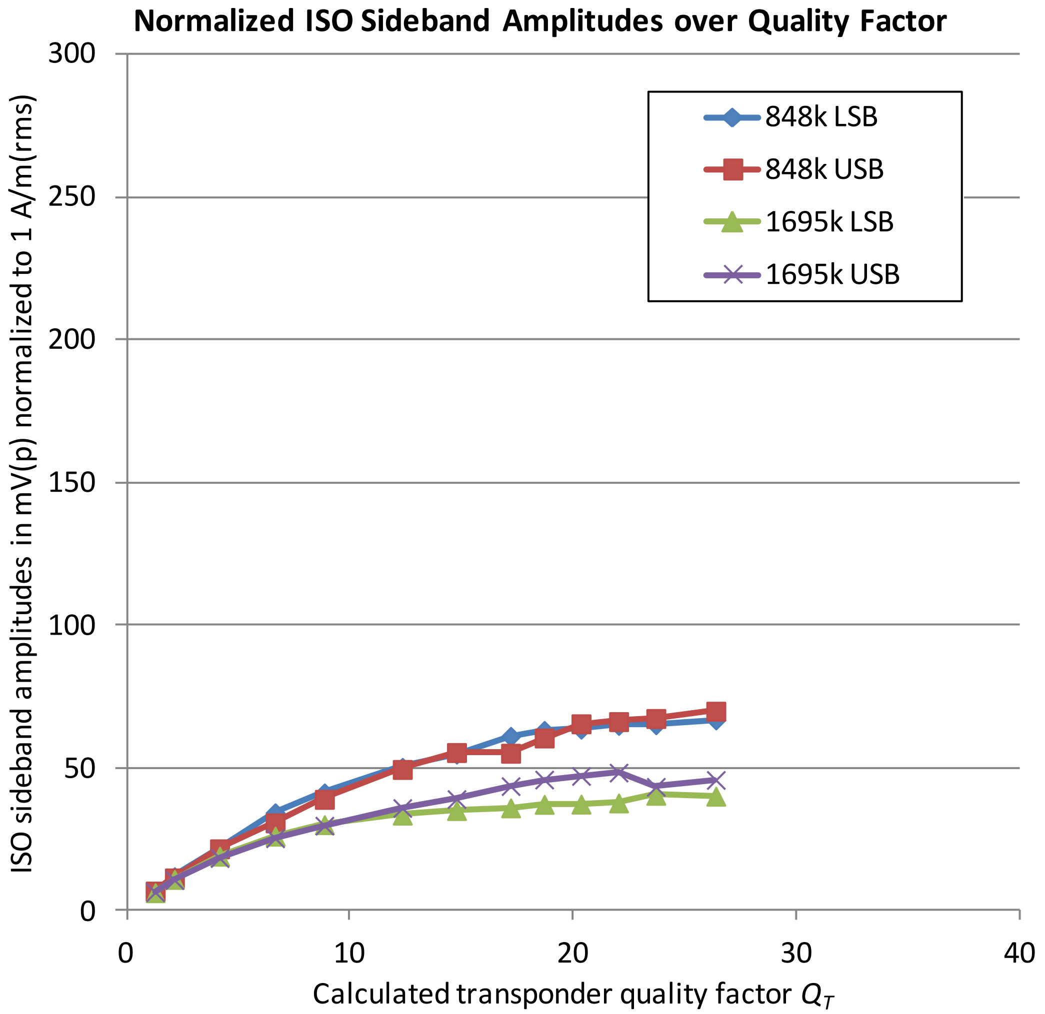
ISO/IEC SBA measurement for Class 2 antenna



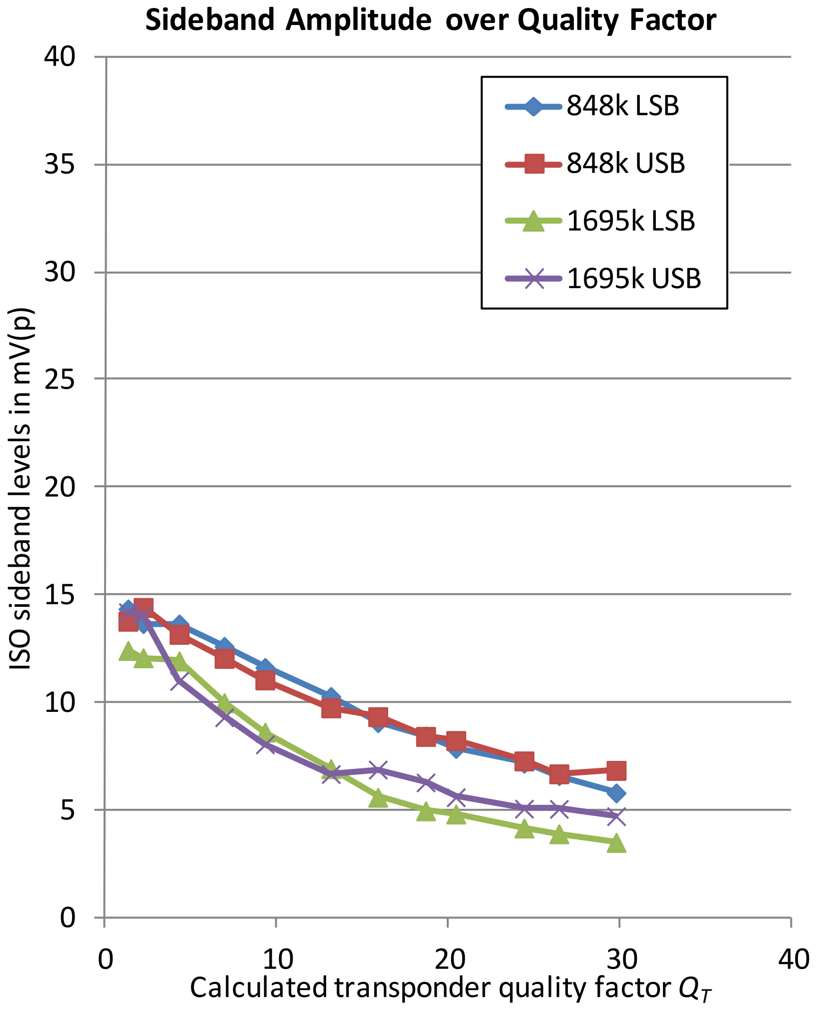


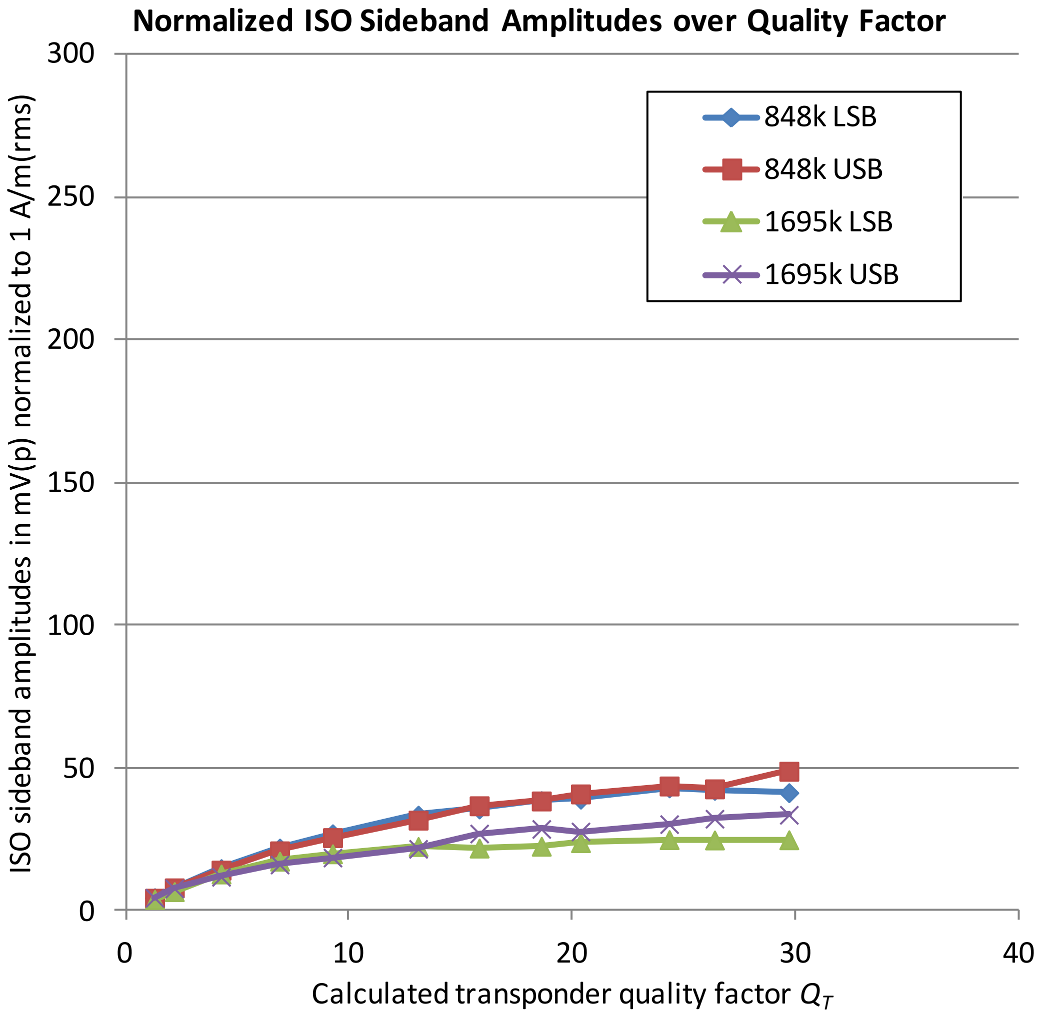
ISO/IEC SBA measurement for Class 3 antenna



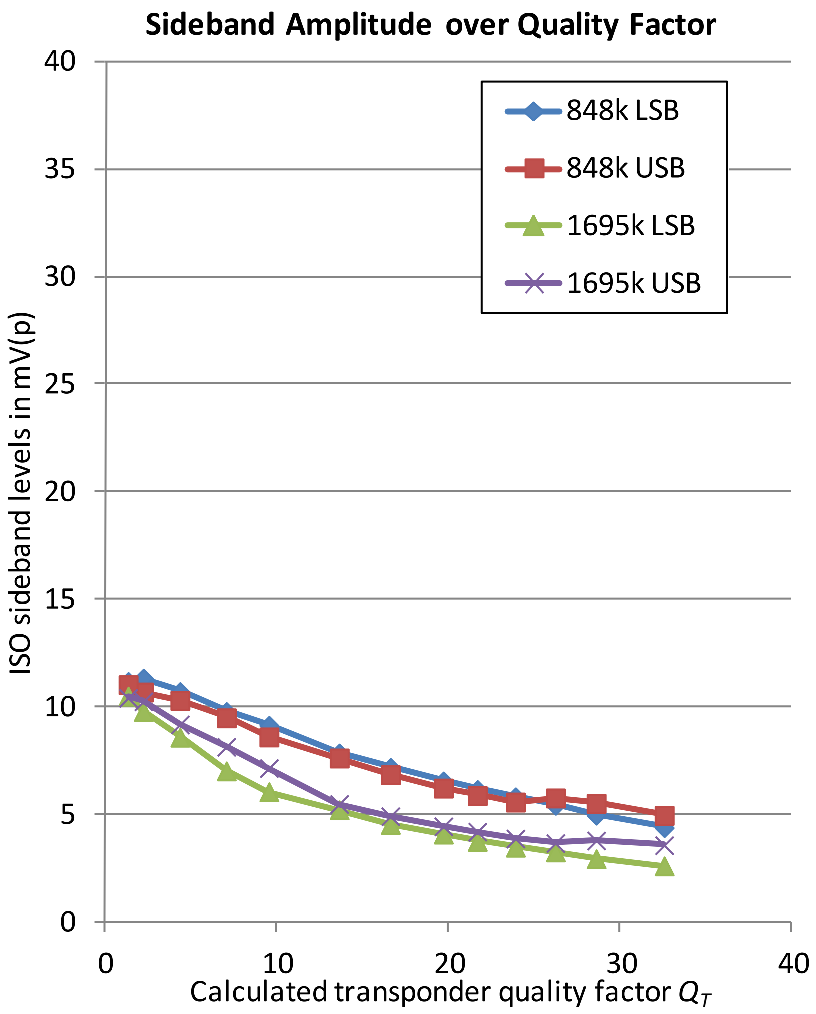


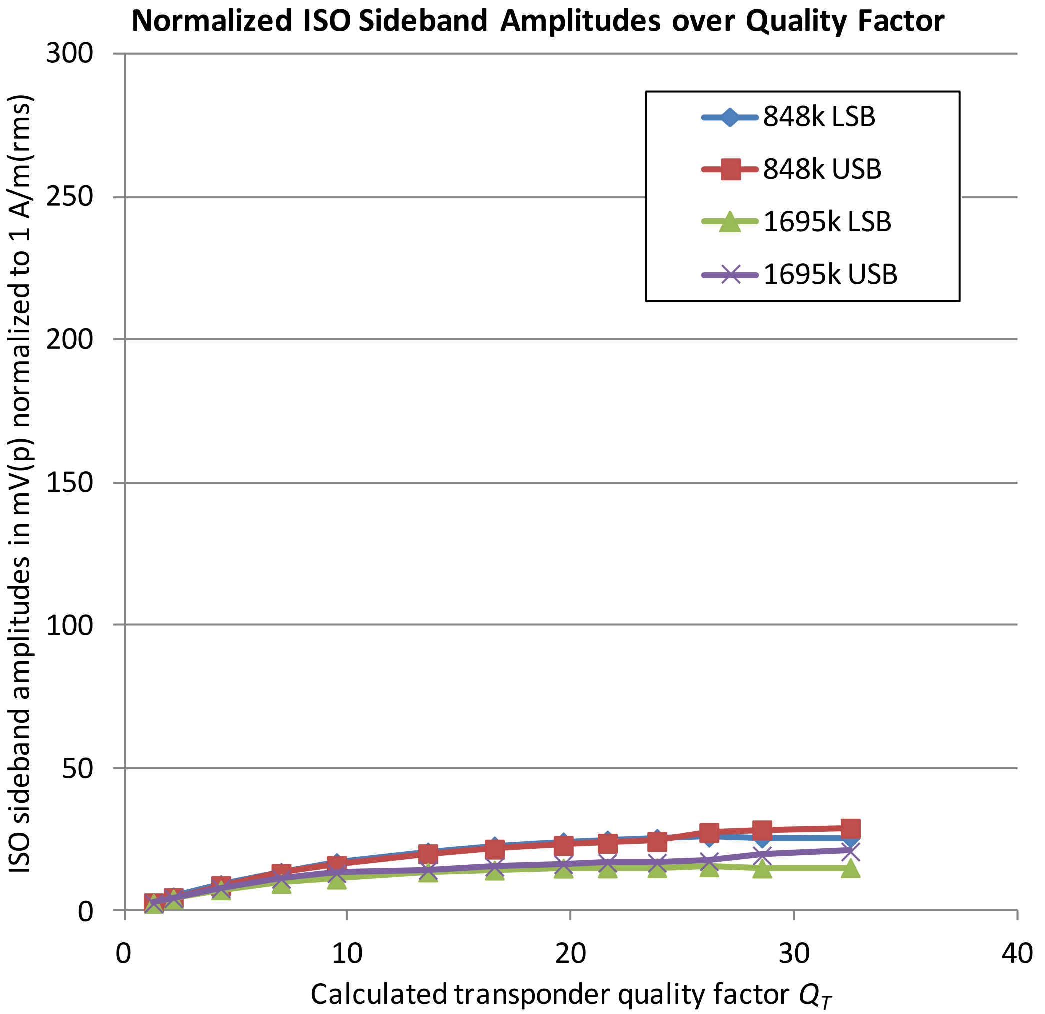
ISO/IEC SBA measurement for Class 4 antenna



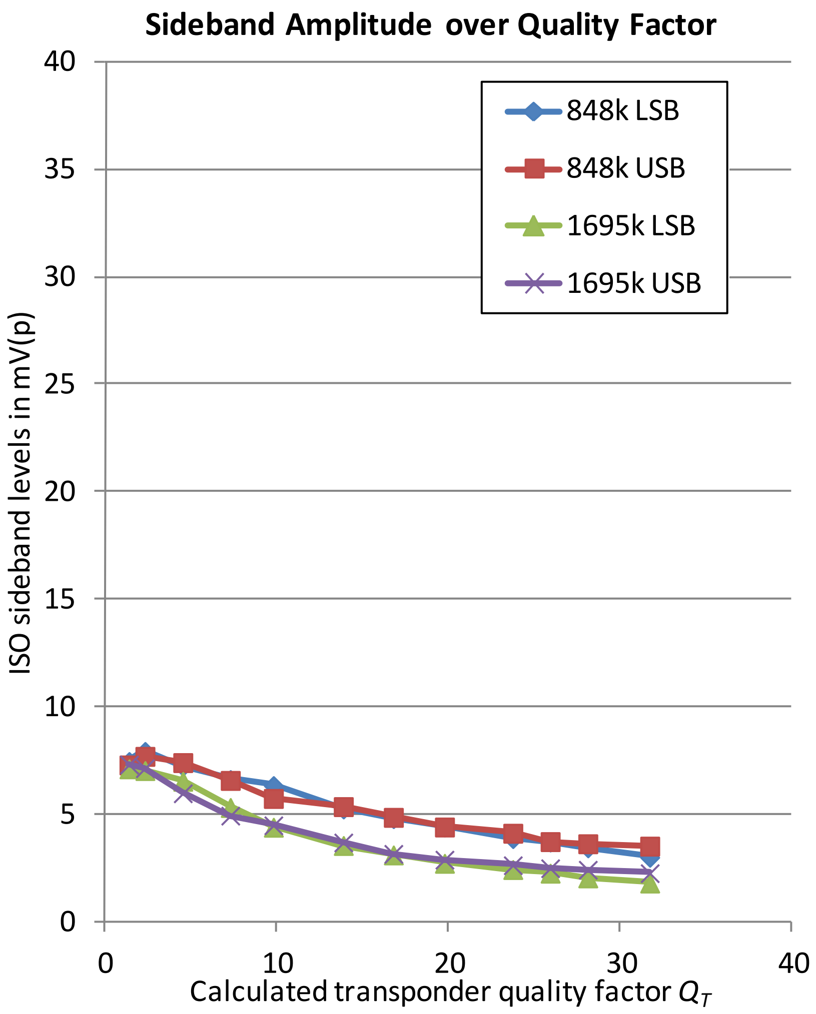


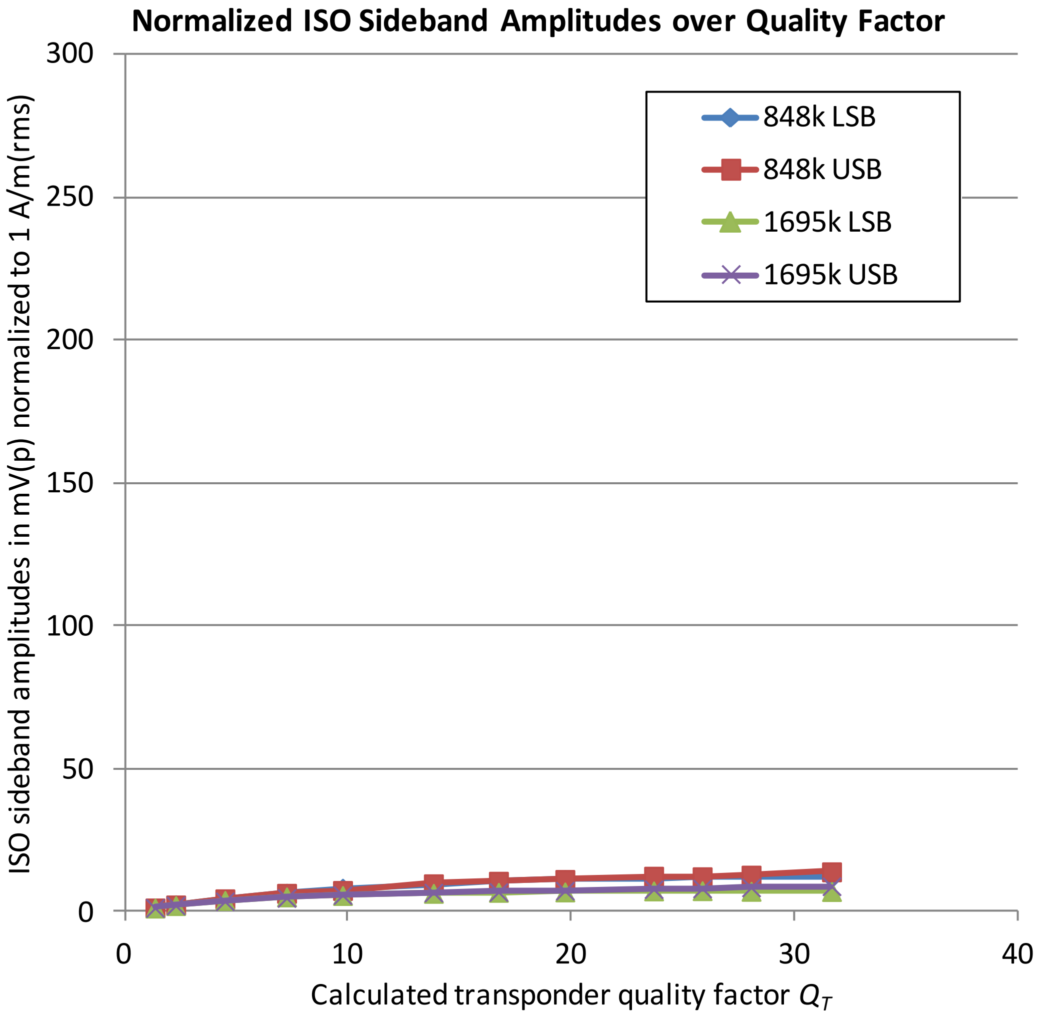
ISO/IEC SBA measurement for Class 5 antenna



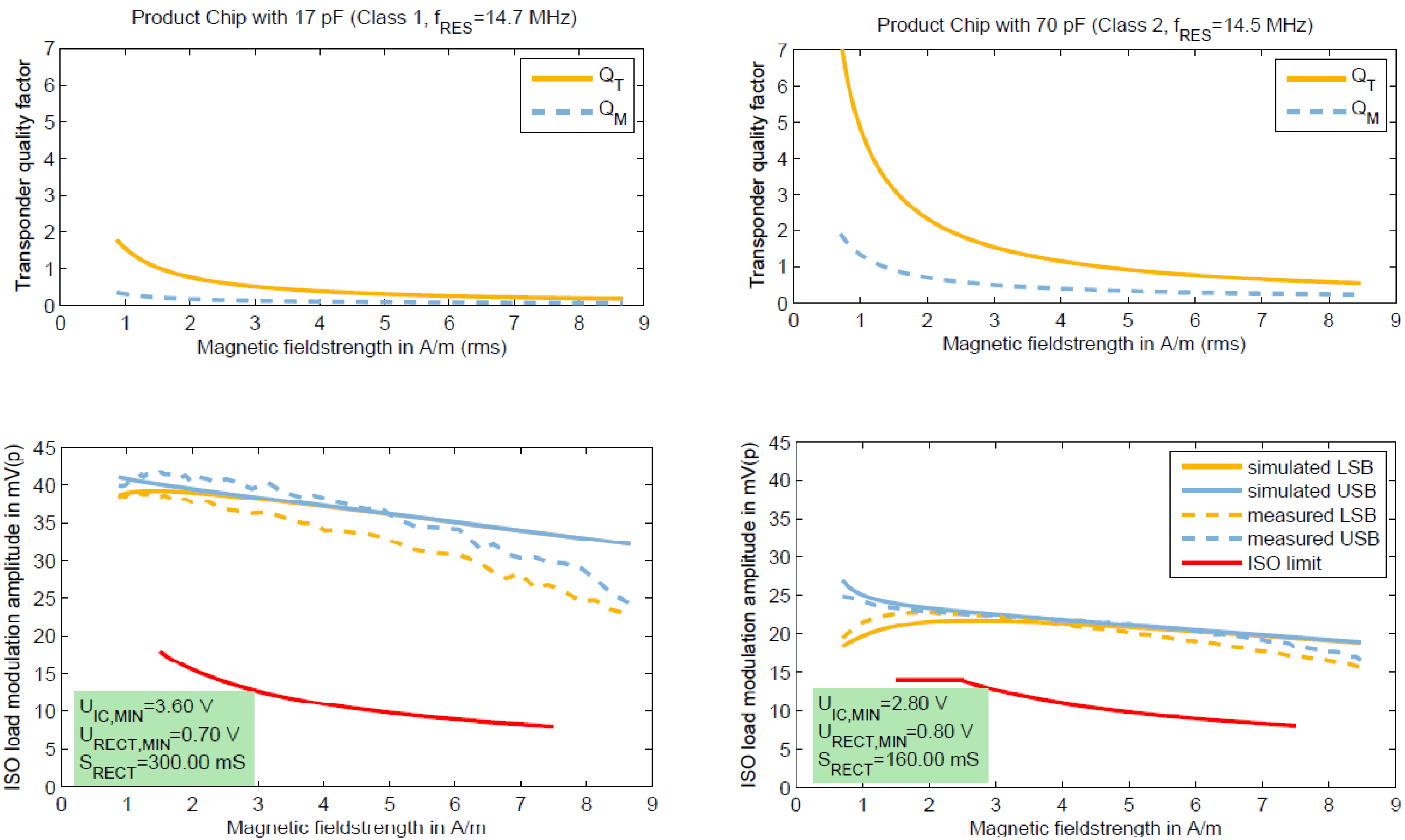


ISO/IEC SBA measurement for Class 1 antenna

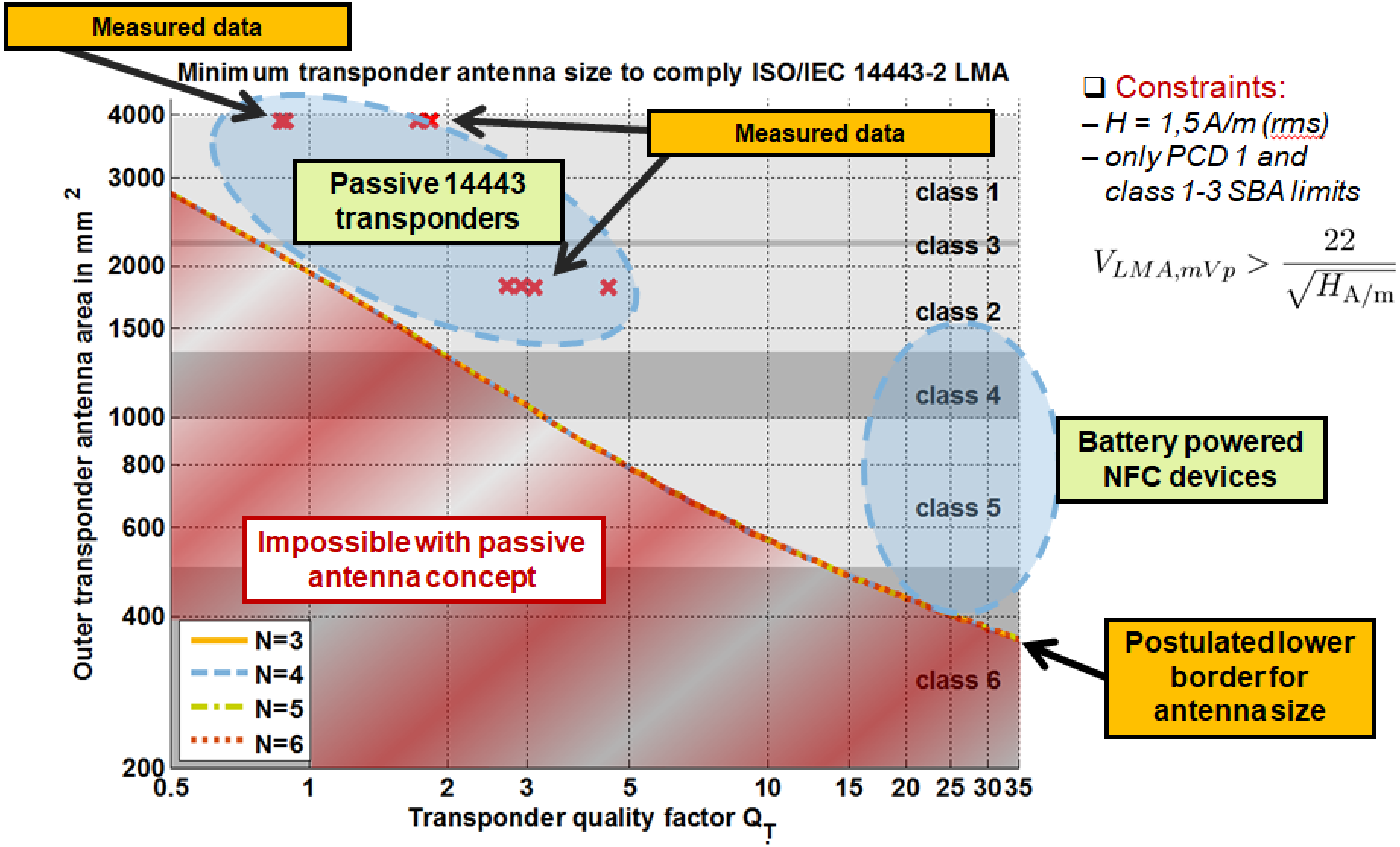




Q_T and ISO/IEC SBA as function of *H*-field strength
Comparison model versus measurement



Minimum loop antenna area limit for ISO/IEC SBA compliance



- Constraints:
  - *H = 1,5 A/m (rms)*
  - *only PCD 1 and class 1-3 SBA limits*

$$V_{LMA,mVp} > \frac{22}{\sqrt{H_{\mathrm{A/m}}}}$$

Example 1: Contactless transponder chip impedance

- We can distinguish 3 phases during communication:
  - Phase 1: Communication reader to card, 100 % AM modulation of carrier *H*-field
  - Phase 2: Un-modulated carrier
  - Phase 3: Transponder load modulation.
- In good contactless chip design, energy and not communication is the limiting factor. This allows to calculate H_{MIN} as function of resonance frequency and other parameters.

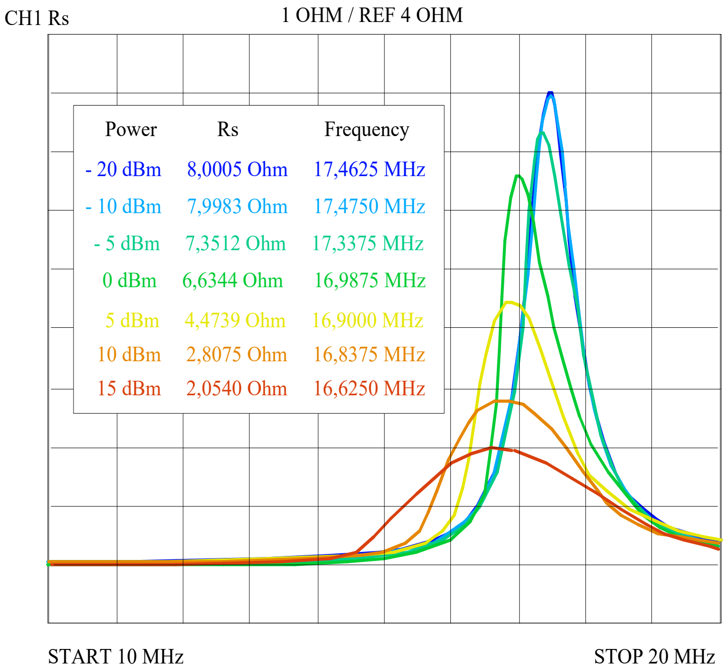
$$H_{MIN} \cong \frac{\sqrt{\left[1-\left(\frac{f_{CAR}}{f_{D1}}\right)^2\right]^2 + \left(\frac{2\pi f_{CAR} L_A''}{R_P}\right)^2}}{2\pi f_{CAR} \mu_0 N A} \cdot U_{MIN}$$

Parameter	Meaning	Unit	Value
f_{CAR}	carrier frequency	MHz	13.56
R_{C0}	eq. parallel chip resistance (measured at 0.3 Vrms)	Ohm	14000
R_{C1}	eq. parallel chip resistance at start of operation (at 2.7 Vrms)	Ohm	1500
U_{MIN}	voltage for start of chip operation	V(rms)	2.7
L_F	inductance of fixture (Cal. Coil)	Henry	2×10^{-7}
L_S	inductance of one Sense Coil	Henry	4.2×10^{-7}
L_A	inductance of card antenna	Henry	1.86×10^{-6}
k_{AF}	coupling factor antenna - fixture	---	0.115
k_{AS}	coupling factor Sense Coil - antenna	---	0.22
R_{SA}	eq. serial antenna resistance (measured at 13.56 MHz)	Ohm	1.7
A	antenna area	m²	0.0014
N	loop antenna turns	---	3.8

- A remaining problem is the resonance frequency measurement…
  - mutual inductance, and
  - chip voltage level
- …must be taken into account properly.

Resonance frequency measurement (1)

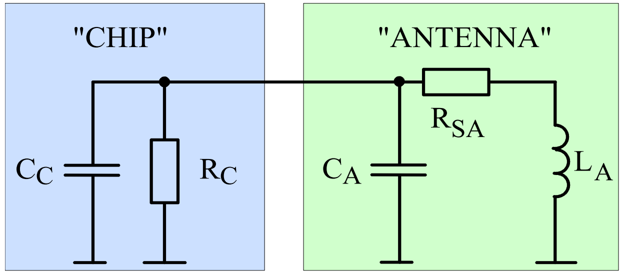
As instruments usually do not allow sufficiently high output levels to measure the resonance frequency in the operating range (fres and Q vary), one option is to measure at low H-fields (where the traces are flat and voltage-independent) and to re-calculate values for operating conditions, based on the known impedance trace.



- 2 aspects need to be taken into account:

1. The well-know Thomson equation (for parallel resonance circuits)... $f_1 = \frac{1}{2\pi\sqrt{LC}}$

...needs to be adjusted to a more appropriate equivalent circuit of the transponder....



$$f_{RES} = \frac{1}{2\pi}\sqrt{\frac{R_C + R_{SA}}{L_A(C_C + C_A)R_C}}$$

Resonance frequency (2)

2. The mutual inductance due to close coupling to other coils in the specified test setup needs to be taken into account.

One option is, to measure the resonance frequency at low *H*-field in the voltage-independent region. The natural frequency (without de-tuning by the measurement coil) can be calculated according to

$$f_{T0} = \sqrt{L_A' \cdot \frac{R_{C0} + R_{SA}}{R_{C0}\, L_A}} \cdot f_{M0} \qquad L_A' = \frac{L_A + L_F}{2} + \sqrt{\frac{(L_A + L_F)^2}{4} - \left(L_A L_F - k_{AF}^{\;2} L_A L_F\right)}$$

Then we can calculate the resonance frequency in the operating point knowing the ΔC...

$$f_{T1} = \frac{1}{2\pi}\sqrt{\frac{R_{C1} + R_{SA}}{R_{C1} L_A \left[\frac{R_{C0} + R_{SA}}{R_{C0} L_A (2\pi f_{T0})^2} + \Delta C_C\right]}}$$

…. and we can even calculate the de-tuned resonance frequency in the measurement setup

$$f_{D1} = \frac{1}{2\pi \sqrt{L_A'' \cdot \frac{R_{C1} + R_{SA}}{R_{C1}\, L_A (2\pi f_{T1})^2}}} \qquad L_A'' = \frac{L_A + 2L_S}{2} + \sqrt{\frac{(L_A + 2L_S)^2}{4} - \left(L_A 2L_S - k_{AS}^{\;2} L_A 2L_S\right)}$$

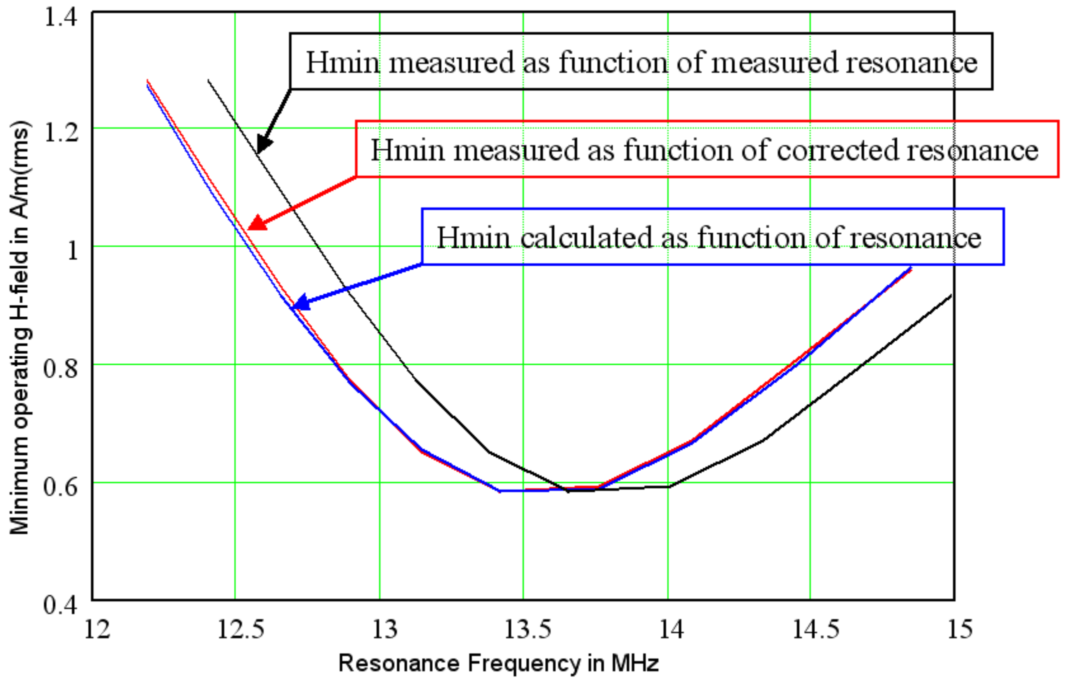
Minimum *H*-field over resonance frequency

With these corrections, the trace of minimum H-field strength for transponder operation can be calculated accurately from chip impedance trace and loop antenna parameters.

- It is also possible to calculate min. and max. allowable resonance frequency to achieve certain H_{MIN}:

$$f_{MIN} = \frac{f_{CAR}}{\sqrt{1+\sqrt{\left(\frac{H_{MIN} 2\pi f_{CAR} \mu_0 NA}{U_{MIN}}\right)^2 - \left(\frac{2\pi f_{CAR} L_A''}{R_P}\right)^2}}}$$

$$f_{MAX} = \frac{f_{CAR}}{\sqrt{1-\sqrt{\left(\frac{H_{MIN} 2\pi f_{CAR} \mu_0 NA}{U_{MIN}}\right)^2 - \left(\frac{2\pi f_{CAR} L_A''}{R_P}\right)^2}}}$$

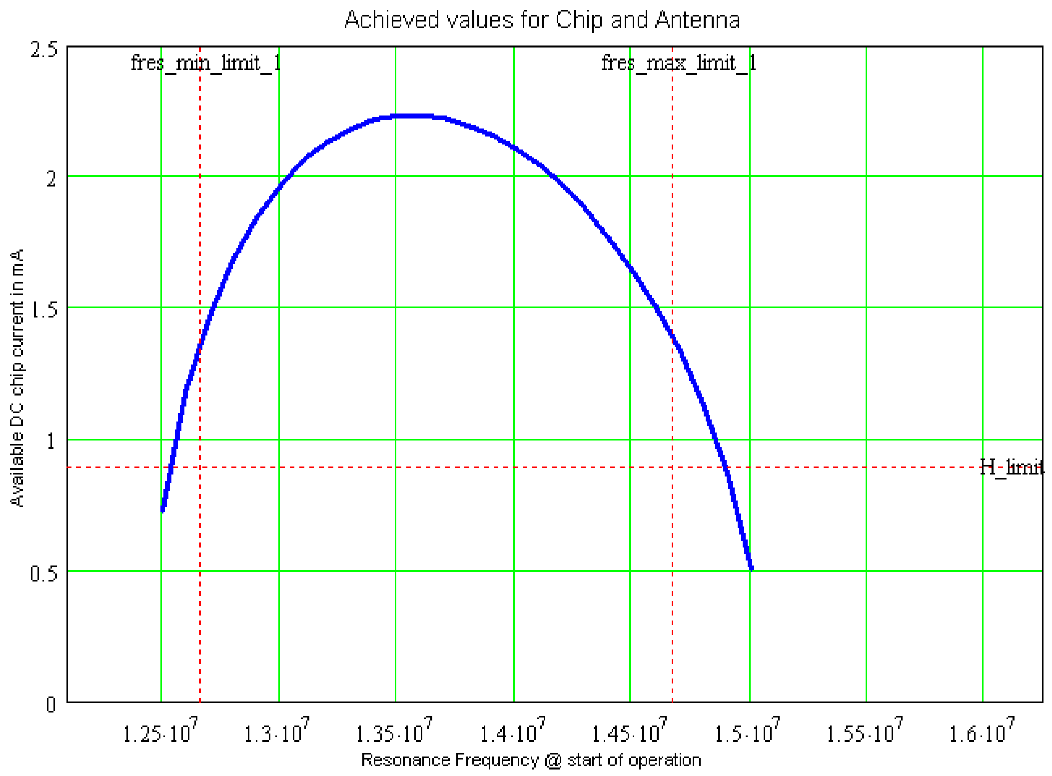


This allows to consider ***tolerances*** *for chip and antenna parameters, or e.g. to optimize operating conditions for the chip, like clock frequency.*

Chip current consideration

Finally, this allows also to consider the available internal Chip current:

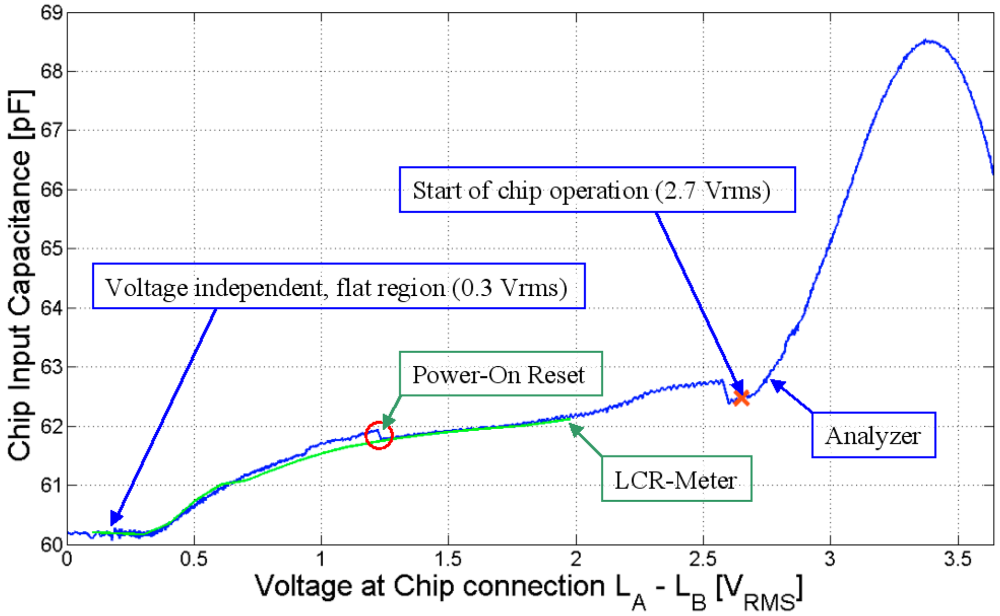
$$I_{DC} = \frac{U_{CHIP} - U_{DROP}}{R_C} = \frac{(U_{CHIP} - U_{DROP}) \cdot (R_A - R_T)}{R_A\, R_T}$$

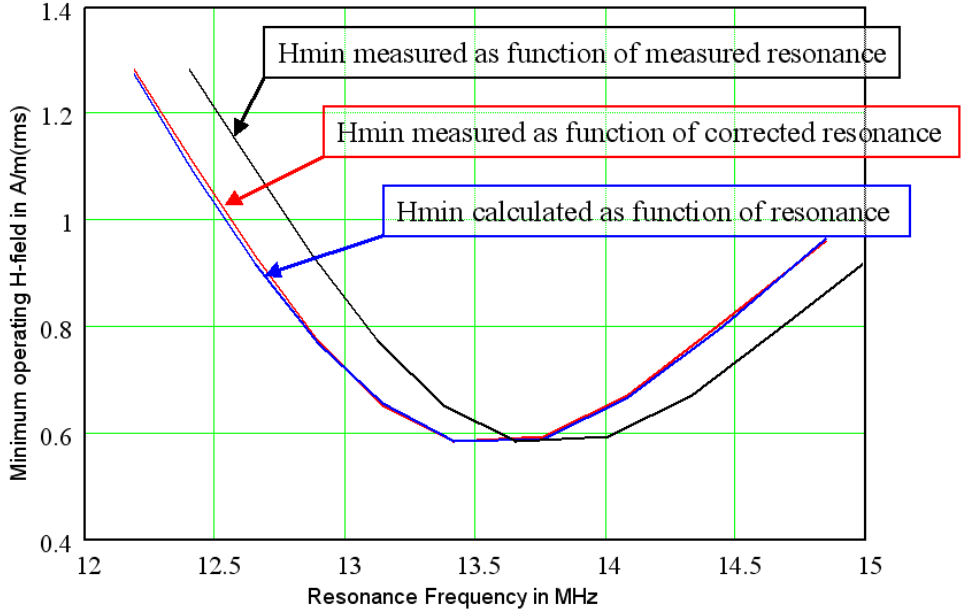


- Here we get
  - I_{DC} = 1,38 mA at the resonance frequency limits
  - I_{DC} = 2,24 mA for optimum (resonance = carrier)
  - calculated for 0,9 A/m and voltage drop of 0,9 V.
  - antenna power loss is 5,9 – 10,6 % (etched antenna).

Conclusions

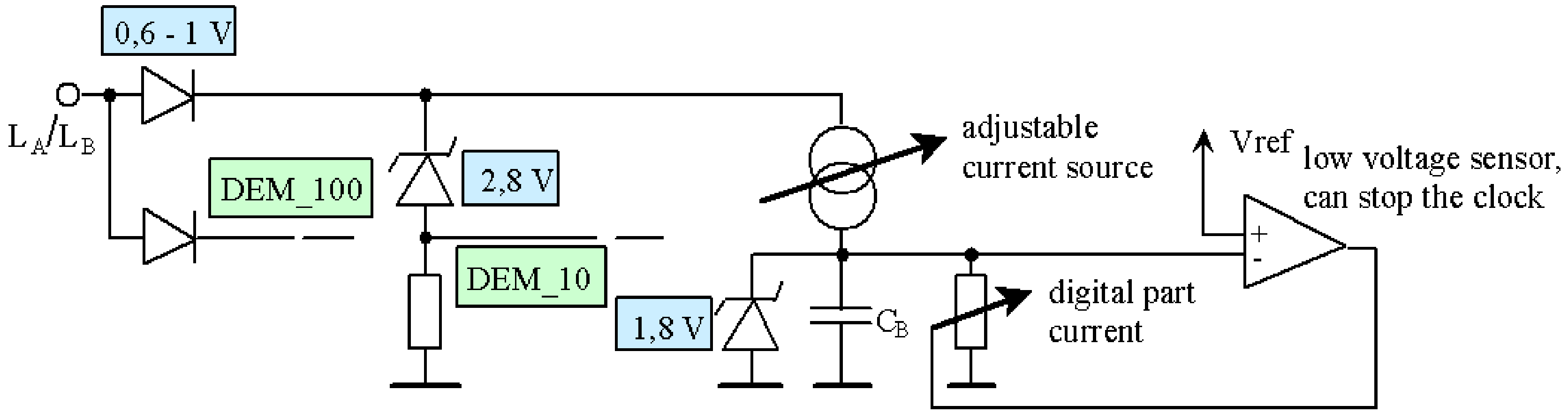
- The way to relate **chip input impedance** to the **contactless card system behaviour** was discussed in detail and applied for an ISO/IEC14443A compatible transponder chip according to the measurement methods of ISO/IEC10373-6.
- As practical example, the *H*-field required for operation was measured as function of resonance frequency. These measurements show a good fit to the quasi-static calculation model based on $R_P - C_P$ for the point of start of operation, for the investigated chip. This closes the loop to applications and proofs the concept.





Example 2: Contactless transponder chip impedance

- A simplified equivalent functional circuit for the SmartCard chip is given:



– The CPU clock can be configured by the user according to application requirements.

– This means, the (expected) required current for operation is set accordingly.

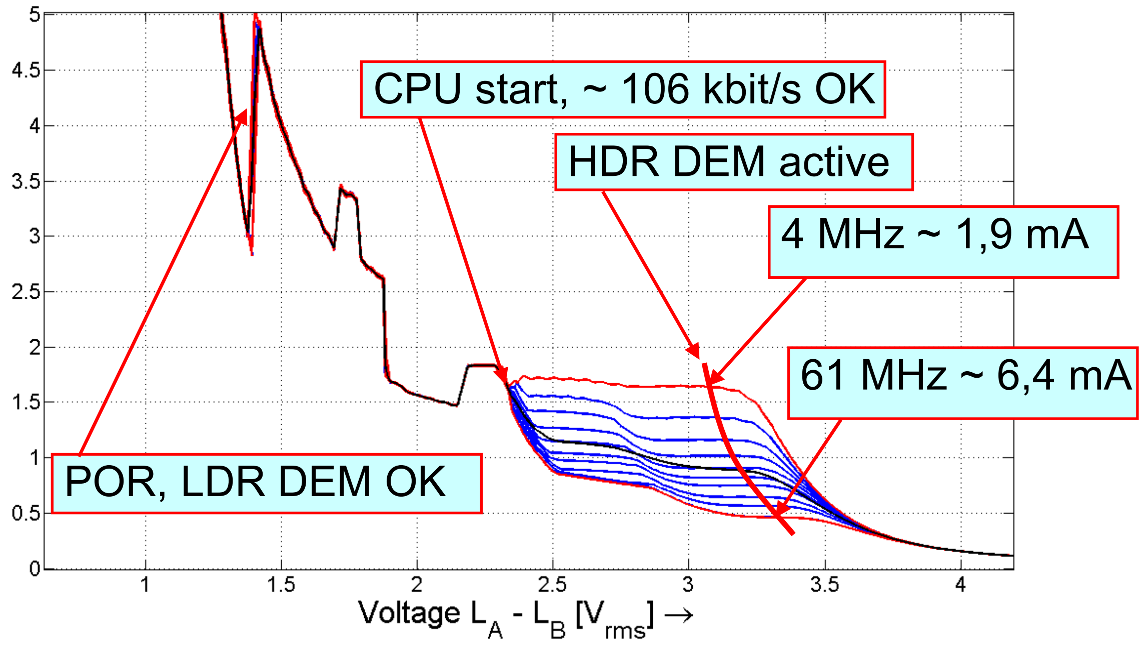
– To prevent chip reset, there is a voltage sensor which can stop the clock (and so the current consumption), if the digital supply voltage drops too much.

– This behaviour can be seen well in the traces for equivalent chip impedance, and allows the identification of specific operating points.

Example 2: Contactless transponder chip impedance

- One Engineering Chip sample was measured 10 times (clock settings 4 ... 61 MHz).
  - A part of the R_P trace is shown for detailed interpretation.
  - The LDR demodulator (on antenna voltage) is principally always functional.

After the power on reset and some switching of security logic (and non intended limiter behaviour) the voltage point for CPU start can be identified. The chip will operate at 106 kbit/s from this point on (H_{MIN} @ 106 is independent of the clock setting).



- The HDR demodulator gets active if the 1st limiter has sufficient current. So the voltage point for start of operation at HDR depends on clock setting.
- R_P and voltage are dependent on clock setting!
- Out of the diagram, a practical assumption for chip current consumtion is 1,6 + 0,08 mA/MHz.
- An estimation for the voltage point at 18 MHz CPU is 3,2 V(rms).

Example 2: Contactless transponder chip impedance

- The analytical model allows us to relate chip impedance to contactless transponder behaviour. One critical question is, how the chip power consumption changes during the modulation pause. This may require to take a duty cycle into account. In principle, H_{MIN} can be calculated with chip and antenna parameters and fits to contactless measurement results on the ISO/IEC test bench.

$$H_{MIN} \approx \frac{\sqrt{\left[1-\left(\frac{f_{CAR}}{f_{RES}}\right)^2\right]^2+\left(\frac{2\pi f_{CAR} L_A}{R_P}\right)^2}}{2\pi f_{CAR}\mu_0 N A_{EFF}} \cdot U_{CHIP,MIN} \cdot F_{DUTY}$$

Data used for calculation:

Antenna (Class 1 testboard)

- L_A........3,08 µH
- N..........4 turns
- outline 74 x 45 mm
- A_{EFF}.....0,0034 m²

Chip (CD081)

- *(DEM100)*
- R_P........1,5 kOhm
- U_{MIN}......2,3 V(rms)

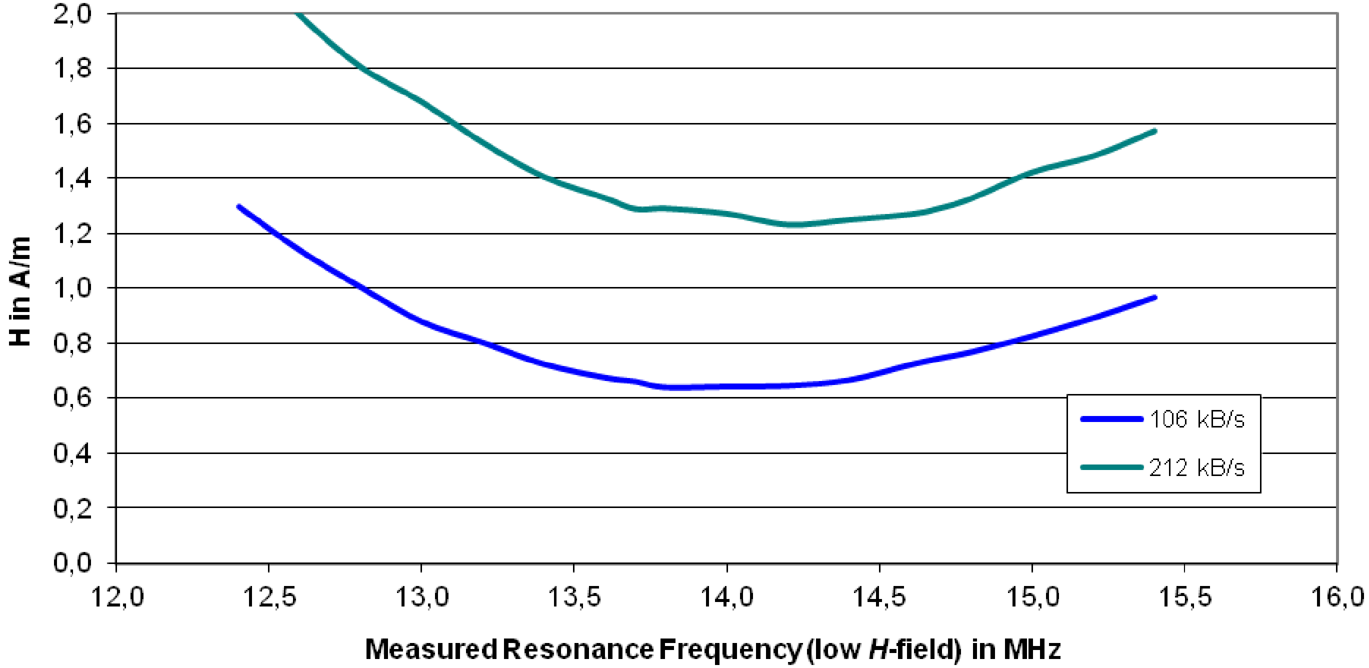
System (ISO/IEC14443)

- f_{CAR}......13,56 MHz
- μ_0.........4 π 10 $^{-7}$
- f_{RES}......15 - 18 MHz
- F_{DUTY}....1,05

- H_{MIN} is 0,42 A/m for 15 MHz and 0,77 A/m for 18 MHz – measured and calculated.

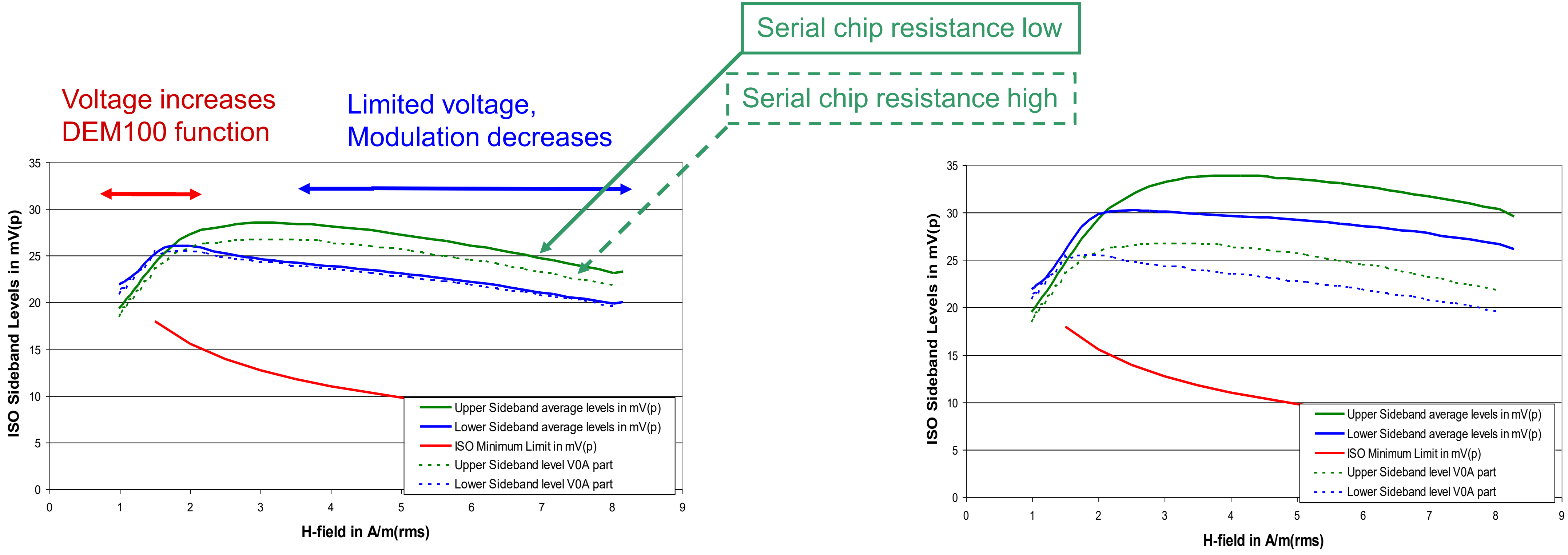
Example 2: Contactless transponder chip impedance

– In addition, we see the typical trace for H_{MIN} over resonance frequency (here for a different chip), for LDR and HDR.
– Note that resonance frequency is measured under low *H*-field conditions in this case – the minimum is not centered at 13,56 MHz carrier frequency.
– More in detail, the minimum for 212 kbit/s (HDR demodulator) is shifted against the minimum for 106 kbit/s (LDR)!



Example 2: Contactless transponder chip impedance

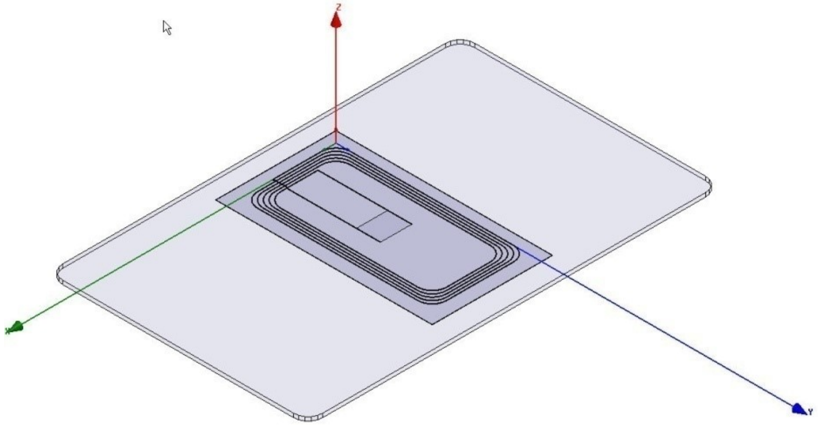
- It is also instructive, to see the influence of limiter voltage and current consumption on the ISO/IEC side band amplitudes over the *H*-field range (for a fixed f_{RES}).
- Higher U_{LIM} increases *SBA*, but only if the required current is already available from *H*-field (means increase of Q_T).
- Less current consumption helps in the critical, low *H*-field region (e.g. clock)



Example 3: Contactless sticker antenna design matrix

- Example: A design matrix of 5 different embedded wire antennas was fabricated in normal card production flow.
- Varied parameters were
  - wire pitch (distance between turns)
  - number of turns

  for equal outline (size).
- Antenna equivalent circuit parameters were measured for
  - air coils, and
  - coils on ferrite foil.

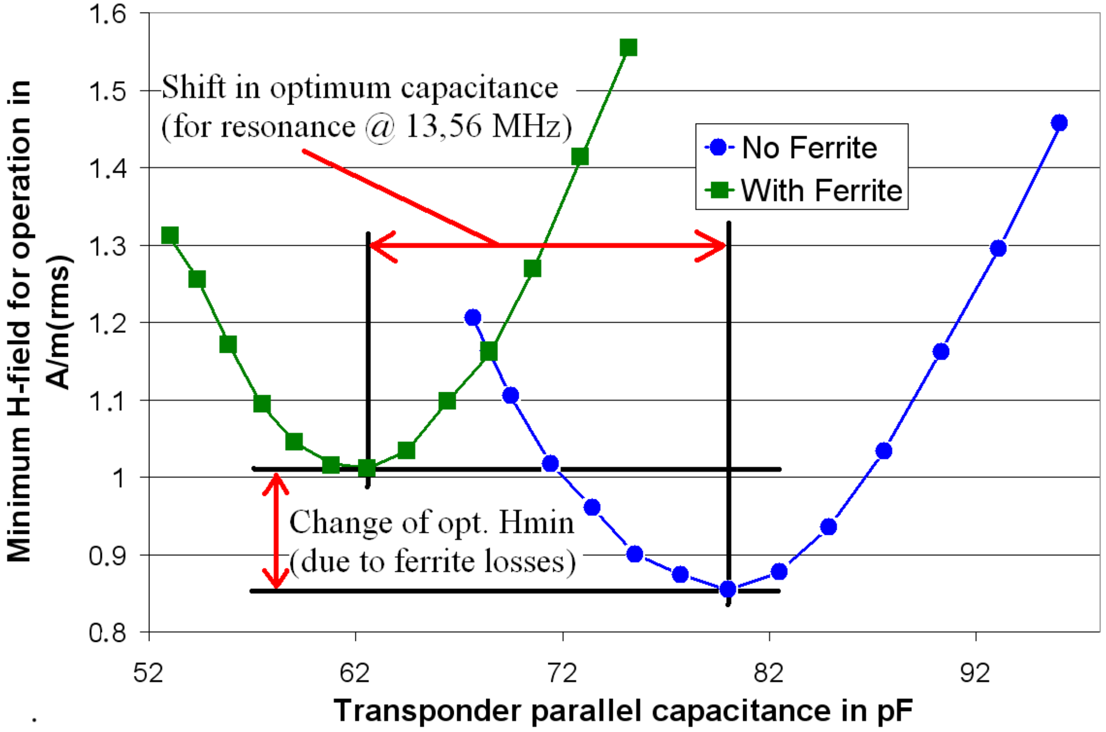


ANTENNA GEOMETRY DATA						
		No 1	No 2	No 3	No 4	No 5
outline	mm	40 x 20				
wire diam.	µm	100				
pitch	mm	0.2	0.5	0.6	0.4	0.2
turns		4	4	5	5	5
Equivalent circuit electrical data for air coils on PVC						
L_A	µH	1.595	1.304	1.692	1.937	2.303
C_A	pF	2.09	1.80	1.55	1.72	2.08
R_A	kΩ	16.97	12.40	17.92	21.81	27.40
Equivalent circuit electrical data for coils on ferrite foils						
rel. perm.	μ_r	45				
thickness	µm	100				
L_A	µH	2.008	1.649	2.162	2.433	2.901
C_A	pF	3.55	3.18	3.80	3.95	3.89
R_A	kΩ	12.85	10.18	11.91	13.80	17.20
Relative increase of inductance due to ferrite sheet						
k_L		1.259	1.268	1.278	1.256	1.259

- Conclusions: Inductance increase due to ferrite. The relative increase is constant. So the inductance for coils on ferrite can be calculated by the inductance for the air coil times a factor k_L.
- In addition, there is a loss increase due to losses in ferrite foil.

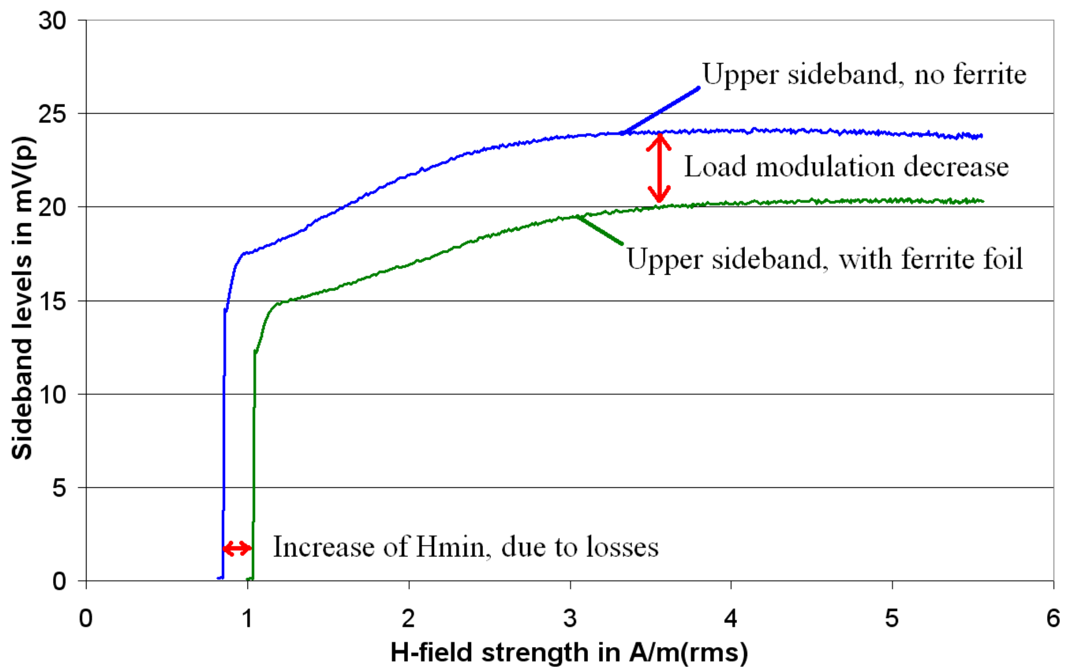
Minimum required *H*-field for operation

- Typically an antenna is designed to allow optimum contactless transponder performance (energy requirements, load modulation) for a selected chip.
- Tolerances in fabrication process (e.g. transponder capacitance) require to consider traces over a resonance frequency tolerance range (to cover all parts out of production).
  - The shift in (antenna) inductance due to ferrite causes a shift in the resonance frequency.
  - For energy-optimum resonance at 13,56 MHz carrier frequency, a different capacitance is required.
  - The resonance frequency tolerance range is similar, but...
  - Due to additional losses in the ferrite, the H_{MIN} achievable with ferrite foil is higher / worse than for the air coil (depending on the ferrite properties).



Load modulation (at upper sideband ($f_C + f_{SC}$))

- Sufficient load modulation is the 2nd main requirement for the transponder at the air interface.
- The level must be high enough to allow error-free communication of transponder to reader, as defined in the standard.
- We compare the phasor of the signal in the upper sideband for energy-optimum free air coil and coil on ferrite transponder (capacitance is adjusted properly).



- We find an increase in the starting point for load modulation, which is caused by the increased H_{MIN} (due to ferrite losses).
- We find a decrease in the load modulation level.
- For this case, the decrease is about 15 - 20 %.
- The reason are, basically, losses of the ferrite foil.

☞ **Basically, the ferrite foil means a transponder *performance degradation* compared to free air coils.**

Thank you for your Audience!

Please feel free to ask questions...

Hinweise – Notizen

Questions for self-evaluation

- What is a contactless transponder? How does an equivalent circuit (linear, time-invariant, one operating point) for a contactless transponder look like?
- A transponder, consisting of a loop antenna of 3 µH, negligible capacitance and resistance, shows a resonance frequency of 15,0 MHz. Estimate the value for the equivalent parallel capacitance at the transponder input terminals!
- Which are the main functional blocks of a contactless transponder? Which amount of current is typically available, for Vicinity and for Proximity transponders? Which type of loop antenna are used for which purpose?
- Explain a measurement setup to characterize the properties of a contactless transponder (to get element values for a simple equivalent circuit). How do typical traces for equivalent input capacitance and equivalent resistance, as function of 13,56 Hz carrier voltage, look like?
- Explain a simple analytical model, to calculate the required *H*-field strength, for a contactless transponder to operate. How does the trace for required minimum *H*-field as function of resonance frequency look like? Explain what happens if the relation of *C/L* is varied, if the transponder current consumption is varied!