

A novel expression for resonant length obtained by using artificial bee colony algorithm in calculating resonant frequency of C-shaped compact microstrip antennas

Ali AKDAĞLI^{1,*}, Mustafa Berkan BİÇER¹, Seda ERMİŞ²

¹Department of Electrical and Electronics Engineering,
Mersin University, Mersin-TURKEY

e-mails: akdagli@mersin.edu.tr, mbbicer@mersin.edu.tr

²Department of Electrical Engineering, University of Texas at Arlington,
Arlington, TX, USA
e-mail: sermis@iep.uta.edu

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Abstract

This paper presents a novel and simple expression for resonant length to calculate the resonant frequency of C-shaped compact microstrip antennas operating on UHF band applications. C-shaped compact microstrip antennas with different physical dimensions and electrical parameters were simulated by means of a software package that employs the method of finite difference time domain. With the aid of the artificial bee colony algorithm, an expression for the resonant length depending on physical dimensions was constructed by using simulation data. The resonant length expression provided less than 1.6% error on average over the simulated 144 antennas. A comparison between the results obtained in this work and previous results presented in the literature is given to show the accuracy of the proposed expression.

Key Words: *Artificial bee colony algorithm, compact microstrip antenna, microstrip antennas, resonant frequency*

1. Introduction

Microstrip antennas (MAs) have evolved from an academic novelty to a commercial reality with wide variety in microwave systems because of their attractive features, such as low profile, planar configuration, low cost, conformal structure, ease in fabrication, and integration with solid-state devices [1-6]. Although MAs have proven to be a significant advance in antenna technology, they suffer from a number of serious drawbacks, including very narrow bandwidth, poor crosspolarization, and low power handling capacity. Most of the studies on patch antennas proposed in the literature have concentrated on rectangular, triangular, and circular MAs, because of their regular shapes. Principally, markets in personal communication systems (PCS), mobile

*Corresponding author: Department of Electrical and Electronics Engineering, Mersin University, Mersin-TURKEY

satellite communication (MSC), direct broadcast television (DBS), wireless local area networks (WLANs), and other miniaturized communication systems demand a small-sized antenna. The size of a regularly shaped MA operating in the UHF band is relatively large. For this reason, conventional MA configurations need to be modified at these frequencies. A compact MA (CMA) with a C-shape may be used rather than the rectangular microstrip antenna (RMA) due to its being about half the size [3,7,8].

In analysis and design of CMAs, analytical techniques, such as the transmission line model [9] or cavity model [10], may not be directly used due to their irregular shapes. Theoretical studies related to CMAs are, therefore, based on experimental or simulation results in general [3,7,8,11-15]. Nowadays, electromagnetic simulation packages, which utilize numerical techniques such as the finite difference time domain (FDTD) method [16] and method of moment [17], have been widely used.

MAs can only operate effectively in the vicinity of the resonant frequency, and a significant disadvantage is that they have very narrow bandwidth, as mentioned above. Therefore, the calculation of resonant frequency is very important. The analysis of microstrip patches in points of resonant frequency is a complex problem because of the fringing fields at the edges. Several methods [3,7,8,11,14] varying in accuracy and simplicity have been presented in the literature for determining the resonant frequencies of CMAs with various shapes, including H, L, O, C, and arrows. In fact, the increasing use of MAs in electronic communication markets forces the use of simple methods for analyzing their performance. Therefore, the expression for resonant length, which can be readily used by the designer without any extensive background, has been considered in this work, and a simple expression in calculating the resonant frequency of a C-shaped CMA is proposed. The expression was extracted from simulation data, which belonged to 144 C-shaped CMAs operating in the UHF band. The XFDTD [18] software package, which uses the FDTD method, was used as an electromagnetic simulation tool. The FDTD model used in XFDTD for simulation of C-shaped CMAs was constructed to determine the resonant frequency. In the simulation, the antenna was assumed to be fed by a coaxial cable with 50 ohm near the center. The source waveform was chosen as Gaussian. The maximum cell size for the meshing process was set to 0.07 cm in a cubical region. Unknown coefficients given in the resonant length expression depending on physical dimensions were determined by the artificial bee colony (ABC) algorithm. The ABC algorithm, which simulates the intelligent foraging behavior of honeybee swarms, was recently introduced by Karaboga for numerical optimization problems [19]. Since the ABC algorithm is simple, robust, and uses few control parameters, we expect that it will gain popularity in a wide application area. The following section explains how the ABC algorithm works; further details can be found in [19-23].

2. Artificial bee colony (ABC) algorithm

Swarm intelligence has become a research interest to many scientists of related fields in recent years. The ABC algorithm [19-23] is one of the most recently defined algorithms among population-based optimization algorithms to find near-optimal solutions to difficult optimization problems by the motivation foraging behavior of honeybee swarms. In swarm intelligence, there are 2 fundamental concepts. These are self-organization and division of labor, which are necessary and sufficient properties to obtain intelligent swarm behavior, such as distributed problem-solving systems that self-organize and adapt to the given environment.

In the ABC algorithm, the colony of artificial bees contains 3 groups of bees: employed bees, onlookers, and scouts. Artificial bees fly around in a multidimensional search space. The employed bees associate with specific food sources depending on their experiences. The onlooker bees choose food sources based on watching

the dance of the employed bees within the hive and adjust their positions. The scout bees search for food sources randomly. The first half of the colony consists of the employed artificial bees and the second half includes the onlookers. The employed bee whose food source has been exhausted by the bees becomes a scout. Both onlookers and scouts are also called unemployed bees. Initially, all food source positions are discovered by scout bees. Thereafter, the nectar of food sources is exploited by employed bees and onlooker bees, and this continual exploitation will ultimately cause the food sources to become exhausted. The employed bee that was exploiting the now-exhausted food source then becomes a scout bee in search of further food sources. In the ABC algorithm, the position of a food source represents a possible solution to the problem, and the nectar amount of a food source corresponds to the quality (fitness) of the associated solution. For every food source, there is only one employed bee. In other words, the number of employed bees is equal to the number of food sources (solutions), since each employed bee is associated with only one food source around the hive.

The main steps of the algorithm are as follows.

Initialization phase: Send the scouts to the initial food sources

REPEAT

Employed bee phase: Send the employed bees to the food sources and determine their nectar amounts

Onlooker bee phase: Calculate the probability value of the sources that are preferred by the onlooker bees

Scout bee phase: Stop the exploitation process of the sources abandoned by the bees and send the scouts into the search area to discover new food sources randomly

Memorize the best solution achieved so far: Memorize the best food source found so far

UNTIL (Cycle = Maximum Cycle Number)

2.1. Initialization phase

In the first step, the ABC algorithm generates a randomly distributed initial population $P(G = 0)$ of SN solutions (food source positions), where SN denotes the size of the population. Each solution x_i is a D -dimensional vector scouted by bees. Here, D is the number of optimization parameters. Each food source, x_i , is a solution vector to the optimization problems that are to be optimized so as to minimize the objective function.

The following definition might be used for initialization purposes:

$$x_i^j = x_{\min}^j + \text{rand} [0, 1] \left(x_{\max}^j - x_{\min}^j \right), \quad (1)$$

where x_{\min}^j and x_{\max}^j are the lower and upper bounds of parameter x_i , respectively. Meanwhile, $i = 1, 2, \dots, SN$, and $j = 1, 2, \dots, D$. In our work, x_{\min}^j and x_{\max}^j were chosen as -2 and 2 , and SN and D were chosen as 20 and 4 , respectively.

2.2. Employed bee phase

After initialization, the population of the positions (solutions) was subjected to repeated cycles, $C = 1, 2, \dots, MCN$ (MCN : maximum number of cycles) of the search processes of the employed bees, onlooker bees, and scout bees. An employed bee produces a modification on position x_{ij} (solution) in its memory depending on the local information (visual information) and evaluates the profitability (fitness value) of the nectar amount

of the new food source v_{ij} (new solution). Provided that the nectar amount of the new source is greater than that of the previous one, the bee memorizes the new position and forgets the old one. Otherwise, it keeps the position of the previous one in its memory. The bees can determine a neighboring food source v_{ij} using the following equation:

$$v_{ij} = x_{ij} + \phi_{ij}(x_{ij} - x_{kj}), \quad (2)$$

where $k \in \{1, 2, \dots, SN\}$ and $j \in \{1, 2, \dots, D\}$ are randomly chosen indexes. Although k is determined randomly, it has to be different from i . ϕ_{ij} is a random number between -1 and 1 . It controls the production of neighboring food sources around x_{ij} and represents the comparison of 2 food positions visually by a bee. As can be seen from Eq. (2), as the difference between parameters x_{ij} and x_{kj} decrease, perturbation on position x_{ij} decreases, too. If the generated parameter value is out of the boundaries, it is shifted into the boundaries. Thus, as the search approaches the optimum solution in the search space, the step length is adaptively reduced.

After production of the new food source v_{ij} , its fitness is calculated and a greedy selection is applied between v_{ij} and x_{ij} . The fitness value of the solution, $fit_i(x_{ij})$, might be calculated for minimization problems using the following equation:

$$fit_i(x_{ij}) = \begin{cases} \frac{1}{1+f_i(x_{ij})} & \text{if } f_i(x_{ij}) \geq 0 \\ 1 + abs(f_i(x_{ij})) & \text{if } f_i(x_{ij}) < 0 \end{cases}, \quad (3)$$

where $f_i(x_{ij})$ is the objective function value of solution x_{ij} .

2.3. Onlooker bee phase

After all employed bees complete the search process, they share the nectar and position information of the food sources with the onlooker bees in the dance area. An onlooker bee evaluates the nectar information taken from all employed bees and probabilistically chooses a food source in relation to its nectar amount. An onlooker bee chooses a food source depending on the probability values calculated, using the fitness values provided by the employed bees. For this purpose, a fitness-based selection technique can be used, such as the roulette wheel selection method. Providing that the new source's amount of nectar is greater than that of the previous one, the bee memorizes the new position and forgets the old one.

The probability value p_i , with which x_{ij} is chosen by an onlooker bee, can be calculated by using the following expression:

$$p_i = \frac{fit_i(x_{ij})}{\sum_{n=1}^{SN} fit_n(x_{ij})}, \quad (4)$$

where fit_i is the fitness value of the solution, which is proportional to the nectar amount of the food source in position i , and SN is the number of food sources, which is equal to the number of employed bees.

2.4. Scout bee phase

The unemployed bees that choose their food sources randomly are called scouts. The abandoned food source is replaced with a new food source by the scouts. In the ABC algorithm, this is simulated by producing a position randomly and using it to replace the abandoned one. Providing that a position cannot be improved further through a predetermined number of cycles, then that food source is assumed to be abandoned. The value of the

predetermined number of cycles is an important control parameter of the ABC algorithm, which is called the “limit” for abandonment. The scout then discovers a new food source to replace x_{ij} . For instance, if solution x_{ij} has been abandoned, the new solution discovered by the scout who was the employed bee of x_{ij} can be defined by Eq. (1).

After each candidate source position v_{ij} is produced and evaluated by the artificial bee, its performance is compared with that of the old one. If the new food source has equal or better nectar than the old source, it replaces the old one in the memory. Otherwise, the old one is retained in the memory. In other words, a greedy selection mechanism is employed as the selection operation between the old and the candidate sources.

3. Problem formulation

The C-shaped CMA is constructed by cutting out a particular area ($l \times w$) from one of the sides of a RMA consisting of a patch of width W and length L , over a ground plane with a substrate of thickness h and a relative dielectric constant ϵ_r , as shown in Figure 1.

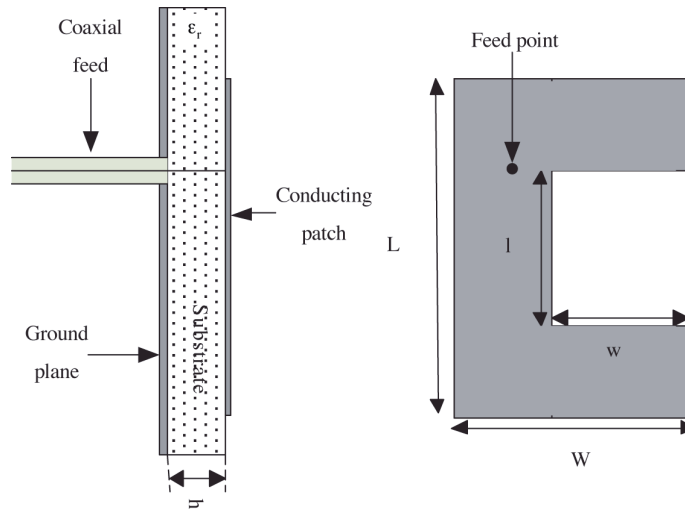


Figure 1. Configuration of a C-shaped CMA.

The resonant frequency of the RMA at dominant TM_{10} mode, which plays a fundamental role in radiations, is calculated as [3]:

$$f_r = \frac{c}{2L_{eff}\sqrt{\epsilon_{eff}}}, \quad (5)$$

where c is the velocity of electromagnetic waves in free space, ϵ_{eff} is the effective dielectric constant that takes into account the effects of the nonuniform medium, and L_{eff} is the effective resonant length given as [3]:

$$L_{eff} = L + 2\Delta L. \quad (6)$$

In the above equation, the fringing effects of the electric fields at the radiating edges of the rectangular patch are accounted for in terms of the extra linear edge extension dimension ΔL .

Because of the transformation from conventional RMA to C-shaped CMA, the resonant length should be modified to take into account the effect of the slot at the nonradiating side for TM_{10} mode. The resonant

frequency should be modified as well, and the resonant length of RMA, L , should yield to that of the C-shaped CMA, L_C . Thus, the equations given below can be used to compute the resonant frequency of the C-shaped CMA:

$$f_r = \frac{c}{2L_{Ceff}\sqrt{\epsilon_{eff}}}, \tag{7}$$

with

$$L_{Ceff} = L_C + 2\Delta L, \tag{8}$$

where L_{Ceff} is the effective resonant length of the C-shaped CMA. For the sake of simplicity, the well-known equations given below for the approximate effective dielectric constant expression, proposed by Schneider [24], and the edge extension, proposed by Hammerstad [25], can be used in Eq. (7) and in Eq. (8), respectively.

$$\epsilon_{r, eff} = \frac{\epsilon_r + 1}{2} + \frac{\epsilon_r - 1}{2} \left[1 + 10 \frac{h}{W} \right]^{-0.5} \tag{9}$$

$$\Delta L = 0.412h \frac{(\epsilon_{r, eff} + 0.3) \left(\frac{W}{h} + 0.264 \right)}{(\epsilon_{r, eff} - 0.258) \left(\frac{W}{h} + 0.8 \right)} \tag{10}$$

The main goal of this work was to introduce an expression for the resonant length (L_C) in calculating the resonant frequency of C-shaped CMAs to be operated at the UHF band; the particular numerical simulations were performed accordingly. The 144 antennas, whose patch dimensions and substrate dielectric constant values are tabulated in Table 1, were simulated by means of a software package called XFDTD [18].

Table 1. Physical and electrical parameters of simulated C-shaped CMAs ($\tan\delta = 0.001$).

| | Patch dimensions (cm) | | | | | ϵ_r | Number of simulations |
|------------------|-----------------------|-----|------------------|--------------------|------|-----------------|-----------------------|
| | L | W | l | w | h | | |
| Antenna group #1 | 3 | 2 | 0.7, 1.2, 1.5, 2 | 0.5, 0.7, 1.2, 1.5 | 0.16 | 2.33, 4.28, 9.8 | 48 |
| Antenna group #2 | 6 | 4 | 1.3, 2, 3, 4 | 0.9, 1.3, 2, 3 | 0.3 | 2.33, 4.28, 9.8 | 48 |
| Antenna group #3 | 9 | 6 | 2, 3, 4, 6 | 1.3, 2, 3, 4 | 0.6 | 2.33, 4.28, 9.8 | 48 |

As described in [3,7], the resonant length of a C-shaped CMA depends on the patch dimensions (L , W , l , and w). Therefore, a model for the resonant length depending on the patch dimensions was constructed by using the simulation data. To find a proper model for L_C , many simulations were carried out; the following expression, which produced satisfactory results, was constructed as:

$$L_C = \alpha_1(L + l) + \alpha_2l \left(\frac{l}{L} \right)^{\alpha_3} + \alpha_4w \left(\frac{w}{W} \right), \tag{11}$$

where the coefficients (α_1 , α_2 , α_3 , and α_4) are optimally determined with the use of the ABC algorithm for the purpose of minimizing the following total percentage error (TPE).

$$TPE = 100 \sum \left| \frac{f_{rs} - f_{rc}}{f_{rs}} \right| \tag{12}$$

Here, f_{rs} and f_{rc} are the simulated resonant frequency and calculated resonant frequency with the use of Eq. (11), respectively. In the optimization process with the ABC algorithm, the values of colony size, number of food sources, and limit were chosen as 20, 10, and 100, respectively.

It is worth noting that other resonant length models, both those simpler than and more complicated than the model given by Eq. (11), were also tried. It was observed that the results of simpler models were not in good agreement with the results of the simulations, and that the more complicated models provided only a little improvement in the results at the expense of the simplicity of expression.

Table 2 gives the coefficients found by the ABC algorithm.

Table 2. Coefficient values found by ABC algorithm for resonant length.

| Index | 1 | 2 | 3 | 4 |
|----------|-----|-------|------|---|
| α | 0.9 | -0.94 | 0.74 | 2 |

By substituting these coefficients into Eq. (11), the resonant length can be written as:

$$L_C = 0.9(L + l) - 0.94l \left(\frac{l}{L} \right)^{0.74} + 2w \left(\frac{w}{W} \right). \quad (13)$$

Consequently, for a given C-shaped CMA, the effective relative dielectric constant $\varepsilon_{r,eff}$ given by Eq. (9), the edge extension dimension ΔL given by Eq. (10), and the above expression obtained in this work were calculated, and the resonant frequency was then determined easily by Eq. (7).

4. Numerical results and discussion

C-shaped CMAs operating at the UHF band were simulated. The ranges of physical dimensions (in cm) and the electrical parameters of 144 antennas were $3 \leq L \leq 9$, $2 \leq W \leq 6$, $0.7 \leq l \leq 6$, $0.5 \leq w \leq 4$, $0.16 \leq h \leq 0.6$, and $2.33 \leq \varepsilon_r \leq 9.8$. By using the simulation data together with the ABC algorithm, a resonant length formula for calculation of the resonant frequency of a CMA was introduced in this work. Figure 2 shows the resonant frequencies obtained from the new resonant length expression and those of the simulated C-shaped CMAs. It is seen from Figure 2 that the calculated resonant frequency results were in very good agreement with the simulation results. As can also be seen from Figure 2, both simulated and calculated frequency values decreased with antenna number for the first and second antenna groups given in Table 1; however, for the third antenna group, the resonant frequency values increased and then continued on to decrease, since the relative dielectric constant value (ε_r) and length of the antenna (L) were more effective on the resonant frequency of the CMAs. The average percentage error for the simulated 144 antennas was found to be better than 1.6%. The firm agreement between our simulated and calculated results supports the accuracy of the resonant length expression proposed in this work.

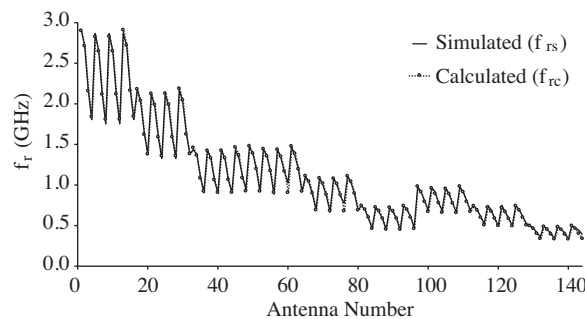


Figure 2. The simulated and calculated resonant frequency values.

To appraise the accuracy and validity of the new resonant length expression obtained by use of our simulation data of 144 C-shaped CMAs with different physical and electrical parameters, we compared our resonant frequency results with the simulation results reported elsewhere [7] and those calculated by previous analysis [7] in Table 3. It can be seen from Table 3 that the resonant frequency formulation presented in this work provides accurate results in general, and the resonant frequency results previously published in the literature [7], which were obtained by using the 3 suggestions in accordance with slot dimensions of C-shaped CMA, are in good agreement with the simulation results in some cases, while others are far off. Nevertheless, our formulation for a C-shaped CMA is more convenient compared to those reported in [7], because it allows us to calculate the resonant length with a simple expression for whole slot dimensions.

Table 3. Comparisons of simulated and calculated resonant frequencies ($L = 6$ cm, $W = 4$ cm, $h = 0.159$ cm, $\epsilon_r = 2.33$, $\tan \delta = 0.001$).

| Slot dimensions (cm) | | Resonant frequencies (GHz) | | | | | Percentage errors (%) | | | |
|----------------------|-----|----------------------------|------------|-------|-------|-------|-----------------------|--------|--------|--------|
| | | Simulated | Calculated | | | | | | | |
| l | w | [7] | This study | [7] | | | This study | [7] | | |
| | | | | #1 | #2 | #3 | | #1 | #2 | #3 |
| 0.5 | 0.5 | 1.562 | 1.657 | 1.502 | 1.630 | — | 6.090 | 3.841 | 4.353 | — |
| 1 | 1 | 1.445 | 1.497 | 1.398 | 1.408 | — | 3.577 | 3.253 | 2.561 | — |
| 1.5 | 1.5 | 1.286 | 1.334 | 1.309 | 1.241 | — | 3.729 | 1.788 | 3.499 | — |
| 2 | 2 | 1.130 | 1.178 | 1.231 | 1.111 | 1.002 | 4.258 | 8.938 | 1.681 | 11.327 |
| 2.5 | 2.5 | 0.991 | 1.035 | 1.164 | 1.008 | 0.928 | 4.442 | 17.457 | 1.715 | 6.357 |
| 4 | 3 | 0.899 | 0.924 | — | 0.893 | 0.856 | 2.759 | — | 0.667 | 4.783 |
| 0.5 | 3 | 0.929 | 0.963 | — | 1.029 | 0.904 | 3.625 | — | 10.764 | 2.691 |
| 1 | 3 | 0.887 | 0.938 | — | — | 0.896 | 5.746 | — | — | 1.015 |
| 0.2 | 3 | 0.964 | 0.982 | — | — | 0.910 | 1.917 | — | — | 5.602 |

Note that, in the simulation process, it was observed the slot width (w), rather than slot length (l), significantly affected the resonant length, and hence the resonant frequency. An increase in w resulted in a decrease in resonant frequency. Thus, increasing slot width w is an effective way to reduce the antenna size. On the other hand, the increase of the slot dimension to reduce the antenna size also gives rise to the degradation of other performances, such as efficiency and bandwidth, as stated in [3]. Therefore, the antenna designer should make a trade-off between the reduction in size and better performances. In future work, we plan to utilize techniques that increase some performances, such as bandwidth and efficiency, by using measurement results of C-shaped CMAs.

5. Conclusion

In this study, a new and simple expression for the resonant length, which yields better accuracy in the resonant frequency of C-shaped CMAs, was proposed and 144 antennas with different patch dimensions and varied substrate dielectric constant values were simulated. Utilizing the simulated data together with the ABC algorithm, which is one of the most recently introduced swarm-based algorithms, an expression was obtained. The simulated CMAs operate over the frequency range of 0.332-2.92 GHz, and hence they are suitable for

UHF band applications in which small size is required. The resonant frequencies resulting from the formulation presented in this work were compared with the simulation results and also with results obtained from the previous method reported in the literature. The proposed expression is easy to compute and will offer the design engineer an accurate estimation of resonant frequency.

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