Automated Antenna Impedance Adjustment for Near Field Communication (NFC)

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***Abstract*—Near Field Communication (NFC) is a very intuitive way to open a communication link, to authenticate, or to implement a payment by simply bringing two mobile personal devices closely together. NFC is based upon reliable contactless card technology and combines most prominent protocol standards in a specification driven by the NFC Forum. Devices with a NFC interface operate at 13.56 MHz via inductive loop antennas. However, these operate operated in a very different environment than contactless cards. Metal, the presence of several other antennas, and market demands for compact electronic devices are driving requirements for antennas to operate on ferrite foils, resulting in significant tolerances on antenna impedance. In NFC Reader mode, the antennas operate in a resonance circuit, making this de-tuning critical. This paper presents a prototype implementation for automated antenna impedance adjustment based upon Digitally Tunable Capacitors (DTCs). To show the benefit, the paper explains efficiency for contactless power transfer by practical measurements, comparing three scenarios—fixed impedance adjustment, matching with tolerance, and automated readjustment using a DTC.**

Keywords—Near Field Communication, NFC Antenna; NFC Forum; Impedance Matching; Digital Tunable Capacitor; Contactless Communication

I. Introduction

Contactless Near Field Communication (NFC) involves the transfer of supply power and bi-directional data transmission. NFC allows a contactless reader to access data in the non-volatile memory of battery-less tags and cards. Antennas used in this context by readers and cards are loop antennas, closely coupled in the reactive near field. An H-field that alternates at the frequency of 13.56 MHz is used as a carrier for energy and communication. For Short-Range Devices (SRD), radio-frequency emission in this frequency band is harmonized up to certain emission limits worldwide, as it is part of the bands for Industrial, Scientific and Medical (ISM) applications. For example, [1] specifies application classes 1 and 9 in Europe, which may be used for NFC. Measurement methods for this frequency range are specified in [2].

To guarantee interoperability, several International Product Standards define the properties of such communication systems at the air interface. Two primary parts of these standards concern power and communication. For the power portion, in the Proximity Base Standard [3], a minimum alternating H-field strength is defined as an equivalent homogenous H-field over the card antenna area that is perpendicular to the antenna plane and a specific antenna arrangement for card testing [4, 6]. This is approximately1.5 A/m(rms) for Class 1 card antennas in ID-1 credit-card size format. For the data transmission aspect from reader to card, properties of the modulation of the carrier frequency are specified. For example, for Amplitude Shift Keying (ASK), there are several time parameters, modulation indices, and settling effects (e.g. overshoots, ringing).

For the most efficient power transmission, the reader antenna operates in a resonance circuit, which can be described by the RF system properties of resonance frequency (f_{RES}) and quality factor (Q). For optimum energy transmission, the resonance frequency should be close to the carrier frequency, and the Q-factor should be rather high, in order to operate the antenna with low amplifier power and still meet the criterion for standard conformance regarding the minimum H-field, as measured at the air interface, (e.g. NFC Forum Reader H_{MIN}).

II. NFC Antenna

The typical NFC antenna is a planar, spiral loop, similar to contactless card antennas.

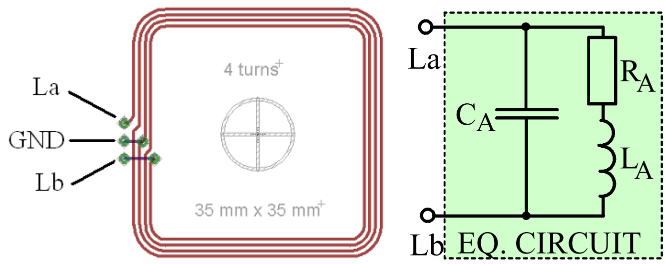


Fig. 1. NFC loop antenna layout (left) and equivalent circuit (right).

TABLE I. NFC ANTENNA GEOMETRY AND ELECTRICAL DATA

Antenna Geometry Data			
	Dimension	***Air Coil***	***Coil on ferrite***
ferrite outline	mm	---	39 x 39
antenna outline	mm	35 x 35	35 x 35
track width	mm	0.4	0.4
track gap	mm	0.4	0.4
number of turns		4	4
Equivalent Circuit Element Values			
Inductance L_A	µH	1.314	1.980
Capacitance C_A	pF	2.351	2.922
Resistance R_A	Ω	0.58	0.85

As the NFC interface of a device is operated in a different environment—for example, on the battery pack of a mobile phone—the loop coils of NFC antennas are constructed on a ferrite layer, to magnetically isolate them and allow the interface to work on metal. The antenna usually is fabricated as a thin (e.g. 200 µm), flexible foil with adhesive on one side, to fix it inside the device. Fig. 1 (left) shows the layout of an NFC loop antenna in a simple geometry, which is used for the measurements presented in this paper. In this case, the conductor of the air coil is 35 µm copper etched on a 1 mm FR4 print board. The outline of the antenna is 35 x 35 mm. A ferrite foil of 39 x 39 mm outline, 100 µm ferrite thickness and relative permeability $\mu_r' \sim 160$ and $\mu_r'' \sim 3$ [10] is fixed on top of the conductor by 10 µm of adhesive layer.

To allow further electrical considerations, we extract an equivalent circuit model that fits well for the frequency range of interest, which may be the carrier frequency of 13.56 MHz and a bandwidth of about +/- 2 MHz for modulation around the carrier. The fundamental parallel resonance frequency of the antenna is well above the carrier frequency, and the quality factor is well above 60, so the equivalent circuit topology can have the structure as shown in fig. 1 (right).

Preferably, an Impedance Analyzer (based upon a bridge), or a Network Analyzer (based upon a directive coupler) can be used to determine the values of the elements in the equivalent circuit. An example of the practical procedure for this context is given in [7]. Table I gives the antenna geometry, and the element values for the conductor on FR4 (Air Coil), as well as on the ferrite foil. Considering the element values, we find the ferrite foil increases the inductance L_A by approximately 50%. Parasitic capacitance C_A is slightly increased, possibly due to a higher dielectric constant of the polymer foil sandwich structure, in which the sintered ferrite material is embedded. Parasitic resistance R_A is also increased. To the effects of specific conductor resistance and skin effect, both valid for air coils operated at high frequencies (HF), the effect of HF losses in the ferrite and adhesive layers is added.

III. NFC READER MODE POWER REQUIREMENTS

The requirement for the minimum power transmission from a contactless reader to a battery-less card, a NFC tag or a NFC device in card mode is specified at the air interface, independent of any implementation.

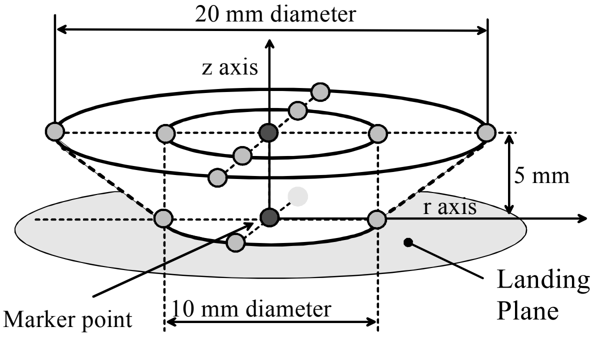


Fig. 2. NFC Forum specified operating volume.

NFC Forum Specifications [5] are most relevant for devices with a NFC interface, although these are based on experiences with the existing Proximity Card Standard [3]. The Continuous Wave (CW) alternating *H*-field emission is measured with a so-called NFC Forum Listener device, an emulation of a contactless card. This device consists of a loop antenna in a resonant circuit and a rectifier with an adjustable load resistor, to build a linear load [5]. Essentially, it allows a DC voltage to be measured as a function of the alternating *H*-field strength for the field component perpendicular to the antenna plane. Three rectangular loop antenna sizes are used for Listener 1 (standard size), Listener 3 (medium size) and Listener 6 (small size). Listener 1 utilizes the same "Class 1" antenna size as used in the ID-1 Credit Card format, which is also applied by the Proximity Test Standard [4] Reference PICC. Fig. 3 shows the equivalent homogenous *H*-field, according to the Proximity Test Standard [4] for NFC Forum Listener 1 Reader H_{MIN} and H_{MAX} conditions.

NFC Forum Reader measurements are made with the Listener antenna center positioned at dedicated points in a specified "Operating Volume" on a "Landing Plane" on the reader antenna, basically in coaxial antenna orientation, as shown in fig. 2. The Listener resonance frequency is adjusted to the 13.56 MHz carrier frequency of the alternating reader *H*-field emission, and the shunt resistor is set to 820 Ω. The NFC Forum minimum reader power definitions are required to exceed a certain DC voltage as specified for each of the 3 Listeners in every measurement point of this Volume.

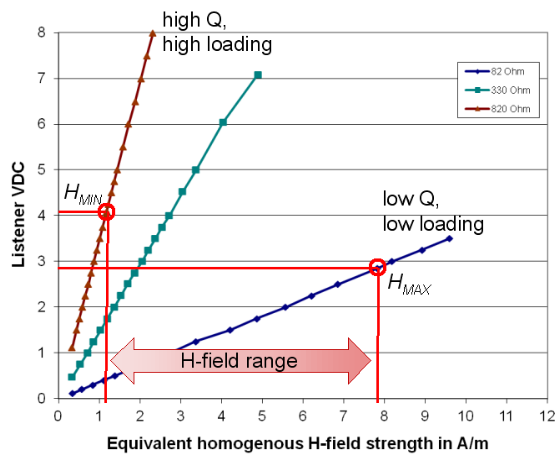


Fig. 3. NFC Forum reader power requirements – Listener 1.

TABLE II. ANTENNA VOLTAGE TO PASS READER HMIN

Coupling to Listener 1			
Distance	***Position***	***Antenna voltage***	***Antenna current***
mm		V(rms)	I(rms)
0	center	1.816	10.765
0	border	1.846	10.943
5	center	2.232	13.256
5	border	2.911	17.256
Coupling to Listener 3			
0	center	1.967	11.660
0	border	2.656	15.744
5	center	3.053	18.098
5	border	4.985	29.550
Coupling to Listener 6			
0	center	3.802	22.538
0	border	3.745	22.200
5	center	3.925	23.267
5	border	5.936	35.188

A practical measurement was made, to determine the voltage and current which that must be applied on the NFC antenna, in order to meet the minimum power requirement. Listeners 1, 3 and 6 were positioned at each specified point in the Operating Volume, and the DC voltage was measured using a voltmeter. A 13.56 MHz sine-wave signal was applied between the antenna terminals La and Lb, measured with an oscilloscope probe (1 MΩ // 8.2 pF) and adjusted until the required Listener DC voltage was met. In this way, the required voltage on the NFC antenna could be identified for every listener, according to tab. II. As can be seen, a maximum voltage of about 6 V(rms), equivalent to about 17 V(pp) is required to pass the Listener 6 Reader H_{MIN} criterion, for this NFC antenna.

Using the equivalent circuit impedance Z_A, which mainly consists of antenna inductance L_A, the related current I_A can be calculated from the measured sine-wave voltage U_A according to

$$I_A = \frac{U_A}{\underline{Z}_A} \approx -j\frac{U_A}{\omega L}. \tag{1}$$

Here, this means approximately 36 mA(rms) antenna current are necessary to meet the NFC Forum Reader H_{MIN} criterion, for this antenna.

Hence, the NFC Forum minimum Reader Power requirement means that, for a certain NFC antenna size (or a certain coupling to Listener 1, 3, 6) a minimum magnetic momentum must be achieved. The magnetic momentum M is given by

$$M = A_E \cdot I_T \tag{2}$$

where A_E is the effective loop antenna area, and I_T is the total current around this area. By a variation of the number of antenna turns around the same area, it is possible to vary the impedance (for air coils $L \sim n^2$), while the total current is equal to $I_T = n \cdot I_A$.

IV. IMPEDANCE MATCHING NETWORK

This antenna current, required to fulfill standard conformance for Reader H_{MIN} criterion, could be directly forced by an amplifier, such as in our measurement, above.

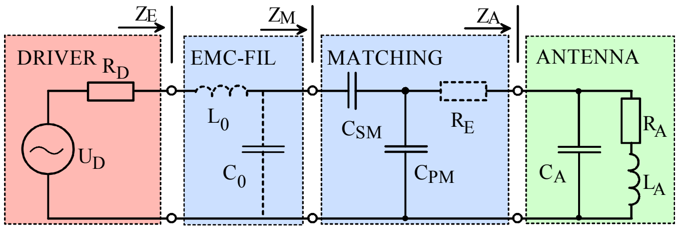


Fig. 4. NFC antenna impedance matching network.

The antenna current can also originate from the energy bouncing between inductance and capacitance, in a resonance circuit. For power efficiency, a NFC antenna is operated in a damped resonant circuit, with resonance close to the carrier frequency. Such a circuit needs to be fed by just a small amount of effective power P_E to compensate damping losses, but the major contribution to the antenna current is the reactive power of the oscillating energy W_M. This relation can be described by the quality factor Q for a circuit, which is

$$Q = \omega\frac{W_M}{P_E} = \omega\frac{I^2 L}{I^2 R_S} = \frac{\omega L}{R_S} \tag{3}$$

For a higher Q-factor, less power needs to be fed into the antenna to achieve the same H-field strength. On the other hand, some modulation bandwidth is needed for the data transmission, and specifications for modulation in the time domain require small time constants. This limits the maximum allowable Q-factor. Considering an equivalent parallel resonance circuit, this means that, for the Proximity Base Standard Type A modulation $Q < 17$, for the base data rate (t_4 requirement at 106 kbit/s), for higher data rates $Q < 8$ (t_6 requirement at 847.5 kbit/s). Moreover, a higher Q-factor results in a deviation of the resonance frequency, which may originate from production tolerances or from mutual inductance in close coupling to a second resonant-loop antenna circuit, further impacting the emitted H-field strength. As shown in fig. 4, an external, serial resistor R_E may be used to reduce the Q-factor of the antenna network.

Without further modification, at this point, the apparent power must be fed into the antenna at the carrier frequency, where the major part is reactive power and only the minority is effective power. The driver amplifier integrated in a NFC chip is typically voltage limited by the supply and has low output impedance (e.g. 3 Ω), so it is close to an ideal voltage source model. This forces the wish for an impedance transformation network, simply called “matching network” in this context, as it matches the antenna impedance to a desired and usually real value R_D, e.g. to 20 … 100 Ω, toward the chip TX output. The general narrow-band matching network in T- or Π topology as described in [8] can match any impedance at the carrier frequency. As the NFC antenna has its first and fundamental parallel self-resonance well above the carrier frequency, we can assume it is a complex inductive load. This allows it to be used in a simplified matching network in L-topology (e.g. as specified in [4] for the PCD antenna), using only two capacitors—C_{SM} and C_{PM} —as shown in fig. 4. In addition to cost and space savings, this is an advantage for power efficiency, as a capacitor component can be fabricated nearly loss-less, with properties very close to the ideal element capacitance for HF (e.g. of type COG or NPO according to the Electronics Industry Association specification). A coil component is a much worse representation of the element inductance. For simplicity reasons, we will neglect R_E in our considerations.

A classic complex network calculation can be used to determine the impedance transformation. The impedance of the equivalent antenna circuit Z_A, without connection to the following network, is given by

$$Z_A = \frac{R_A + j\omega L_A}{1 + j\omega R_A C_A - \omega^2 L_A C_A} \quad (4)$$

After the matching network, Z_A is transformed to Z_M

$$Z_M = \frac{1 + j\omega Z_A (C_{SM} + C_{PM})}{\omega (jC_{SM} - \omega C_{SM} C_{PM} Z_A)}\text{, and substituted} \quad (5)$$

$$Z_M = \frac{1 + j\omega R_A [C_{SM} + (C_A + C_{PM})] - \omega^2 L_A [C_{SM} + (C_A + C_{PM})]}{j\omega C_{SM} [1 - \omega R_A C_{SM} (C_A + C_{PM}) - \omega^2 L_A (C_A + C_{PM})]} \quad (6)$$

The impedance transformation network of C_{SM} and C_{PM} shall match Z_A to a real impedance, a resistance of desired value R_D, which means $\mathrm{Im}(Z_M) \equiv 0$ and $\mathrm{Re}(Z_M) \equiv R_D$. This uncovers conditions for the values of C_S and C_P, which are as follows:

$$C_{SM}(C_{PM}) = \frac{R_A L_A}{(\omega L_A)^2 R_D [1 - \omega^2 L_A (C_A + C_{PM})]} \quad (7)$$

and $$C_{PM} = -\frac{p}{2} \pm \sqrt{\frac{p^2}{4} - q} \quad (8)$$

for $$p = \frac{2\omega^2 L_A C_A - 2}{\omega^2 L_A}$$ and (9)

$$q = \frac{R_A (1 + R_A)}{(\omega L_A)^6} - \frac{R_A}{\omega^4 R_D L_A{}^4} - \frac{2C_A}{\omega^2 L_A} + C_A{}^2 . \quad (10)$$

Only positive solutions have a physical meaning for capacitances C_{SM} and C_{PM}.

For efficiency reasons and to minimize heat dissipation, the integrated driver is typically a class D amplifier. This means it switches between the internal positive supply and GND so that the carrier frequency of the output signal has rectangular wave shape. A Fourier series of an ideal square-wave signal is given by

$$f(t) = \frac{4A}{\pi} \left[\sin(\omega t) + \frac{\sin(3\omega t)}{3} + \frac{\sin(5\omega t)}{5} + \ldots \right] = \frac{4A}{\pi} \sum_{m=1}^{\infty} \frac{\sin((2m-1)\omega t)}{2m-1} \quad (11)$$

This consists of the fundamental sine-wave amplitude and several harmonics. As the intended emission at harmonics frequencies violates the frequency emission regulation, a so-called Electromagnetic Compatibility (EMC) filter is inserted after the driver output. This EMC filter is a LC low-pass filter with a cut-off frequency typically in the range of 14 … 16 MHz. It has low insertion loss in the pass-band for the fundamental 13.56 MHz sine-wave carrier, but a good attenuation in the stop-band for unwanted harmonics. As the square-wave driver output signal is voltage-limited by the amplifier supply, Fourier analysis shows the amplitude of the fundamental sine-wave frequency is $4/\pi$ higher than for the square-wave amplitude A. Moreover, the EMC filter also performs an impedance transformation, so the driver output is transformed from a voltage source toward a current source. The magnitude of this depends on the filter properties, for example, Q, resonance-frequency, and f_C. This means there is no voltage limitation behind the filter. The impedance Z_E at this point is given by

$$Z_E = \frac{Z_M + j\omega L_0}{j\omega C_0 Z_M - \omega^2 L_0 C_0} \quad (12)$$

At this point, we actually have the general matching network in T-topology, modified by an additional capacitor C_0. This also means a change in the requirement for NFC antenna impedances, not only complex inductive loads can be matched.

On the other hand, the EMC filter affects the bandwidth and time-domain properties of modulation. However, the Q-factor of the antenna circuit is not the only relevant aspect. The difference between the EMC filter resonance and the antenna circuit resonance must be considered, and RF behavior cannot be simply modeled by one equivalent resonance circuit, and its quality factor.

For the context of automated antenna impedance matching as presented in this paper, the situation is, again, a bit different: Only the impedance Z_E at the TX output is known and can be measured. The antenna impedance Z_A is unknown, and C_{SM} and C_{PM} can be adjusted in steps within a certain range, to adjust the Z_E to the intended value of R_D. Moreover, the Digitally Tunable Capacitor (DTC) has slight losses, depending upon capacitance, operating frequency, and voltage handling requirements, as described in fig. 8 of chapter VI. Automated antenna impedance matching based upon relays and a capacitor array was developed a decade ago for Vicinity readers, and is commercially available [11]. Specifically, for small NFC antennas, previous attempts based on conventional CMOS switches could not be implemented successfully, because of parasitics [12]. The improvements achieved using the DTC with this prototype for the power transmission aspect and energy efficiency in NFC applications are significant, as shown by measurements in chapter VII. The next section of this paper will discuss tolerances and aspects that motivate automated impedance adjustment for NFC.

V. IMPEDANCE TOLERANCES IN NFC ANTENNA NETWORK

In contrast to a proximity reader antenna for the infrastructure market, a NFC antenna for the mobile market operates in a difficult environment. For integration in a smartphone, the antenna must be very thin and small in size. Moreover, it must be able to operate on metal parts, e.g. the accumulator pack. For most applications, this requires the use of ferrite materials, such as thin polymer or sintered ferrite foils that can conduct at least a part of the alternating magnetic flux between the antenna and metal parts of the phone. Although there has been significant progress in the development of very thin and flexible ferrite foils, as well as the offering of a part with relative permeability (e.g. $\mu_r' > 80 \ldots 160$), and low HF losses (e.g. $\mu_r'' < 3 \ldots 5$), manufacturers still specify quite high tolerances for these parameters (e.g. +/- 15 %), resulting in significant production spread (e.g. +/- 7.5 % L_A). As the design of smartphones requires technical adaptations, the length for the connection between the chip and matching network, which are typically on the main PCB; and the antenna, which may be somewhere on the back cover, can vary. This results in variable parasitics, meaning the antenna impedance will also vary. Additionally, there are extended temperature requirements for the entire antenna construction. Despite the fact that many of the antenna equivalent circuit elements are temperature dependent (e.g. the specific conductance of the loop track conductor), standard conformance to the contactless properties of the air interface is required for the full temperature range, to guarantee interoperability. For a conventional matching network with fixed components, this means a sufficient margin has to be foreseen for all these properties, in order to operate according to standard conformance, even under load mismatch conditions. As they have a very slow changing rate compared to the communication properties (with time constants in milliseconds), we consider these aspects as (almost) static tolerances, as listed in table 3 for typical values. Additionally, we can consider dynamic aspects caused by the coupling of two contactless devices' antenna resonant circuits. In the context of contactless proximity communication standards, this effect is known as "card loading," which refers to a de-tuning of the reader antenna resonant circuit—for example, in resonant circuit properties, a change of f_{RES} and Q in an equivalent circuit description, or a change of element values (e.g. inductance). An adaptation of the antenna impedance matching can at least compensate for most of the negative effects caused by the tolerances and coupling. As the antenna can then operate at the intended optimum impedance, this saves margin on several parameters (e.g. power), which is necessary for operating NFC technology in standard conformance with all operating conditions. Considering aspects in the time domain, one can differentiate impedance re-adjustment for static aspects such as production spread, slow variation, and temperature dependency; as well as highly dynamic aspects, and varied coupling. Additionally, for system integrators such as smartphone companies, a rapid design-in phase offers some flexibility for the antenna adjustment, reduced PCB space, and lower external component costs.

TABLE III. TOLERANCES FOR PARTS OF NFC ANTENNA

	Item	***Parameter***	***Tolerance***
static	ferrite foil	μ_R	± 15 %
	cable length	*mm*	0 … 50
	air coil inductance	μH	± 2 %
slow variation	temperature	*°C*	- 25 … + 85
dynamic	coupling	*k*	0 … 0.6

VI. DIGITALLY TUNABLE CAPACITOR

Peregrine Semiconductor's Digitally Tunable Capacitor (DTC) is a variable capacitor controlled by a Serial Programmable Interface (SPI). The SPI controls CMOS switch FETs that connect and disconnect high Q metal insulator metal (MIM) capacitors, as shown in fig. 5. The DTC is integrated on a monolithic RFIC that requires no external bias voltage generation or interface circuitry.

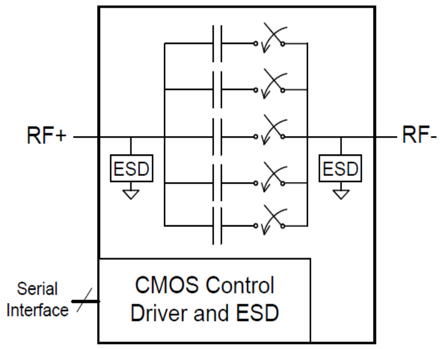


Fig. 5. DTC block diagram.

The DTC is developed in Peregrine's UltraCMOS® Silicon-on-Sapphire (SOS) process. It uses proprietary switching and FET stacking technology that take advantage of the highly-insulating characteristics of the sapphire substrate. FET stacking enables the creation of high-voltage FETs that enable the high linearity and power handling of the DTC. The capacitance is determined by the parallel combination of "on" and "off" MIM capacitor FET switch paths. By binary weighting of each MIM capacitor in the DTC, a linear and monotonic tuning curve is achieved, as shown in fig. 6.

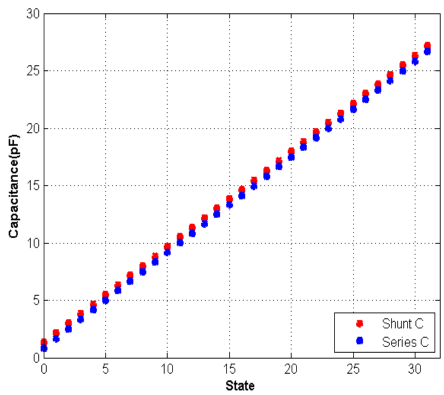


Fig. 6. Serial and parallel capacitance of DTC vs. state.

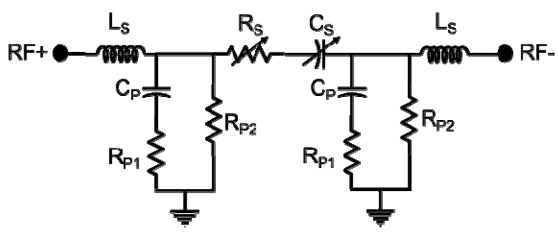


Fig. 7. DTC equivalent circuit model.

The DTC can be modeled using a simple three-terminal circuit, as shown in fig. 7. The model includes all parasitics, and it is accurate in both series and shunt configurations. It correlates important parameters (e.g. C, tuning range, SRF, Q and losses) very closely to measured data.

The DTC model consists of three main components: (1) tuning core comprised of R_S and C_S, (2) package inductance L_S, and (3) shunt parasitic network consisting of C_P, R_{P1} and R_{P2} [9]. In series configuration, the DTC tuning or series capacitance, C_S, is seen between RF+ and RF- ports. Since C_P is connected to ground it doesn't impact the capacitance between RF+ and RF-. C_P does, however, impact the DTC's RF performance, and must be taken into account when designing the end application. In shunt configuration, RF- is typically grounded and RF+ is connected to the signal. The package inductance, L_S, effectively shorts out parasitic shunt network on the RF- side of the circuit. In shunt, a higher total capacitance, $C_T = C_S + C_P$, is seen between RF+ and RF- as shown in fig. 7. The DTC's overall dissipative losses include losses in the shunt parasitic network and tuning core. They are defined by the quality factor Q. In general, Q is defined in the shunt configuration because the dissipative losses depend on source and load impedances when the DTC is connected in series. In fig. 8, the DTC Q in shunt configuration, as seen at RF+, is a combination of the DTC tuning core Q_S and parasitic networks, Q_P. The DTC Q is state dependent and changes with frequency, due to the frequency dependencies of the tuning core and shunt parasitic networks. The DTC Q is traded off for high voltage handling, large tuning range, fine capacitance resolution, minimum capacitance and small die size. All of these are critical parameters for antenna impedance matching, which is a common DTC application.

The DTC's high linearity (≥ 65 dBm), high voltage handling (30V RF Vpk), good Q, high tuning range, small 2x2 mm^2 package, and simple SPI interface make it very attractive for antenna impedance and aperture tuning. The DTC enables the antenna's efficiency and radiation pattern to be optimized for a specific frequency band, and to compensate for environmental, and human effects. In comparison to other tunable capacitor technologies, it offers the most comprehensive combination of performance parameters, as shown in table IV.

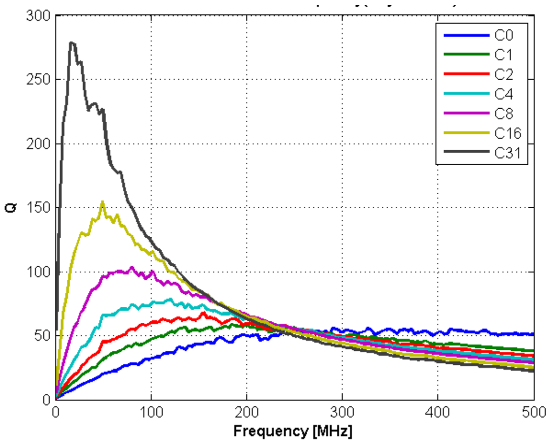
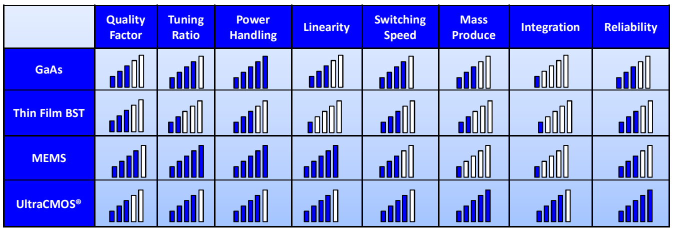


Fig. 8. Measured shunt Q vs. frequency for major capacitance states.

TABLE IV. TUNABLE CAPACITOR TECHNOLOGY COMPARISON*



(*SOURCE: PEREGRINE SEMICONDUCTOR CORPORATION)

VII. NFC COUPLING SCENARIOS

To visualize the advantage of impedance matching for the aspect of energy transmission, we present measurement data for three scenarios of coupling between the 35 mm reader antenna on ferrite to the NFC Forum Listener 3 device. This Listener device emulates a resonant card loop antenna circuit, and is used to evaluate the alternating H-field emitted by the contactless reader against the minimum limit defined in the NFC Standard [5]. A simple set-up for the variation of distance is shown in fig. 12.

Scenario (a) refers to ideal impedance matching of the circuit shown in fig. 4 to the desired value (here, 50 Ohm) at the operating frequency 13.56 MHz using fixed capacitors. These are typical lab conditions. Scenario (a) is shown by square points in red color.

Scenario (b) considers fabrication tolerances. This means a complex load mismatch, still using fixed capacitances. For our case, we consider the maximum tolerance of the ferrite foil μ_R as specified by the manufacturer. A 15 % tolerance cause 7.5 % tolerance for antenna inductance, as the ferrite increases the air coil inductance by about 50 %. Scenario (b) is shown by triangle points in green color.

Scenario (c) considers impedance tracking and adjustment to 50 Ohms using DTCs for the serial and the parallel capacitance in fig. 4. This is shown in blue color. The values for serial capacitance C_{SM} and parallel capacitance C_{PM} and the voltage levels at the antenna connection are shown in fig. 13, for this scenario.

The impedance at the operating frequency for the three scenarios over varied distance of the 35 mm reader antenna and the NFC Forum Listener 3 in coaxial arrangement is shown in the Smith Chart of fig. 9. For the maximum measured distance between the antennas, the matching impedance of (a) and (c) is close to the intended value of 50 Ohms. Scenario (b) shows a complex, capacitive impedance.

If the Listener gets closer to the reader antenna, scenario (a) shows the impedance gradually diverges from 50 Ohm, approaching a lower impedance. For automatic impedance matching in scenario (c), the impedance is scattering closely around the intended value of 50 Ohms, depending on measurement accuracy for impedance tracking and the available capacitance step size for compensation. Scenario (b) shows a systematic behavior, similar to scenario (a), so the significance of the mismatch decreases with higher coupling.

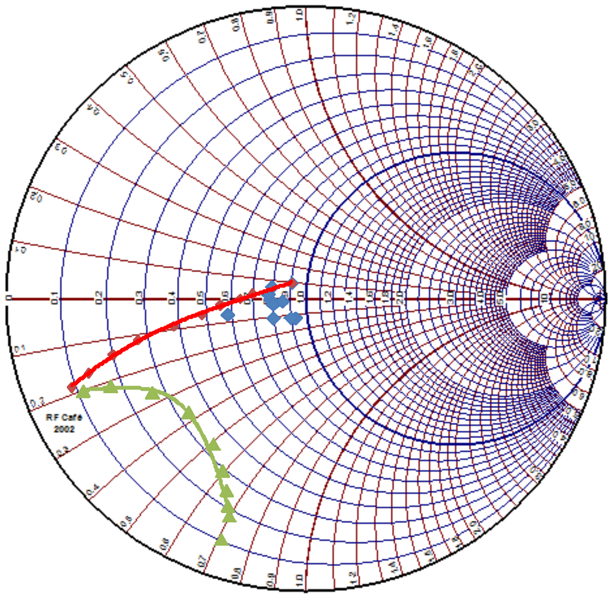


Fig. 9. Smith Chart of matching impedance for 3 scenarios at 13.56 MHz for varied coupling distance.

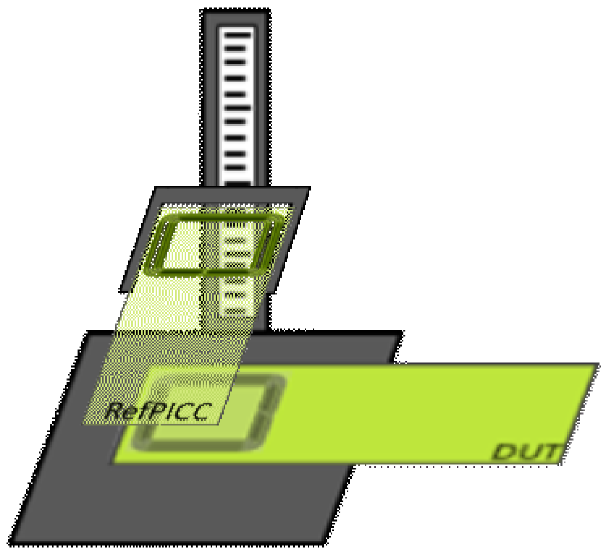


Fig. 12. Near-field coupling scenarios measurement.

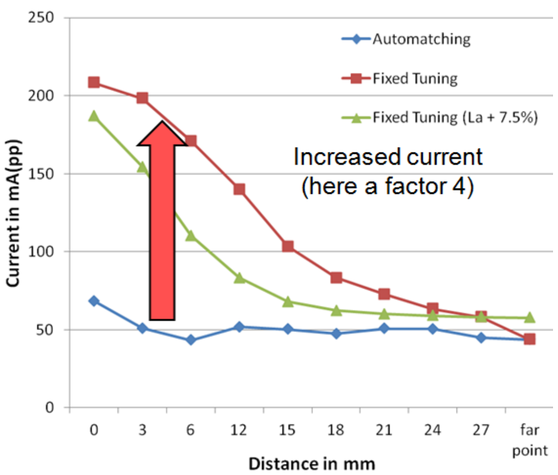


Fig. 10. Current consumption of the antenna network.

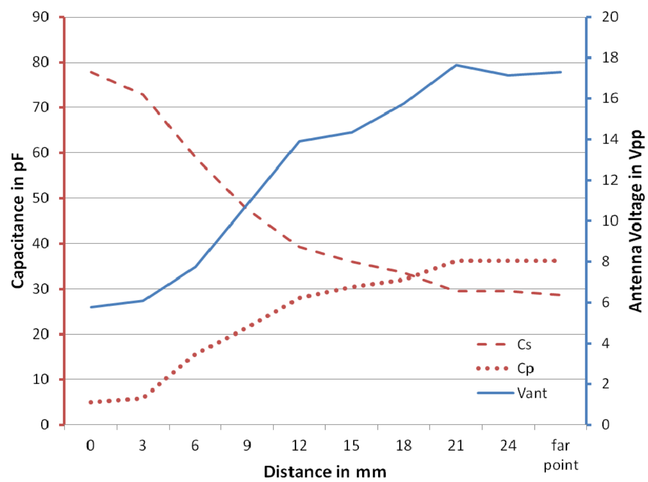


Fig. 13. Capacitance and voltage range for Automatching.

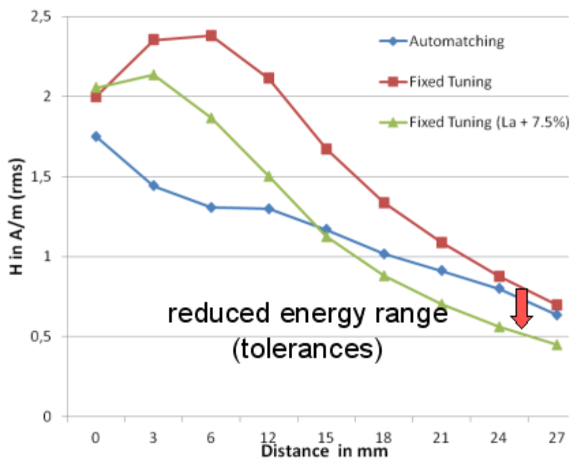


Fig. 11. Equivalent homogenous *H*-field over distance.

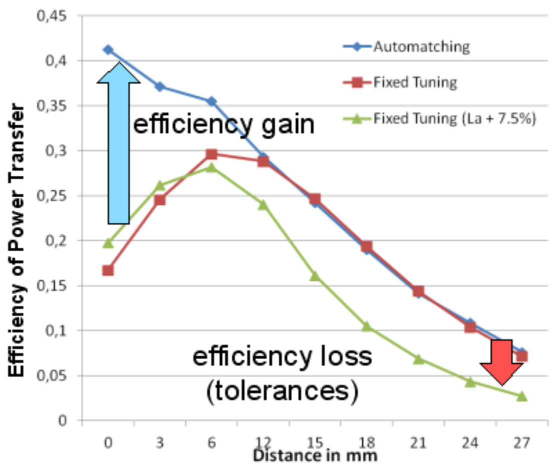


Fig. 14. Efficiency in contactless power transmission.

Fig. 10 shows the HF current at 13.56 MHz which the integrated amplifier must provide to the antenna network. For the maximum distance, or when no Listener is present near the reader antenna ("far point") the current is equal for scenario (a) and (c), close to 50 mA(pp) in this case. It is also similar for scenario (b). For smaller distance, in scenarios (a) and (b) the current increases, as the amplifier output voltage is fixed and the antenna network impedance gets low. For automatic impedance matching in scenario (c) the current remains almost constant (as far as the impedance can be adjusted to 50 Ohms).

Typical integrated amplifiers for NFC or proximity reader chips are able to drive about 200 mA output current single-ended. Since the antenna network impedance decreases for fixed matching, it is necessary to have headroom for the driver current increase in close coupling to a card, to avoid output overload. This requires the design of an antenna network impedance (without card loading) that is higher than necessary—only a part of the available amplifier power can actually be used to power a card in longer distance to a reader (in this case, 50 mA). For automatic impedance matching, according scenario (c), it is possible to design the antenna network impedance lower, to fully use the available output power for long distances to a card. This means that, for the same amplifier output current (and resonance and *Q*-factor in the antenna network), we can extend the energy range to power up a contactless card. In the other case, it allows the integration of a smaller amplifier power to achieve the same *H*-field strength (e.g. to meet standard compliance for the reader H_{MIN} criterion).

Fig. 11 shows the equivalent homogenous *H*-field emitted by the 35 mm reader antenna for the 3 scenarios, over a varied distance to the NFC Forum Listener 3. For maximum distance, in scenario (a) and (c), a similar *H*-field strength is achieved, as the same RF power is fed into the antenna network (impedance close to the intended 50 Ohms). As mentioned above, the *H*-field could be higher for automatic impedance matching, as we use only a quarter of the available driver current, in this case. Moreover, with impedance mismatch due to tolerances in scenario (b), the *H*-field is decreased because resonance is shifted too far away from the operating carrier frequency. For decreasing distance to the Listener device, the *H*-field increases stronger in scenario (a) and (b) than in scenario (c). The *H*-field increase in scenario (c) can be described by the Biot-Savart law, which is valid in the inductive near-field, depending on constant alternating conductor current and conductor geometry. For (a) and (b) this conductor current is not constant—it will increase, due to the lower matching impedance. Additionally, the resonance frequency will shift away from the operating frequency, which is counter-productive, as this causes the *H*-field to decrease for very high coupling.

Fig. 14 shows the efficiency of the contactless energy transmission as a relation between the RF power available from the Listener (or a Card) and the effective power fed into the Reader antenna. Fixed ideal matching (a) and automatching (c) are equal for longer distances, while the power transfer is less efficient for mismatch due to tolerances. In close coupling, automatching (c) means an efficiency gain over scenario (a) and (b), where the Reader antenna resonance frequency is shifted due to significant mutual inductance, caused by the presence of the Listener antenna.

VIII. Conclusions

This paper has shown a successful implementation of automatic antenna impedance adjustment for Near Field Communication (NFC). In contrast to contactless card technology, loop antennas for NFC are integrated in smartphones or tablet PCs. Impedance mismatch is much more significant here, as such antennas are fabricated on thin ferrite foils, and operate in close connection to metal parts, and other antennas. A highly-integrated, CMOS-based Digitally Tunable Capacitor (DTC) was used for impedance adjustment. Considering 3 scenarios, the advantage of automatic antenna impedance adjustment regarding amplifier power and efficiency was illustrated by a comparative measurement series. The presented prototype is able to fulfil NFC Forum Reader H_{MIN} requirements.

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