TIME-DOMAIN MULTI-OBJECTIVE OPTIMIZATION OF ANTENNAS

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ABSTRACT

A planar dipole antenna is analyzed using time-domain integral equation (TDIE) method. In order to compensate the influence of the shape of the excitation pulse and to suppress dispersion phenomena, an inverse filtering is applied in the time domain using the cyclic convolution.

In order to keep computations in the time domain, an objective function is formulated in terms of time-domain parameters. A global optimum is sought by genetic algorithms and particle swarm optimization.

The antenna is required to exhibit the maximum bandwidth, the maximum gain, and the minimum dimensions at the same time. Since these objectives are conflicting, a multi-objective approach is applied, and the set of Pareto optimum solutions is computed.

1. INTRODUCTION

The analysis of antenna systems by the Time-Domain Integral-Equation (TDIE) method has become popular recently. Exciting an antenna by a narrow Gaussian pulse, TDIE can produce values of an observed quantity on all the frequencies covered by the excitation pulse spectrum. Compared to the method of moments, which has to be run separately on each harmonics of interest, TDIE can provide higher efficiency [1].

Due to the frequency domain nature of antenna parameters, time responses of computed quantities have to be converted to the frequency domain, and here, the objective function is formulated. In order to eliminate the necessity of Fourier transforming the time responses in each iteration step, the objective function has to be composed in the time domain directly [2]. Since several requirements on antenna parameters are conflicting, the optimization procedure is asked to provide sets of Pareto-optimal solutions in the global sense.

So far, the multi-objective cost function was composed in the frequency domain, and the set of Pareto-optimal solutions was computed using evolutionary algorithms [3] or particle swarm methods [4].

In the proposed method, TDIE is applied to analyze a planar dipole as a canonical structure (Section 2). Inverse low-pass filters process computed time-domain responses in order to eliminate dispersion errors and suppress the influence of the shape of the excitation pulse (Section 3). The filtered responses are used to compute time-domain parameters of the antenna (Section 4). A multi-objective cost function consists of conflicting criteria considering the maximum bandwidth, the maximum gain and the minimum size of the antenna; the set of Pareto-optimal solutions is obtained by Genetic Algorithms (GA) and Particle Swarm Optimization (PSO) as described in Section 5. Section 6 concludes the paper.

2. TIME-DOMAIN NUMERIC MODEL

The basic principles of the time-domain multi-objective optimization of antenna structures are explained considering a simple canonical antenna – a planar dipole on a dielectric substrate (see Figure 1).

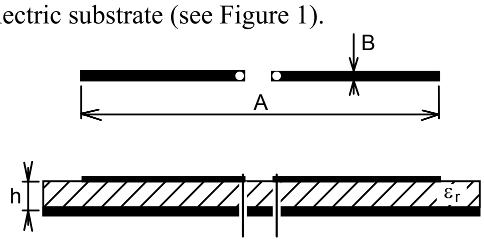

Figure 1. The canonical structure: a planar dipole on a dielectric substrate.

The antenna is analyzed in the time domain applying the TDIE. Thanks to the small width of the dipole, transversal currents can be neglected, and the distribution of the longitudinal component of the current density vector is the only unknown quantity.

The planar dipole is divided to N_z = 40 elements; and the current density is considered to be constant over an element. Applying Dirac weighting, Electric Field Integral Equations (EFIE) are transformed to the set of algebraic linear equations [5]. In the EFIE, the Green functions are approximated using [6], [7]. The analysis is based on the explicit formulation with $\Delta z = c\Delta t$; Δt denotes time step, c is velocity of light and Δz is spatial discretization step in the direction of the dipole axis.

The antenna is excited by a linearly polarized plane wave (the electric field intensity vector is oriented in parallel to the dipole). The wave illuminates the structure perpendicularly (with respect to the substrate). Since the antenna is going to be designed for the central operation frequency 3 GHz, the time response of the incident wave is identical with the Gaussian pulse superposed on a carrier f_c = 3 GHz. The pulse amplitude is E_0 = 120 π mV/m, and the pulse width T = 0.5 LM (Figure 2a), where LM stands for light meter. Computing the pulse spectrum (Figure 2b), the excitation wave can efficiently excite harmonics from the interval $f \in$ <1 GHz, 5 GHz>.

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Time-domain analysis results in time responses of currents on discretization segments. Currents on antenna segments in the time instant ($m\,\Delta t$) are described by

$$\mathbf{I}(m\,\Delta t) = \begin{bmatrix} I\left(m\,\Delta t, \Delta z\right) \\ I\left(m\,\Delta t, 2\Delta z\right) \\ \cdots \\ I\left(m\,\Delta t, N_{z-1}\Delta z\right) \end{bmatrix}, \tag{1}$$

where $^{\mathrm{T}}$ denotes the transpose, N_z is the number of antenna segments, Δz is the sampling step of space, Δt is the sampling step of time and m is the time step index.

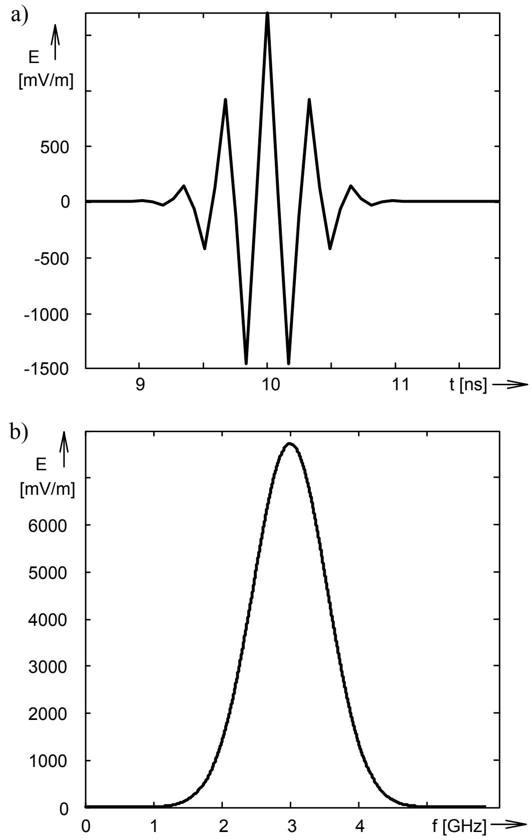

Figure 2. Excitation pulse: a) temporal response; b) spectral response.

Current distribution (1) can be influenced by the shape of the excitation pulse, and might suffer from dispersion errors. That is the reason for developing a special filtering technique, which compensates those errors.

3. TIME-DOMAIN INVERSE FILTERING

In order to suppress dispersion errors at higher frequencies, the ideal low-pass hard limiting FIR (finite impulse response) filter is used. The ideal transfer function

$$H_i(k) = \begin{cases} 1/E_i(k) & k \le f_{cr}/\Delta f \\ 0 & k > f_{cr}/\Delta f \end{cases} \tag{2}$$

is zero over the critical frequency f_{cr} and is reciprocally proportional to the spectrum of the Gaussian pulse below the critical frequency in order to eliminate the influence of the magnitude of the excitation. In (2), the symbol Δf denotes the sampling step of frequency and k is the index of the frequency step.

The ideal transfer function (2) is transformed to the time domain

$$h(n) = \frac{1}{N}\sum_{k=0}^{N-1}\left\{ H(k)\,\exp\left(j\,\frac{2\pi}{N}\,n\,k \right)\right\} \tag{3}$$

with n denoting the time index, N being the number of samples within the time window of the discrete Fourier transform and k being the frequency index.

By applying cyclic convolution

$$I_{corr}(m\,\Delta t, i\,\Delta z) = \sum_{n=0}^{N-1}\left\{ h\left[\mathrm{mod}_N(n)\Delta t\right]\cdot \right. \\ \left. \cdot\, I\left[\left(\mathrm{mod}_N(n-m)\Delta t, i\,\Delta z\right)\right]\right\}, \tag{4}$$

dispersion errors of the computed current distribution can be suppressed.

The corrected current distribution is used to compute time-domain parameters of the investigated antenna.

4. TIME-DOMAIN PARAMETERS

The corrected time response of the current distribution on the antenna (4) can be used to compose the time-domain far-field directivity pattern:

$$E_\vartheta(m\,\Delta t, \vartheta) = \frac{\mu_0\,\Delta z}{4\,\pi\,r}\,\sin(\vartheta)\cdot \\ \cdot \sum_{n=1}^{Nz-1}\left\{ \frac{I_{corr}\left[\left(t - \frac{\Delta r_n}{c}\right) + \Delta t,\; n\,\Delta z\right]}{2\Delta t} - \right. \\ \left. - \frac{I_{corr}\left[\left(t - \frac{\Delta r_n}{c}\right) - \Delta t,\; n\,\Delta z\right]}{2\Delta t} \right\}. \tag{5}$$

Here, the first time derivative of the current is approximated by the central difference. If the time instant $(t - \Delta r_n/c) \pm \Delta t$ does not meet the sampling moment, the actual value of the current is estimated using linear interpolation between neighboring current samples. The symbol Δr_n denotes the space shift of waves radiated by different antenna segments.

Exploiting the time-domain directivity pattern (5), the gain of the dipole in the direction ϑ can be calculated according to

$$D(m\,\Delta t, \vartheta) = 2\,\frac{\left| E_\vartheta(m\,\Delta t, \vartheta)\right|^2}{\sum_{s=0}^{180}\left| E_\vartheta(m\,\Delta t, \theta_s)\right|^2 \sin(\theta_s)\Delta\theta}\,. \tag{6}$$

Antenna parameters computed in both the domains can be directly compared using Parseval's theorem.

$$\sum_m \left| E_\vartheta(\vartheta, m\,\Delta t) \right|^2 \Delta t = \frac{1}{2\pi} \sum_u \left| E_\vartheta(\vartheta, u\,\Delta\omega) \right|^2 \Delta\omega \quad (7)$$

By integrating electric field intensities from frequency domain and time domain over the whole range of analysis, we can obtain mean-value directivity patterns, which have to correspond to each other.

5. TIME-DOMAIN OPTIMIZATION

The canonical planar antenna is going to be optimized from the viewpoint of the maximum gain, minimum dimensions and the prescribed bandwidth.

The maximum gain criterion is reduced to the requirement of the maximum radiation in the normal direction $\vartheta = 0°$ (perpendicular to the surface of the antenna substrate). Considering Parseval's theorem, the criterion can be formulated directly in the time domain in the mean-value sense

$$\min_{\mathbf{x} \in R^n} \left\{ P_{req} - \frac{1}{Z_v} \sum_m \left[E_\vartheta(0, m\,\Delta t)^2 \, \Delta t \right] \right\} . \quad (8)$$

Minimizing (8) with respect to the n-dimensional vector of state variables $\mathbf{x}$, the mean-value energy density in the normal direction $\vartheta = 0°$ approaches a prescribed energy density P_{req} (Z_v is the characteristic impedance of the free space surrounding the antenna). Thanks to Parseval's theorem (8), the mean-value energy density computed in the time domain is equivalent to the mean-value one computed in the frequency domain.

The maximum bandwidth criterion has to be initially formulated in the frequency domain. If the antenna is excited by the voltage U = 1 V, the input impedance equals $Z(\omega) = 1 / I_{feed}(\omega)$, where $I_{feed}(\omega)$ denotes the frequency response of the current in the feeding gap of the dipole. Consequently, the reflection coefficient is

$$s_{11}(\omega) = \frac{\dfrac{1}{I_{feed}(\omega)} - Z_0}{\dfrac{1}{I_{feed}(\omega)} + Z_0} = \frac{1 - Z_0\, I_{feed}(\omega)}{1 + Z_0\, I_{feed}(\omega)} \quad (9)$$

with Z_0 being the characteristic impedance of the feeder (frequency independent).

The frequency response of the current in the feeding gap equals to

$$I_{feed}(\omega) = \frac{1}{Z_0} \frac{1 - s_{11}(\omega)}{1 + s_{11}(\omega)} . \quad (10)$$

If the required frequency response of the reflection coefficient is substituted to (10), the frequency response of the corresponding feeding current is obtained. Exploiting inverse fast Fourier transform, the current can be mapped into the time domain $I_{feed}(t)$. If TDIE analysis of the antenna produces the same time response of the feeding current, we can conclude the antenna is of the required bandwidth without leaving the time domain. The bandwidth criterion can be formulated as follows:

$$\min_{\mathbf{x} \in R^n} \sum_m \left[I_{feed}(m\,\Delta t) - I_{corr}(m\,\Delta t) \right]^2 . \quad (11)$$

Here, $I_{corr}(m\,\Delta t)$ is the corrected current (4) in the feeding gap.

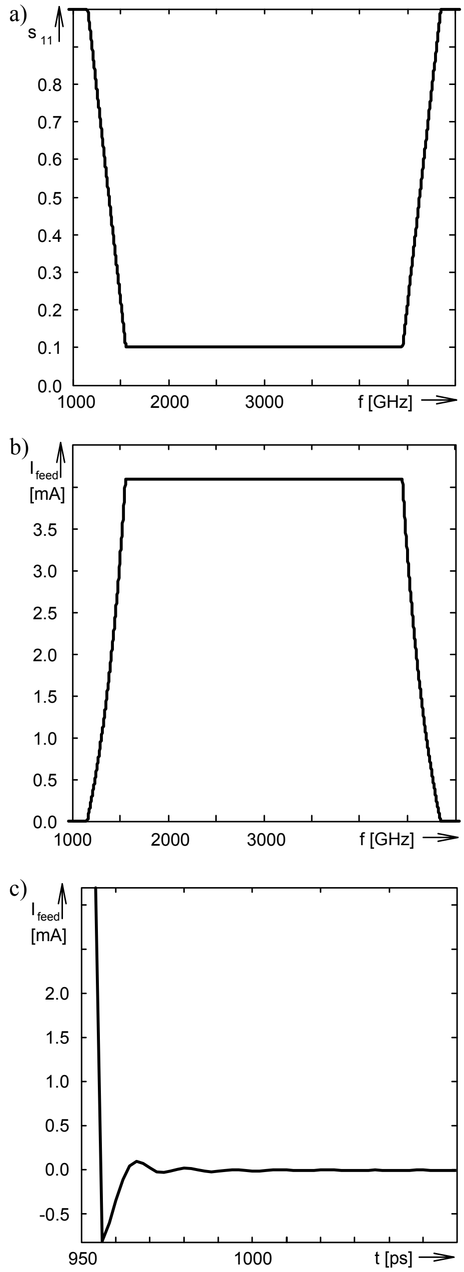

Figure 3. Bandwidth criterion: a) required frequency response of reflection coefficient, b) corresponding frequency response of current in feeding gap, b) corresponding time response of current in feeding gap.

Finally, the criterion of antenna minimum dimensions can be converted into minimizing the antenna volume

$$\min_{\mathbf{x} \in R^n} \left\{ V(\mathbf{x}) \right\} \quad (12)$$

In case of the planar dipole

$$V(\mathbf{x}) = A\, B\, h$$

with A and B being the length and the width of the dipole, and h being the height of the substrate.

5.1. Multi-objective formulation

The planar dipole is going to be optimized considering the criteria (8), (11) and (12).

In (8), $E_\vartheta(0, m\,\Delta t)$ is computed using (5), the required energy density is set to $P_{req} = 100$ J·m^{-2}.

In (11), frequency response of the reflection coefficient and the corresponding time response of the current in the feeding gap are adopted from Figure 3: reflection coefficient at the antenna input is required to be on the level –20 dB from 1.5 GHz to 4.5 GHz.

The above-formulated optimization problem is going to be solved by GA and PSO. In both the cases, the state vector consists of four rational state variables

$$\mathbf{x} = \begin{bmatrix} A & B & h & \varepsilon_r \end{bmatrix}^{\mathrm{T}} \tag{13}$$

with A being the length and B the width of the planar dipole, h is the height and ε_r the dielectric constant of the substrate.

During the optimization, state variables can vary in the following limits:

A ∈ <10 mm; 300 mm>;
B ∈ <0.01 mm; 0.10 mm>;
h ∈ <10 mm; 60 mm>;
ε_r ∈ <1.0; 2.0>.

Block diagram of the multi-objective optimization is depicted in Figure 4.

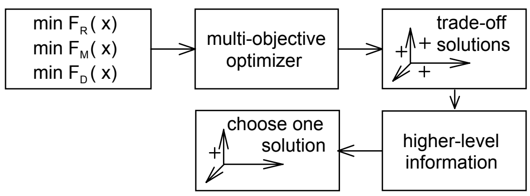

Figure 4. Block diagram of the multi-objective optimization: radiation objective F_R (8), matching objective F_M (11), dimensional objective F_D (12).

Results obtained by GA and PSO, and their mutual comparison are given in the following paragraphs.

5.2. Genetic algorithm

The multi-objective optimization problem is solved using a conventional genetic algorithm [8]:

- Each generation consists of 20 individuals; individuals are binary coded using 8 bits.
- Optimization is run 20 times over 50 generations.
- Probability of cross-over is set to 90 %, probability of mutation to 10 %.
- Population decimation is used as a selection strategy; elitist strategy is applied.

In Table 1, the best solutions obtained by the genetic algorithm are listed.

Table 1. Best optimization results obtained by the genetic algorithm.

	#1	#2	#3
F_R [V^{2}s/m^2]	99.9	100.7	100.0
F_M [A^2]	79.1	75.0	79.3
F_D [m^3]	38.3	117.5	36.3
A [mm]	44.0	59.8	41.7
B [mm]	0.1	0.1	0.1
h [mm]	27.4	59.2	27.4
ε_r [−]	1.4	1.0	1.2

In the column #1, the solution of the minimum radiation criterion is given. The column #2 gives the best matching solution. The minimum dimension solution is listed in the column #3.

Table 2. Best optimization results obtained by the particle swarm algorithm.

	#1	#2	#3
F_R [V^{2}s/m^2]	101.0	101.1	101.2
F_M [mA^2]	71.5	70.9	71.0
F_D [mm^3]	91.9	93.9	90.6
A [mm]	227.9	231.3	238.9
B [mm]	0.1	0.1	0.1
h [mm]	58.0	60.0	59.4
ε_r [−]	1.0	1.0	1.1

5.3. Particle swarm optimization

The problem is solved using a conventional particle swarm optimization [9]:

- A swarm consists of 20 agents.
- Optimization is run 20 times over 50 iterations.

- The inertial weight is linearly decreased from the value 0.9 in the initial iteration to the value 0.4 in the last one. Both the personal scaling factor and the global one are set to 1.49.
- The space of state variables is surrounded by absorbing walls.

In Table 2, the best solutions obtained by the particle swarm optimization are listed. In the column #1, the solution of the minimum radiation criterion is given. The column #2 gives the best matching solution. The minimum dimension solution is listed in the column #3.

6. CONCLUSIONS

In the paper, a novel multi-objective design procedure is proposed. In order to reach a good efficiency of the procedure, the design is fully executed in the time domain.

The design procedure consists of time-domain analysis by the time domain integral equation method, and a dispersion correction based on an inverse filtering and a cyclic convolution. Results of the analysis are used to formulate time-domain parameters, and compose partial cost functions of a multi-objective problem. Pareto optimal solutions are computed by the particle swarm optimization and genetic algorithms.

Results obtained by genetic algorithms are slightly better compared to those obtained by the particle swarm optimization. Nevertheless, the value of partial objective functions is quite high, and therefore, further improvement of the optimization engine is required.

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