PEEC-Based Multi-Objective Synthesis of NFC Antennas in the Presence of Conductive Structures

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Abstract ─ Near Field Communication (NFC) techniques are widely used within everyday activities, e.g., contactless payment systems or authentication. Regardless of the application typically the requirements on the antenna structure are manifold. Frequently limitations in the available space make the antenna design quite challenging especially if other conductive structures are close to the NFC antenna. In the present paper we propose to synthesize the geometry of proximity integrated circuit card (PICC) antennas according to class 6 in the presence of nearby metallic structures. The optimization relies on the differential evolution strategy. The computation of the forward problem is based on the partial element equivalent circuit (PEEC) method.

Index Terms ─ NFC antennas, numerical optimization, partial element equivalent circuit method.

I. INTRODUCTION

Within the contactless communication technologies the NFC services have found a mass market in the last decade. Nearly all new mobile devices like smart phones or tablet PCs are equipped with NFC technologies. Although the functionality of these devices has become very complex, they tend to become smaller in size. Hence, this leads to a reduced space for the certain services. Therefore, the requirements on the NFC antenna design are increasing. Typically the antenna designer has to find a suitable structure which enables the operation of the NFC device in the three dimensional NFC operating volume (see Fig. 1) [1] which is defined by the NFC Forum.

Since the communication at the operating frequency of 13.56 MHz is established in the near field of the antennas, typically loop antennas like the one shown in Fig. 2 are utilized. Following the common design rules for the design of a PICC, the NFC transponder IC and the antenna structure should result in a resonant circuit at the operating frequency [2]. Typically the input capacitance of the NFC transponder IC is not sufficiently large to fulfill this requirement, hence an external tuning capacitor is needed [2]. In addition to the tuning to the operating frequency, also the power transmission between the NFC devices has to be taken into account which is affected by an additional matching circuitry. Especially in terms of standard compliance this behavior is essential. Typically the external matching circuit is developed subsequently to the design of the antenna structure [3], hence the NFC device does not necessarily result in an optimum design. Therefore, in the present paper we propose to optimize the antenna structure and the needed matching circuit in parallel during the numerical optimization process taking into account conductive structures which can be close to the NFC antenna. To enable this process the PEEC-method [4] is applied since it permits a direct treatment of lumped components and the discretized antenna structure in a single system of equations.

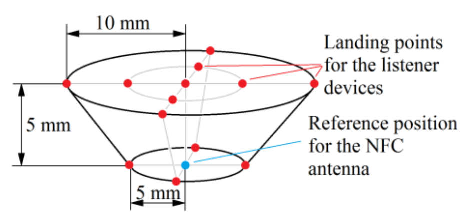

Fig. 1. NFC Operating Volume defined by the NFC Forum. Compliance tests have to be carried out at each point in the volume.

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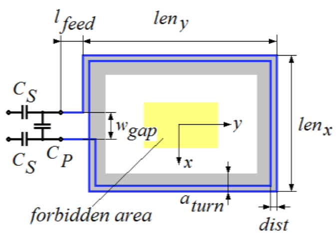


Fig. 2. Typical NFC antenna structure connected to a matching circuitry. For class 1 antennas a forbidden area is present; for class 6 no forbidden area is given.

It has been shown that stochastic optimization strategies deliver reasonable good results especially when the behavior of the objective function in the multi-dimensional parameter space is not very well known like it is the case for the present optimization task. Thus, for the present optimization task a fundamental version of the differential evolution (DE) strategy [5] has been chosen.

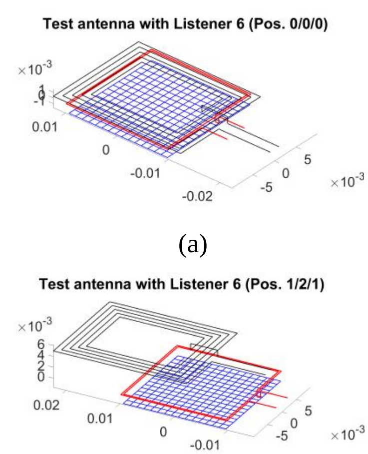
II. READER POWER REQUIREMENTS IN THE NFC FORUM OPERATING VOLUME

A major test criterion within the standard compliance tests is the so called reader power requirements test. According to this test the NFC device is operated in reader mode (the device acts as polling device) and should conduct the communication to the NFC listening devices in card mode. Within this test the generated field strength of the polling device is measured with three standardized so called listener devices (*Listener* 1, 3 and 6) at specific points in the NFC Forum operating volume. The field strength levels are measured in terms of voltages at specific test resistances (see Table 1). Two requirements have to be fulfilled for all listener devices: the so called H_{min}-test (the voltage at the resistance must exceed a lower limit) and the H_{max}-test (the voltage at the resistance must not exceed an upper limit). These test resistances are the load resistances of a bridge rectifier circuitry connected to the listener antennas. In order to enable a frequency domain investigation the non-linear rectifier is modeled in terms of a linear resistance. The resistance values for the six test cases summarized in Table 1 are determined based on measurements utilizing a standardized polling device and a subsequent least-squares approximation.

For the numerical optimization the NFC antennas under test as well as the listener devices have been modeled in terms of one-dimensional PEEC stick elements [4]. To take into account conductive material close to the antenna a dense grid structure is used. Figure 3 shows such test configurations. Numerical tests have shown that the strongest influence of the conductive structure is given when it has roughly the same dimensions as the antenna under test. Hence, such configurations are tested in our first investigations. The design parameters for the first test case (class 6 antenna) are $\mathbf{p}_{cl6} = [len_x, len_y, dist, a_{turn}, C_S, C_P, R_P]$. The design parameters for the antenna geometry are limited according to the corresponding ISO/IEC definitions. For the test case it is assumed that the antenna is manufactured on a FR-4 substrate material with a thickness of 1.55 mm. In the PEEC model therefore the smallest distance between the metal structure and the antenna under test is mainly defined by the thickness of the substrate. The objective set consists of the maximum current I_{IC} the NFC IC is able to deliver to the antenna, the antenna's quality factor Q_{Ant} as well as of the power levels at the listener devices computed from the voltages at the specific listener resistances ($H_{minList1}$, $H_{maxList1}$, $H_{minList3}$, $H_{maxList3}$, $H_{minList6}$, $H_{maxList6}$). Applying fuzzy functions [6] for all objectives a scalar objective function can be defined:

$$f(\mathbf{p}) = \mu\left(I_{IC}(\mathbf{p})\right) + \mu\left(Q_{Ant}(\mathbf{p})\right) + \\ + \sum_{i=1,3,6} \mu\left(H_{min} L_i(\mathbf{p})\right) + \sum_{i=1,3,6} \mu\left(H_{max} L_i(\mathbf{p})\right). \tag{1}$$

The test problems (1) are minimized by the DE strategy.



(a)

(b)

Fig. 3. PEEC-model for the numerical optimization process; Test antenna (red) with metal grid (blue) and Listener 6 antenna (black). (a) Listener 6 at position 0/0/0 according to the standard. (b) Listener 6 at position 1/2/1.

Table 1: Load resistance values and voltage levels

		Listener 1	Listener 3	Listener 6
H_{min}	R_{List} in Ω	450	300	175
	V_{Test} in V	4.1	3.14	3.79
H_{max}	R_{List} in Ω	50	35	20
	V_{Test} in V	2.85	2.5	2.23

III. RESULTS AND DISCUSSION

Due to the fact that for all points in the operating volume and for all listener devices the induced voltage has to be computed, a large number (3x14x2) of forward problems has to be solved for each individual of the population. For the class 6 test problem we have obtained a parameter set given to be $\mathbf{p}_{cl6}$ = [0.0197*m*, 0.0197*m*, 339*μm*, 0.0374, 368*pF*, 570*pF*, 0.7*k*Ω]. The results have been obtained for a population size of n = 30 and it_{max} = 500 iterations. As can be seen from Fig. 4 the global minimum could not be attained. This is due to the H_{min} limit for the *Listener 1* test. Adapting (1) by introducing weighting functions could be a reasonable way to overcome this problem. Figure 5 shows the influence of the metal grid on the antenna impedance and Figs. 6 (a) and (b) show how the listener devices influence the antenna impedance due to the so called card loading effect.

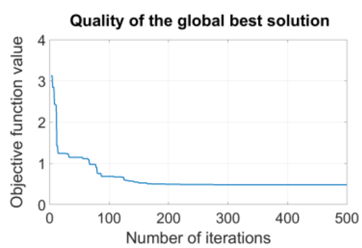


Fig. 4. Progress of the quality of the global best solution.

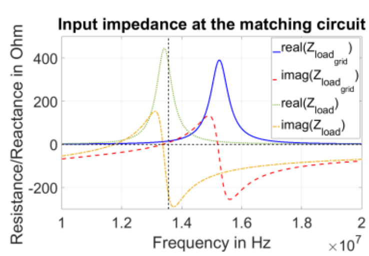
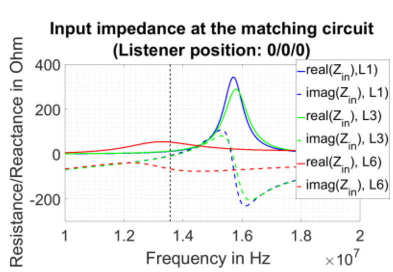
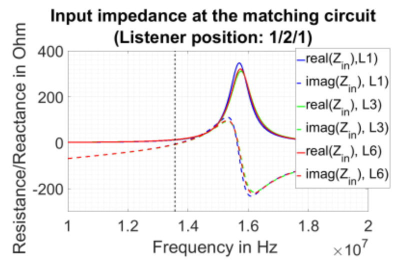


Fig. 5. Influence of the metal grid on the impedance at the matching circuit. Solid and dashed line: input impedance of the optimized antenna in presence of the conductive material. Dotted and dash-dotted line: conductive material is absent.



(a)



(b)

Fig. 6. Influence of the card loading on the input impedance: (a) Listeners at position 0/0/0; strongest card loading and detuning effect. (b) Listeners at position 1/2/1; reduced card loading and hardly any detuning effect.

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