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Design, optimization, and realization of a wire antenna with a 25:1 bandwidth ratio for terrestrial communications

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Abstract: Wire antennas can be made wideband if the antenna is loaded with passive elements and connected to a lossless matching network. However, realization of the load component values and matching network can easily become impractical. In this study, using only a surface mount and standard component values, antenna loads and a matching network are optimized using genetic algorithms. The optimized design achieves a 25:1 bandwidth ratio, from 20 MHz to 500 MHz, with a maximum voltage standing wave ratio (VSWR) of 3.5 and minimum system gain of –5 dBi. The antenna system gain at azimuth is taken as the objective function and an exact penalty function is formulated to take into account the VSWR over the design frequency band. A loaded antenna is built and measured to corroborate the simulations results. The realized antenna is only $0.14\,\lambda$ long at 20 MHz.

Key words: Broadband antenna, loaded wire antenna, genetic algorithms, exact penalty functions

1. Introduction

Wire antennas are usually perceived as the simplest form of communication antennas due to their omnidirectional radiation pattern, high efficiency, and ease of construction. However, their narrowband nature has been the center of research and is considered a major drawback for many applications. Although antenna designs for ultra-wideband systems with circular, elliptic, rectangular, and monocone shapes have been around for some time, these antennas take up too much space in lateral dimensions when they are scaled to high frequency (HF)/very HF bands. In this respect, wire antennas are still attractive and they can be easily integrated into vehicles as standalones or with a combination of other antennas.

Fundamental limits on antenna bandwidth were established in the past for electrically small antennas based on spherical wave expansion of radiated fields [1,2]. When bandwidth encompasses multiple resonances, such mathematical bounds cannot be readily formulated in terms of the electrical size of the antenna. Loading the antenna with passive elements to obtain wideband operation was first suggested by Brueckman [3]. Since then, numerous studies addressed this issue using optimization methods [4–8] or semianalytical tools backed with optimization [9]. In earlier works, genetic algorithms (GAs) were successfully applied and very satisfactory results were reported (an extensive bibliography appears in [10]). However, optimization may result in a very sensitive design and/or complicated load/matching network structure, while providing the desired wideband match and system gain. In addition, earlier attempts at the realization of optimized designs were carried out on scaled prototypes rather than on actual antenna dimensions and component values. In this study, however,

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we use the exact physical dimensions of the antenna. The system gain of the loaded antenna and its impedance match to a 50-Ω source over the prescribed frequency range were design objectives in previous studies and in this work.

Since in a typical loaded antenna optimization one faces a nonlinear, mixed-integer, and bound-constrained optimization problem, the formulation of the objective function plays a vital role to obtain a satisfactory, convergent result. It is one of the goals of this study to construct a new objective-function formulation that yields extremely broadband wire antenna designs that are robust relative to changes in load values and positions. We achieve this objective by formulating an exact penalty function to account for the impedance mismatch [expressed in terms of the voltage standing wave ratio (VSWR)] to the system gain, thereby reducing the original multiobjective optimization to that of a single one. With this formulation, a very promising optimized antenna configuration is obtained. All of the component values, including the wideband balun transformer in the matching network, are of standard values and surface-mount type for ease of construction.

2. Antenna design and optimization

Consider the loaded antenna illustrated in Figure 1. The optimization problem can be stated as:

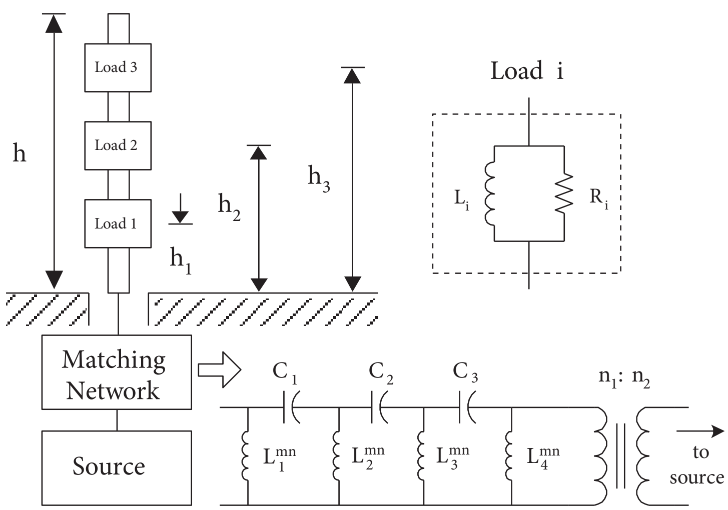

Figure 1. Loaded antenna over an infinite ground plane with the matching network and source (h = 2.125 m, h_1 = 0.033 m, h_2 = 0.46 m, and h_3 = 1.60 m).

$$\begin{array}{l} \text{Maximize} \quad f(\vec{X}) \\ \text{subject to} \quad VSWR(\vec{X}) \ \leq \ 3.5 \\ \text{where } \vec{X} = \{x_1, x_2, ..., x_{NOPT}\} \ and \ \ l_i \leq \ x_i \ \leq \ u_i \ , \ \ i = 1, ..., NOPT \end{array} , \tag{1}$$

where f is the objective function and is related to the system gain, $\vec{X}$ is the set of optimization variables corresponding to the position and values of the loads and elements of the matching network, VSWR is the voltage standing wave ratio obtained using $\vec{X}$, and $NOPT$ is the total number of optimization variables. Each x_i of $\vec{X}$ has a lower and upper bound of l_i and u_i, respectively. Load positions can only take integer values, whereas the rest may be continuous variables. The function f is defined as:

$$f(\vec{X}) \ = \sum_{j=1}^{N^f} (G_{sys,\,j}(\vec{X}) \ - \ G_{sys}^0)^3, \tag{2}$$

where N^f is the number of frequency points selected in the frequency range of operation, $G_{sys,j}(\vec{X})$ is the system gain at the azimuth at the jth frequency, and G_{sys}^0 is set to 0 dBi. The system gain is defined as $G_{sys} = D\,\eta_{rad}\,\eta_{mismatch}$, where D, η_{rad}, $\eta_{mismatch}$ represent the directivity, radiation efficiency, and mismatch factor, respectively. The radiation efficiency takes into account the loss associated with the antenna. Since the antenna material is assumed as a perfect electric conductor (PEC), antenna loss is due to resistors used in the loads. The impedance mismatch of the antenna to 50 Ω is formulated in terms of the mismatch factor in the system gain. Because the nonlinear constraints are a part of the main objective function f, maximization of the system gain with constraints on the VSWR is preferred over the minimization of the VSWR with constraints on the system gain. The nonlinear inequality constraint function of $VSWR(X)$ can be formulated as an exact penalty function to the optimization problem of Eq. (2). By doing so, one transforms the nonlinearly constrained optimization problem to a simple bound-constrained one. An exact penalty function is formulated for this task. Exact penalty functions, as first proposed by Zangwill [11], gained considerable attention in solving nonlinear programming problems [12–14]. Discussions of the use of penalty functions with GAs are found in the works of Michalewicz and Janikow [15], Ricardson et al. [16], and Homaifer et al. [17]. The form of the penalty function used in our analysis is:

$$p(\vec{X}) = \sum_{i=1}^{N^f} \varepsilon_i \left(1 - VSWR_i(\vec{X})\right)^3$$
$$\text{and } \varepsilon_i = \begin{cases} 8, & VSWR_i \geq 4.0 \\ 4, & 3.0 \leq VSWR_i < 4.0 \\ 2, & 2.0 \leq VSWR_i < 3.0 \\ 0, & VSWR_i < 2.0 \end{cases}, \tag{3}$$

where i and $VSWR_i$ represent the frequency index and VSWR at the ith frequency, respectively. The optimization problem with this penalty function is restated as:

$$\begin{aligned} &\text{Maximize} \quad F(\vec{X}) = f(\vec{X}) + p(\vec{X}) \\ &\text{subject to} \quad l_i \leq x_i \leq u_i, \quad \forall x_i \in \vec{X}. \end{aligned} \tag{4}$$

The GA-dependent parameters used during the optimization are chosen as follows: population size, $N_{pop} = 100$; crossover probability, $p_{cross} = 0.85$; and mutation probability, $p_{mutation} = 0.008$. The maximum number of generations is selected as 200, and a binary tournament is used as the selection operator.

A computer program was developed to numerically solve an integral equation by the method of moments for the electric current on the loaded antenna and to compute the near- and far-zone quantities therefrom. The numerical results of this code were checked with a commercial field solver, FEKO. During optimization, the code developed by the present author was used, but FEKO was used to check the final antenna performance. All of the results shown in this manuscript were obtained using FEKO. A GA code was also developed for the optimization routine. A monopole antenna of height $h = 2.125$ m was chosen as the antenna structure to be optimized over an infinite ground plane. The antenna was assumed to be fed by a transmission line with a characteristic impedance of 50 Ω. The design specifications were operation from 20 to 500 MHz (25:1 bandwidth), with a minimum system gain of –5 dBi at the azimuth and a maximum VSWR of 3.5. The quantity and the type of the loads were not among the design parameters, nor were the topology and the number of elements in the matching network. A set of loaded antennas was selected, with optimization on each member to be performed separately. On each antenna topology, the location of the loads, component values of the loads, and component values of the matching network were coded in the input vector $\vec{X}$. The same load topology depicted in Figure 1 was used for all of the candidate antennas, whereas high- and low-pass T and π topologies were considered for matching networks. By varying the number of loads and elements in the matching networks, 40 different loaded antenna matching network configurations were obtained and GA optimization was carried out on each configuration independently. Among all of these candidate structures, only one design was found that satisfied all of the design criteria. The types of loads, their respective locations on the monopole, and the element values in each circuit are given in the first rows of Tables 1 and 2. A close inspection on these optimized values reveals that some components have a very small effect on the antenna's performance. Therefore, a reduced model is formed and tabulated in the second rows of Tables 1 and 2. In the reduced model, the third load is a simple resistor and the matching network consists of only 2 elements: a shunt inductor and a balun transformer with a 2:1 turn ratio. The shunt inductor value closest to the balun transformer is modified from 49.8 μH to 2.2 μH after a simple iteration. During the simulations, all of the inductors are assumed ideal, i.e. no loss resistance. The VSWR performance of the optimized design with reduced component values is presented in the second columns of Tables 1 and 2, and the unloaded antenna are illustrated in Figure 2. The system gain of the optimized antenna at different elevation angles is evaluated and compared to the directivity at the horizon of the unloaded antenna in Figure 3. No considerable change in the system gain is observed at $\theta = 85^\circ$, whereas a substantial change in the system gain occurs at $\theta = 80^\circ$. We also numerically studied the effects of the load positions on the antenna's performance. We observed that the position of the first load was critical, and the others had minimal impact on the performance when the loads were displaced by one segment. The system gain was not affected considerably by a load displacement of one segment up or down. Most of the dips in the loaded antenna gain performance follow those of the unloaded antenna, where the antenna length becomes the integer multiple of the operation wavelength, which is consistent with the dipole antenna theory.

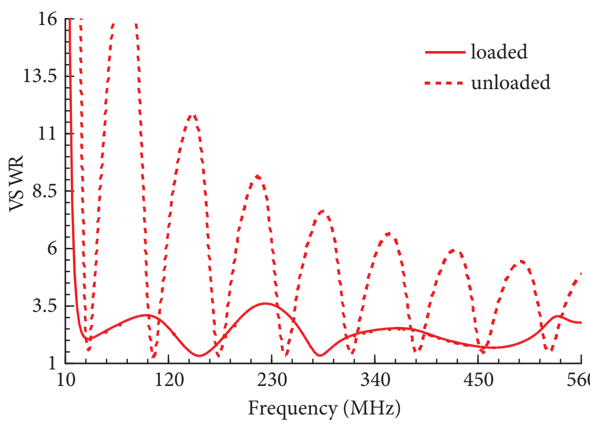

Figure 2. Comparison of the VSWR of the optimized and unloaded antennas with terminals connected to a 50-Ω transmission line.

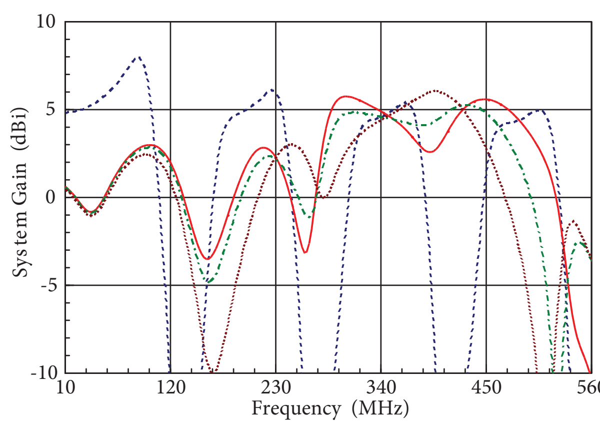

Figure 3. Comparison of the directivity of the unloaded antenna and system gain of the optimized antenna for different elevation angles: $\theta = 90^\circ$, $\theta = 85^\circ$, $\theta = 80^\circ$.

The efficiency of the overall system with all of the losses due to load resistors and impedance mismatch taken into account is shown in Figure 4. The directivity and gain of the antenna without the matching network are also displayed in Figure 4. If there were no resistors in the loads, the directivity and gain would be equal because the antenna is assumed as a PEC and the inductors are ideal. The finite Q of the inductors can also be incorporated into the analysis, but the resistors in the loads constitute most of the loss. The reduction in the radiation efficiency is clear when the gain and directivity are compared to each other in Figure 4.

Table 1. Component values of the antenna loads.

	Optimization results	Reduced model	Standard component values
L_1 (nH)	46	46	47
R_1 (Ω)	994	994	1000
L_2 (nH)	190	190	180
R_2 (Ω)	1510	1510	1500
L_3 (nH)	2760		
R_3 (Ω)	705	705	680

Table 2. Component values of the matching network.

	Optimization results	Reduced model	Standard component values
L_1^{mn} (μH)	2.106		
C_1 (μF)	7.33		
L_2^{mn} (μH)	9.2		
C_2 (μF)	3.68		
L_3^{mn} (μH)	6.07		
C_3 (μF)	1.874		
L_4^{mn} (μH)	49.08	2.2	2.2
n_1:n_2	2:1	2:1	2:1

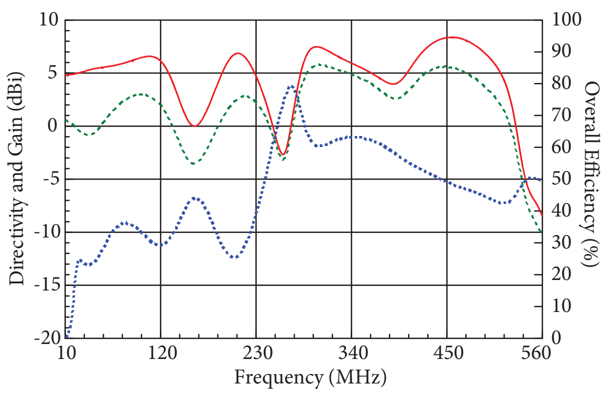

Figure 4. Comparison of the directivity and gain after losses from the load resistors, but excluding the mismatch factor. Efficiency of the overall system with all losses taken into account is on right axis.

3. Realization of optimized design

The first step in the realization process is to replace the optimized component values with standard surface mount components that are readily available from passive component manufacturers. The reduced design is further modified for this purpose and standard component values are given in the third rows of Tables 1 and 2. We used air-core high-Q Coilcraft 1008-type inductors (Q = 75, SRF > 1.2 GHz) with a 5% tolerance, 0805-type resistors, and a Minicircuits TC4-1WG2 wideband balun transformer in the matching network, which is rated from 10 MHz to 800 MHz and has about a maximum 1-dB insertion loss in the target bandwidth, according to the manufacturer's datasheet [18]. The only troublesome component was the large-value inductor used in the matching network. Normally, one can easily create such a component using high-μ magnetic core materials, but, instead, a surface mount counterpart was used with a compromise on its lower Q compared to the ones used in the loads. The loads and matching network were soldered on double-sided FR4 printed circuit board (PCB) with a 1.57-mm board thickness. The antenna was divided into 4 sections and the loads were placed between the sections. When one section of antenna was soldered to the top part of the PCB, the other section was soldered to the bottom part of the board. The current continuity is maintained with through-hole plated vias from one side of the PCB to the other. The antenna is measured on a 1.5-m^2 finite ground plane. Prototypes of the PCB, first load, antenna with 1 load only, and loaded antenna with 3 loads are shown in Figures 5a–5e. To validate the prototype antenna, first, 1 load and the matching network with only the balun transformer were measured. Measurements were carried out with a network analyzer (Rohde & Schwarz ZVB 20). The height of the monopole is 46 cm and the configuration of this structure is illustrated in Figure 5d. At this height, the first resonance of the unloaded antenna occurs at 163 MHz. Measurement results for the VSWR are shown in Figure 6, and the gain simulations are shown in Figure 7. The design achieves a 4:1 bandwidth ratio, from 125 MHz to 500 MHz, and the antenna is 0.2λ long at 125 MHz, which is slightly less than the first resonance of the unloaded antenna (0.25λ) but it has a much wider bandwidth and flat gain. This simple measurement reveals that the first load being closest to the antenna feed point plays an essential role in achieving a wideband operation. Next, the remaining sections of the loaded antenna were put together and the optimized matching network (shunt inductor and balun) was connected to the antenna terminals for the full antenna measurements. The results are illustrated in Figure 8. Although some deterioration in the VSWR performance at some frequencies was observed, the target design specification VSWR of <3.5 was met. The general corroboration of the simulation and measurement were satisfactory considering the finite ground size and deviations from the ideal antenna simulation to the practical realization. Gain measurements were quite difficult due to the lack of a calibrated outdoor measurement range. However, we carried out the gain

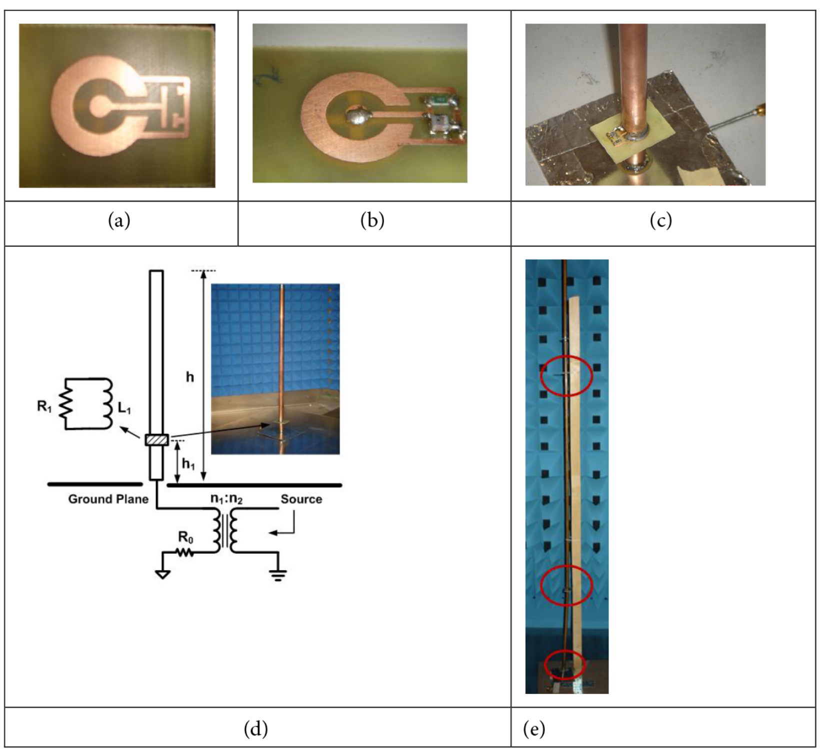

Figure 5. a) Antenna load PCB, b) first load, c) first load and short monopole, d) 1-load-only antenna, and e) 3-load (optimized) antenna (red circles show the load locations).

measurements at certain frequency points: 200, 300, 430, and 500 MHz. We used a wideband biconical antenna as the transmitter (hooked to a CW signal generator, R&S SMB100), and we connected a spectrum analyzer (R&S FSV 30) to the antenna under test. That way, we were able to carry out relative gain measurements with the loaded antenna and tuned dipole antennas at the measurement frequencies. Ground reflection and signal coupling from outside sources were observed, but the spectrum analyzer was able to identify any modulated signal. We were unable to carry out lower frequency measurements due to strong coupling from outside sources. The results are displayed in Figure 9. The antenna to ground coupling and insertion loss of the wideband balun transformer led to lower than expected measured gain values. The worst case gain measurement was off by about 1.8 dB from its simulated data and the best case was about 1.1 dB lower than the expected value.

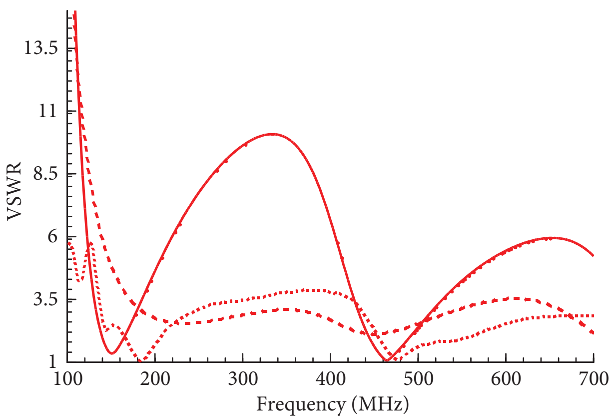

Figure 6. Unloaded and 1-load-only (Figure 5d) antenna: simulated and measured VSWR.

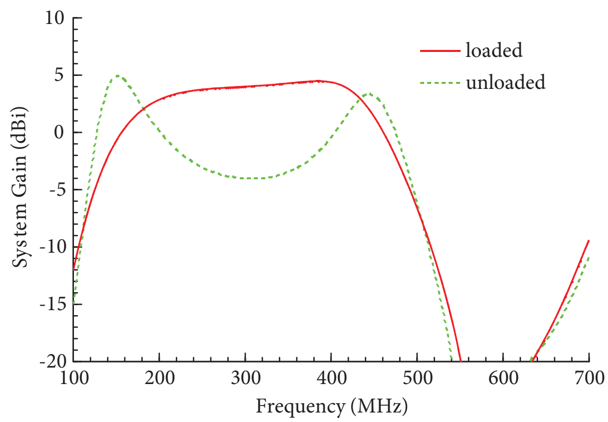

Figure 7. Unloaded and 1-load-only (Figure 5d) antenna: simulated system gain.

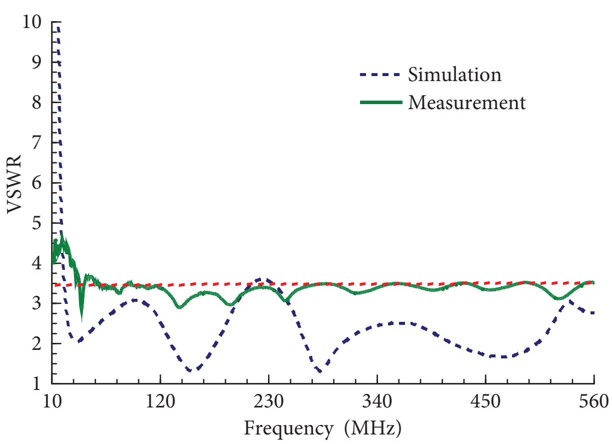

Figure 8. Wideband loaded antenna (3 loads and matching network): simulated and measured VSWR.

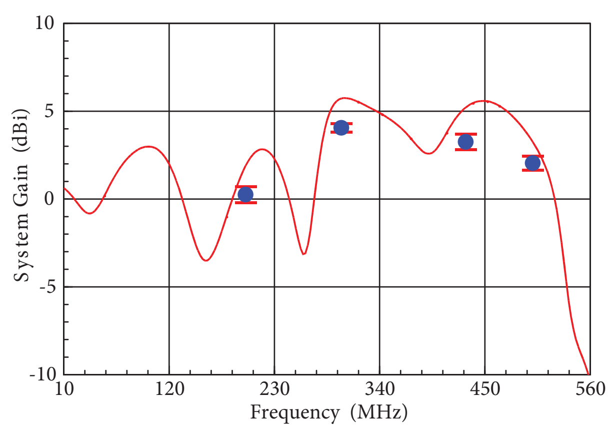

Figure 9. Simulated and measured antenna gain.

4. Conclusions

A wire antenna loaded with passive components was optimized for broadband operation from 20 MHz to 500 MHz, with the design goals of system gain and impedance match. The objective function used in the optimization was formulated using exact penalty functions, which led to a fast convergent result. The optimized design was replaced with a reduced model and in the reduced model component values were modified for standard surface mount component values. The sensitivity of the optimized design was very robust, such that these changes on the component values had little effect on the design objectives. This is mainly attributed to the objective function formulation. The antenna was built and measured for the impedance match. A VSWR of less than 3.5 was measured over the majority of the target band. Imperfect ground contacts and lack of a large ground plane at lower frequencies are thought to be sources of the discrepancy. Despite this disagreement, we see relatively good corroboration of the simulations with the measurements. Even with only 1 load and balun transformer in the matching network, the design achieves a 4:1 bandwidth ratio, from 125 MHz to 500 MHz. Gain measurements were performed at discrete points using tuned dipole antennas. Although the measurement setup was a little ad hoc, the results were on average 1.5 dB worse than the simulated data due to an insufficient ground plane in our setup. Better measurements can be carried out at a calibrated outdoor reflection range, which is very scarce in the HF/ultra-HF bands. Overall, we think that the optimized antenna serves as a good candidate for frequency hopping terrestrial communication systems.

Acknowledgments

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