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DERVİŞ KARABOĞA

KERİM GÜNEY

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A Simple Formula Obtained Using Tabu Search Algorithm for the Radiation Efficiency of a Resonant Rectangular Microstrip Antenna

Derviş Karaboğa, Kerim Güney
Department of Electronic Engineering,
Engineering Faculty, Erciyes University,
38039, Kayseri-TURKEY

Abstract

A new simple formula for the radiation efficiency of a resonant rectangular microstrip patch antenna is presented. The formula is obtained by using a tabu search algorithm, which is a quite new optimization technique based on the principles of intelligent problem solving. The formula is valid for substrates with relative permittivities between 1 and 12.8 and for the complete range of thicknesses normally used. The results obtained by using this new simple formula are in conformity with those reported elsewhere. The formula can also be used in the calculation of the radiation efficiency of dipoles.

Key words: *Microstrip antenna, rectangular, radiation efficiency, tabu search*

1. Introduction

In recent years, microstrip antennas have aroused great interest in both theoretical research and engineering applications due to their low profile, light weight, conformal structure, low cost, reliability, and ease in fabrication and integration with solid-state devices [1-5].

An efficient use of microstrip antennas requires a knowledge of radiation efficiency, which relates the power radiated in space waves to the total radiated power (including surface waves). The surface waves exist due to the interface between air and the dielectric substrate that separates the radiating element from the ground plane. For infinitely long and lossless structures, the surface wave propogates and attenuates in the directions parallel and perpendicular to the interface, respectively. Surface wave power launched in an infinitely wide substrate would not contribute to the main beam radiation and so can be treated as a loss mechanism. In general, if the thickness of the substrate on which the antenna is etched is very small compared to the wavelength of interest, the power propagated via the surface wave modes is negligible, so that the effects of the substrate on the efficiency may be ignored. However, for an antenna radiating at the resonance of higher-order modes, the radiation efficiency decreases as some power propagates via surface wave modes. Moreover, unwanted radiation results when the surface wave encounters a discontinuity (e.g., the edge of the substrate). As a surface wave reaches the antenna's edge, it is scattered, producing both a reflected surface wave and a radiated wave. The presence of secondary sources of radiation on the dielectric edges proved most troublesome in practice, as it contributes to secondary lobes and to cross-polarized radiation. A large surface wave excitation also causes an undesirable energy coupling between elements of an array or between adjacent arrays.

Surface wave effect has been determined by a number of investigators [6-20]. Uzunoğlu et at. [6] determined the radiation efficiency of dipoles by employing a dyadic Green's function for a Hertzian dipole printed on a grounded substrate together with an assumed current and distribution. James and Henderson [7] estimated that surface wave excitation is not important if $h/\lambda_0 < 0.09$ for $\epsilon_r \cong 2.3$ and $h/\lambda_0 < 0.03$ for $\epsilon_r \cong 10$, where h is the thickness of the dielectric substrate and λ_0 is the free-space wavelength. The criterion presented by Wood [9] is more quantitative: $h/\lambda_0 < 0.07$ for $\epsilon_r = 2.3$ and $h/\lambda_0 < 0.023$ for $\epsilon_r = 10$ if the antenna is to launch no more than 25% of the total radiated power as surface waves.

The most important of the results published is by Pozar [11]. He presented radiation efficiency against normalized substrate thickness. The radiation efficiency data were calculated with a moment method solution of a printed rectangular radiating element on a grounded dielectric slab. The moment method solution uses the rigorous dyadic Green's function for the grounded dielectric slab, and so includes the exterior fields, making calculations for surface wave excitation and mutual coupling possible. It was found by Pozar that the surface wave excitation is generally not important for thin substrates, normally of the order of $h < 0.01\lambda_0$. An interesting observation in Pozar [11] was the similarity between the radiation efficiency for the dipole and the patch. It was also shown that the radiation efficiency does not depend on the feed location of the dipole or the patch, or on the patch width W.

An approach to the analysis of microstrip antennas that is applicable also to relatively thick substrates using the relevant Green's function was presented by Perlmutter et al. [13]. This approach resembles the method used by Uzunoğlu et al. [6] and Van der Paw [21] for various other problems. A certain current distribution was assumed along the upper conductor, which is typical of the geometry of the element. The current in the radiating element was obtained by cavity or equivalent transmission line models. The surface wave excitation was then found from the assumed currents by the appropriate Green's function in the Fourier domain. It has been shown [13] that increasing h causes a larger fraction of the power to be coupled into surface waves. But this fraction is independent of the patch width W to a very good approximation.

Mosig and Gardiol [14] presented the dynamic analysis of microstrip structures. It was shown that the mixed-potential integral equation for stratified media provides a rigorous and powerful approach. The Green's functions belonging to the kernel of the integral equation were expressed as Sommerfeld integrals, in which surface wave effects are automatically included.

Bhattacharyya and Garg [16] proposed a general approach for the determination of power radiated via the space wave and surface wave from the aperture of an arbitrarily shaped microstrip antenna. The magnetic current model has been used for this, and the analysis has been carried out in the Fourier domain to determine the effect of the substrate. It has been observed that for $h/\lambda_d < 0.02$, where λ_d is the wavelength in the substrate, the effect of surface waves can be ignored. The results obtained by Bhattacharyya and Garg [16] confirmed the results obtained by Pozar [11], but they did not provide extra material.

In Jackson and Alexopoulos [18], an approximate formula for the radiation efficiency of a resonant rectangular microstrip patch has been derived. They derived this formula from approximations of a rigorous Sommerfeld solution, and it was not empirical. They showed that the radiation efficiency decreases much more rapidly with increasing substrate thickness when a magnetic substrate is used, and that for $h/\lambda_o \geq 0.05$ the radiation efficiency results calculated from the approximate formula are not in very good agreement with the exact results obtained from a rigorous Sommerfeld solution.

From the studies cited above we see that the certain way of calculating the radiation efficiency of rectangular microstrip antennas involves the complicated Green's function methods and integral transformation techniques.

Tabu search, which is one of the modern heuristic optimization procedures, is a quite new and promising optimization algorithm for difficult problems [22-24]. It has the ability of getting out of local minima and finding global optimal solutions for multimodal problems in a reasonable time although the traditional optimization algorithms fail to produce global optimal solution for such problems. This optimization algorithm has been succesfully applied for several engineering problems from different areas [25-28]. In a previous work [28], we introduced an effective side length expression for the resonant frequency of triangular microstrip antennas. This effective side length expression was obtained efficiently by a modified tabu search algorithm.

From the previous works on the radiation efficiency it is seen that the relation between the radiation efficiency and the characteristic parameters h/λ_0 and ϵ_r is quite complex. Therefore, in order to produce an accurate model for this relation, a powerful optimisation algorithm is required. In this work, a new simple formula for the radiation efficiency of rectangular microstrip antennas is optimally obtained by the tabu search algorithm. This formula explicitly shows the dependence of the radiation efficiency on the characteristic parameters of a patch antenna. Thus, the radiation efficiency of rectangular microstrip antennas can be accurately and easily calculated by the proposed formula without the need for complicated Green's function methods or integral transformation techniques. The results obtained from this formula are in very good agreement with the results available in the literature even when $h(\epsilon_r)^{1/2}/\lambda_0$=0.31.

2. Radiation Efficiency of Rectangular Microstrip Antennas

Consider a rectangular 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. The radiation efficiency due to surface waves is defined as follows

$$\eta = \frac{P_{sp}}{P_{sp} + P_{su}} \tag{1}$$

where P_{sp} is the power radiated in space waves and P_{su} is the power radiated in surface waves. $P_{sp} + P_{su}$ is then the total power delivered to the printed antenna element. Although P_{sp} is easily found, P_{su} must be obtained by complicated Green function methods.

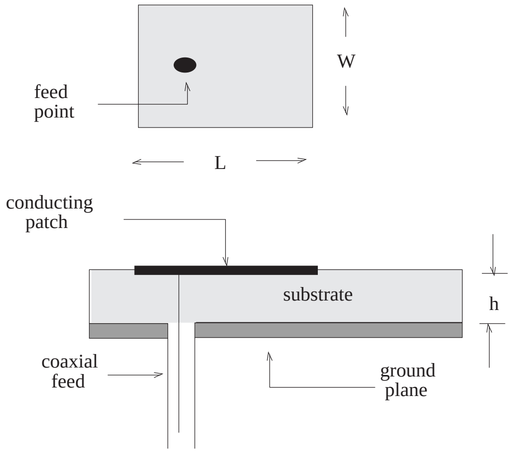

Figure 1. Geometry of rectangular microstrip antenna

In this study, in order to determine the radiation efficiency of a rectangular microstrip antenna we will concentrate on the radiation efficiency results reported by Pozar [11], Perlmutter et al. [13] and Bhattacharyya and Garg [16], because their results agree with those presented by other scientists in the literature. The results calculated by Pozar [11] using a moment method approach for a substrate with relative permittivity ϵ_r=12.8 are given in Figure 2. The peak in the curve can be practically taken as linear to the point where the TE_1 mode can propagate. The results calculated by Perlmutter et al. [13] using the electric surface current model are presented in Figures 3-5 for ϵ_r=2.2, 4.0, and 9.8. In Figure 6, the results of the magnetic current model proposed by Bhattacharyya and Garg [16] for ϵ_r=2.55 are given. From the plots we see that as the thickness increases, the radiation efficiency decreases. This is due to the fact that as the thickness increases, the surface wave power increases and power via the space wave is reduced. The curves also indicate that a lower value of ϵ_r results in a higher efficiency. From Figures 2-3 and 5 one can also easily see that the width W of the patch has almost no effect on the value of η: the difference between the η-values for a patch (dotted curve) and a dipole (broken curve) is less than 0.02 for ϵ_r=2.2, and nearly zero for ϵ_r=12.8. As we are only interested in resonant antennas, the physical length L of the patch is not of importance; it is determined by

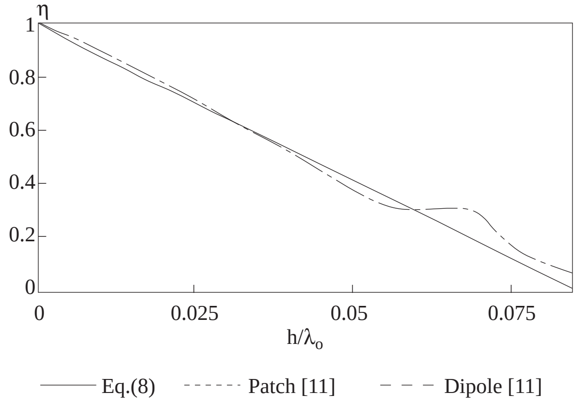

Figure 2. Radiation efficiency for patch antenna and dipole on substrate with ϵ_r=12.8

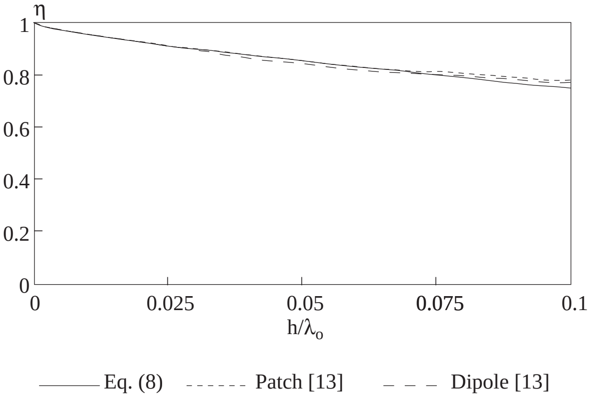

Figure 3. Radiation efficiency for wide and narrow patch antenna on substrate with ϵ_r=2.2

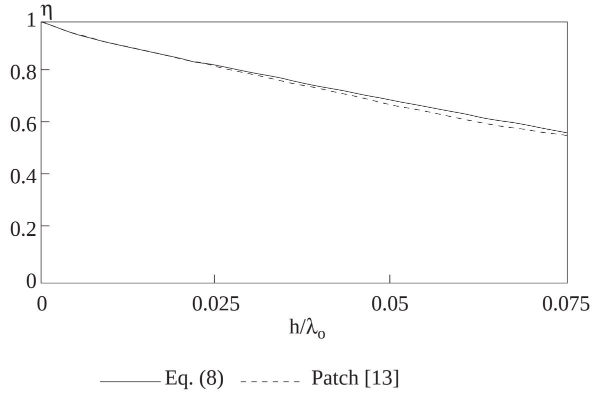

Figure 4. Radiation efficiency for wide patch antenna on substrate with ϵ_r =4.0

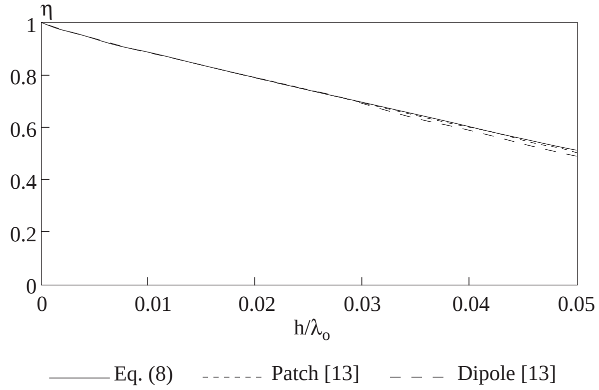

Figure 5. Radiation wave efficiency for wide and narrow patch antenna on substrate with ϵ_r =9.8

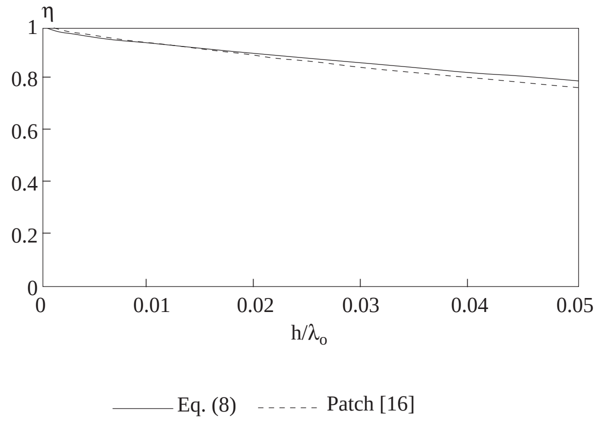

Figure 6. Radiation wave efficiency for wide patch antenna on substrate with ϵ_r =2.55

$$L = \frac{c}{2f_r\sqrt{\epsilon_e}} - 2\Delta L \tag{2}$$

where c is the velocity of electromagnetic waves in free space, ϵ_e is the effective relative dielectric constant for the patch, f_r is the resonant frequency, and ΔL is the edge extension. ϵ_e and ΔL depend on ϵ_r, h and W. Thus, the length L is determined by W, h, ϵ_r and f_r. Therefore, only two parameters are needed to describe the radiation efficiency: ϵ_r and h/λ_0.

The problem in the literature is that a formula as simple as possible for the calculation of the radiation efficiency must be obtained, but the results obtained by the formula must be in good agreement with the results produced by the complicated methods requiring large computing time, such as Green function methods or integral transformation techniques. In this work, a new simple formula obtained by the tabu search algorithm is presented to compute the radiation efficiency. First, a model for the formula is chosen and then the unknown coefficients of the model are optimally found by the tabu search algorithm. This new formula provides a faster solution and enables ease of implementation for the radiation efficiency calculation.

In the following sections, the tabu search algorithm used in this paper and the application of the tabu search to the problem are described briefly.

3. Tabu Search Algorithm

Tabu search is a general heuristic search procedure devised for finding a global minimum of a function, which may be linear or non-linear [26-27]. The modern version of the algorithm was developed by Glover [22-24]. It has a flexible memory to retain the information about the previous steps of the search, using it to create and exploit new solutions in the search space. A step of tabu search starts with a present solution x_{now} having an associated set of feasible solutions Q, which can be obtained by applying a simple modification to x_{now}. This modification is called a *move.* In order to avoid a local minima in search space, the move to $x^\star$ is applied even if $x^\star$ is worse than x_{now}. However, this can cause the cycling of the search. To avoid cycling as much as possible, a tabu list is introduced. The tabu list stores all tabu moves that are not permitted to be applied to the present solution. The moves stored in the tabu list are those carried out most frequently and recently. Therefore, in order for a move to be classified as tabu or not, criteria called *tabu restrictions* are employed. The use of a tabu list decreases the possibility of cycling because it prevents the return within a certain number of iterations to a solution visited recently. After a subset of feasible solutions, $Q^\star$, are produced according to the tabu list and evaluated for the problem, the next solution is selected from $Q^\star$ and the tabu list is updated. The solution evaluated as best is selected as the next solution x_{next}. This loop is repeated until a specified stopping criteria is satisfied.

The tabu search employed in this work had two tabu restrictions, which were based on recency and frequency memories:

$$\begin{aligned} \text{recency}(x^\star) >\, &= \text{recency limit} \\ \text{frequency}(x^\star) <\, &= \text{frequency limit} \end{aligned} \tag{3}$$

The recency of a move is the difference between the current iteration count and the last iteration count at which that move was made. The frequency measure is the count of changes of the move.

Tabu restrictions might prevent the search from moving a solution that has not been visited yet, or they might even sometimes cause all available moves to be classified as tabu. For these reasons, the tabu restrictions should be ignored when a freedom is required. An *aspiration* criterion is employed to determine which move should be freed in such cases. In the tabu search used in this work, the following aspiration criterion was employed when all available moves are classified tabu: a tabu move that loses its tabu status by the least increase in the value of current iteration is freed from the tabu list.

4. Application of Tabu Search to the Problem

As mentioned earlier, firstly a model is selected for the formula of the radiation efficiency. In order to find the proper model for the radiation efficiency formula, many experiments were carried out in this work. After many trials, the following model was chosen:

$$\eta = 1 + \alpha_1 F^{\alpha_2} G^{\alpha_3} \epsilon_r^{\alpha_4} + \alpha_5 F^{\alpha_6} G^{\alpha_7} \epsilon_r^{\alpha_8} \tag{4}$$

where $F = (\epsilon_r - 1)$ and $G = h/\lambda_0$. It is clear from Eq.(4) that the model depends on ϵ_r and h/λ_0 only as discussed in section 2. The unknown coefficients $\alpha_1 \ldots \alpha_i \ldots \alpha_8$ in Eq.(4) are optimally determined by the tabu search algorithm. The term F in Eq.(4) assures that η=1 for an air dielectric.

A solution is represented in the string form of 8 real numbers (coefficients values) and has an associated set of neighbors. The initial solution used by the tabu search at the start consists of randomly produced coefficient values. Coefficients can have positive or negative values between -5 and 5. A neighbor of the present solution is produced by the addition of a randomly generated number between -1 and 1 to a non-tabu coefficient of the present solution. Hence, at each iteration the maximum number of neighbors to be produced is 8. The recency and the frequency limits used in this work for tabu restrictions in Eq.(3) are

$$\begin{aligned} \text{recency limit} &= 0.75 \times \text{number of coefficients} \\ \text{frequency limit} &= 1.5 \times \text{average frequency} \end{aligned} \tag{5}$$

where average frequency is the average change of all coefficient values.

In order to calculate the performance of a neighbor, first the formula Eq.(4) is established with the coefficient values obtained from the neighbor $x^\star$. Second, η is computed by this formula for the three different values of ϵ_r and a predetermined interval of (h/λ_0). Next, the performance of the neighbor is calculated by the following formula:

$$p(x^\star) = A - (1/N) \sum_{j=1}^{N} (\eta_t(j) - \eta(j))^2 \tag{6}$$

where A is a positive constant selected large enough so that the p value is positive for all possible solutions, N is the total number of efficiency values employed for the optimization process, and η_t and η represent, respectively, the radiation efficiency values obtained by the well-known complicated Green function methods [11, 13] and by the formula Eq.(4) established with the coefficient values produced from the neighbor $x^\star$.

Lastly, the performance values of all neighbors are compared and the neighbor that produces the maximum performance is selected as the next solution. This process is repeated until a given stopping criterion such as iteration number is satisfied.

5. Simulation Results and Discussion

In the optimization process, the data sets obtained from the well-known complicated methods [11, 13] for different dielectric permittivities and substrate thicknesses were used. In the test stage, η was computed by the proposed formula obtained using the tabu search algorithm for unseen data sets in the optimization stage.

One hundred seven data sets consisting of $\epsilon_r, h/\lambda_0$ and η_t values used for the optimization process were generated from the moment method approach [11] for ϵ_r=12.8 and from the electric surface current model [13] for ϵ_r=2.2 and 4.0.

The tabu search algorithm was run for 400 iterations and the following optimum values for the unknown coefficients of the model given in Eq.(4) were found:

$$\begin{aligned} \alpha_1 = -3.66 \quad \alpha_2 = 1.83 \quad \alpha_3 = 1.06 \quad \alpha_4 = -1.32 \\ \alpha_5 = -2.48 \quad \alpha_6 = 2.48 \quad \alpha_7 = 0.5 \quad \alpha_8 = -3.12 \end{aligned} \tag{7}$$

The following radiation efficiency formula is then obtained by substituting the coefficient values given by Eq.(7) into Eq.(4):

$$\eta = 1 - 3.66F^{1.83}G^{1.06}\epsilon_r^{-1.32} - 2.48F^{2.48}G^{0.5}\epsilon_r^{-3.12} \tag{8}$$

Figures 2-4 show the optimization results. The solid curves in these figures represent the results obtained by using Eq.(8). It can be clearly seen from Figures 2-4 that the results of the proposed formula were similar to the results of moment method [11] and Green function method [13].

In order to test the proposed radiation efficiency formula Eq.(8), the results of the electric surface current model [13] for ϵ_r=9.8 and the magnetic current model [16] for ϵ_r=2.55 with different substrate thicknesses, which are not used in the optimization process, are compared with the results of Eq.(8) in Figures 5 and 6, respectively. It is very apparent from Figures 5 and 6 that the radiation efficiency for wide and narrow patch antennas on subsrates with different substrates thicknesses is computed with high accuracy.

Both the optimisation and test results illustrate that the performance of the formula is quite robust and precise. The results of the proposed formula are compared with those of Pozar [11], Perlmutter et al. [13], and Bhattacharyya and Garg [16], and the error is within 0.023, which is tolerable for most design applications.

We also used the data sets for ϵ_r=2.2, 9.8 and 12.8 in the optimisation process and the data sets for ϵ_r=4.0 and ϵ_r=2.55 in the test process. In this case, the same model given in Eq.(4) was chosen and different coefficient values were found. It was observed that the results obtained are in good agreement with the results of the moment method [11], the Green function method [13] and the magnetic current model [16].

It also must be emphasized once more that more accurate results can be obtained with higher order models than that in Eq.(4), at the expense of the simplicity of the formula. However, it seems practical to use such a simple formula as Eq.(8) that lends insight into the dependence of the radiation efficiency upon the various parameters such as thickness h and relative dielectric constant ϵ_r. In spite of its simplicity, the formula provides quite accurate results in many cases.

As the difference between radiation efficiency for the dipoles and patches is always less than 0.02, the proposed formula Eq.(8) can also be used for dipoles.

Since the formula presented in this work has high accuracy in the range of $1 \leq \epsilon_r \leq$12.8 and $0 < h/\lambda_d \leq$0.31 and requires no complicated mathematical functions, it can be very useful for the development of fast CAD algorithms. Using this formula, one can calculate the radiation efficiency of rectangular patch antennas by hand calculator, without possessing any background knowledge of microstrip antennas. For engineering applications, the simple formulas are very usable. Thus the formula given by Eq.(8) can also be used for many engineering applications and purposes.

6. Conclusions

A new simple formula is presented for the radiation efficiency of a rectangular microstrip antenna. It is optimally obtained by the tabu search algorithm and only depends on h/λ_0 and ϵ_r. The good agreement between the results produced from the proposed formula and the Green function, moment and magnetic current methods supports the validity of the formula. It is valid for dipoles and patches, and useful for substrates with relative permittivities between 1 and 12.8 and for the complete range of thicknesses normally used. It also provides insight into the fundamental influence of the substrate parameters on the radiation efficiency. We expect that the tabu search algorithm and the proposed formula will find wide application in high frequency printed antennas, especially at the millimeter wave frequency range.

References

[1] Bahl, I. J. and Bhartia, P., *Microstrip Antennas,* Artech House, Dedham, MA, 1980.

[2] Carver, K. R. and Mink, J. W., "Microstrip Antenna Technology", *IEEE Trans. Antennas Propagat.,* Vol. AP-29, Jan. 1981, pp. 2-24.

[3] James, J. R. and Hall, P. S., *Handbook of Microstrip Antennas*, IEE Electromagnetic Wave Series No. 28, Peter Peregrinus Ltd, London, 1989, Vols. 1 and 2.

[4] Lo, Y. T., Wright, S. M. and Davidovitz, M., "Microstrip Antennas", in K. Chang (Ed.), *Handbook of Microwave and Optical Components* (Vol. 1), New York, Wiley, 1989, pp. 764-889.

[5] Zürcher, J. F. and Gardiol, F. E., *Broadband Patch Antennas,* Artech House, 1995.

[6] Uzunoğlu, N. K., Alexopoulos, N. G. and Fikioris, J. G., "Radiation Properties of Microstrip Dipoles", *IEEE Trans. Antennas Propagat.,* Vol. AP-27, Nov. 1979, pp. 853-858.

[7] James, J. R. and Henderson, A., "High-frequency Behaviour of Microstrip Open-circuit Terminations", *IEE J. Microwaves, Optics, and Acoustics,* Vol. 3, 1979, pp.205-218.

[8] Lo, Y. T., Solomon, D. and Richards, W. F., "Theory and Experiment on Microstrip Antennas", *IEEE Trans. Antennas Propagat.,* Vol. AP-27, March 1979, pp. 137-145.

[9] Wood, C., "Analysis of Microstrip Circular Patch Antennas", *IEE Proc. Pt. H,* Vol. 128, 1981, pp. 69-76.

[10] Rana, I. E. and Alexopoulos, N. G., "Current Distribution and Input Impedance of Printed Dipoles", *IEEE Trans. Antennas Propagat.,* Vol. AP-29, Jan. 1981, pp. 99-105.

[11] Pozar, D. M., "Considerations for Millimeter Wave Printed Antennas", *IEEE Trans. Antennas Propagat.,* Vol. AP-31, Sept. 1983, pp. 740-747.

[12] Mosig, J. R. and Gardiol, F. E., "Dielectric Losses, Ohmic Losses and Surface Wave Effects in Microstrip Antennas", in *Int. U.R.S.I. Symposium*, Santiago de Compostela, Aug. 1983, pp. 425-428.

[13] Perlmutter, P., Shtrikman, S. and Treves, D., "Electric Surface Current Model for the Analysis of Microstrip Antennas with Application to Rectangular Elements", *IEEE Trans. Antennas Propagat.,* Vol. AP-33, March 1985, pp. 301-311.

[14] Mosig, J. R. and Gardiol, F. E., "General Integral Equation Formulation for Microstrip Antennas and Scatterers", *IEE Proc. Pt.H,* Vol. 132, Dec. 1985, pp. 424-432.

[15] Roudot, B., Terret, C., Daniel, J. P., Pribetich, P. and Kennis, P., "Fundamental Surface-wave Effects on Microstrip Antenna Radiation", *Electron. Lett.,* Vol. 21, 1985, pp. 1112-1114.

[16] Bhattacharyya, A. K. and Garg, R., "Effect of Substrate on the Efficiency of an Arbitrarily Shaped Microstrip Patch Antenna", *IEEE Trans. Antennas Propagat.,* Vol. AP-34, Oct. 1986, pp. 1181-1188.

[17] Nauwelaers, B. and Van De Capelle, A., "Surface Wave Losses of Rectangular Microstrip Antennas", *Electron. Lett.,* Vol. 25, May 1989, pp. 696-697.

[18] Jackson, D. R. and Alexopoulos, N. G., "Simple Approximate Formulas for Input Resistance, Bandwidth, and Efficiency of a Resonant Rectangular Patch", *IEEE Trans. Antennas Propagat.,* Vol. AP-39, March 1991, pp. 407-410.

[19] Güney, K., "Space-wave Efficiency of Rectangular Microstrip Antennas", *Int. J. of Electronics,* Vol. 74, 1993, pp. 765-769.

[20] Güney, K., "Space-wave Efficiency of Electrically Thick Circular Microstrip Antennas", *Int. J. of Electronics*, Vol. 78, 1995, pp. 571-579.

[21] Van der Paw, L. J., "The Radiation of Electromagnetic Power by Microstrip Configurations", *IEEE Trans. Microwave Theory Tech.,* vol. MTT-25, 1977, pp. 719-725.

[22] Glover, F., "Future Paths for Integer Programming and Links to Artificial Intelligence," *Computers and Operation Research*, Vol. 13, 1986, pp. 533-549.

[23] Glover, F., "Tabu Search-part I," ORSA *Journal on Comput.* Vol.1, 1989, pp. 190-206.

[24] Glover, F., "Tabu Search-part II," ORSA *Journal on Comput.,* Vol.2, 1990, pp. 14-32.

[25] Reeves, C. R., *Modern Heuristic Techniques for Combinatorial Problems,* McGraw-Hill Book Company, Maidenhead, Berkshire, SL6 2QL, 1995.

[26] Karaboga, D. and Kalinli, A., "Tuning PID Controllers Using Tabu Search Algorithm", *IEEE Int. Conf. on Systems, Man and Cybernetics*, Beijing, China, 1996, pp.134-136.

[27] Karaboga, D., "Design of Fuzzy Logic Controllers Using Tabu Search algorithm", *Biennial Conf. of the North American Fuzzy Information Processing Society-NAFIPS*, Berkeley, California, USA, 1996, pp. 489-491.

[28] Karaboga, D., Güney, K., Kaplan, A. and Akdaglı, A., "A new effective side length expression obtained using a modified tabu search algorithm for the resonant frequency of a triangular microstrip antenna", *Int. Journal RF. and Microwave CAE,* Vol. 8, 1998, pp. 4-10.