Searching for the Optimal Shapes of Ultra-Wideband Monopole Antennas

#Kian Paran [1], Masoum Fardis [2], Ali Abolghasemi [3]
Radio Communications Group, Iran Telecommunication Research Center
PO Box 14155-3961, Tehran 14399-55471, Iran
[1] kianparan@itrc.ac.ir, [2] fardis@itrc.ac.ir, [3] ali_abl@itrc.ac.ir

1. Introduction

The optimization of ultra-wideband (UWB) monopole and dipole antennas are mostly done by choosing a particular shape and tuning the geometrical parameters of it [1]-[3]. In few works, optimization has been performed not to obtain the optimum parameters of a particular shape, but to find the optimal shape of antenna [4]-[6]. In these works, the geometry of antennas is described in a general manner allowing the antennas to take different shapes during the optimization process. However, none of these general descriptions could produce all or most of the shapes for UWB monopole and dipole antennas which have been reported in the literature. Some of these general descriptions are also incompatible with some optimization methods like genetic algorithm (GA). In this paper, a new approach to UWB antenna design is described. This approach is based on a general description for the geometry of UWB monopole antennas which is capable of producing almost all possible shapes for these antennas. This general description is also compatible with different optimization methods (especially GA). In this work, the general description is used for the optimization of non-planar rotationally-symmetric monopole antenna with finite ground plane.

2. Optimization Process

During the optimization process, the "optimization tool" generates set or sets of parameters at each iteration. Each set of parameters corresponds to an antenna according to the "general description of antennas geometry". Antennas are analyzed using an "electromagnetic simulator" and for each antenna, the value of objective function is calculated. This value reversely shows the fitness of the antenna with regard to the optimization goals. At subsequent iterations, the optimization tool uses these values and corresponding sets of parameters to generate new sets of parameters which are expected to exhibit better fitness.

2.1 General Description of Antennas Geometry

The proposed scheme to generally describe the geometry of a rotationally-symmetric monopole antenna with finite ground plane is illustrated in Figure 1. The primary profile of the antenna is formed by 12 control points, 4 points for shaping the ground (U_0-U_3), 4 points for shaping the lower part of radiating element (V_0-V_3), and 4 points for shaping the upper part of radiating element (W_0-W_3). The final profile consists of two splines, one forming the cross-section of shaped ground and the other forming the cross-section of radiating element. In Figure 1, a, b, c, and l are the geometrical parameters of the feeding coaxial line and t is the thickness of lower plate. Moreover, $\Delta\rho_{max}$ is the maximum allowable distance between the control points and the outer conductor of coaxial line, Δz_{max} is the maximum allowable distance between control points and $\rho-$axis, and $\Delta\rho_{grd}$ is the maximum allowable range for ground plane to extend beyond the shaped part.

U_0, V_0, and W_0 are positioned along the outer conductor of coaxial line ($\rho = b$), the inner conductor of coaxial line ($\rho = a$), and the axis of symmetry ($\rho = 0$), respectively. Second points (U_1, V_1, W_1), third points (U_2, V_2, W_2), and forth points (U_3, V_3, W_3) are positioned at same distance

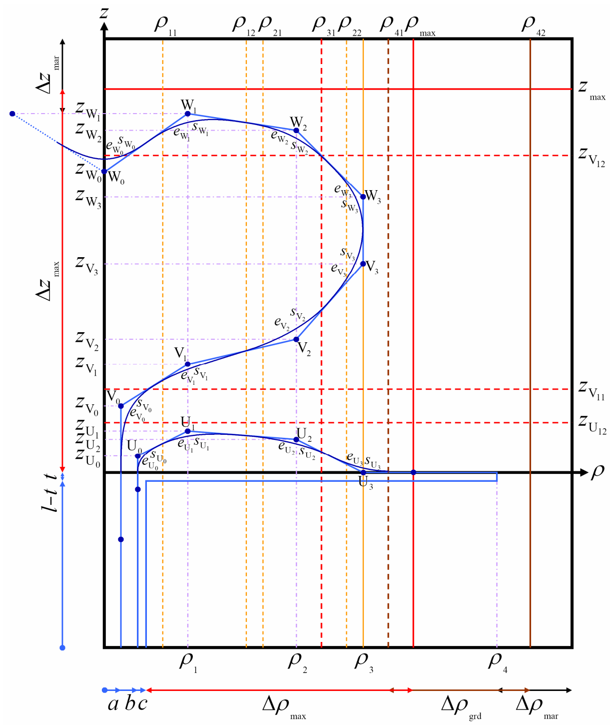


Figure 1: The proposed scheme to generally describe the geometry of a rotationally-symmetric monopole antenna with finite ground plane.

from the axis of symmetry ($\rho=\rho_1$, $\rho=\rho_2$, and $\rho=\rho_3$ respectively, where $c<\rho_1<\rho_2<\rho_3<\rho_{max}$). The last control point of the ground (U_3) is positioned on ρ–axis and other control points of the ground are below a specified level ($0<z_{U_i}<z_{U_{12}}$, $i=0,1,2$). V_0 is below a specified level ($z_{V_0}<z_{V_{11}}$) and other control points of the lower part of radiating element are between $z=z_{V_{11}}$ and $z=z_{V_{12}}$. Each control point of the upper part of radiating element (W_i) is between the corresponding control point of the lower part (V_i) and $z=z_{max}$.

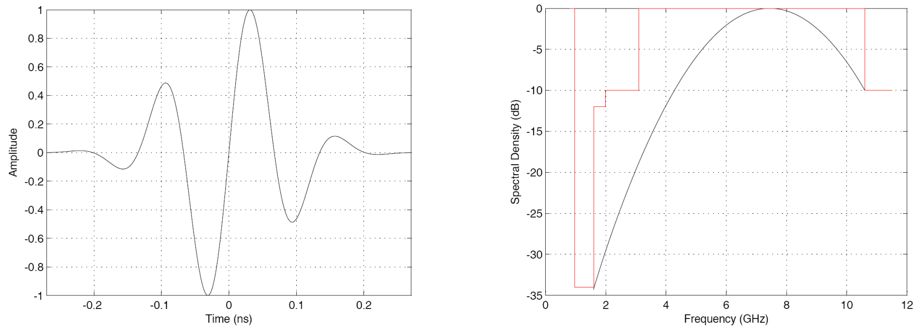
Special kind of spline is used to derive the final profile. This spline replaces each edge of a given polygon by a curve with specified expansion and sharpness which are determined respectively by expansion and sharpness factors assigned to that edge. An expansion and a sharpness factor should be assigned to each control point shown in Figure 1 ($0<e_{X_i}, s_{X_i}<1$, $X\equiv U, V, W$, $i=0,1,2,3$).

a, b, c, l, t, $\Delta\rho_{max}$, Δz_{max}, $\Delta\rho_{grd}$, $z_{U_{12}}$, $z_{V_{11}}$, and $z_{V_{12}}$ are constant parameters which are appointed prior to the optimization process. ρ_1, ρ_2, ρ_3, ρ_4, z_{U_0}, z_{U_1}, z_{U_2}, z_{V_0}, z_{V_1}, z_{V_2}, z_{V_3}, z_{W_0}, z_{W_1}, z_{W_2}, z_{W_3}, e_{X_i}, and s_{X_i} ($X\equiv U, V, W$, $i=0,1,2,3$), each could be considered as a constant parameter or an optimization parameter.

A wide variety of shapes could be generated using the proposed scheme, including polygons with sharp edges, polygons with rounded edges and different curved shapes. Therefore, the general description is capable of producing almost all possible shapes for monopole antennas. The proposed scheme never generates self-intersecting or discontinuous shapes. An uninterrupted and smooth transition of radiating pulse from feed line to free-space (or vice versa) could be readily provided by shaping the cross-section of radiating element (especially the lower part of it) and the cross-section of ground in a proper manner, which can be carried out by finding the best positions for control points and the optimum values of spline factors through an optimization process. This general description is compatible with different optimization methods (especially GA) and there is not any possibility for unacceptable shapes to be generated during the optimization process.

2.2 Electromagnetic Simulator

The electromagnetic analysis of antennas is carried out by the RSS code, which is an efficient finite-difference time-domain (FDTD) tool for analyzing the rotationally-symmetric structures. This code is based on the FDTD formulation in cylindrical coordinates taking into account the rotational symmetry of structure and excitation. Therefore the performed simulations are two-dimensional instead of three-dimensional and the required memory space and CPU-time are significantly low. With low CPU-time requirements, the implementation of different optimization methods (especially the population-based methods) becomes practicable. The inputs of the RSS code include the specifications of the spectral mask, the structure, and the required outputs. The code automatically generates an excitation signal which fits into the specified spectral mask. For example, Figure 2 shows a modulated Gaussian pulse along with its spectral density which fits into the Federal Communication Commission (FCC) spectral mask for indoor systems.



(a) (b)

Figure 2: (a) A modulated Gaussian pulse and (b) its spectral density which fits into the FCC spectral mask for indoor systems.

2.3 Objective Function and Optimization Procedure

The optimization process has two main goals; minimizing the reflection coefficient of antennas over the operating band and reducing the time-domain distortion of radiated pulses. In some cases, the reduction of variations in the energy pattern is added to these goals. The objective function is a weighted sum of terms, each considered to satisfy one of these goals.

In this work, the optimization of UWB antennas is performed by applying a hybrid procedure. First, the global optimization is carried out using the Matlab GA optimizer. Then, the procedure is completed by a local optimization using the pattern search method.

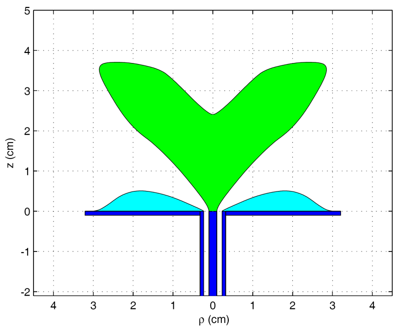


Figure 3: An optimized profile for UWB monopole antenna with finite ground plane.

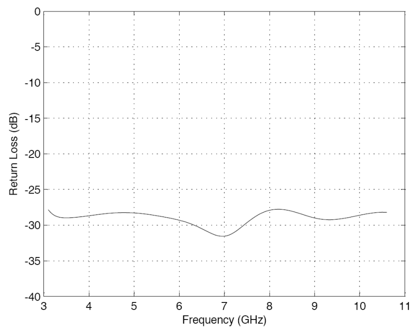
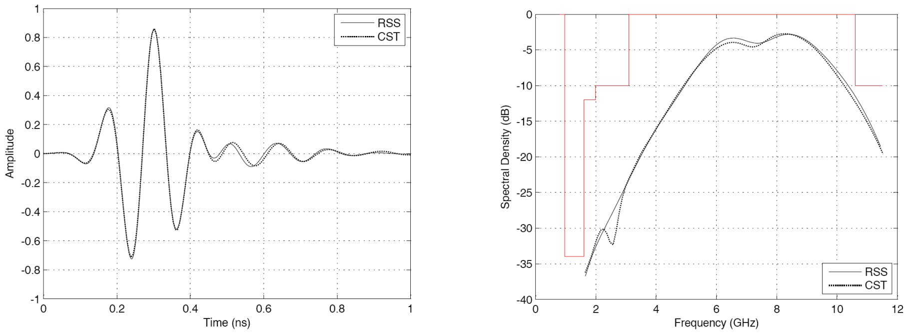


Figure 4: Return loss of the optimized antenna.

3. Numerical Results

In this section, an optimized profile for UWB monopole antenna with finite ground plane is presented which is obtained by the predescribed optimization process. In this case, the optimization process is performed to design an antenna suitable for UWB indoor applications which is fed through a 50 Ω coaxial line. The values of Δz_{max}, $\Delta\rho_{max}$, and $\Delta\rho_{grd}$ are chosen equal to 4 cm, 3 cm, and 1.5 cm respectively. During the GA search, all expansion and sharpness factors are fixed equal to 1 and 0.5, respectively. But during the pattern search, these factors are considered as tunable parameters. Figure 3 shows the optimized profile. Antenna has a diameter and height of 5.70 cm and 3.71 cm, respectively. The diameter of ground plane is 6.41 cm. The return loss of antenna is shown in Figure 4. The maximum return loss in 3.1-10.6 GHz band is -27.8 dB. The radiated



(a) (b)

Figure 5: (a) Radiated waveform of the optimized antenna in $\theta = 90^\circ$ and (b) its spectral density.

waveform in $\theta = 90^\circ$ (calculated by RSS and CST Microwave Studio) and its spectral density are shown in Figure 5. There is excellent agreement between RSS and CST calculated data. Figure 6 presents the normalized correlation (correlation factor) between the input signal of antenna and signals detected by virtual probes placed at far-zone along different elevation angles. The correlation factor is above 0.9 at most angles. The energy pattern of the antenna is shown in Figure 7. The average power of pulse in $\theta = 90^\circ$ is only 1.6 dB less than maximum.

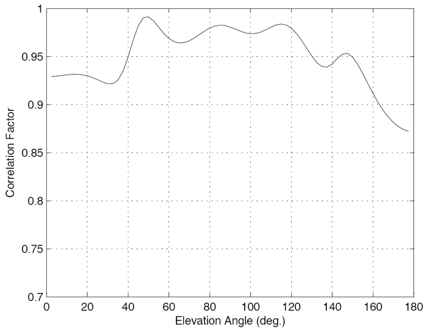


Figure 6: Correlation factor for the optimized antenna as a function of elevation angle.

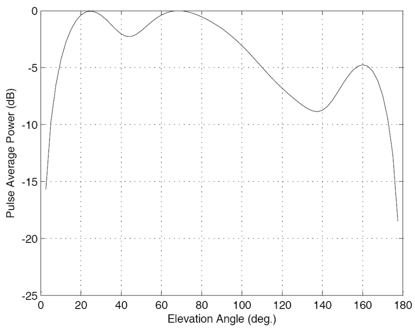


Figure 7: Energy pattern of the optimized antenna.

4. Conclusions

The numerical results show the reliability and effectiveness of the whole process. These results also show considerable improvement regarding antenna size and operational characteristics in comparison with similar antennas reported in the literature.

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