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Evolutionary Optimization of Asymmetrical Pixelated Antennas Employing Shifted Cross Shaped Elements for UHF RFID

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Abstract: The design and optimization of antennas for specific boundary conditions and parameters, such as size and frequency, for a given application, is a highly complex and time consuming process, which usually involves elaborate computer-aided software packages and/or methods. Additionally, trade-offs and co-dependencies have to be considered, when optimizing for a specific parameter, i.e., a high antenna gain goes usually hand-in-hand with a large antenna. Therefore, we implemented a method that involves the automated design and optimization of asymmetrical pixelated antennas using evolutionary algorithms, where arbitrary parameters can be optimized for chosen boundary conditions. In contrast to other approaches, shifted cross elements were employed as pixels to avoid point contact defects. We present results for antennas with an exemplary resonant frequency of 868 MHz and sizes of 3×3 , 4×4 and 6×6 cm. The agreement between measurements and simulations for the antenna gain and reflection coefficient is excellent, with a maximum error of 1.15% for the single resonant frequency (relative error) and 1.35 dB for the antenna gain (mean absolute error).

Keywords: UHF RFID; evolutionary algorithms; optimziation; pixelated antennas; fragmented antennas

1. Introduction

Even today, more than a century after Heinrich Hertz first examined wave propagation according to Maxwell's theory, antennas and specifically their design remains an active research field. Examples include the design of antennas for medical applications [1], antenna (arrays) for terahertz communications and photodetectors [2,3], magnetoelectronic antennas [4] and recently also antennas for 5G applications [5]. The core problem of antenna design is that each antenna must be specifically chosen or designed for certain boundary conditions and thus inevitably, there is always a tradeoff between the antenna gain and the antenna size or the impedance respectively. The size of an antenna is inherently determined by its chosen resonant frequencies, and thus it cannot simply be reduced for a given topology, without changing the frequency. Furthermore, simple structures such as dipole antennas aside, antenna design and optimization is a highly complex mathematical problem and thus a time-consuming and costly process. This is why usually computer-based methods such as simulation software packages have to be employed [6,7].

To develop antennas for specific scenarios with challenging boundary conditions or multiple parameters that have to be optimized, such as for multi-carrier systems, a step towards a fully automated antenna design needs to be taken in order to reduce development time. Using pre-defined topologies



such as dipole-structures or thin wire antennas for optimization can lead to problems due to the fact that the optimization's potential is limited to the maximum performance of the pre-defined topology. Thus, techniques are used for topological optimization such as Scalar Isotropic Material with Penalization (SIMP) as well as level set method (LSM). SIMP algorithms inevitably generate structures with zig zag boundaries and LSM algorithms tend to simplify the topology of the model, thus limiting the discovering ability [8].

Another technique for topology optimization was introduced by dividing a predefined area into small pixels, leading to pixelated or fragmented antennas [9–19]. However, most of them lack a correct handling of singular point contacts and/or measurement results, i.e., impedance measurements and the antenna gain [9–13,15–17,19,20]. Additionally, in a majority of cases symmetric structures are optimised, which further limits the solution space [9–15,21]. In studies of asymmetric topologies, the feedpoint is placed after optimization with the help of characteristic mode analysis [22]. This results in different feed points for different resonant frequencies and, furthermore, simulations were not compared to gain and reflection coefficient measurements.

We present results on pixelated antennas for UHF RFID at 868 MHz that were optimized using the simulation tool Sonnet Software combined with an evolutionary algorithm implemented in Matlab. The presented method results in a fast and efficient optimization, with a mean time of two hours for generating antennas with sizes of 4×4 cm (correspond to $0.11 \times 0.11 \lambda$). In order to deal with point contacts, shifted crosses as pixels for defined contacts between single elements are implemented. Additionally, symmetry was not used as a boundary condition in order to not limit the solution space. With the implemented algorithm antennas of three different sizes have been designed and optimized. Their performance (i.e., reflection coefficient and antenna gain) is confirmed in experiments. The agreement between simulation and experimental results is excellent, thus supporting the quality of the presented method.

2. Employed Optimization Technique

To achieve the desired high degree of automation, a pre-defined area has to be initially pixelated. In principle, the pixels can be represented by any geometrical shape. However, rectangles lead to singularities, as depicted in Figure 1a, which in turn would lead to a decrease of simulation accuracy [23] and introduce errors in the measurement, due to the limited production accuracy. Regular hexagon pixels as depicted in Figure 1b are thus a superior choice. However, because of restrictions to rectangular cells in some simulation tools such as Sonnet Software, errors are again introduced due to the limited resolution of the angled sides of the hexagon. Thus, the structure used in this publication is cross-shaped as depicted in Figure 1c. This structure also exhibits no singularities and is ideal for simulation tools that employ rectangular cells. Every second row is shifted by half an element in order to avoid non-conducting areas between the crosses. How this pixelation process manifests on a pre-defined area can be seen in Figure 2a.

Figure 1 also shows the division of the geometry into different cells. Sonnet Software suggests a cell size smaller than 1/20 of the wavelength. Further specifications refer to geometric smallest sizes which correspond to 1/4 of the cross size for the cross structure. The cross size may therefore be a maximum of $4 \times 1/20$ of the wavelength. Furthermore, the elements should be chosen to be small enough not to restrict the simulation space too much, which depends mainly on the maximum possible antenna size defined as a boundary condition. Thus, the pre-defined area is pixelated with shifted cross shaped structures as depicted in Figure 1c. Every cross has a Boolean value that represents a conductive or non-conductive element (0,1). If the value of an element is 1, a 35 um thick copper layer is placed on top of the substrate. After the construction of this pixelated area, all Boolean values are combined into a matrix, which can be adjusted by an evolutionary algorithm.



Figure 1. Possible connections between copper elements of different shape: (**a**) rectangles, (**b**) hexagons, (**c**) crosses. The red elements show vertical and diagonal neighbours. In (**a**) it is shown that vertically spaced elements result in an adequate connection, whereas diagonal elements result in singularities, due to a (theoretically) infinitesimally small connection. In (**b**) and (**c**) no singularities can occur, regardless of how neighbouring elements are connected to each other. In (**c**) the cross size (S_{cross}) is defined and its seperation into different Sonnet Software cells with size S_{cell} is shown.

The algorithm itself is implemented in Matlab by calling the *ga*-function. At the beginning of the optimization, the evolutionary algorithm generates a random initial population with a uniform distribution as depicted in Figure 2b. This population is handed to the electromagnetic simulation tool Sonnet Software via the Sonnet Software Matlab Plugin. Sonnet simulates the structures of the initial population and feeds the parameters needed for the calculation of a fitness function, such as the reflection coefficient, into Matlab. With this information, a second population is generated by using evolutionary methods such as selection, crossover and mutation. First the fitness score is scaled by the squareroot of the rank of an individual. The rank is equal to the individual's position inside of the sorted scores. The selection function determines the parents for the crossover and mutation function. A line is generated on which each individual's length is proportional to its scaled fitness function. The algorithm moves along this line in steps of identical size. Each time the algorithm lands on an individual it is selected as a parent. Thus, an individual has the chance to be chosen several times as a parent. This is followed by the crossover function. It builds a child crossover from two parents. First a random bit-string is generated. If an entries value inside the bit-string is 1 the child inherits the value from parent 1, otherwise from parent 2. The mutation function works in two steps: first elements are selected with a probability of 1 %. In a second step these elements are replaced by random values (0,1) [24].

This second population is again simulated with Sonnet and the result of the fitness function is used to form a third population with the help of evolutionary methods. This process is continued iteratively until a maximum limit for the number of populations is achieved or the termination criterion for the fitness function is reached. The termination criterion of the fitness function is chosen to be a reflection coefficient of -15 dB or a maximum of 100 populations needed for the optimization.

A problem that may arise is that no solution can be found for these termination criteria. This is a consequence of a too small number of crosses (or too large cross size). Further design considerations can be found in Section 3.3.

To proof the plausibility of the optimization conducted with Sonnet Software, post-optimization simulations are carried out employing Ansys HFSS. Therefore, all reflection coefficients as well as antenna gain simulations shown in this paper have been computed with Ansys HFSS. The difference between optimization result (Sonnet) and post-optimization simulation (Ansys HFSS) is outlined by their relative difference. A flowchart of the proposed concept is shown in Figure 2.



Figure 2. Flowchart of the proposed optimization technique. (**a**) First a predifined area is pixelated. (**b**) After pixelation an initial population is created with Matlab and fed into Sonnet where the antenna is simulated. The results are then handed back to Matlab and the fitness function is computed from the optimized parameters. The population is rated and if it does not meet the termination criteria, a new one is created based on the first optimization.

3. Results and Discussion

The proposed method is tested for the exemplary application scenario of Ultra-High-Frequency Radio Frequency Identification (UHF RFID). There is usually no prior knowledge of the transponder's position relative to a interrogator in RFID applications which is why the reflection coefficient is chosen as the fitness function, instead of the directivity. Due to regulations in Europe for UHF RFID, as a target a single resonant frequency of 868 MHz is chosen [25]. Also worth mentioning is the fact that the most efficient rectifier structures for UHF RFID tags have a balanced input such as Differential-Drive CMOS Rectifiers. However, these do not necessarily have to be connected to antennas that have a balanced output. This is due to the fact that for RFID chips, isolated from ground, there is no difference between balanced and unbalanced. Therefore, UHF RFID antennas do not necessarily need to be balanced, extending the solution space [26].

The boundary conditions are initially set to allow the antenna to evolve in a 6×6 cm planar area with a cross size of 4 mm on a 1.55 mm thick hydrocarbon ceramic substrate (RO4350B, ROGERS [27]). With all boundary conditions and the fitness function for a single resonant frequency of 868 MHz configured, the optimization resulted in the antenna depicted in Figure 3a. Additional antennas of different sizes (3×3 cm, 4×4 cm) were also simulated and verified by measurements.



Figure 3. Different exemplary antennas generated with the proposed method. (**a**) 6×6 cm and 4 mm cross size, (**b**) 4×4 cm and 2 mm cross size, (**c**) 3×3 cm and 2 mm cross size. The red structure in the center of the respective antennas mark the ports.

3.1. Impedance Measurement

Due to the asymmetrical balanced nature of the produced antennas, the measurement method published by Qing et al. [28] is chosen for the measurement of the antenna parameters. A differential fed asymmetrical balanced antenna can be represented by a two port network. Therefore, it is possible to determine the antennas differential impedance Z_D by measuring the two-port scattering parameters. Considering the same currents I_0 are present in both arms of the antenna, the normalized impedance is expressed as

$$\widetilde{Z_{\rm D}} = \frac{V_{\rm D}}{I_0} = \frac{V_1 - V_2}{I_0}.$$
 (1)

Based on the definition of the Z-parameters, it is possible to calculate the normalized differential impedance

$$Z_{\rm D} = Z_{11} - Z_{21} - Z_{12} + Z_{22}.$$
 (2)

The absolute impedance can be calculated using $Z_D = \widetilde{Z_D} \cdot Z_0$ and converting the Z to S parameters which results in

$$Z_{\rm D} = 2 Z_0 \frac{1 - S_{11} S_{22} + S_{12} S_{21} - S_{12} - S_{21}}{(1 - S_{11}) (1 - S_{22}) - S_{21} S_{12}}$$
(3)

This equation is implemented in a Matlab script which is able to read out VNA scattering parameter values.

Prior to the measurement, the VNA is calibrated using TOSM calibration [Rohde und Schwarz, ZV-Z170]. In order to eliminate the influence of the test fixture, a standard port extension technique of the employed VNA using shorted test fixture connectors is used. After calibration and port extension, the scattering parameters are measured and the differential impedance is calculated via Equation (3).

For Antenna A (Figure 3a) the measured resonant frequency (f_{meas}) is 874.9 MHz with a reflection coefficient ($S_{11,meas}$) of -17.21 dB and the simulated resonant frequency (f_{sim}) is 861.5 MHz with a reflection coefficient of -16.06 dB ($S_{11,sim}$) as depicted in Figure 4a. The optimizations target frequency is 868 MHz which means that the relative error (ϵ) between optimization and the measured resonant frequency is 0.79%. The difference in resonant frequency between initial optimization and post-optimization simulations (Δ) is 0.75%, thus demonstrating the excellent agreement between simulation and experiment.

The differences between simulation and measurement of the reflection coefficient amplitudes and resonant frequencies can be explained by the experimental setup, which leads to a slight detuning of the resonant frequency. Furthermore, the accuracy of the employed electromagnetic simulation tools and the accuracy of the employed measurement method further limit the agreement.

Two additional antennas (Antenna B: Figure 3b, Antenna C: Figure 3c) have been developed, in order to further verify the proposed method. Again, the resonant frequency is chosen at 868 MHz and the

reflection coefficient is used as the fitness function. This time the antenna areas are chosen to be 4×4 cm and 3×3 cm, respectively, both with a cross size of 2 mm. The optimization results of the antennas are depicted in Figure 3b,c. The measured and simulated reflection coefficients are depicted in Figure 4b,c respectively. The results of all Antennas A–C are presented in Table 1.



Figure 4. Reflection coefficient plots of the manufactured antennas from the simulations shown in Figure 3. (a) 6×6 cm, (b) 4×4 cm, (c) 3×3 cm.

Table 1. Comparison of resonant frequencies and reflection coefficients.

Antenna	f _{sim} [MHz]	S _{11,sim} [dB]	f _{meas} [MHz]	S _{11,meas} [dB]	ffl [%]	Δ[%]
Antenna A	861.5	-16.06	874.9	-17.21	0.79	0.75
Antenna B	863	-15.87	875.1	-38.08	0.81	0.58
Antenna C	873.5	-15.99	878.8	-8.32	1.15	0.63

3.2. Antenna Gain Pattern Measurement

To verify the capability of radiating electromagnetic fields, the antenna gain patterns are obtained at the antenna's respective measured resonant frequencies. The simulated far field 3D antenna gain patterns are shown in Figure 5 (1) for Antenna A (a), Antenna B (b) and Antenna C (c). Furthermore, simulations and measurements of the antenna gains are compared for azimuth (sphercial coordinates: $\vartheta = 90^\circ$, φ) in Figure 5 (2) and elevation angles (spherical coordinates: ϑ , [$\varphi = 0^\circ, \varphi = 90^\circ$]) in Figure 5 (3) for Antenna A (a), Antenna B (b) and Antenna C (c).

To measure the antenna's total system gain patterns, we used a horn antenna as a reference inside an anechoic chamber. With the help of the Friis transmission equation, it is possible to calculate the ratio between a receiver antennas received power $P_{\rm R}$ and a transmitting antennas transmitted power $P_{\rm R}$:

$$\frac{P_{\rm R}}{P_{\rm T}} = G_{\rm R} \ G_{\rm T} \underbrace{\left(\frac{\lambda}{4 \ \pi \ d}\right)^2}_{1/D_{\rm f}} \tag{4}$$

The ratio depends on the antenna gain values of the receiving antenna G_R and transmitting antenna G_T as well as the free-space path loss factor D_f . By connecting the two antennas to a VNA, the power ratio is calculated with the measured scattering parameters using:

$$\frac{P_{\rm R}}{P_{\rm T}} = |S_{12}|^2 = |S_{21}|^2 \tag{5}$$

By knowing the reference antennas gain G_{ref} and measuring the distance between the two antennas *d* it is possible to calculate the wanted antenna gain G_{meas} by

$$G_{\rm meas} = |S_{21}|^2 \frac{D_{\rm f}}{G_{\rm ref}} \tag{6}$$

This measurement is performed twice (horizontal and vertical reference antenna) to obtain the total system gain. Due to the asymmetrical, differential structure of the optimized antennas a quarterwave sleeve Balun has to be employed [29]. Otherwise unbalanced currents occur on the coaxial cable, thus making the coax cable no longer shielded but rather a radiating element leading to errors such as pattern squint.



Figure 5. Simulated 3D antenna gain pattern (1) and the simulated and measured azimuth (2) and elevation antenna gain patterns (3) for the antennas A (**a**), B (**b**) and C (**c**) depicted in Figure 3a–c.

Antenna A exhibits a simulated maximum gain (G_{sim}) of 1.3 dBi compared to a measured maximum gain of 1.49 dBi (G_{meas}). The mean absolute error (MAE) of the gain at azimuth angles is 1.32 dB, the MAE of the gain at elevation angles at $\varphi = 0^{\circ}$ is 0.92 dB and at $\varphi = 90^{\circ}$ 1.03 dB.

The results of Antennas A–C are presented in Table 2.

Table 2. Comparison of measured and simulated antenna gains.

Antenna	G _{sim} [dBi]	G _{meas} [dBi]	MAE _{azi} [dB]	MAE _{ele0} [dB]	MAE _{ele90} [dB]
Antenna A	1.3	1.49	1.32	0.92	1.03
Antenna B	-1.37	-0.11	0.96	0.59	0.91
Antenna C	-3.9	-2.02	0.87	1.35	1.3

The mean development time of the presented antennas was 2.65 h (6×6 cm), 2.04 h (4×4 cm) and 4.8 h (3×3 cm) using a simulation setup consisting of a Ryzen Threadripper 2990WX processor (AMD, Santa Clara, CA, USA), 128 GB DDR4-3000 (HyperX, Fountain Valley, CA, USA) RAM, 512 GB XPG SX8200 Pro M.2 PCIe (ADATA, New Taipei City, Taiwan) SSD and a ROG STRIX X399-E mainbord (Asus, Taipei, Taiwan).

If the boundary conditions become more and more challenging (such as antennas submerged in conducting material with a badly defined permittivity, multiple resonant, small size), a fully automated design and optimization process is expected to save time and costs compared to conventional approaches (e.g. capacitive-, inductive- and dielectric loading, stubs), due to the low amount of human resources needed during the optimization process itself.

Compared to other reported RFID-antennas high antenna gains can be achieved, while maintaining small dimensions, which is usually a challenging task, as can be seen from Table 3. In order to compare antennas of different design and topology, the factor Dn is introduced, which is the maximum dimension (diagonal) normalized to the wavelength. This is the same criterion used to determine electrically small antennas [30]. Antenna A exhibits a gain of 1.4 dBi, thus outperforming structures of similar Dn [31,32] or having comparable characteristics [33]. Antenna B and Antenna C also show a good performance considering their size, as can be seen in comparison to other structures [31,32,34].

Table 3. Comparison of different published antennas. Publications marked with an asterisk (*) did not directly measure the antenna gain and publications marked with a cross (x) only included simulations of the gain.

Antenna	Material	$X \times Y$ [cm]	Dn [%]	Gain [dBi]	Freq. [MHz]
[33] (*)	FR4	7.77 imes 3.55	26.22	1.75	920
[34] (*)	EPDM	4 imes 4	16.23	-13.8	860
[31]	PTFE	8.28 imes 1.95	24.59	-0.53	866.5
[32] (x)	FR4	8×5	27.06	-1.6	860
А	RO4350B	6×6	24.57	1.4	868
В	RO4350B	4 imes 4	16.38	-1.4	868
С	RO4350B	3×3	12.28	-3.9	868

3.3. Design Considerations

First findings showed that the simulation accuracy of Sonnet is not increasing with a cell size of smaller 0.58% of the wavelength for these specific pixelated antennas. Therefore, the maximum cross size is equal to 2.32% of the wavelength. If larger crosses are required, the cell size should be bisected until the described criterion for the cell size is met. Furthermore, it is assumed that the antenna gain depends slightly on the cross size.

First investigations have shown that the minimum number of crosses ($n \times n$) to create a possible topology with an impedance of 50 ohms is approximately determined by the following empirical formula:

$$n = 3.743 + e^{3.918 - 19.6078A_{\text{size}}}$$

 A_{size} is one sidelength of the quadratic pixelated antenna per wavelength. This observation is limited to antennas of sizes in between 5.79% and 34.74% sidelength per wavelength. Also, this formula is derived from a very limited dataset. Further research must be done to confirm this formula and measurements need to be made. However, at this point it should facilitate the entry into this optimization process.

From the optimization process itself it was observed that smaller pixels (or more pixels $n \times n$) do not lead to an improved antenna performance. At a certain point described at the above formula, a smaller pixel size did only result in a longer optimization time.

4. Conclusions

This paper presents the implementation of evolutionary algorithms for the optimization of pixelated UHF RFID antennas for 868 MHz. The presented method uses shifted crosses as individual pixels in order to avoid point contacts and generates asymmetrical differential structures. The 2.5 D MoM simulation software Sonnet is employed, leading to mean optimization times of just 2.04 h for an antenna size of 4×4 cm.

To check the validity of the implemented method, measurements of the reflection coefficients and total system gains in a fully anechoic chamber were conducted. The agreement between simulations and experimental results is excellent and within an error of 1.15 % for the resonant frequency and 1.35 dB for the antenna gain. Furthermore, the developed antennas perform very well concerning the gain in comparison to structures of comparable maximum dimensions. Thus, the implemented optimization concept employing shifted crosses for pixelation proves to be an excellent method for designing antennas. Additionally, it expands on the well established method on genetic evolution of pixelated antennas by eliminating point defects and increasing the solution room by optimizing asymmetric structures, which is especially relevant for UHF RFID tags.

The influence of cross and antenna size on the resonant frequency, bandwidth and antenna gain will be investigated in future research. Furthermore, the presented method will be extended to optimize antennas for directivity, multi-objective optimization, which includes the use in harsh environments and challenging boundary conditions. An example of this are badly defined material properties of surrounding objects, as is the case for encapsulated electronics and tagged devices.

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