Active Load Modulation for Contactless Near-Field Communication

Michael Gebhart and Markus Wobak, *Member, IEEE*, Erich Merlin and Christoph Chlestil

***Abstract*— To integrate NFC functionality in Smartphones and mobile, personal devices requires small loop antennas and specific constructions. For card mode operation there is a physical limit for the minimum antenna size to achieve standard conformance with conventional, passive load modulation. Active load modulation (ALM) can overcome this limitation and allows to construct very small antennas, but other problems arise to fit into existing infrastructure. We consider NFC antennas and present a new ALM concept in construction and function, which can overcome these problems, and we present first comparative results for the performance gain.**

I. Introduction

There is no doubt, Contactless Communication Technologies have found a huge mass market in the last decade. Such a conventional system usually consists of a data base linked to a fixed infrastructure, offering several reader terminals towards the air interface. Signals and system properties are defined by the Standards at this air interface. On the other side, there is a high quantity of contactless transponders acting as the mobile devices, offering a non-volatile read/write memory. Such battery-less transponders are typically integrated in contactless cards or smart labels, as the electrically functional part, but can also be integrated in any other objects, e.g. watches, books or goods. A contactless transponder consists of the loop antenna, directly assembled to an integrated chip, consisting of an analogue part (rectifier, voltage limiter, clock extraction of the HF carrier, demodulator and load modulator) and a digital part (processor or state-machine with operating system, non-volatile memory). Seen from RF System perspective, it builds up a resonant circuit with load mismatch (which is varied by the alternating *H*-field strength) in the antenna circuit. A contactless terminal reader consists of a loop antenna, a load matching network (to match the antenna to requirements of the chip), an EMC filter and an integrated (e.g. multi-protocol) reader chip. Seen from RF System perspective, the antenna resonant circuit has resonance at carrier frequency and a higher *Q*-factor for power-efficient *H*-field emission.

Contactless Near-Field Communication (NFC), integrated in mobile personal devices like Smartphones or Tablet PCs, has the ability to offer real world-wide interoperability to the existing contactless HF Standards. Originally patented by Philips and Sony in 2003 [1], then described in ECMA Standards 340 and 351 [2, 3] and consisting of 14443A base data rate (BDR) and FeliCa 212 and 424 kbit/s, it was adopted to ISO/IEC later on [4]. In 2004 the NFC Forum was initiated, an industry association which up to now consists of more than 160 members and also describes NFC [5]. Protocols have been extended to 14443B, 15693 and even more specific, 18000-3. Moreover, a full NFC device can operate in several modes. The initiator (NFC reader) – target (NFC card) mode allows the same NFC device either to operate like a contactless reader, or like a contactless transponder (card). Alternatively there is the peer to peer mode, which means, both devices operate in half-duplex like contactless readers, switching off their HF carrier field after data transmission.

However, to have the benefit of multi-standard and reader-card interoperability, the NFC interface must be compliant to already defined contactless air interfaces, e.g. to the Proximity Standard [11]. NFC card mode is probably the basic functionality, and one mainly limiting contactless system property is the load modulation (LM), especially for small antennas. For integration of NFC functionality into Smartphones, the available space for the antenna is very limited. This requires small antenna sizes and thin, flexible constructions. But conventional, so-called passive load modulation (PLM) is physically limited by the available antenna size [13]. Moreover, at the popular positions in the phone, e.g. around the camera or on the back cover over the battery pack, the NFC antenna is affected by metal objects in close coupling. This requires the use of thin ferrite foils, to magnetically “isolate” the antenna from the surrounding parts, to be able to operate the contactless technology in these environments at all [9]. However, these foils and the surrounding metal create additional losses, so the load modulation is further reduced. This requires new antenna concepts, to overcome the LM bottleneck. In this work, we present the “active load modulation” (ALM) concept, which is able to overcome this limitation.

II. Loop antennas

A. Fundamentals of loop antennas

Conventional antenna design for Contactless Technologies in the HF range means loop antenna design. Such a structure is a distributed component with inductance as the main network element. A broad-band representation of a loop antenna structure can be a ladder network of

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M. Gebhart, E. Merlin and C. Chlestil are with NXP Seminconductors Austria GmbH, Mikron-Weg 1, 8101 Gratkorn, Austria (phone: +43 3124 299-0, e-mail: michael.gebhart@nxp.com).

M. Wobak is with the Dept. of Microwave and Photonics, Graz University of Technology, Inffeldgasse 12, 8010 Graz, Austria (e-mail: markus.wobak@ieee.org).

several resonators up into the GHz range [6]. However, for considerations in the HF range, it is usually sufficient to consider only the fundamental, parallel resonance. So the ladder network can be simplified to a damped parallel resonance circuit for most considerations.

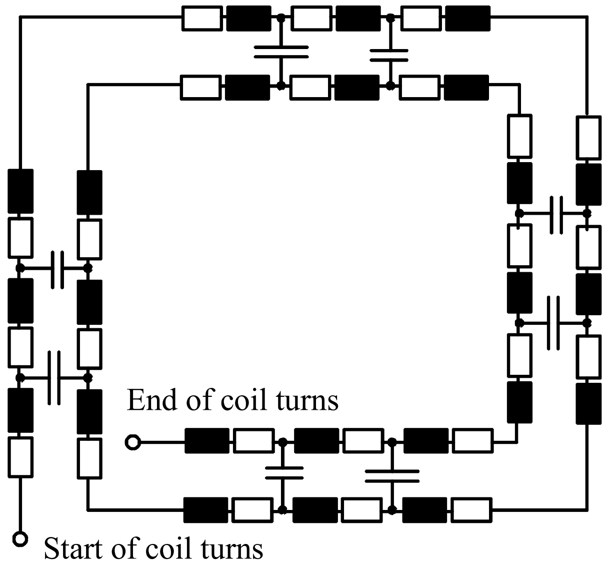

Fig. 1. Loop antenna as distributed component (similar to [10]).

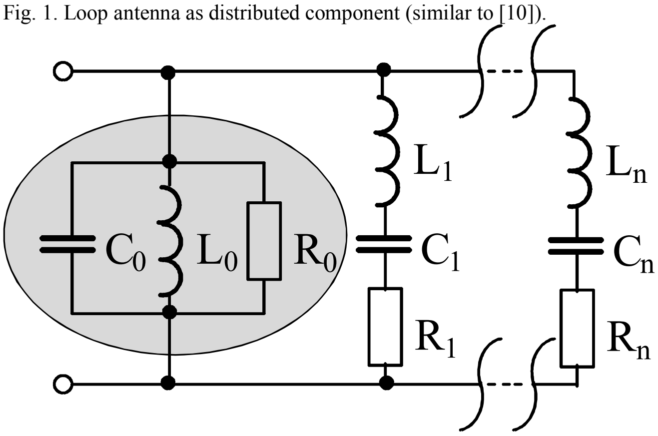

Fig. 2. Ladder network representing the equivalent network of the antenna.

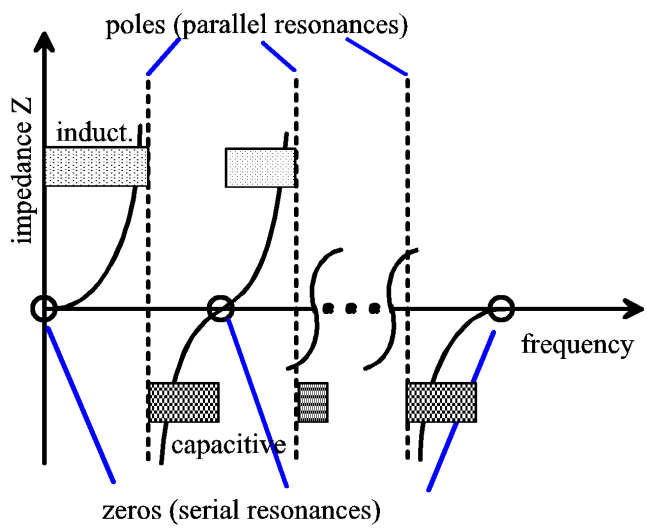

Fig. 3. Impedance of the loop antenna over a wide frequency range.

This simplified equivalent circuit, the parallel resonant circuit of fig. 2, can also be described by RF system properties, resonance frequency f_{RES} and quality factor Q. If the loop antenna is connected to an integrated NFC chip, the capacitance and the resistance values may vary over H-field, but for a simplified, linear consideration the same topology of the equivalent circuit is still valid. If two such resonant circuits are coupled by the alternating H-field, the coupling factor k is a third RF system property to describe the system.

In a conventional reader to card coupling system, the transponder consumes power out of the emitted alternating reader H-field, which causes a loading to the reader antenna circuit. For a fixed coupling, power transmission can be maximized for resonance at the carrier frequency 13.56 MHz of the alternating H-field and a high Q-factor for both resonance circuits.

Consequently this also means the highest loading to the reader. Typically the card modulates one of the two RF system properties, resonance or quality factor, to transmit data to the reader by load modulation. As the modulation of data also requires a certain bandwidth, there is an upper limit for the Q-factor, given by the time constant. Proximity Smartcards are typically operated at a comparatively low Q-factor (e.g. Q = 3 at H_{MIN}), while multi-standard readers are operated at higher Q-factors (e.g. 25) for efficient H-field emission.

B. Ferrite foils

In applications where the loop antenna has to be placed on metal objects, e.g. on the battery pack of a mobile phone, thin ferrite foils are used to conduct the magnetic flux between antenna and metal. Such foils are available either as polymer foils or as sintered ferrite foils. The polymer material is available on reels for cost-effective industrial production. It has good mechanical properties, e.g. high flexibility, but rather limited magnetic properties, e.g. medium permeability. For the sintered ferrite sheets it is the opposite; mechanical properties are rather poor, the material is rigid and only available in sheets, but magnetic properties can be much better.

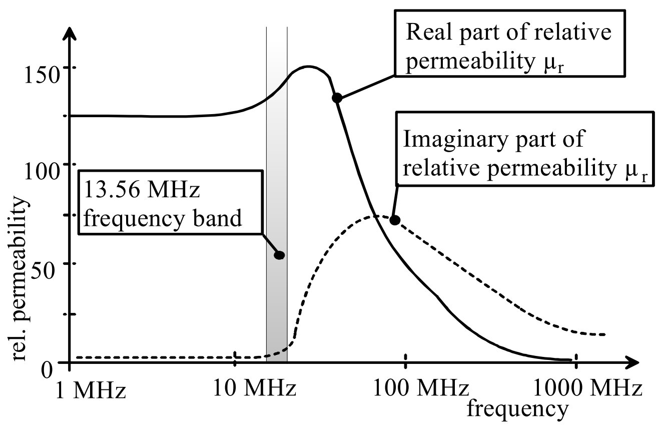

Fig. 4. Relative permeability of ferrite foils for alternating H-field.

The mainly interesting property is the relative permeability μ_r at the intended operating frequency. The real part of μ_r should be high (e.g. 100) as it is a measure of the amount of magnetic flux, which can be conducted in a thin sheet, and the imaginary part of μ_r should be very low (e.g. < 3) as it is a measure for the HF losses in the material. Fig. 4 shows the typical frequency dependency of both parameters. If the right material is chosen, it performs well at 13.56 MHz, but higher frequencies, e.g. harmonics emission, will be attenuated much. The ferrite also increases antenna inductance and affects antenna tuning, while metal close by will have the opposite effect and decrease inductance. To fabricate a more or less ambient-independent antenna one can build a stack consisting of antenna conductor, ferrite foil and metal backplane, as described in [9].

III. Options for Active Load Modulation

A. *Options to generate active load modulation*

Active load modulation in this context means to provide the 13.56 MHz AC antenna current by a driver amplifier circuit. This is possible for battery-powered devices like the NFC device which already have an integrated driver for NFC reader mode. Moreover, it allows to overcome the limit for "passive" load modulation, which allows higher antenna current only for higher antenna *Q*-factors and so is associated with longer time constants, affecting modulation bandwidth. This means to use the transmitter to actively drive the antenna also for NFC card mode allows to increase the load modulation and to transmit high data rates.

The target, however, is to achieve interoperability with existing contactless systems and infrastructure. So, if the same signals are generated at the reader antenna, both passive and active card modulation are equal. This means not only to achieve the load modulation amplitude levels required by the standard, but it requires the device operating in card mode also to be synchronous (in phase) to the 13.56 MHz carrier frequency, provided by the reader alternating HF field. Phase synchronity is required at least during the transmission of one data frame from target to initiator, as the initiator is the time reference for the contactless communication system. As we consider two independent devices with independend oscillators, this is typically hard to achieve for all cases. It can be done

- in time domain by synchronizing a PLL to the reader clock during non-modulated times,
  - protocol specific, e.g. for 14443A base data rate, using the non-modulated half bit of the manchester coding for re-synchronization, or
  - restricting data frame length, e.g. using only short frames and synchronize before every frame with accurate PLL,
- in space domain,
  - e.g. using a zero-coupling antenna to split up the *RX* and *TX* path for the chip.

Such a zero-coupling antenna allows the NFC device in card mode to receive and synchronize to the opposite reader carrier phase even during card mode transmission times, as the transmitted card mode signal is strongly attenuated to the *RX* path.

B. *Construction of the zero-coupling ALM antenna*

If there is only one loop antenna for *RX* and *TX* path, the *RX* path is saturated by the actively transmitted signal in card mode. So the antenna can be split up into two loops with a common *GND* connection, for *TX* and *RX*, as shown in fig. 5. Considering the antenna plane, the *TX* coil will emit *H*-field of positive magnetic flux inside the conductor loop, and of negative magnetic flux outside the conductor. If the amount of positive magnetic flux is equal to the amount of negative magnetic flux integrated over the antenna area, no voltage is induced in the *RX* loop antenna. This means a zero-coupling condition between *TX* and *RX* coil.

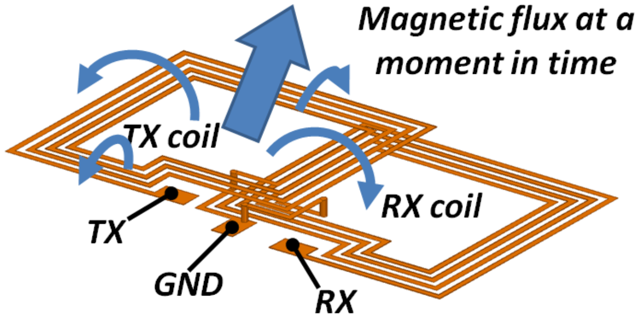

Fig. 5. Layout of the symmetric zero-coupling loop antenna conductor.

The exact geometry of such a zero-coupling antenna can be simulated using HFSS [17]. A current source is connected between *TX* coil and *GND*, forcing an AC current of defined amplitude at the carrier frequency. The voltage induced in the *RX* coil is measured, and the voltage at the *TX* coil is measured. For a given antenna outline, in this case 30 x 17 mm, the size of the loops and the corresponding overlap is varied in small steps and each of these geometries is simulated.

If we evaluate the induced voltage amplitudes of the loops as a function of this lateral distance, we find a minimum voltage, indicating the position for minimum coupling.

The coupling between *RX* and *TX* coil can be calculated according to

$$k = \frac{U_{RX}\sqrt{L_{RX}}}{U_{TX}\sqrt{L_{TX}}} \quad (1)$$

where U_{TX} is the voltage amplitude applied at the *TX* loop, L_{TX} is the inductance of the *TX* loop, U_{RX} is the voltage measured at the *RX* loop and L_{RX} the corresponding inductance. The simulation is iterated until a target criterion for minimum coupling is achieved, e.g. at 0.5 % as shown in fig. 6.

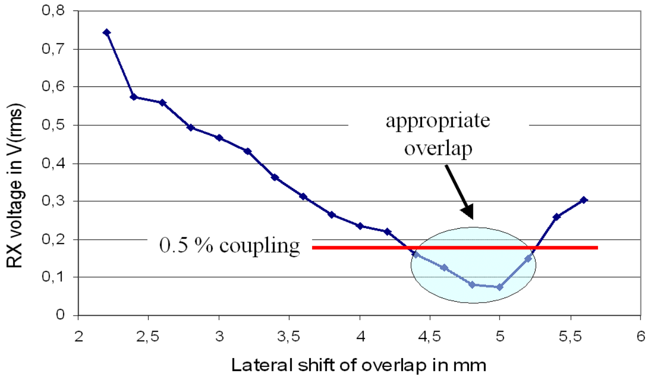

Fig. 6. Optimizing loop overlap for minimum coupling in HFSS simulation.

C. Layer structure of prototype ALM NFC antenna

An industrialized prototype layer stack construction of the NFC ALM antenna is shown in fig. 7.

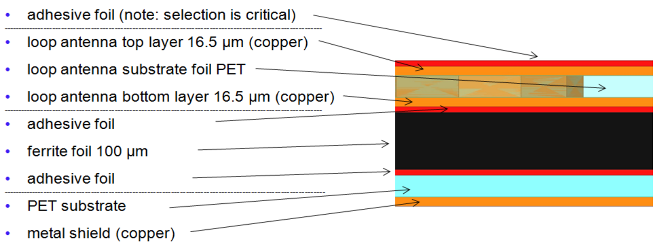

Fig. 7. Layer stack of prototype industrial NFC ALM antenna.

As the antenna might be sticked inside a Smartphone back cover, the top layer of the antenna is an adhesive foil. Below we find the antenna conductor top layer and bottom layer on a thin foil substrate, which might be PET. In this case we consider an etched antenna and the conductor is copper of 16.5 µm thickness. Below the antenna is a sintered ferrite foil of 100 µm thickness which is a bit larger in size as the antenna outline, sticked to the antenna again by an adhesive foil. In the lowest layer we find the metal shield or backplane, again as an etched foil which is sticked to the layer structure. For simulation of the zero-coupling condition, the whole stack must be considered, as ferrite and adhesive have an impact on the spatial distribution of the emitted *H*-field and so have an impact on the coupling between the coils.

D. Driver current signal

The principal signal sequence of the half-duplex communication according to ISO/IEC14443A base data rate (BDR) is shown in fig. 8. The upper trace shows the induced voltage of the *RX* coil. We can see the modulated envelope of the 13.56 MHz carrier signal at the end of a Reader-to-Card transmission. After the frame delay time the Card-to-Reader transmission starts, shown in the lower trace for the driver current. Bursts of 8 cycles of the 13.56 MHz signal, synchronous to the opposite reader carrier frequency, build the Manchester-encoded data format.

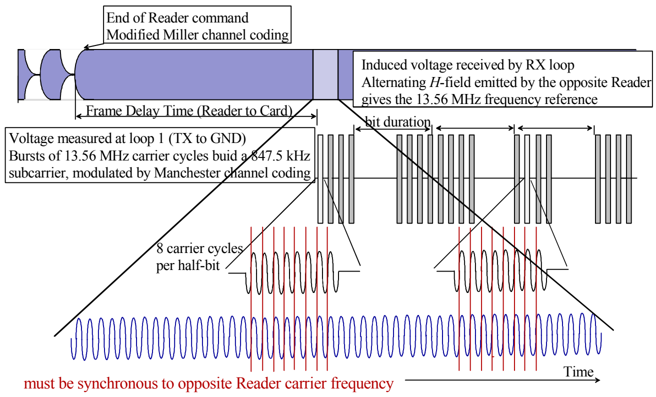

Fig. 8. Communication according ISO/IEC14443A BDR in ALM mode.

After the frame delay time the Card-to-Reader transmission starts, shown in the lower trace for the driver current. Bursts of 8 cycles of the 13.56 MHz signal, synchronous to the opposite reader carrier frequency, build the Manchester-encoded data format.

E. Reader mode operation

For NFC initiator or Reader Mode operation, both loops of the ALM antenna are driven by the differential output of the integrated amplifier. As in conventional operation, an external matching network and an EMC filter adjust the antenna impedance to the requirements of the driver stage. As the antenna is a complex, inductive load and the first (parallel) self-resonance is above the operating frequency of 13.56 MHz, a simple matching network can be used, instead of the *T*- or π–topologies, which are capable to match any complex load [6]. The simple network consists of only 2 components: A serial and a parallel capacitor. As a capacitor can have very low, negligible losses at HF frequencies if it is fabricated with the right dielectric material (e.g. C0G according to the Electronics Industry Association (EIA) specification), this is not only a cost-effective solution regarding the bill of (external) material (BOM), but also an energy efficient solution, compared to the π or *T* network for which at least one of the 3 components is an inductor. Fig. 9 shows the schematics of the differential matching network and the EMC filter.

The matching network allows to adjust a resonance close to the carrier frequency at a quality factor in the range of 25, which is higher than for contactless cards. This allows efficient *H*-field emission and is one essential aspect in reader mode operation. The EMC filter is a LC low-pass at a resonance slightly above the carrier, e.g. at 14.5 MHz. It attenuates the higher order harmonics emission and it boosts the sine-wave voltage amplitude to values higher than the chip power supply. Furthermore, both resonances define a channel bandwidth (for modulation), which is the second essential aspect. The same network of fixed external components has to be used also in card mode, but in principle estimations can be done in a general way, using RF system properties.

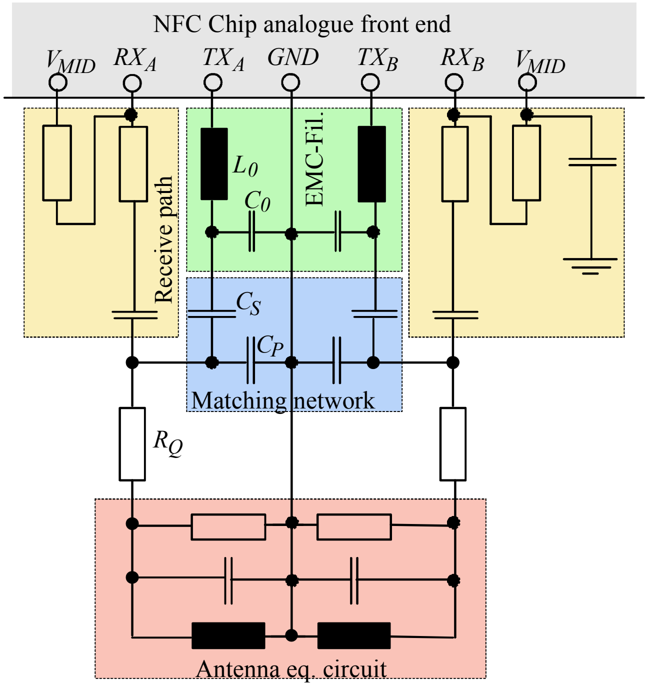

Fig. 9. Differential matching network and EMC filter topology.

Such estimations allow, for example, to calculate the minimum antenna area which is needed to generate certain load modulation side-band amplitudes (SBA), to pass the requirements for contactless operation.

F. First comparative results

To validate the intended improvement in Card mode, the zero-coupling antenna of fig. 5 was operated in ALM mode with PN547, the latest NFC chip of NXP Semiconductors. For comparison, the same antenna (both loops) was also operated in the conventional, PLM mode.

For both cases the communcation distance was measured to 3 different chips operated as readers, the PN544 connected to a conventional 30 x 50 mm loop antenna, it´s precessor PN512 connected to the same antenna, and the RC663 proximity reader chip connected to a larger 70 x 110 mm antenna. As fig. 10 shows, the overall reading distance could be improved significantly for the same test conditions in these cases.

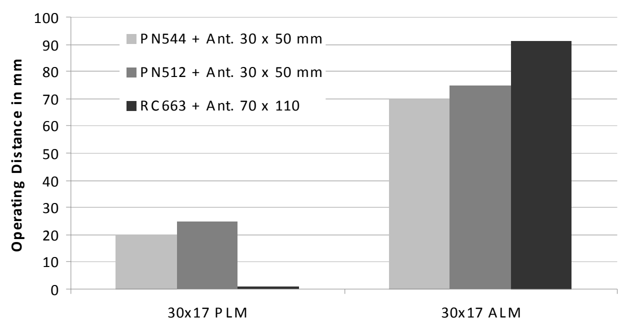

Fig. 10. Comparison of operating distance achieved with ALM and PLM.

This leads to the question, how small can the antenna be to meet the standard requirements for the air interface with the available output current for integrated NFC chips, considering NFC card mode only?

IV. Options for Improvement

A. Minimum antenna size to achieve standard compliance

In this section we analyze, how small the ALM antenna can be, to achieve standard conformance regarding load modulation. We select the Proximity base standard ISO/IEC14443 for this consideration, and a driver current which is typically available from integrated NFC chips.

The driver current of the battery powered NFC device in card mode required to exceed the minimum limit for side-band amplitudes of the proximity base standard can be estimated using a simplified network model of the transmission link. We consider the antenna current (rms current in one conductor turn) and RF system properties (f_{RES}, Q, $k_{SCA,TP}$) independent of the specific matching network.

A current source feeds an on-off-keying modulated pulse signal

$$i_{MOD}(t) = \hat{I}_{MOD}\,\mathrm{rect}\left(t, {}^{16}\!/_{f_C}\right)\cos\left(2\pi f_C t\right) \qquad (2)$$

with

$$\mathrm{rect}(t,T) = \begin{cases} 1 & \ldots \quad \mathrm{mod}(t,T) < T/2 \\ 0 & \ldots \quad \text{elsewhere} \end{cases}$$

into the equivalent circuit of the NFC antenna. The resonance frequency of the emitting circuit is tuned to the carrier frequency, so $f_{RES} = f_C$. The quality factor is set to 1 by selecting an appropriate value of R_{Qlim}.

We consider the proximity test standard ISO/IEC10373-6 and load modulation measurement method [11] using a PCD1 antenna.

The simplified network containing the active load modulating device, the contactless link and the measurement device is shown in fig. 11. The load modulation signal is captured with the Sense Coil A at the Helmholtz bridge point with a probe connected to an oscilloscope. Our simulation chain consists of LT Spice [7] and Matlab [8]. The topology of the equivalent circuit of fig. 11 is modeled in LT Spice, the element values, coupling and load modulation analysis are calculated in Matlab.

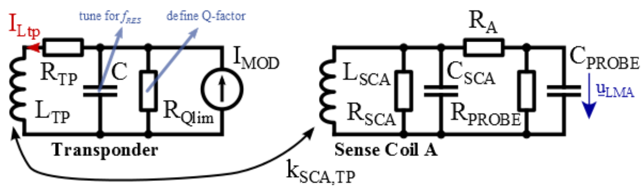

Fig. 11. Equivalent network for NFC device and measurement set-up.

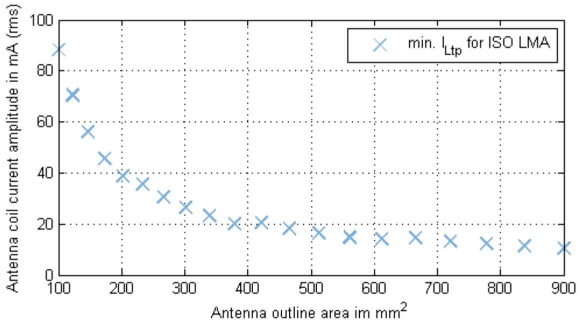

Fig. 12. Minimum required current per conductor turn as function of loop antenna size, to achieve ISO/IEC SBA standard compliance [12].

Typically we start with an antenna outline. Based on antenna geometry we calculate values for the elements of the NFC device in card mode (L_{TP}, R_{TP}, C, R_{QLIM}). The capacitance is chosen such that resonance is equal to carrier frequency and R_{QLIM} is chosen such that $Q \sim 1$. In the next step, the coupling ($k_{SCA,TP}$) of the NFC antenna to the fixed Sense Coil A is estimated using the Von Neumann integral formula. For this network, the Spice simulation is performed and u_{LMA} is recorded over 6 sub-carrier periods. The evaluation of SBA in frequency domain is performed in Matlab, using the DFT function proposed in the test standard [12]. The Spice simulation is started with a low current amplitude and iterated in steps of increased current, until the criterion for load modulation is passed, meaning that both side-band amplitudes exceed the minimum limit of 18 mV(p) at H_{MIN} = 1.5 A/m(rms). This whole procedure is repeated for a set of antenna outlines (100 … 900 mm²), as shown in fig. 12. As a result, we find a required minimum antenna area of about 100 mm² to achieve standard compliance for an antenna current of 90 mA(rms). To note: This does not consider any losses like in the matching network or in ferrite material, and it refers to the active *TX* coil of the ALM antenna only.

B. *Asymmetric zero-coupling antenna*

To improve the card mode performance, to increase the load modulation side-band amplitudes for the same overall antenna size and the typically available driver current from an integrated chip even further, it is possible to use unequal sizes for the *TX* and the *RX* coil of the zero-coupling antenna. Provided that the input stage of the NFC chip in card mode can still receive the signal of the opposite reader, e.g. using an appropriate pre-amplifier for low signal levels or even an automatic gain control (AGC) concept for a wide input dynamic range, the *TX* coil can be made larger than the *RX* coil. This principle is shown in fig. 13. The major part of the antenna area with an outline of 10 x 14 mm is consumed by the *TX* coil. This is about the minimum size, which allows to pass the load modulation amplitude requirements for NFC card mode with the typically available antenna current (close to 100 mm² antenna area). For the reader mode, of course, the situation is different. There is no chance to pass requirements for standard compliance with such a small antenna, although communication with other small antennas can be possible. In addition, due to the asymmetric design, the matching network is different and it is more difficult to have the dedicated *GND* point for all operating conditions, as common mode currents caused by parasitic capacitance to the environment may cause a shift of the virtual ground.

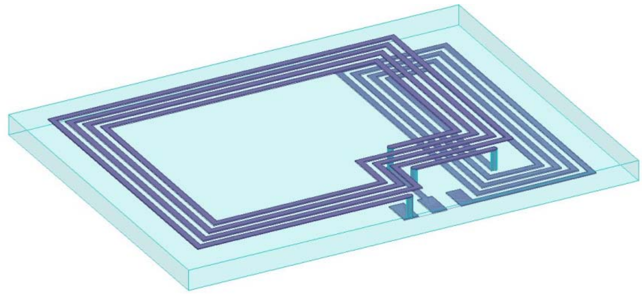

Fig. 13. Asymetric ALM antenna, optimized for smallest area in NFC card mode.

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