Evolutional Design of Small Antennas for Passive UHF-band RFID

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This paper presents evolutional design of antennas for passive IC tags used at UHF-band. The shape of wire antennas is optimized using the genetic algorithm (GA) aiming at maximization of feeding power to the IC tag to lengthen the communication distance as well as minimization of the antenna size. The characteristics of the antennas printed on a dielectric substrate are evaluated using the moment method in the optimization processes. Genotypes for GA are introduced to express the shapes of lattice antennas which include loops and floating lines, and spiral antennas. It is shown that optimized antennas satisfy the required condition, and have smaller sizes in comparison with conventional meander antennas.

***Index Terms*—evolutional design, genetic algorithms, moment methods, wire antennas.**

I. Introduction

RADIO frequency identification (RFID) is widely used for wireless recognition and tracking. The RFID operating at UHF-band is promising for many applications in various fields such as transportation systems, access control, livestock identification, immobilizer, electric payment and so on [1] [2]. These RFID systems consist of a reader/writer (R/W) and IC tags. The R/W transmits query signal by electromagnetic waves to IC tags attached on target objects.

The RFID could be used for sensor networks which measure environmental data. The active IC tags including sensors seem suitable for use for this application. However, these active devices require maintenance costs because batteries must be exchanged periodically. Thus wireless senores embedded in IC tags based on passive RFID technology are preferable for these applications, because they get power from the R/W by electromagnetic waves.

For measurement of environmental data at long distance, it is necessary to transmit the power to the IC chip as efficiently as possible. On the other hand, from a practical point of view, decrease in the antenna size is desirable. It is, however, uneasy to satisfy these requirements because the power efficiency depends on antenna properties and the properties are very sensitive to the antenna shape. For this reason, high performance antennas designed by GA have been presented [3]-[5]. In [6], the authors have presented optimization of meander line antenna (MLA) to maximize the antenna gain and realize impedance matching between the antenna and IC chip [5]. However, it has been difficult to obtain more sophisticated antenna shapes for further reduction in their sizes.

In this work, we optimize the shapes of the planar lattice antenna (PLA) which includes loops and floating lines as well as spiral meander line antenna (SMLA). To do so, genotypes for GA are introduced to express the complicated shapes of the these antennas. We optimize the antenna shape aiming at maximization of the feeding power to the load and reduction of antenna size. The optimized result will be comparatively described.

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Digital Object Identifier inserted by IEEE

II. Optimization Approach

This section describes optimization method for the antennas using the real-coded GA (RGA). To make the discussion closed, genotype of the conventional MLA is also described.

A. Representation of antennas

1) MLA

The antenna length has to be adjusted to operation frequency. For example, half-wave dipole antenna length at 950 MHz is around 15cm. Because the dipole antenna is too large to be attached on small objects, MLAs with folded wires are widely used.

Figure 1(a) illustrates the genotype and phenotype of MLA used in the RGA, where only the left hand side of MLA is shown because of the right-left symmetry. The shape of MLA is represented by six genetic loci in this simple example.

The procedure to generate the antenna shape of MLA from the gene is described in the followings.

i. We set a straight line antenna on a base line, and divide it into segments. The lengths of each segment follow the genes representing horizontal length.
ii. Each segment is moved downward by distances described in the gene.
iii. Both ends of each segment are connected to the adjacent segments.
iv. The right hand side is similarly formed.

Note here that the whole length of the antenna line is not kept constant in this representation

2) PLA

PLAs are formed with lattice-shaped metallic lines. The procedure to generate PLA from the gene is described in the following.

i. A lattice is generated.
ii. A gene whose value ranges between 0 and 10 is assigned to each edge of the lattice.
iii. If the value of each gene is larger than 5, we set a metallic line along the edge. Otherwise, the edge is open.
iv. The right hand side of the antenna is similarly formed.
v. A part of the antenna is masked to reduce antenna size. This process simplifies the resultant shape of the antenna.

Note here that this method can change the size and whole length of the antenna as well as its topology. Figure 1(b) shows an example of PLA, where the antenna is formed on the 2×3 lattice. The PLA is expected to have better performance in comparison with MLA because the former has additional flexibilities to include branches, loops and floating lines.

Figure 2(a) shows an example of PLA generated by BLX-α crossover [8] for the RGA.

3) SMLA

The procedure to generate the gene is described in the following.

i. A lattice is generated.
ii. A gene coded by real numbers is assigned to each node.
iii. The metallic line is drawn from the current node to the adjacent node which has the greatest nodal value given by the gene in the surrounding 4 nodes. At this time, the nodes to which lines have already been connected are excluded.
iv. The opposite side of the antenna is similarly formed.

This procedure is repeated until either the length of line reaches at a given length or the current node is surrounded by the connected nodes. Figure 1(c) shows the genotype and phenotype of SMLA, where each gene value is positive integer and chromosome has 10 genetic loci for simplicity. In Fig. 1(c) only the left hand side of SMLA is shown because of the right-left symmetry. Note that the whole length of the antenna line which heavily depends on antenna input impedance is not kept constant in this representation.

The SMLA can also be generated from the genes used for the PLA. In this sense, the search space for the SMLA is included in that for the PLA. However, in our experience, the

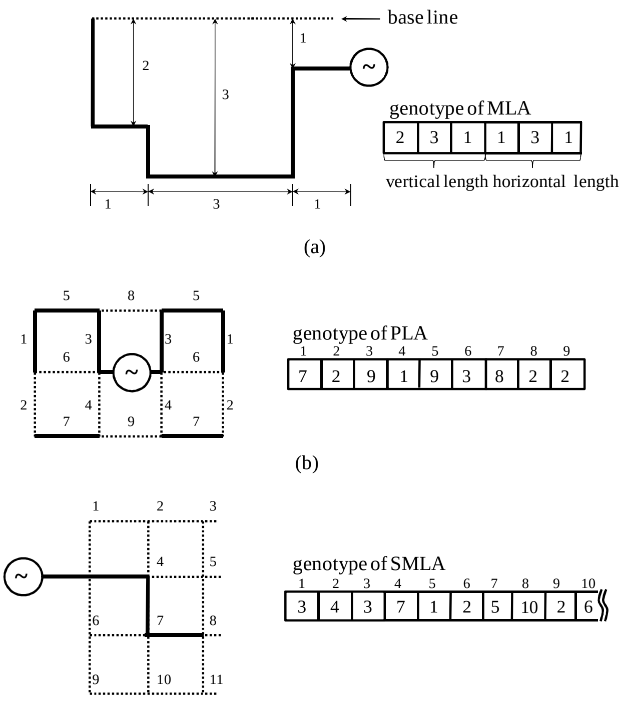


Fig. 1. Geno-and phenotypes. (a) MLA. (b) PLA. (c) SMLA.

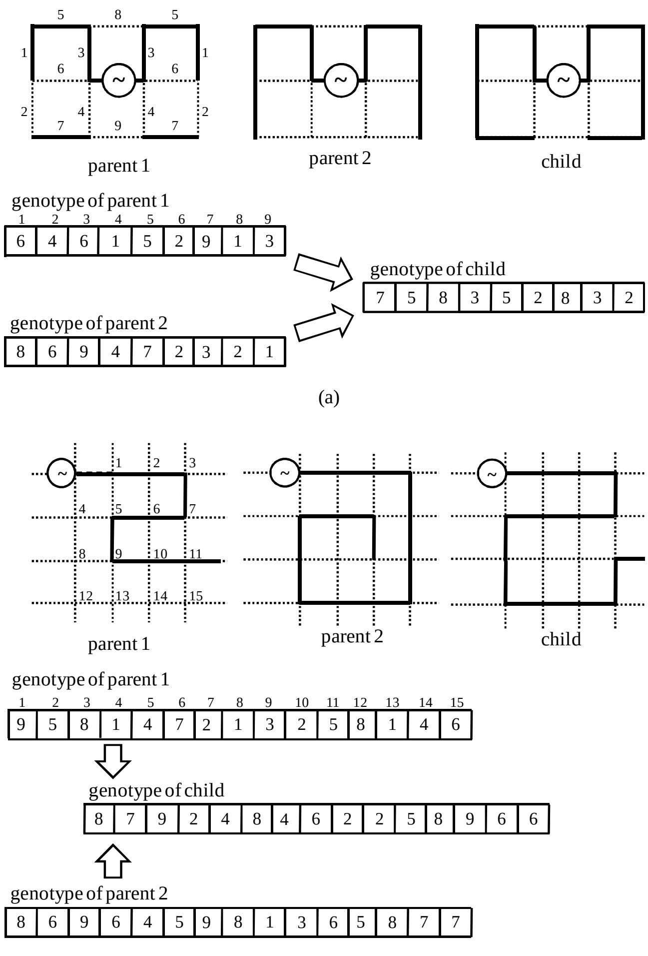


Fig. 2. Geno-and phenotype in BLX-α crossover operation. (a) PLA. (b) SMLA.

optimization based on the PLA has difficulty to generate the SMLAs because of its wide search space. On the other hand, the spiral antennas can easily be generated from the gene shown in Fig. 1(c). It is shown in [7] that alignment of current vectors in spiral wire antennas can reduce the antenna self-resonant frequency. For this reason, we expect that the antenna with spiral structure might yield better performance in comparison with the conventional MLA and PLA.

The crossover operation in the GA should generate the child with properties inherited from the parents. The present genotypes satisfy this requirement, as shown in Fig.2.

The present genotypes can be employed for optimization in other engineering fields which include, for example, design of planar spiral inductors used in analog ICs, filters for elastic and electromagnetic waves and so on.

B. Evaluation

We compute the antenna characteristics such as input impedance, radiation pattern and antenna gain with the moment method [9]. In the moment method, we solve the system of linear equations.

$$[V]=[Z][I], \tag{1}$$

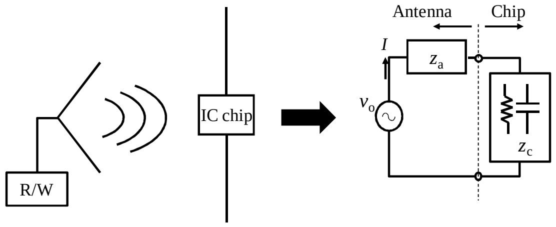


Fig. 3. Equivalent circuit of the R/W and an IC tag.

to obtain the current distribution, where [V] is the voltage vector, [I] the current vector and [Z] the impedance matrix composed of the mutual impedance between each segment. The entity z_{mn} for m-th and n-th segment is given by

$$z_{m,n} = \mathrm{j}\omega\mu\varphi^{\mathrm{f}}_{(m,n)}\Delta \boldsymbol{l}_m \cdot \Delta \boldsymbol{l}_n + \frac{1}{\mathrm{j}\omega\varepsilon\Delta l_m}\left\{\varphi^{\mathrm{c}}_{(m^-,n^-)} + \varphi^{\mathrm{c}}_{(m^+,n^+)} - \varphi^{\mathrm{c}}_{(m^+,n^-)} - \varphi^{\mathrm{c}}_{(m^-,n^+)}\right\}, \quad (2)$$

where, $\Delta \boldsymbol{l}$ denotes the tangential vector of each segment. The potential φ is also given by

$$\varphi_{(m,n)} = \frac{1}{\Delta l_n}\int_{\Delta l_n} \frac{\exp\left(-\mathrm{j}kR_{(m,n')}\right)}{4\pi R_{(m,n')}} dl\ , \quad (3)$$

where k is the wave number, and $R_{m,n}$ the distance between m-th and n-th segment.

In practical application, the RFID antennas are often printed on dielectric sheets. The antenna properties are changed by the effect of the dielectric materials. In this work, we consider the effect of the dielectric substrate on which the antennas are printed by assuming that the substrate is infinitely wide. The dielectric substrate can be modeled with the image charge approach presented in [10] [11], where the validity of this method has fully been confirmed. When the substrate is sufficiently thick, we can consider the effect of the substrate by introducing an image charge inside the substrate. On the other hand, for thin substrates, we have to take the reflection from the boundaries of the substrate into account. In this case, two image charges have to be put for the original image charge and these image charges must be compensated by other image charges, and these processes have to be infinity repeated. In conclusion, φ^c in (2) is replaced by

$$\varphi^{\mathrm{c}}_{\mathrm{new}} = \varphi^{\mathrm{c}} + \kappa\varphi^{\mathrm{c}}_0 - \sum_{i=1}^{\infty}\kappa^{2i-1}\left(1-\kappa^2\right)\varphi^{\mathrm{c}}_{2i-1}\ , \quad (4)$$

where, κ is defined by

$$\kappa = \frac{1-\varepsilon_r}{1+\varepsilon_r}\ . \quad (5)$$

In this paper, we truncate the infinite series by twenty image charges. Figure 3 shows the effects of each image charge.

C. Objective Function

The aim of this optimization is to maximize the feeding power to the load and miniaturize the antenna area. Figure 3 shows the Thevenin equivalent circuit of the IC tag, from which the consumption power at the load is evaluated assuming the incident plane waves. In Fig. 3, v_{o} is received open voltage, $Z_{\mathrm{a}}=R_{\mathrm{a}}+\mathrm{j}X_{\mathrm{a}}$ the input impedance of the tag antenna, $Z_{\mathrm{c}}=R_{\mathrm{c}}+\mathrm{j}X_{\mathrm{c}}$ the impedance of the load, I the current flowing at the load. I and the consumption power of the load P_{c} is obtained from (6) and (7).

$$I = \frac{v_{\mathrm{o}}}{Z_{\mathrm{a}} + Z_{\mathrm{c}}} \quad (6)$$

$$P_{\mathrm{c}} = \mathrm{Re}\left\{Z_{\mathrm{c}} I I^*\right\} \quad (7)$$

Thus, the optimization problem is defined as (8).

$$kP_{\mathrm{c}} + \left(1 - \frac{S}{S_{\max}}\right) \rightarrow \max \quad (8)$$

where S is the antenna size and $S_{\max}$ the maximum size, and k in the first term is the weighting constant to balance the first and second terms.

When the effect of the second term in the objective function is negligible, the impedance matching between Z_a and Z_c would hold for the optimal antenna, that is, Z_a of the optimized antenna would be the complex conjugate of Z_c. Note that the input voltage v_o depends on the antenna structure in this problem.

D. Optimization method

We employ the GA for the optimization, whose processes are summarized as follows:

i. Generate N initial individuals randomly.
ii. Evaluate the objective function for each individual, and preserve the better three individuals for elite individuals.
iii. Test the stop criterion. If it is satisfied, stop the procedures.
iv. Make pairs by roulette selection, and apply the crossover operation to generate two children. The best one is a candidate of the descendent.
v. Apply the crossover and mutation to individuals with probabilities P_c and P_m.
vi. The elite individuals are transferred to the descendent population
vii. Back to step ii until the end criterion is satisfied.

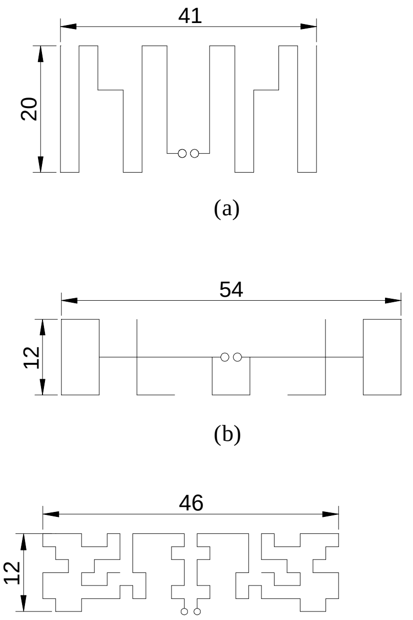
Here, the optimization parameters are set as follows: N=200, P_c=100%, P_m=3%, α=0.5 in BLX-α crossover operation and the maximum generation is 1500. To avoid convergence to local optima, 25% individuals are randomly generated every generation.

III. Optimization Result

We optimize the shape of MLA, PLA and SMLA respectively. The R/W transmits the electromagnetic wave at 956MHz and the power is 4WEIRP, which correspond to the legal frequency and power in Japan for RFID operation. The distance between the R/W and IC tags is assumed to be 7m. The power density and electric field intensity are 6.5mW/m^2 and 1.78V/m, respectively at the IC tag. We assume that the loaded impedance of IC tags is 30-j350 Ω, and the IC tag is attached on the glass-epoxy layer whose thickness is 1.6mm and relative permittivity 4.1.

Figure 4 shows the optimized antenna shapes which have the best performance in 10 random seeds, and TABLE I summarizes the mean properties, which includes the properties of half wavelength dipole for comparison.

In Table I it can be seen that the feeding powers of the



(a) (b) (c)

Fig. 4. Optimized antennas. (a) MLA. (b) PLA. (c) SMLA1. (unit: mm)

TABLE I

Properties and feeding power of antennas

	input impedance (Ω)	size (mm^2)	feeding power (μW)
h-dipole	73.1+j42.5	-	9.0
MLA	25.1+j350.9	820	96.7
PLA	28.9+j349.8	648	103.4
SMLA1	34+j344.0	567	94.2

optimized antennas are about ten times as great as that of the half wavelength dipole. This means that the communication distance can effectively be longer using the optimized antennas. The areas of the optimized PLA and SMLA are found to be smaller than that of the MLA.

They are significant advantages for wireless sensing in which long communication distance and size reduction are strongly required. The minimum power to operate IC chip used for typical IC tags ranges from a few to some tens μW. Thus the optimized antennas have enough performance for practical applications. It is concluded that the proposed optimization method can find small PLA and SMLA which can be advantageously used for the wireless sensing based on the RFID technology.

In addition to the above results, the optimization of SMLA is also found to yield very small antenna with area of 297 mm^2 shown in Fig. 5 which has 78.4 μW for the feeding power. Although this feeding power is a bit less than those of the optimized antennas shown in Fig. 4, this tiny antenna would be useful for IC tags which must be put on limited area. In contrast to SMLA, it is difficult to generate such small antennas comparable to the antenna shown in Fig.5 for MLA and PLA.

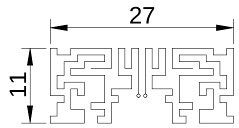


Fig. 5. Smallest SMLA obtained by optimization (unit: mm)

IV. Conclusion

Evolutional antenna design methods for wireless environmental or physical sensor devices based on passive RFID are proposed. Genotypes are introduced to generate shapes of PLA and SMLA for optimization based on GA. It is shown that the feeding powers of the optimized antennas are about ten times as great as that of the dipole antenna. The sizes of optimized PLA and SMLA are smaller than the optimized MLA. The optimization of SMLA can also yield a very small antenna whose area is about half of those of other optimized antennas.

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