Automatic Impedance Matching for 13.56 MHz NFC Antennas

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Abstract—**This paper deals with the concept, the implementation and the verification of an automatic impedance matching circuit for NFC antennas with a frequency of 13.56 MHz. Besides an introduction to manual tuning and its issues, the fundamental components of an automatic tuning system are outlined. A lab-scaled prototype is built and demonstrated. In the end, the successful operation of this system is tested with several different antennas.**

I. INTRODUCTION

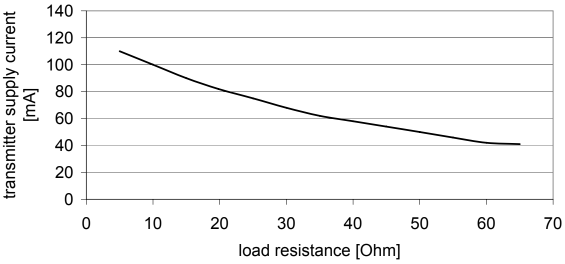
The number of mobile devices equipped with Near Field Communication (NFC) technology is steadily increasing. Especially mobile phones tend to become smaller and smaller. They differ in shape and size and there are usually tough space-saving requirements. Antennas have to fit casings of mobile devices. Consequently, using standardized NFC antenna designs is not the optimal solution with these devices. As a result, these non-standard antennas have varying characteristics, such as inductance and resistance. Current NFC transmission modules require the antenna circuitry to be manually matched with the integrated circuit (IC). This step is important to maximize the power of the emitted RF (radio frequency) field, and therefore, to maximize the range of the transmission module [1] and the quality of the transmitted signal, while keeping the power consumption of the transmitter low. Manual matching of the antenna characteristics is a rather lengthy and complicated procedure.

There is a history of automating the matching procedure for technologies where space-saving is not a main effort. With citizen's band radio and ham radio, devices range from simple SWR (standing wave ratio) meters to fully automatic ATUs (antenna tuning units). An SWR meter allows even an inexperienced user to optimize an antenna whereas ATUs usually do not require any user interaction at all. These approaches have also been successfully implemented into long-range RFID technology. Unfortunately, ATUs typically use relays and other large discrete components. Consequently, they do not fit into mobile handsets.

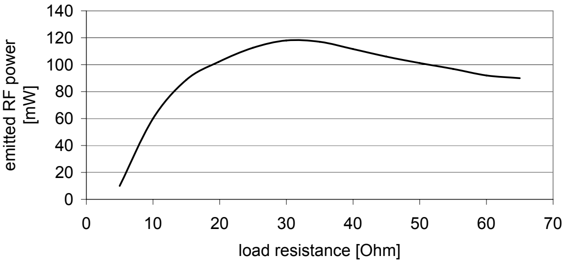
As a result of the complicated nature of manual impedance matching, automatic tuning significantly simplifies the development of RF applications. Therefore, once integrated into NFC transmission modules, automatic tuning will boost the usability of such integrated circuits. This paper provides an insight into automating the tuning procedure for 13.56 MHz NFC antennas while using maximum possible integrable components.

II. MANUAL IMPEDANCE MATCHING

NFC transmission module ICs use external antennas to communicate with other NFC/RFID enabled devices. The antennas vary in shape and size, whereby each antenna has different impedance measured at its clamps. The impedance of the antenna is the load resistance of the NFC IC's transmitter circuit.



(a) Transmitter supply current vs. load resistance



(b) Emitted RF power vs. load resistance

Fig. 1. Power consumption and power emission vs. load resistance for NXP's PN511 NFC transmission module at the operating frequency of 13.56 MHz [2].

Fig. 1 shows the relation between transmitter supply current, emitted RF power and the load resistance at the transmitter's clamps (at 13.56 MHz). The maximum power of the emitted RF field is yielded at 30 ohms while the transmitter supply current decreases with increasing load resistance. Thus, the optimum in terms of supply current is reached with a high (above 60 ohms) load resistance and the optimum in terms of emitted RF power is at 30 ohms. Fig. 1 suggests that a good trade-off between transmitter supply current and emitted RF power is at 40 to 50 ohms [2]. Therefore, the impedance of the antenna should be matched to $50 \pm j0$ ohms.

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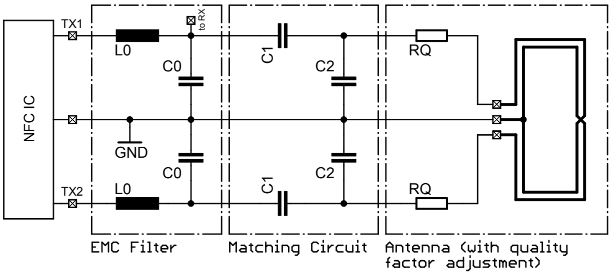


Fig. 2. Symmetric NFC antenna topology with EMC filter, matching circuit, quality factor damping resistors and antenna coil [2].

To achieve the matching, the antenna circuitry (Fig. 2) consists of three parts:

- an electromagnetic compatibility (EMC) filter (L_0, C_0),
- a matching circuit of series and parallel capacitors (C_1, C_2) to perform the actual tuning,
- and the antenna with quality factor damping resistors (R_Q).

The EMC filter reduces harmonics of the 13.56 MHz carrier and performs an impedance transformation. It must have a fixed resonance frequency which is the sum of the operating frequency and the highest subcarrier. The highest data rate for NFC is 424 kbps with Manchester coding [3]. Therefore, the highest subcarrier is 848 kHz. This results in a resonance frequency of 14.408 MHz.

The coil of the antenna produces the magnetic (RF) field. The antenna has additional quality factor damping resistors (R_Q). These resistors are necessary to obtain a certain pulse shape as required by the standard [3].

Manual tuning is accomplished by measuring the reflection coefficient (S_{11} parameter) of the antenna circuitry (Fig. 2, clamps TX1 and TX2) at the operating frequency of 13.56 MHz. The impedance of the antenna circuitry follows the equation [4]

$$Z\left(S_{11}\right) = Z_L \cdot \frac{1 + S_{11}}{1 - S_{11}} \text{ with } Z_L = 50\,\Omega. \tag{1}$$

Consequently, an impedance of 50 ohms is obtained when S_{11} is zero at 13.56 MHz. Matching is achieved by alternately adjusting the capacitors C_1 and C_2. Fig. 3 plots the reflection coefficient S_{11} of a matched antenna for frequencies ranging from 10 to 20 MHz with a marker at 13.56 MHz.

III. AUTOMATIC IMPEDANCE MATCHING

Manual tuning of the matching circuit takes long and requires good sense of choosing the right capacitor values. Moreover, expensive equipment such as an impedance analyzer or a network analyzer is needed. Therefore, automatic tuning significantly simplifies the development of RF applications. There are several existing methods of automatic impedance matching for other RF technologies. For example, automatic tuning devices for long-range RFID readers use large non-integrable components such as relays to achieve the tuning. Many NFC devices are mobile handsets, thus, it is not possible to realize this type of automatic tuning circuit for NFC. The ideal automatic tuning circuit consists of only integrable parts. The following sections present the concept and the implementation of the automatic impedance matching circuit. The complete automatic tuning setup, as shown in Fig. 4, consists of a measuring circuit, a matching circuit and a controller.

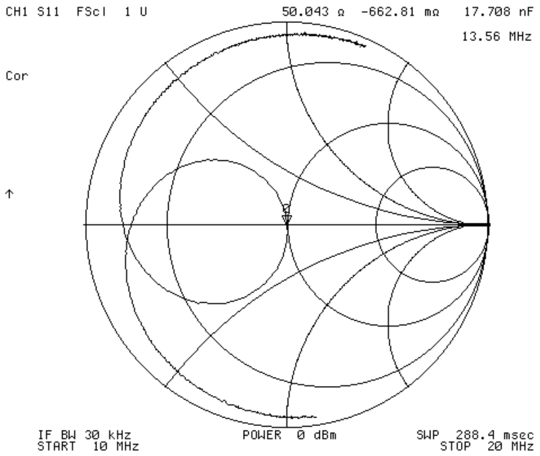


Fig. 3. Sweep measurement of the reflection coefficient S_{11} of a matched antenna between 10 and 20 MHz with a marker at 13.56 MHz.

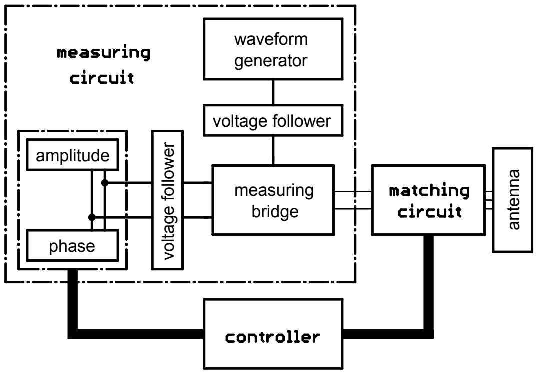


Fig. 4. Automatic tuning system design split into its three components: measuring circuit, matching circuit and controller component.

A. Measuring Circuit

The measurement for manual tuning is done with an impedance analyzer or a network analyzer. A network analyzer uses a directional coupler to determine the reflection coefficient of the antenna circuitry. As discussed in [5], using a directional coupler has several major disadvantages, such as power dissipation and difficulties with embedding into an IC.

1) Measuring Bridge: Ref. [5] proposes an alternative to the determination of the reflection coefficient. The impedance of the antenna circuitry (at the frequency of 13.56 MHz) is measured instead. More precisely, the impedance is compared to a 50 ohms resistor. Fig. 5 shows the matching of the antenna impedance using a Wheatstone bridge. The measuring bridge's DC source is replaced with a waveform generator providing a 13.56 MHz sinusoidal signal. The resistors R_1, R_2 and R_3 each have a fixed value of 50 ohms. Based on Kirchhoff's circuit

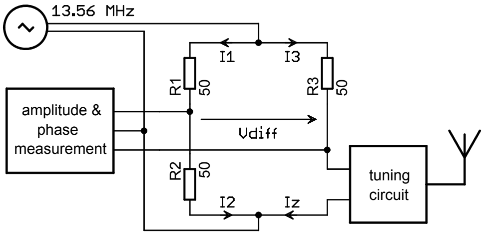


Fig. 5. Measurement system based on a Wheatstone bridge with a sinusoidal supply of 13.56 MHz.

laws, the Wheatstone bridge is described by the equations

$$I_1 - I_2 + I_{\mathit{diff}} = 0, \tag{2}$$

$$I_3 - I_Z - I_{\mathit{diff}} = 0, \tag{3}$$

$$I_1 \cdot R_1 - I_3 \cdot R_3 = V_{\mathit{diff}} \tag{4}$$

and

$$I_1 \cdot R_1 + I_2 \cdot R_2 - I_3 \cdot R_3 = I_Z \cdot Z. \tag{5}$$

The antenna circuitry's impedance Z matches 50 ohms,

$$Z = R_2 \cdot \frac{R_3}{R_1} = 50\,\Omega, \tag{6}$$

when the bridge is balanced ($V_{\mathit{diff}} = 0$). Therefore, the antenna is tuned when both – the magnitude and the phase of V_{diff} – are zero. The voltages $I_2 \cdot R_2$ and $I_Z \cdot Z$ are used instead of directly measuring V_{diff}.

2) Amplitude Measurement: Measuring rectifiers are used to rectify the magnitudes of $I_2 \cdot R_2$ and $I_Z \cdot Z$. Each rectifier cuts off the negative half-wave of its input signal [6]. The resulting signals are low pass filtered and amplified to fit the input range of an analog-digital converter. The difference between the two signals is calculated after analog-digital conversion.

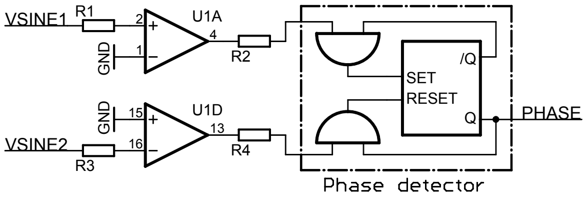


Fig. 6. Non-inverting and inverting rectangle shaper and the phase detector of a 74HC4046A integrated circuit used for phase offset measurement.

3) Phase Measurement: The sinusoidal signals $V_{SINE1} = I_2 \cdot R_2$ and $V_{SINE2} = I_Z \cdot Z$ are shaped into rectangular signals. At the same time one of the signals is inverted (or shifted 180 degrees). These steps are necessary to transform the input signals into the operating range of the phase detector. Then, the phase of V_{diff} is determined with the phase detector of a 74HC4046A phase-locked loop integrated circuit (Fig. 6). This IC outputs the phase offset as a pulse-width modulated (PWM) signal. That PWM signal is low pass filtered and then fed into an analog-digital converter. The average voltage of the pulse-width modulated signal has a linear relation to phase offsets between -135 and 135 degrees.

4) Verification: The measuring circuit is verified with a manually tunable antenna circuitry. The manual tuning circuit is based on Fig. 2. The capacitors C_1 and C_2 are replaced with trimmer capacitors. This antenna circuitry is connected to the measuring bridge. The trimmer capacitors are tuned until both the amplitude measurand and the phase measurand approximate zero. In the next step the antenna circuitry is measured with a network analyzer instead of the measuring circuit. Fig. 7 plots the result of this measurement. The S_{11} parameter for 13.56 MHz is close to zero. This verification procedure has successfully been repeated with several different NFC antennas. The deviation of the S_{11} parameter (at 13.56 MHz) is approximately identical to all antennas. This suggests that the deviation is a result of component variations in the measuring circuit.

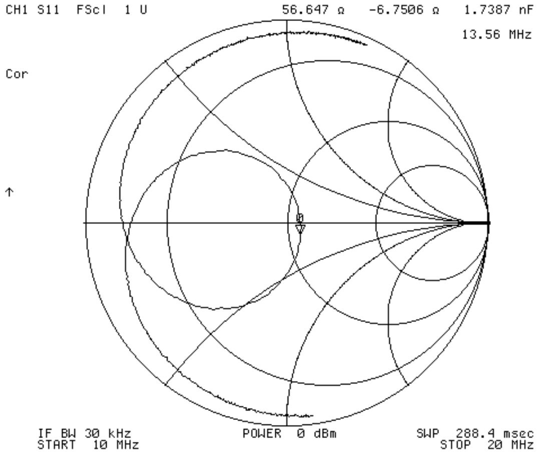


Fig. 7. Sweep measurement of the reflection coefficient S_{11} of the manually matched antenna between 10 and 20 MHz with a marker at 13.56 MHz.

B. Matching Circuit

Matching is done by varying the capacitance of C_1 and C_2 (Fig. 2). Ref. [5] suggests three types of variable capacitors:

- trimmer capacitors,
- capacitance diodes and
- capacitance arrays.

Mechanic trimmer capacitors are neither integrable nor electronically controllable [5]. With capacitance diodes there is insufficient isolation between the signal voltage and the control voltage [5]. Thus, the best of these options is to use capacitance arrays.

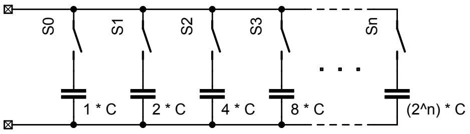


Fig. 8. Network of parallel capacitors

A capacitance array is a network of parallel switched capacitors (Fig. 8). The capacitors are graded with powers of two to achieve a binary coded capacitance value.

The capacitance array is made electronically controllable with semiconductor switches. As the capacitor values range from 1 to 50 pF, low-capacitance DMOS switches are used. The capacitors C_1 and C_2 are replaced with these capacitance arrays. The arrays are switched in a way that both instances of C_1 (and both instances of C_2 respectively) have the same value.

The DMOS switches have parasitic effects which make them operate differently to ideal switches. There is parasitic capacitance between the switched pins during off-state and between the signal pins and ground. These parasitics narrow the range of the capacitance arrays and therefore, narrow the range of tunable antennas. Moreover, there is an on-state resistance that influences the antenna's quality factor. Thus, additional investigation of this problem is subject to prospective research.

C. Controller

A microcontroller is used to analyze the measurands and to control the capacitance arrays. The microcontroller has an integrated analog-digital converter to digitize the amplitude values and phase values.

As proof of concept, a primitive tuning algorithm has been developed. The optimal adjustment of C_1 and C_2 is where the magnitude and the phase offset are the closest possible to zero. Both C_1 and C_2 have an impact on the magnitude as well as the phase offset. When each pair of measurands is considered a point on a two-dimensional plane, its distance d to zero can be calculated by the formula

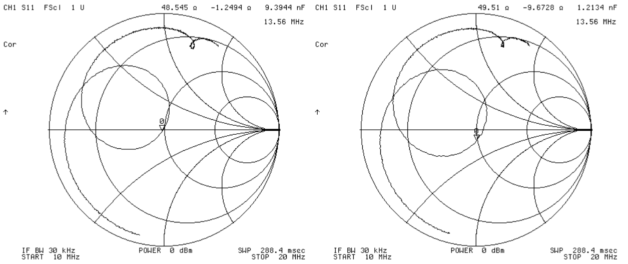
$$d^2 = A^2 + \varphi^2, \tag{7}$$

with the magnitude A (as the first coordinate) and the phase offset φ (as the second coordinate). Hence, the tuning algorithm has to find the minimum distance. The actual algorithm sweeps through all combinations of C_1 and C_2 and searches the lowest value of d^2. The antenna circuitry is tuned to this combination of C_1 and C_2.

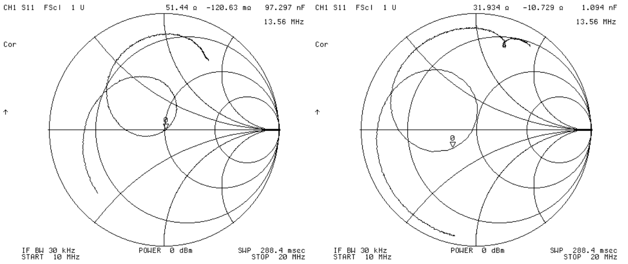
TABLE I

LIST OF TESTED ANTENNAS

	Antenna 1	Antenna 2	Antenna 3	Antenna 4
Turns	6	6	4	6
R_a	4.93 Ω	8.82 Ω	4.83 Ω	5.16 Ω
L_a	3.12 μH	3.16 μH	1.7 μH	3.49 μH
C_a	9.84 pF	10.16 pF	6.99 pF	6.35 pF
C_1	14 pF	19 pF	27 pF	13 pF
C_2	55 pF	49 pF	124 pF	54 pF



(a) Antenna 1 (b) Antenna 2



(c) Antenna 3 (d) Antenna 4

Fig. 9. Sweep measurement of the reflection coefficient S_{11} of the automatically matched antennas between 10 and 20 MHz with a marker at 13.56 MHz.

The complete automatic tuning system has been tested with four different NFC antennas. The four antennas have symmetric rectangular coils with average dimensions of about 50 mm by 30 mm and four to six turns. Table I lists the tested antennas with the number of turns and the values of their series equivalent circuits [2], [5]. Moreover, it specifies the necessary values for manually tuning C_1 and C_2 (with L_0 and C_0 of the EMC filter at 560 nH and 220 pF) as obtained through simulation. The results were examined with a network analyzer. The algorithm found the optimum values for C_1 and C_2 with each of the four antennas. Fig. 9 shows the smith charts for these antennas. With three of the four antennas, the marker (13.56 MHz) is almost exactly at zero. While antenna 4 is still tuned to an acceptable result, this is an example for the low resolution of the capacitance arrays. Antenna 4 (with a binary switching value of three for C_1) and antenna 2 (with a binary switching value of zero for C_2) mark the lower limit of the capacitance arrays: C_1 can be tuned if a capacitance of more than 13 pF is required and C_2 can be tuned if a capacitance of more than 49 pF is required.

IV. SUMMARY AND OUTLOOK

This paper presents an approach to future integration of automatic impedance matching capabilities into NFC transmission module ICs. The concept of an automatic tuning system is explained. The various aspects of the system, with a major focus on the measurement, are pointed out. Proof of concept is given by the implementation and the verification of a lab-scaled prototype. The proper operation of the automatic impedance matching system could be confirmed.

The optimization of the capacitance arrays, the improvement of the tuning algorithm, as well as the integration of the whole system into a single IC are subject to future research.

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