Multi-Objective Synthesis of NFC-Transponder Systems based on PEEC Method

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The Near Field Communication (NFC) technique finds wide applications in many aspects of modern life, 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. Beside geometrical limitations also the matching of the antenna structure to the analog front end of the NFC transponder IC has to be taken into account. In the present paper the optimization of an NFC antenna structure including the needed matching circuit in the multi-objective sense is proposed. Due to its simplicity and the consequently reduced computational effort the Partial Element Electric Circuit (PEEC) method is applied to carry out the needed field computation in the so called NFC operating volume. Furthermore, the PEEC method offers the possibility to simply connect lumped components to the antenna structure within the numerical analyses, which enables the optimization of the matching circuit parallel to the optimization of the antenna structure. The optimization relies on a stochastic optimization strategy, namely the firefly algorithm. In the present paper an extended version of the general firefly algorithm is applied.

Index Terms—Firefly optimization, Impedance matching, Near field communication, Partial equivalent electric circuit

I. INTRODUCTION

NFC SERVICES, which belong to the contactless communication technologies, have found a mass market in the last decade. Especially the numbers of mobile devices like smart phones or tablet PCs equipped with NFC technology has rapidly grown in the last years. These devices tend to become smaller in size or the functionality has become very complex which leads to a reduced space for the certain services. Hence, the requirements on the NFC antenna design are increasing. Typically the antenna designer has to find an optimum structure which enables the operation of the NFC device in the three dimensional NFC operating volume [1] which is defined by the NFC Forum.

Due to the operating frequency of 13.56 MHz an inductive coupling between the NFC antennas is utilized to establish the communication. Hence, in general loop antennas (e.g. as shown in Fig. 1) are deployed. In connection with the NFC transponder IC these antenna structures should result in a resonant circuit [2]. Since typically the input capacitance of the NFC transponder IC is not sufficiently large to tune the self-resonance frequency of the loop antenna to the carrier frequency, an external tuning capacitance is needed [2]. Besides tuning also the matching between the antenna impedance and the IC impedance is essential to maximize the power transmission. Hence, an external matching circuit which fulfills both requirements has to be applied. Typically the external matching circuit is developed subsequently to the design of the antenna structure [3].

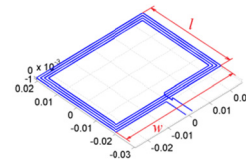In the present paper we propose to optimize the antenna structure and the needed matching circuit in parallel during the numerical optimization process. To enable this process the PEEC-method is applied since it permits a direct treatment of lumped components and the discretized antenna structure in a single system of equations. If the behavior of the objective function in the multi-dimensional parameter space, like in the present case, is not well known, stochastic optimization strategies like Particle Swarm Optimizers (PSO) should be preferred [4]. Among PSO algorithms, the Firefly Algorithm (FFA) has been shown to achieve reasonably good results if one is interested in finding locally best solutions, too [5].

Fig. 1. Typical NFC loop antenna design (dimensions in m).

II. PEEC-METHOD

The main advantage of the PEEC method introduced by Ruehli [6] compared e.g. to the finite element method lies in the fact that the air volume needs not to be discretized. Due to the free-space Green's function $G(\mathbf{r},\mathbf{r}')$ within the electric field integral equation

$$\frac{\mathbf{J}(\mathbf{r},\omega)}{\sigma} = \frac{-j\omega\mu_0}{4\pi}\int_\Omega \mathbf{J}(\mathbf{r}',\omega)G(\mathbf{r},\mathbf{r}')d\Omega' - \frac{1}{4\pi\varepsilon_0}\nabla\int_\Omega \rho(\mathbf{r}',\omega)G(\mathbf{r},\mathbf{r}')d\Omega', \tag{1}$$

the electric field intensity is described in the whole problem domain. This approach results in a limitation to homogenous

media. In (1) **J** is the current density, **r** and **r'** represent the field point and source point vectors, respectively, ω is the angular frequency, ρ is the charge density, μ_0 and ε_0 are the permeability and the permittivity, respectively.

The basic idea is now to discretize the conductive structure in volume cells, in the present case into thin cylindrical stick elements, and derive equivalent lumped electric circuits for these cells [6]. Due to the description of the antenna structure in terms of these lumped electric circuits an extension with concentrated lumped components connected to the antenna structure is straight forward. Now the resulting linear equivalent circuit system can be solved in terms of SPICE-like circuit simulators. To obtain the magnetic flux density **B** from the calculated current distribution Biot-Savart's law is applied to each stick element:

$$d\mathbf{B}\left(\mathbf{r}\right) = \frac{\mu_0}{4\pi} Id\mathbf{l} \times \frac{(\mathbf{r} - \mathbf{r}')}{\left|\mathbf{r} - \mathbf{r}'\right|^3}. \qquad (2)$$

In (2) I is the current flow in the corresponding stick element, $d\mathbf{l}$ gives the orientation of the element and **r** and **r'** represent the field point and source point vectors, respectively.

III. EXTENDED FIREFLY ALGORITHM

Applying stochastic optimization strategies using simplified sequences of complex natural processes for the optimization of technical design problems has become an approved approach over the last decades. Therefore, in the present work, an extended FFA is used to solve the p dimensional and bound constrained numerical parametrization problem. The applied extended FFA, which utilizes an additional clustering algorithm [7], is based on the following rule:

$$\mathbf{x}_i^{t+1} = \mathbf{x}_i^t + \beta_0 e^{-\gamma r_{ij}} \left(\mathbf{x}_j^t - \mathbf{x}_i^t\right) + \alpha \boldsymbol{\varepsilon}_{ij}. \qquad (3)$$

In principle (3) describes the movement of the particles in the swarm, where r_{ij} is the distance between any two fireflies i and j at their positions $\mathbf{x}_i$ and $\mathbf{x}_j$. The attractiveness between any two fireflies is given by $\beta_0 e^{-\gamma r_{ij}}$, where γ is the so called light absorption factor. The third term in (3), also referred to as levy flight, is a randomization of the particle movement where $\boldsymbol{\varepsilon}_{ij}$ is a random vector and α being the randomized parameter.

IV. NFC ANTENNA OPTIMIZATION

The test configuration to be optimized is shown in Fig. 2(a). The coupled antenna structure consists of a so called polling device and the antenna structure to be optimized. The position of the antenna to be optimized can be modified according to the definition of the NFC operating volume. For the first test problem the shape of the antenna should be limited to rectangular antenna configurations. The optimization variables corresponding to the antenna structure are the length l and the width w of the antenna as well as the number of turns n. The variables for the matching circuit are the capacitance values C_p and C_s of the matching circuit shown in Fig. 2(b). All variables are collected to the vector **h**.
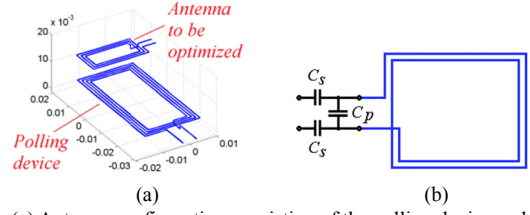

Fig. 2. (a) Antenna configuration consisting of the polling device and the antenna structure to be optimized. (b) Antenna structure to be optimized connected to the matching circuit.

For the first test problem the matched antenna impedance should be optimized to a certain impedance value (e.g. 50 Ω) at the operating frequency while keeping the antenna area below a certain limit. Hence, introducing fuzzy membership functions and scalar weights for the antenna impedance μ_{ZAnt} and the antenna area μ_{AAnt} a scalar objective function can be defined:

$$f(\mathbf{h}) = (w_1 + w_2) - w_1 \mu_{ZAnt}(\mathbf{h}) - w_2 \mu_{AAnt}(\mathbf{h}). \qquad (4)$$

As can be seen from Fig. 3 first tests show satisfying results while keeping the computational times within an acceptable margin.
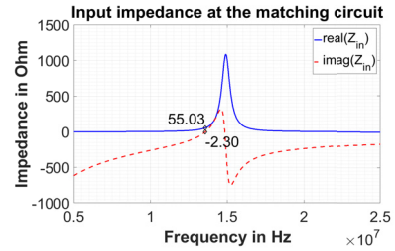

Fig. 3. Computed input impedance at the terminals of the matching circuit.

In the full paper the optimization problem will be extended including several other objectives (e.g. power transmission, bandwidth). Furthermore, a comparison of the results obtained with the FFA with those of other stochastic optimizers is planned. Also algorithmic details will be presented together with other antenna designs.

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