Optimization of Ultrashort Pulse Duration with Usage of Genetic Algorithms by Criteria of Peak Voltage Maximization in PCB Bus

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***Abstract*—Importance of a genetic algorithms (GAs) usage in investigation of an ultrashort pulse peak voltage in multiconductor structures of printed circuit boards (PCB) is highlighted. Trapezoidal ultrashort pulse propagation along the conductors of real PCB multiconductor bus was simulated. With the usage of GAs an optimization of the whole ultrashort pulse duration and severally of the rise, top and fall durations was made by criteria of peak voltage maximization in the PCB bus. The optimization was run 5 times with the following parameters: the number of chromosomes in population – 3, 5; the number of populations – 5, 10, 25, 50, 75; mutation coefficient – 0.1; crossover coefficient – 0.5. A voltage maximum which is revealed with the whole ultrashort pulse duration variation by 16% exceeds the steady state level when the whole duration is near 0.13 ns. A voltage maximum by 36% exceeding the steady state level is revealed and localized with variation of ultrashort rise, top and fall durations. A maximum crosstalk value which is 24% of steady state level is revealed and localized for this case. For the last voltage and crosstalk maximums, the whole ultrashort pulse duration is near 1 ns. A good repeatability of results is shown.**

Keywords*—*ultrashort pulse; optimization; genetic algorithms; maximization criteria; printed circuit board; peak voltage.

I. Introduction

Electric signal propagation in multiconductor transmission lines (MCTL) is properly studied [1]. However particular aspects of ultrashort pulses propagation along conductors of high density printed circuit boards (PCB) are investigated insufficiently. It can be the reason of its uncontrolled propagation [2]. It is important to reveal and localize signal peak values because it may help to determine places of possible mutual parasitic influences and interference, thus it would be possible to take necessary measures in order to ensure electromagnetic compatibility. Moreover, it can help to choose places to install sensors for control of useful signals and monitoring of interference that is also important for improvement of radioelectronic equipment noise immunity and reliability [3].

It is effective to use computer simulation in such researches rather than measurements as it is necessary to obtain waveforms at multiple points along each conductor of complex structures. Besides, signal distortion by the input impedance of measuring probe has influence on the accuracy of voltage amplitude measurements. The quasi-static approach is widely used for analysis of PCB interconnections, because the accuracy of circuit analysis is often unacceptable, while electromagnetic analysis often requires large computation costs. Theoretical bases of quasi-static response calculation for an arbitrary network of MCTL sections are described in [4, 5]. Algorithms for calculation of time response based on this theory are developed [6] and allow calculation of current and voltage values only in network nodes.

Basic expressions and algorithm of current and voltage values calculation, that allow improved calculation of time response at any point along each conductor of MCTL section of an arbitrary network in TALGAT software, are implemented in [7]. This paper also contains the investigation of two-turn microstrip meander line that proves the necessity of more detailed research. For this reason, one-turn meander line in parameter range was examined [8].

Inasmuch single sections of ideal coupled lines are investigated in these papers, similar investigation of real PCB bus of autonomous navigation system [9] and ultrashort pulse maximum localization along bus conductors with variation of boundary conditions [10] have been carried out. The bus with a variation of ultrashort pulse duration has been investigated in [11], however, only 3 durations of the ultrashort pulse with fixed choice were considered. Meanwhile, the bus investigation with variation of the ultrashort pulse duration is important for radioelectronic equipment performance and interference immunity increasing. Indeed, for performance increasing duration of useful signals is decreased, while shorter interfering signals are more dangerous. But it is effective to use optimization in investigations with variation of ultrashort pulse duration, because it lets to investigate a wider range of ultrashort pulse durations, and obtained results will be more accurate. Calculation of peak values of an ultrashort pulse can take much time and there are a lot of variants of ultrashort pulse duration. Due to this fact, it is useful to use evolutionary algorithms, GAs in particular. It is known that GAs are widely used by researchers for electromagnetic and radio waves propagation tasks. The number of papers devoted to this

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problem and published in high quoting international journals increases every year. A search in the Scopus database shows that there are 65762 conference papers and 94510 journal papers related to GAs from 1977 to 2016 [12] that is significantly exceeds a number of papers, where other evolutionary methods are used.

The purpose of this work is to investigate the peak voltage levels in the PCB bus of autonomous navigation system with usage of an optimization of the ultrashort pulse durations by means of GAs based on the peak voltage maximization criteria.

II. Theory

A. Response Calculation

Frequency domain equations are used for calculation of voltage and current response in MCTL section [7]:

$$\mathbf{V}(x) = \mathbf{S}_V\,(\mathbf{E}(x)\mathbf{C1} + \mathbf{E}(x)^{-1}\mathbf{C2}), \quad (1)$$

$$\mathbf{I}(x) = \mathbf{S}_I\,(\mathbf{E}(x)\mathbf{C1} - \mathbf{E}(x)^{-1}\mathbf{C2}), \quad (2)$$

where $\mathbf{S}_V$ and $\mathbf{S}_I$ are the matrixes of modal voltages and currents; $\mathbf{E}(x)$ is the diagonal matrix $\{\exp(-\gamma_1 x),\ \exp(-\gamma_2 x),\ \ldots,\ \exp(-\gamma_{N_k} x)\}$ and γ_{N_k} is the propagation constant for k-th MCTL section, N_k is number of conductors of a k-th MCTL section, x is the coordinate along the MCTL section. Calculation of $\mathbf{S}_V$, $\mathbf{S}_I$ and $\mathbf{E}(x)$ is described in [6]. **C1**, **C2** are constant vectors calculated as

$$\begin{bmatrix}\mathbf{C1}\\ \mathbf{C2}\end{bmatrix} = \begin{bmatrix}\mathbf{S}_V & \mathbf{S}_V\\ \mathbf{S}_V\mathbf{E}(l) & \mathbf{S}_V[\mathbf{E}(l)]^{-1}\end{bmatrix}^{-1}\begin{bmatrix}\mathbf{V}(0)\\ \mathbf{V}(l)\end{bmatrix}, \quad (3)$$

where $\mathbf{E}(l)=\mathbf{E}(x)$ for $x=l$; l is the length of the MCTL section; $\mathbf{V}(0)$ and $\mathbf{V}(l)$ are constant vectors describing the voltage at the ends of the MCTL section, determined after the solution of equation for circuit with n MCTL sections with lumped elements at the ends:

$$\mathbf{V}(s) = \left(s\mathbf{W} + \mathbf{H} + \sum_{k=1}^{n}\mathbf{D}_k\mathbf{Y}(s)_k\mathbf{D}_k^t\right)^{-1}\mathbf{E}(s), \quad (4)$$

where $s=j\omega$, where ω is angular frequency; **W**, **H** are matrices of order $A\times A$ describing the lumped memory and memoryless elements of network, respectively (A is the number of parameters, which are calculated by modified node potential method); $\mathbf{D}_k = [i, j]$ with entries $l_{i,j} \in \{0, 1\}$, where $i \in \{1, \ldots, N_k\}$, $j \in \{1, \ldots, 2N_k\}$ with one nonzero value in each column, is the selector matrix that maps the terminal currents of the k-th MCTL section; $\mathbf{Y}(s)_k$ is the conductance matrix of the k-th MCTL section; $\mathbf{V}(s)$ is the vector of node voltage waveforms; $\mathbf{E}(s)$ is a constant vector with entries determined by the independent voltage and current sources.

The algorithm used for calculation of response is described in [6]. First of all, initial time domain excitation is transformed to frequency domain by means of forward fast Fourier transformation (FFT). Then calculations of (1)–(4) are carried out. The obtained result is transformed to time domain by means of inverse FFT.

B. Structure under Simulation

PCB bus of autonomous navigation system was taken as a structure for investigation. PCB fragment is presented in Fig. 1, and its circuit diagram in Fig. 2.

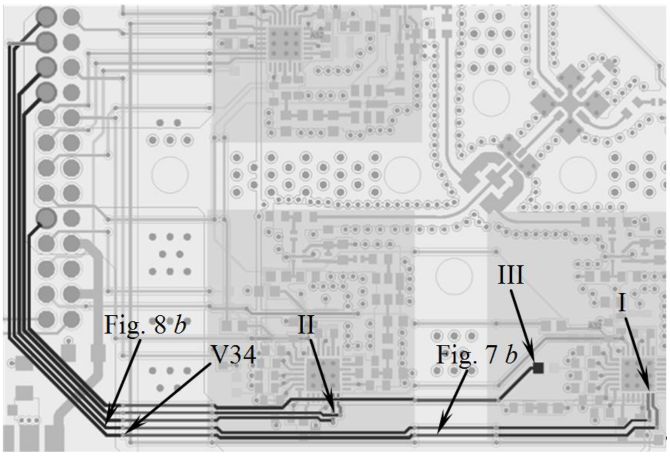

Fig. 1. Investigated bus on the PCB fragment

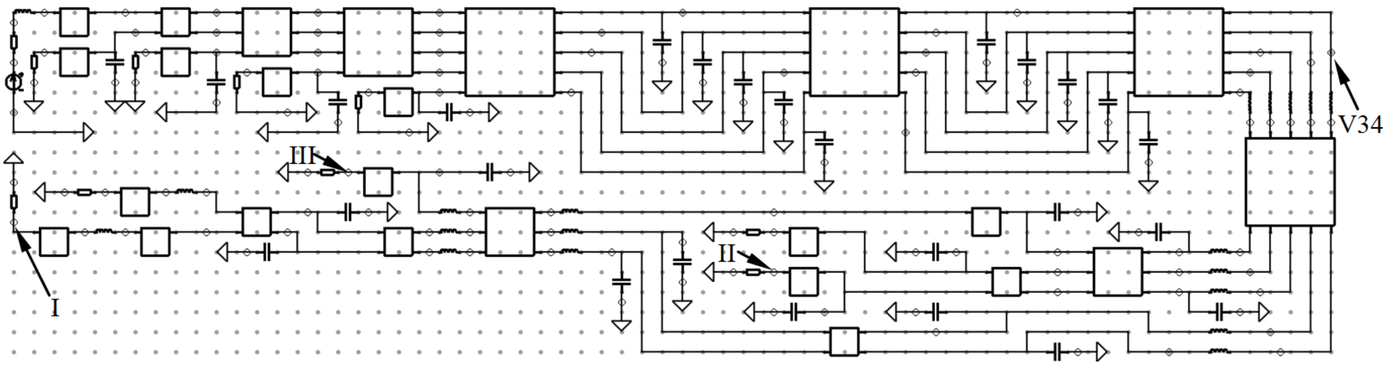

Fig. 2. PCB bus circuit diagram in TALGAT software

50 Ohm resistors are connected to the ends of each bus conductors. Conductor bend and via are approximately modeled as capacitance of 1 pF and inductance of 1 nH, respectively. Cross sections of each MCTL section are modeled and **L** and **C** matrixes are calculated according to PCB stack parameters. The calculation is made without losses.

C. Excitation Parameters

A trapezoidal ultrashort pulse with electromotive force amplitude of 1 V and with variation of its durations was chosen as excitation. The investigation consists of 2 parts. In the first part, the whole ultrashort pulse duration (t_Σ) was ranged from 3 down to 0.03 ns. In the second part, the rise (t_r), flat top (t_d), and fall (t_f) durations were severally ranged from 1 down to 0.01 ns. For example, forms of three pulses (two ones from the bounds of the range, and one inside the range) from the first part of the investigation are presented in Fig. 3.

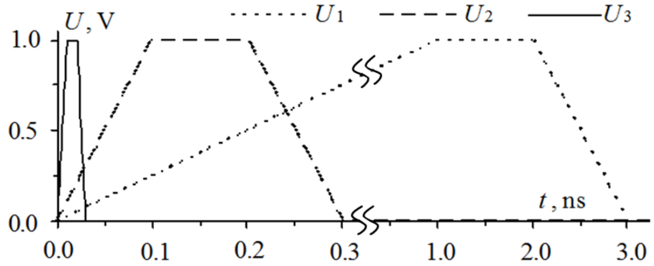

Fig. 3. Excited pulse waveforms from the 1-st part of the investigation

The first pulse (U_1) has rise, top and fall times of 1 ns, the second (U_2) – 100 ps, and the third (U_3) – 10 ps, so the whole durations are 3; 0.3; 0.03 ns. Such choice of excitation parameters is determined by fact that in such way not only useful signals but interference are considered.

D. Optimization Parameters

GAs, the most popular evolutionary algorithms, are inspired by Darwin's natural selection. GAs can be real or binary-coded. In a binary-coded GA, each chromosome encodes a binary string [13]. The most commonly used operations are crossover, mutation and selection. Selection operator chooses two parent chromosomes from the current population according to a selection strategy. Most popular selection strategies include roulette wheel and tournament selection. Crossover operator combines two parent chromosomes in order to produce one new child chromosome. Mutation operator is applied with a predefined mutation probability to a new child chromosome. GA usage let us exclude the blind search. The real-coded GA was run with the following parameters: mutation coefficient – 0.1; crossover coefficient – 0.5. One parameter – the whole ultrashort pulse duration was optimized in the first part, when the duration range was from 3 ns to 30 ps, the number of chromosomes was 5, the numbers of populations were 5, 25 and 50. A peak voltage in preset node of PCB bus of autonomous navigation system was maximized. Therefore an aim of the optimization in the first part of the investigation was to define the whole ultrashort pulse duration values, with which the peak voltage in V34 node (shown by arrows in Fig. 1 and 2) of PCB bus will be the highest.

The rise, flat top and fall durations were severally optimized in the second part of the investigation when the duration range was from 1 ns to 10 ps, the numbers of chromosomes were 3 and 5, the numbers of populations were 5, 25, 50 and 75. A sum of peak voltages from the ends of the PCB bus conductors located in the points I, II and III (shown by arrows in Fig. 1 and 2). These points are the places where the bus conductors are connected to the other PCB components. An aim of the second part of the investigation was to define the rise, flat top and fall duration values of the ultrashort pulse, with which the sum of voltages in the preset points will be maximal.

III. SIMULATION RESULTS

GA operation results of the first part of the investigation are shown in Table I, where N_P is the number of populations. Signal waveforms with the highest voltage maximum value (0.58 V) from the last line of the table are presented in Fig. 4, where U_b is the voltage at the input of the line and U_{max} is the maximum.

TABLE I. RESULTS OF GA OPERATION FOR t_Σ

N_P	t_Σ, ns	U_{max}, V
5	1.936584	0.530
10	1.913967	0.537
50	0.128297	0.580

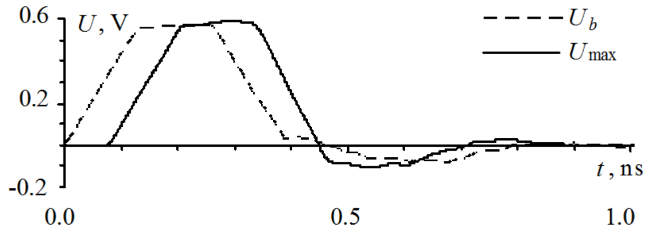

Fig. 4. Signal waveforms for the last line of Table I

GA operation results, including calculation of time (t), for rise, flat top and fall time of the ultrashort pulse are presented in Table II (the number of chromosomes is 3) and Table III (the number of chromosomes is 5). GA was run 5 times for each combination of the chromosomes number and the population number. It was made in order to check the repeatability of the fitness function results. A diagram of the U_{max} values repeatability with different number (n) of fitness function calculations is shown in Fig. 5. The number of fitness function calculations is defined as a product of the number of chromosomes and the number of populations.

Dependences of the maximum voltage values and the average (of 5 runs) calculation time on the number of calculations are shown in Fig. 6. 20 voltage waveforms were calculated in the each segment along each conductor of each MCTL section from Fig. 2 with the obtained results for the highest fitness function value (run 2 from Table III, when the number of populations was 75). But only waveforms at the conductor beginning (U_b) and end (U_e) and also with voltage maximum (U_{max}) values are presented. Presented results are only for an active and one passive conductor with the highest amplitude of the crosstalk.

TABLE II. RESULTS OF GA OPERATION FOR 3 CHROMOSOMES

N_P	Number of a run	t, s	t_r, ns	t_d, ns	t_f, ns	U_{max}, V
5	1	301.827	0.692	0.699	0.3340	0.507710
	2	374.913	0.745	0.690	0.1960	0.510236
	3	374.016	0.291	0.999	0.0727	0.518469
	4	333.273	0.972	0.713	0.2090	0.510192
	5	391.764	0.747	0.327	0.0101	0.546158
10	1	648.345	0.4830	0.750	0.1440	0.511593
	2	425.569	0.4220	0.482	0.0207	0.543905
	3	439.833	0.5110	0.814	0.0240	0.543271
	4	448.875	0.6980	0.937	0.0129	0.550312
	5	465.820	0.0651	0.829	0.0163	0.547927
50	1	2078.44	0.6920	0.938	0.0106	0.550997
	2	2385.75	0.1810	0.996	0.0102	0.551670
	3	2073.93	0.9620	0.826	0.0111	0.551141
	4	2380.27	0.0129	0.974	0.0115	0.554244
	5	2076.47	0.7270	0.865	0.0114	0.550982
75	1	3220.33	0.0200	0.7522	0.01104	0.553684
	2	3017.33	0.8927	0.7844	0.01122	0.551010
	3	3232.79	0.0111	0.5440	0.02232	0.554159
	4	4454.49	0.6021	0.9595	0.01034	0.551760
	5	3245.76	0.4864	0.9259	0.01004	0.551706

TABLE III. RESULTS OF GA OPERATION FOR 5 CHROMOSOMES

N_P	Number of a run	t, s	t_r, ns	t_d, ns	t_f, ns	U_{max}, V
5	1	441.407	0.989	0.0114	0.800	0.551147
	2	452.437	0.500	0.0199	0.879	0.545629
	3	486.692	0.447	0.0356	0.582	0.534152
	4	486.508	0.707	0.0251	0.127	0.531801
	5	510.564	0.111	0.0550	0.954	0.524602
10	1	983.870	0.663	0.0119	0.925	0.550284
	2	1045.06	0.487	0.0100	0.772	0.551331
	3	1133.29	0.429	0.0102	0.652	0.549775
	4	1204.64	0.894	0.0111	0.923	0.550668
	5	1280.82	0.951	0.0184	0.719	0.547373
50	1	3679.80	0.9160	0.0108	0.874	0.551185
	2	3689.23	0.3980	0.0114	0.938	0.551207
	3	3686.37	0.7300	0.0103	0.761	0.551353
	4	3649.92	0.0135	0.0104	0.820	0.553568
	5	3673.96	0.6580	0.0103	0.789	0.551315
75	1	5951.78	0.7402	0.01123	0.931	0.551358
	2	5707.05	0.0123	0.01214	0.549	0.554590
	3	5479.93	0.6261	0.01045	0.785	0.551505
	4	5818.87	0.0108	0.01432	0.658	0.552927
	5	5880.29	0.8017	0.01031	0.870	0.551700

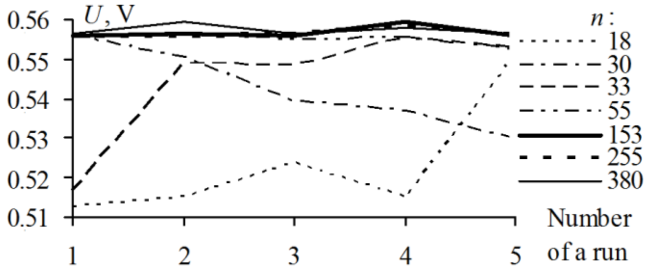

Fig. 5. U_{max} values for 5 runs with different n

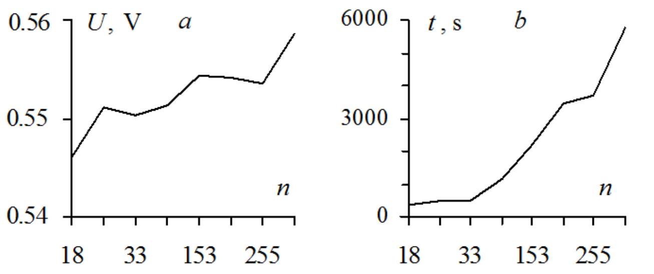

Fig. 6. Dependences of the maximum voltage values (*a*) and the average calculation time (*b*) on *n*

Voltage waveforms along the active conductor are shown in Fig. 7 *a*, and the ultrashort maximum location is shown in Fig. 7 *b*. Voltage waveforms along the passive conductor are shown in Fig. 8 *a*, and the crosstalk maximum location is shown in Fig. 8 *b*.

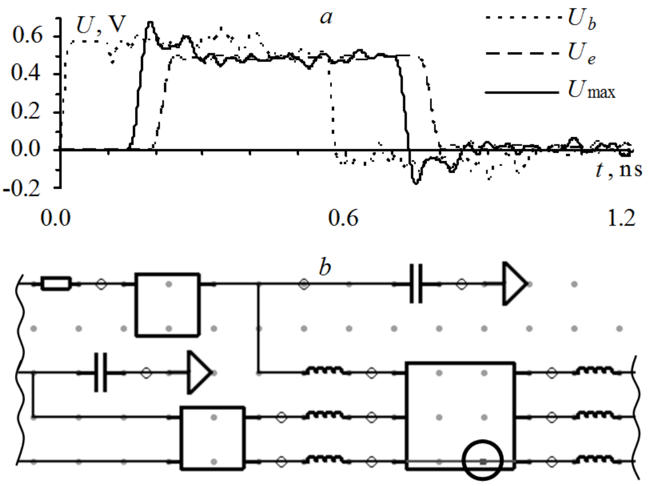

Fig. 7. Voltage waveforms along the active conductor (*a*) and the voltage maximum location (*b*)

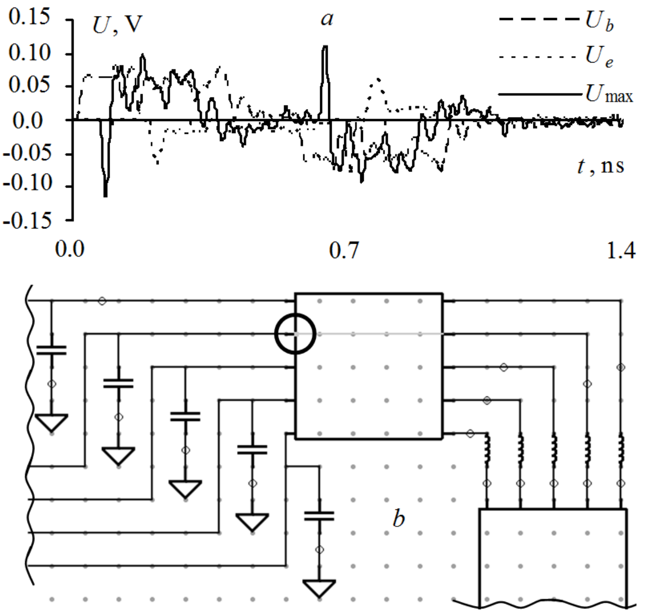

Fig. 8. Voltage waveforms along the passive conductor (*a*) and the crosstalk maximum location (*b*)

IV. Discussion of Results

Let us consider the optimization results from the first part of the investigation. They show that with the increasing number of calculations, the fitness function value increases (Table I). The revealed voltage maximum is 0.58 V (Fig. 4) that is by 16% higher than the steady state level when the whole ultrashort pulse duration is near 0.13 ns.

Let us consider the optimization results from the second part of the investigation. Like in the first part, they show that with the increasing number of calculations, the fitness function value increases (Fig. 6 *a*) but the calculation time also increases (Fig. 6 *b*). With the maximal number of calculations the fitness function value is 0.55459 V (Table III) and the average (of 5 runs) calculation time is 5767.5 s. The fitness function results show a good repeatability when a number of calculations is 255 and 380, the results differ only in the third decimal place.

Voltage maximum in the active conductor is revealed and localized with the optimized parameters (short rise and fall times, and maximal flat top duration) which are obtained at the run 2 (the number of chromosomes is 5 and the number of populations is 75) from Table III. The revealed voltage maximum is 0.68 V (Fig. 7 *a*) that is by 36% higher than the steady state level. The maximum is located in the segment 6 (Fig. 7 *b*) in MCTL section of another layer of PCB. Moreover, the crosstalk maximum is revealed and localized in segment 1 in one of the five-conductor transmission line sections. The crosstalk maximum is 0.12 V that is 24% of steady state level.

V. Conclusion

The investigation shows the importance of an optimization with GAs usage for revelation and localization of signal peak values or sum of several signals under the excitation of the ultrashort pulses with different durations. For instance, as we can see from Table I, the maximal value of the fitness function is 0.58 V, in Table II it is 0.5543 V, and in Table III it is 0.5546 V.

This paper considers the variation in parameter range only of one excitation, but it is easy to consider any other excitations, for example, electrostatic discharge, Gaussian pulse, etc. Also, the investigation is carried out only with variation of excitation parameters without any attempts of decreasing of revealed voltage maximums. It is useful to carry out an investigation with decrease of the revealed voltage maximums in future. It can be made by correction of the circuit diagram of PCB bus of spacecraft autonomous navigation system. The results of GA usage show the ability to discard the blind search and to solve more complex optimization tasks, for example, the influence of ultrashort pulse durations on the voltage peak values along the active and the passive conductors of the whole PCB. It is important to emphasize that the main GA parameters were constant in this paper. However, there are papers where variation of the crossover or mutation coefficient significantly influences on the repeatability and accelerates an optimization process. Future investigations of the authors will be dedicated precisely to these tasks. Such approach will allow to minimize the interference influence and to exclude the upsets of integrated circuits of spacecraft critical devices.

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