Optimizing Multiband Antennas Using Simulated Annealing

Mudrik Alaydrus and Thomas F. Eibert

Abstract— **The increasing demand for wireless communication services makes it necessary to use several frequency bands with a single device such as a mobile phone or a laptop computer. Consequently, antenna functionalities must be available in the various frequency bands and the ideal case is to have a single multiband antenna, which works at the desired frequencies. The design of multiband antennas is a challenging problem and in this work, Simulated Annealing is used as a powerful optimization method, which controls the design flow of such antennas. In order to evaluate the antenna characteristics of the various antenna realizations within the design process, a powerful Integral Equation Technique accelerated by the Multilevel Fast Multipole Method is used.**

Keywords— **Antenna, dualband antenna, Integral equation technique, multiband antenna, optimization, Simulated Annealing, triband antenna**

I. Introduction

THE need of the mankind to communicate with and to exchange information to each other, fuels the development of various communication technologies, components and especially applications. Most of the communication applications or systems often differ in frequencies from each other. In recent time, there are several communication components developed for different frequencies, including antennas. Antennas become one of the most important components in today modern communication systems. As an essential part in wireless communication, antennas play a significant role for getting the overall performance of the system. By designing an antenna, there are several characteristics to be met, such as the gain, the radiation pattern and the input impedance over a certain frequency interval [Balanis,1998]. In order to predict these important characteristics, several calculation methods are available, so that we have an approximation at hand before fabricating the antenna structure and measuring these quantities. All computation methods are based on the most general representation of electromagnetic phenomena, the Maxwell's equations [Balanis,1989]. In this work, we apply an Integral Equation Method (e.g. see [Rao,1982]), which can be accelerated by the Multilevel Fast Multipole Method (MLFMM) (e.g. [Eibert,2005]) to a small group of planar antennas in order to gain some new results and understanding for helping antenna engineers to design their components.

The advances of telecommunication systems, forced by the increasing demand in communication channel [Benksy,2004], [Olexa,2005], require sophisticated antenna characteristics, like broadband behaviors and sometimes multiband performances [Liu,2003], [Martinez,2003], [Ang,2003], [Nepa,2004].

It is therefore recommended to design antennas with those characteristics by applying an optimization method [Rao,1996]. Optimization is a process to finding an optimum, which can be complicated if there are several goals and constraints to be met and there are several parameters to be varied. The well-known Simulated Annealing Technique is a so-called global optimization method. With this method, we can get out from the 'local minimum-traps' [Aarts,1989] by allowing to accept conditions with higher costs.

In this work, we design antennas with several demands and characteristics by combining the Integral Equation Method and Simulated Annealing.

II. Simulated Annealing Controlled Integral Equation Method

A. Review of Surface Integral Equation Method

For the solution of the antenna problem with open conducting bodies, the electric field integral equation (EFIE) is used. EFIE couples the incident elelctric fields to the induced surface current density and is given by [Eibert,2005]

$$\hat{n} \times \left[\hat{n} \times \left(\iint_A \left[\bar{\boldsymbol{G}}_J^E(\boldsymbol{r}, \boldsymbol{r'}) \cdot \boldsymbol{J}_A(\boldsymbol{r'}) \right] da' + \boldsymbol{E}^{inc}(\boldsymbol{r}) \right) \right] = 0 \,, \quad (1)$$

where A is the surface of the scattering or radiation object and $\boldsymbol{J}_A(\boldsymbol{r'})$ is the unkown surface current density. $\bar{\boldsymbol{G}}_J^E(\boldsymbol{r}, \boldsymbol{r'})$ is the free space dyadic Green's function given by

$$\bar{\boldsymbol{G}}_J^E(\boldsymbol{r}, \boldsymbol{r'}) = -j\frac{\omega\mu}{4\pi}\left(\bar{\boldsymbol{I}} + \frac{1}{k^2}\nabla\nabla\right)\frac{\mathrm{e}^{-jk|\boldsymbol{r}-\boldsymbol{r'}|}}{|\boldsymbol{r}-\boldsymbol{r'}|} \,. \quad (2)$$

Next the radiating or the scattering structure is replaced by equivalent surface currents. The surface current density is discretized into small surface patches, normally triangular elements. To find the Method of Moments (MoM) solution of the integral equation, the unknown current density on the surface A is expanded in terms of a set of basis functions (also known as expansion functions). The most widely used basis functions are triangular Rao-Wilton-Glisson (RWG) vector basis functions $\boldsymbol{f}_n$ [Rao,1982] so that,

$$\boldsymbol{J}_A(\boldsymbol{r'}) = \sum_n J_n \boldsymbol{f}_n(\boldsymbol{r'}) \quad (3)$$

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where $\bar{\boldsymbol{I}}$ is the unit dyad and k is the wavenumber in the considered medium. Also, $\boldsymbol{f}_n$ and $\boldsymbol{f}_m$ are Rao-Wilton-Glisson expansion and testing functions, respectively [Rao,1982]. Thirdly, the integral equation is converted into a matrix equation using a set of testing functions (also known as weighting functions). In practice there are two very popular choices of weighting functions. The *Galerkin* procedure uses the same basis and weighting functions. The collocation or point matching method uses the Dirac delta functions, which is equivalent to testing the operator at the sample points. Applying the *Galerkin* procedure, the resulting linear equation system has the form

$$[Z]\{x\} = \{b\}, \tag{4}$$

where $[Z]$ is the full coupling matrix, $\{b\}$ is the excitation vector, and $\{x\}$ represents the unknown surface current density.

Finally, the unkown surface current density is determined by solving matrix equation (4). Once the surface current density is known, the scattering and radiation characteristics can be determined by applying numerical quadrature rules over triangular elements.

If an iterative linear equation solver is used to solve eq. (4), the MLFMM according to the very efficient implementation in [Eibert,2005] can be employed to solve large equation systems in a very efficient manner.

B. Review of Simulated Annealing

Optimization is the process of making something better. An engineer or scientist conjures up a new idea and optimization improves on that idea. This initial idea contains certain input parameters yielding a relatively not so good result. The optimization procedure tries to make variations in the parameters, which yield new results and using this new additional information to make some improvement on the idea. A computer is the perfect tool to help us carrying-out the optimization process. We feed the computer some data and get the result as solution. At this point, there are several important questions, whether the solution is unique, and whether the solution is the best solution. Optimization is the math tool that we rely on to get these answers.

The terminology "best" solution implies that there is more than one solution and the solutions are not of equal value. The definition of best is relative to the problem at hand, its method of solution, and the tolerances allowed.

Searching the cost surface (all possible function values) for the minimum cost lies at the heart of all optimization routines. Usually, a cost surface has many peaks, valleys, and ridges.

Random walk is the brute force approach to optimization which looks at a sufficiently fine sampling of the cost function to find the global minimum. If we want to find the minimum of the function $f(x, y) = x \sin(4x) + 1.1y \sin(2y)$ in the region $0 < x < 10$ and $0 < y < 10$, we begin for example at the point $(x, y) = (0, 0)$ as start point or initial condition. Then, we sample the region with the interval 0.1 that yields a total of $101^2 = 10201$ evaluations of the cost function. The accuracy of the result can be enhanced by using a sample of 0.01, yielding 1 002 001 evaluations. If the number of parameters used is larger than 2, say 4, so the numbers of evaluations become 104 060 401 and 1 004 000 000 000, respectively [Haupt,2004].

Gradient descent is an optimization algorithm that approaches a local minimum of a function by taking steps proportional to the negative of the gradient (or the approximate gradient) of the function at the current point. If instead one takes steps proportional to the gradient, one approaches a local maximum of that function; the procedure is then known as gradient ascent. Gradient descent is also known as steepest descent, or the method of steepest descent. Because the process of solution finding occurs in negative gradient, the end solution depends on the chosen start parameter (Fig.1).

Simulated annealing is a generalization of a Monte Carlo

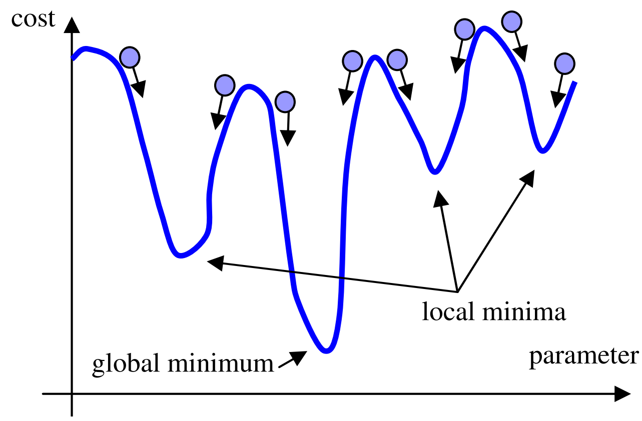

Fig. 1. Trapping of local minima

method for examining the equations of state and frozen states of n-body systems [Metropolis,1953]. The concept is based on the manner in which liquids freeze or metals recrystalize in the process of annealing. In an annealing process, a melt, initially at high temperature and disordered, is slowly cooled so that the system at any time is approximately in thermodynamic equilibrium after reaching certain low-energetic crystalline structures. As cooling proceeds, the system becomes more ordered and approaches a "frozen" ground state at T=0. Hence, the process can be thought of as an adiabatic approach to the lowest energy state. If the initial temperature of the system is too low or cooling is done insufficiently slowly, the system may become quenched forming defects or freezing out in metastable states (i.e. trapped in a local minimum energy state).

The original Metropolis scheme was that an initial state of a thermodynamic system was chosen at energy E and temperature T, holding T constant the initial configuration is perturbed and the change in energy dE is computed. If the change in energy is negative, the new configuration is accepted. If the change in energy is positive, it is accepted with a probability given by the Boltzmann factor $e^{-(dE/T)}$. This processes is then repeated sufficient times to give good sampling statistics for the current temperature, and then the temperature is decremented and the entire process repeated until a frozen state is achieved at $T = 0$. By analogy, the generalization of this Monte Carlo approach to combinatorial problems is straight forward [Kirkpatrick,1983]. The current state of the thermodynamic system is analogous to the current solution to the combinatorial problem, the energy equation for the thermodynamic system is analogous to the objective function, and ground state is analogous to the global minimum. The major difficulty (art) in implementation of the algorithm is that there is no obvious analogy for the temperature T with respect to a free parameter in the combinatorial problem. Furthermore, avoidance of entrainment in local minima (quenching) is dependent on the "annealing schedule", the choice of initial temperature, how many iterations are performed at each temperature, and how much the temperature is decremented at each step as cooling proceeds. Fig. 2 shows the flow chart of the Simulated Annealing for optimizing engineering problems.

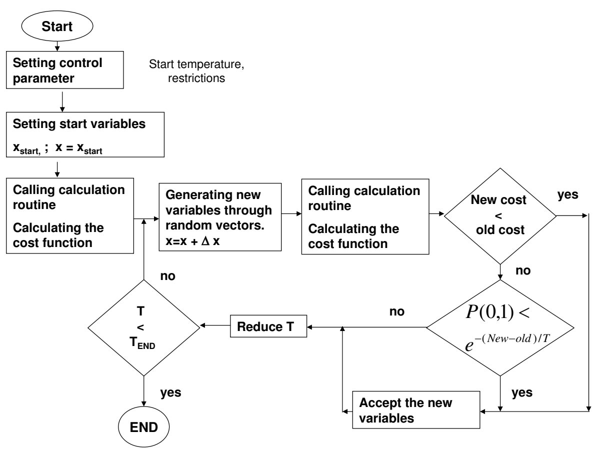

Fig. 2. Flow chart.

The function for temperature reduction used in this work is

$$T_i = T_0 \alpha^i \tag{5}$$

$T_0 = 5000$ is the initial high temperature, $T_i = 0.0015$ is the end temperature, $\alpha = 0.997$, and i is the step.

III. Results

In this work, we design antennas, that are able to work in several frequency bands, so-called multiband antennas. Such antennas must be designed so, that their important characteristics, like input impedances, gain, radiation diagrams meet best values in the desired frequency bands. In this work, we limit our observation to input impedances and restrict our attention just on metallic planar antennas on conducting surfaces as given in Fig.3. However, in calculation we did not consider the ground and the coaxial connector. Instead, we take the image antenna into the calculation and we use a delta gap voltage as the excitation at the symmetry point.

In the optimization process, we vary the dimensions H_1

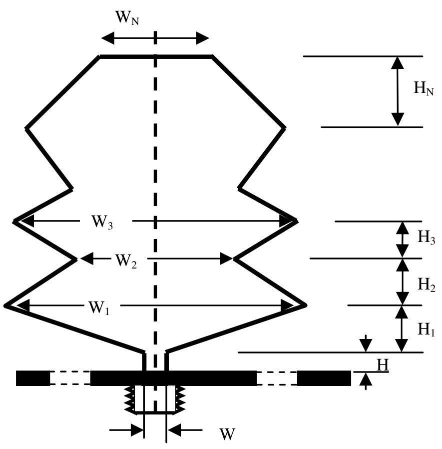

Fig. 3. Generic model of the designed multi band antennas.

to H_N and W_1 to W_N. N can be chosen arbitrarily, so that a very large spectrum of antenna form can be taken into account. However, in order to keep the geometrical dimensions of the antennas small, we can define several constraints, for example here we used the total height must be smaller than 100 mm. The height H and the width W of the feeding plane are kept constant 5 mm and 2 mm, respectively.
The cost function chosen has the following form

$$F = \sum_{i=1}^{M} \mathrm{e}^{(S_{11(dB,f_i)}+10)} , \tag{6}$$

so that if the reflection factor S_{11} at desired frequencies is worse than -10 dB, the cost will be exponential high. And on the other side, if the reflection factor is much more better than -10 dB, the reduction of the cost function is not substantial. This cost function was introduced to guarantee, that the reflection factor in all desired frequency points is better than -10 dB. The limit -10 dB can certainly be changed to other values. M is the number of frequency points involved in the optimization process.

A. *Dual band antenna 0.9 GHz and 2.4 GHz*

Our first problem is to design a dual band antenna working at the frequencies 0.9 GHz and 2.4 GHz. The initial structure is chosen arbitrarily with $N = 3$, $W_1=W_2=W_3=H_1=H_2=H_3=10$ mm. Fig. 4 shows the cost function gained during the optimization process. With the initial geometry, the reflection factor at 0.9 GHz is about -0.11 dB and at 2.4 GHz about -2.41 dB, so that the initial cost is very high. The simulated annealing varies the geometry in random way, sometimes we get better costs and sometimes we get out from this minimal traps by accepting worse costs, as we can see in Fig.4. However, in order to make sure, that we will not lose our good result, we always save this actual best result. Eventually, if we cannot find the global minimum at the end of the process, we can take back this saved result.

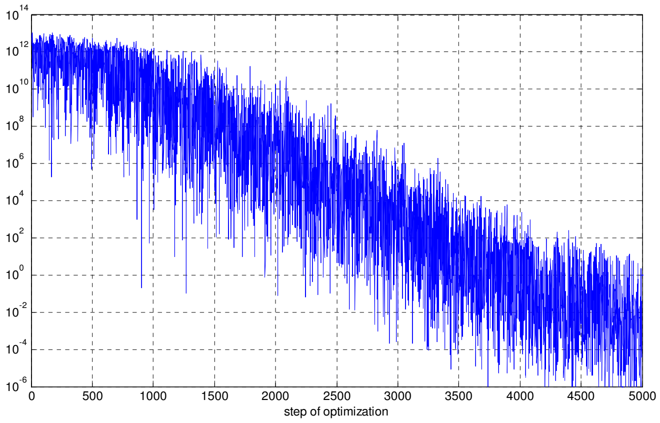

Fig. 4. Value of the cost function during the optimization process.

Fig. 5 shows the geometry of the into small triangles discretized antenna as output of the optimization process. The overall length of the antenna is 64 mm. The current distribution on the antenna at the frequency 0.9 GHz is also shown. As the current on the feeding position is known, we can calculate the input impedance of the antenna, and then the reflection factor.

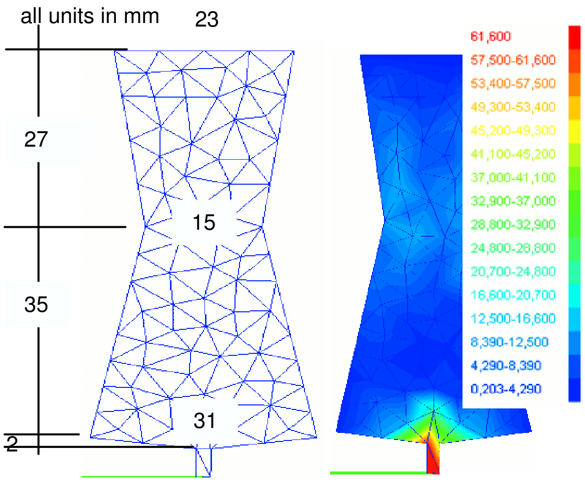

Fig. 5. Geometry of the design dual band antenna and current distribution at 0.9 GHz

The scattering factor S_{11} is depicted in Fig. 6. The combination of integral equation method and simulated annealing in this work gives a very good reflection characteristic in the desired frequency bands. A measurement with Agilent E8363A network analyzer validates the result. As a comparison we show also results obtained by the program WIPL-D [Kolundzija,2000].

B. *Dual band antenna 2.4 GHz and 5.8 GHz*

Another dual band antenna is designed to check the performance of the procedure used. The second dual antenna works at the frequencies 2.4 GHz and 5.8 GHz. The structures obtained with the Simulated Annealing are depicted in Fig.7 (left).

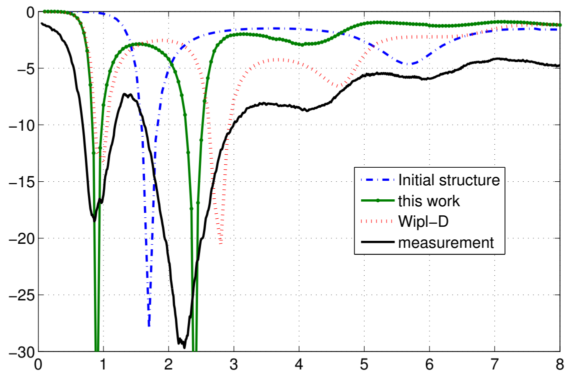

Fig. 6. Reflection factor of designed dual band antenna, S_{11} in dB and frequency in GHz

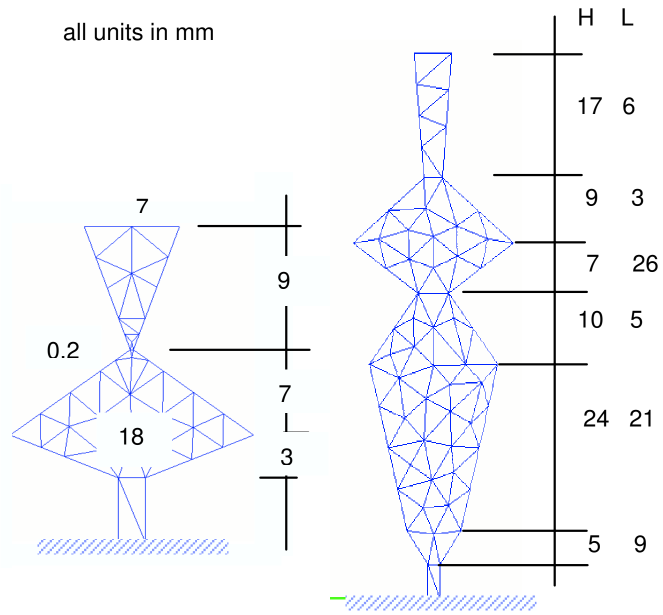

Fig. 7. Geometry of the design dual band antenna and triband antenna.

Fig.8 shows the scattering parameter S_{11} for a dual band antenna for frequency bands 2.4 GHz and 5.8 GHz, again with the geometry we can get a very good reflection performance. Measurement confirms the results.

C. *Triband antenna 0.9 GHz, 2.4 GHz and 5.8 GHz*

A triband antenna for the frequencies 0.9 GHz, 2.4 GHz and 5.8 GHz is also optimized (Fig.7 right). In optimizing this triband antenna, we must use $N = 6$ to get minimal reflection factor in all three frequency points.

Fig.9 shows the results for the triple band antenna designed in this work, again we can see the consistency of the

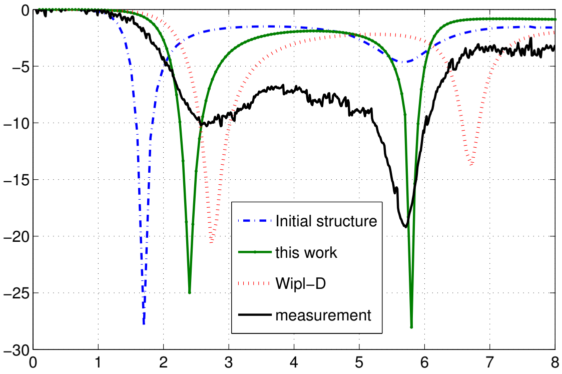

Fig. 8. Reflection factor of designed dual band antenna, S_{11} in dB and frequency in GHz

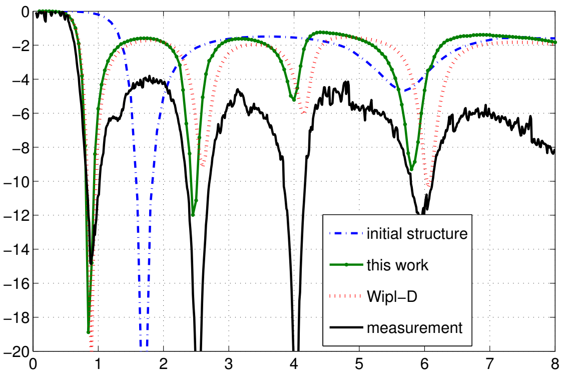

Fig. 9. Reflection factor of designed triple band antenna, S_{11} in dB and frequency in GHz

results with exception at the frequency 4 GHz, we obtain additional minimum here.

The deviations between calculations and measurements originate probably from the different modelling. We made the measurement using a finite ground plane and SMA connector, and calculations with the complete antenna structure and delta gap voltage. Also, WIPL-D uses the thin-wire model at the feed location, whereas our approach works with triangular patches in the whole model.

IV. Conclusions

Combination between computational electromagnetics, i.e. integral equation method, and optimization method, Simulated Annealing, shown in this work gives us insight and aspiration in designing antennas with arbitrary characteristics and geometrical shapes. Some deviations are observed, which come probably from different modelings in calculations and measurements.

V. Acknowledgment

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