Influence of Ultrashort Pulse Duration on Its Peak Values Localization in PCB of Spacecraft Autonomous Navigation System

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Abstract – **Importance of research on specific aspects of ultrashort pulse propagation and voltage peak values localization along printed circuit board (PCB) multiconductor bus is highlighted. Simulation of a trapezoidal ultrashort pulse propagating along conductors of the bus with a different number of excited conductors, fixed variation of the whole ultrashort pulse duration (3; 0.3; 0.03 ns) and a duration optimized by genetic algorithms has been carried out. In the case of one excited conductor, the maximum value exceeds by 18% the ultrashort pulse amplitude at the input and the greatest (by modulus) minimum value is -36% of 0.5 V level lower the level of zero. In the case of two conductors, the highest maximum value exceeds by 20% the ultrashort pulse amplitude at the input and the minimum is -40% of 0.5 V level lower the level of zero. It is shown that significant signal excess is observed with decreasing of ultrashort pulse duration both for maximum and minimum. Also, localization of voltage peak values is inconstant: they appear in different parts of PCB bus including different PCB layers. With the usage of optimization, a voltage maximum in the given conductor exceeds the 0.5 V level by 16%, when the whole duration of an ultrashort pulse is near 0.13 ns.**

Index Terms – **ultrashort pulse, printed circuit board, localization, voltage peak values, genetic algorithms, optimization.**

I. Introduction

ELECTRIC signal propagation in multiconductor transmission lines is properly studied [1]. However particular aspects of ultrashort pulses propagation along conductors of high density printed circuit boards (PCB) are investigated insufficiently. 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 (EMC). 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 [2].

It is effective to use computer simulation in such researches rather than measurements as it is necessary to obtain waveforms at various points along each conductor of complex structures. 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 often unacceptable, while electromagnetic analysis often requires large computation costs. Theoretical bases of quasi-static response calculation for an arbitrary network of multiconductor transmission line sections are described in [3, 4]. Algorithms for calculation of time response based on this theory are developed [5] 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 transmission line section of an arbitrary network in TALGAT software, are implemented in [6]. 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 [7]. Inasmuch single sections of ideal coupled lines are investigated in these papers, similar investigation of real PCB bus of autonomous navigation system [8] and ultrashort pulse maximum localization along bus conductors with variation of boundary conditions [9] have been carried out. However, the bus investigation with variation of ultrashort pulse duration hasn't been done. Meanwhile, it is important for radio electronic equipment performance and interference immunity increasing. For performance increasing duration of useful signals and interfering signals is decreased. 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 (EAs), genetic 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 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 [10].

II. Problem Definition

The purpose of this work is to investigate the ultrashort pulse localization along PCB bus of an autonomous navigation system with pulse duration variation (with fixed and optimized by GA durations of ultrashort pulse). To achieve the purpose, it is necessary to solve following tasks. First of all, it is necessary to describe shortly theoretical basis of simulation. Then it is useful to present the investigated bus and its circuit diagram, as well as results of signal maximum and minimum localization along its conductors with fixed variation of excitation duration, and also the results of GA usage for an easier case: in the given part of one of the bus conductors. The main results of these tasks solution are presented in the next paragraphs.

III. Theory

A. Response Calculation

Frequency domain equations are used for calculation of voltage and current response in multiconductor transmission line section [6]:

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

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

where $\mathbf{S}_V$ and $\mathbf{S}_I$ are the matrixes of modal voltages and currents which calculation is described in [5]; $\mathbf{E}(x)$ is the diagonal matrix $\{\exp(-\gamma_1 x), \exp(-\gamma_2 x), \ldots, \exp(-\gamma_{N_{COND}} x)\}$ and γ_i is the propagation constant for i-th mode, x is the coordinate along the transmission line section; **C1**, **C2** are constant vectors. To find $\mathbf{V}(x)$ and $\mathbf{I}(x)$ for each transmission line section of network, we must calculate **C1** and **C2** from equation

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

where $\mathbf{E}(l)$=$\mathbf{E}(x)$ for x=l, where l is the length of the transmission line section; $\mathbf{V}(0)$ and $\mathbf{V}(l)$ are constant vectors describing the voltage on the near and far ends of the transmission line section, determined after the solution of equation for circuit with n multiconductor transmission line sections with lumped elements of 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 $\mathbf{W}, \mathbf{H} \in \Re^{N\times N}$ are constant matrices describing the lumped memory and memoryless elements of network, respectively, and $\Re^N$ is the node-space of network; $\mathbf{E}(s) \in \Re^N$ is a constant vector with entries determined by the independent voltage and current sources; $\mathbf{D}_k = [i\ \ j]$ with elements $l_{i,j} \in \{0, 1\}$, where $i \in \{1, \ldots, N\}$, $j \in \{1, \ldots, 2N_{COND}\}$ with a maximum of one nonzero in each row or column, is the selector matrix that maps the terminal currents of the distributed subnetwork to the nodal space of the linear network and N_{COND} is number of conductors of a transmission line section; $\mathbf{V}(s) \in \Re^N$ is the vector of node voltage waveforms appended by independent voltage source currents and linear inductor current waveforms of linear network; $\mathbf{Y}(s)_k \in \Re^{2N_{COND}\times 2N_{COND}}$ is the admittance matrix having complex dependency on frequency, which are described in terms of transmission line parameters.

The algorithm used for calculation of response is described in [5]. 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. 50 Ohm resistors are connected to the ends of each bus conductors. Conductor bend and via are approximately simulated as capacitance of 1 pF and inductance of 1 nH, respectively. Cross sections of each transmission line section are modeled according to PCB stack parameters.

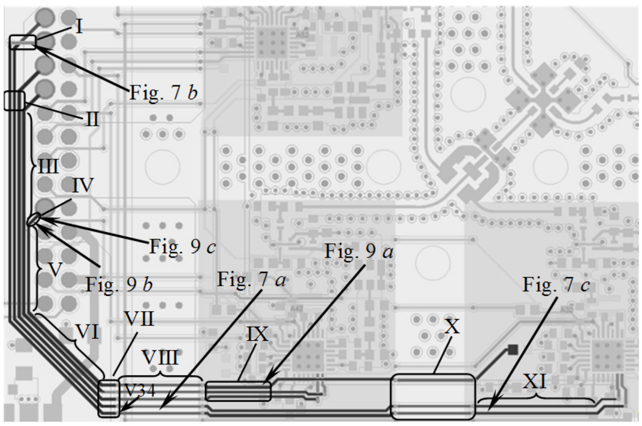

Fig. 1. Investigated bus on PCB fragment.

Two cases different by number and location of voltage generators were considered. In the first case, one generator connected to the first conductor (Fig. 3 *a*) was used. In the second case, two generators connected to first and 5th conductors (Fig. 3 *b*) were used (in these figures, generators are shown by arrows). In both cases, calculations were carried out and signal waveforms were obtained along each of five conductors with different excitations, but results are presented only for active conductors because they are of a major interest.

To obtain signal waveforms along defined conductor, it is necessary to choose A and B points. Calculation will be carried out between these points, which are presented in Fig. 4 for the both cases.

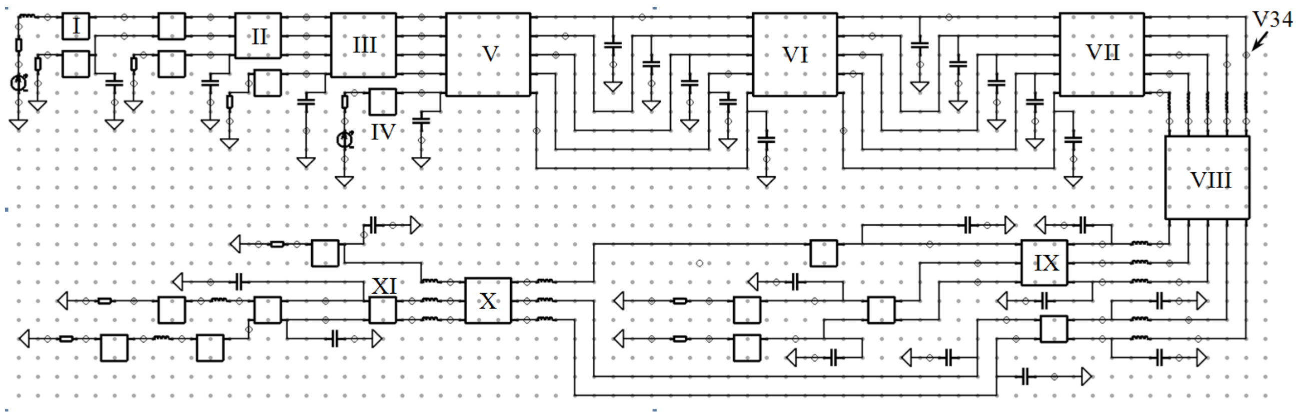

Fig. 2. PCB bus circuit diagram (with two generators) in TALGAT software.

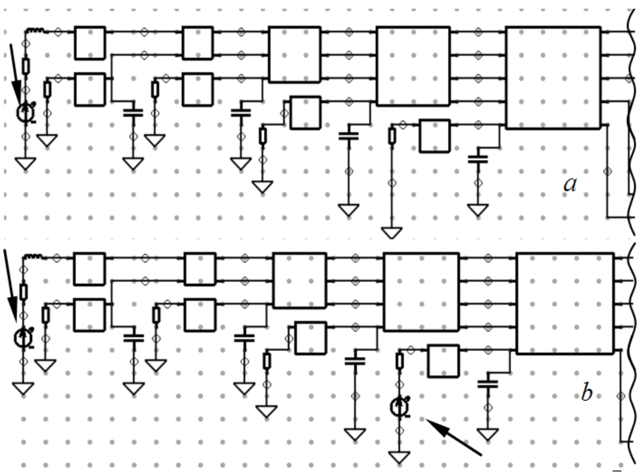

Fig. 3. Diagram fragment for cases with one (*a*) and two (*b*) generators.

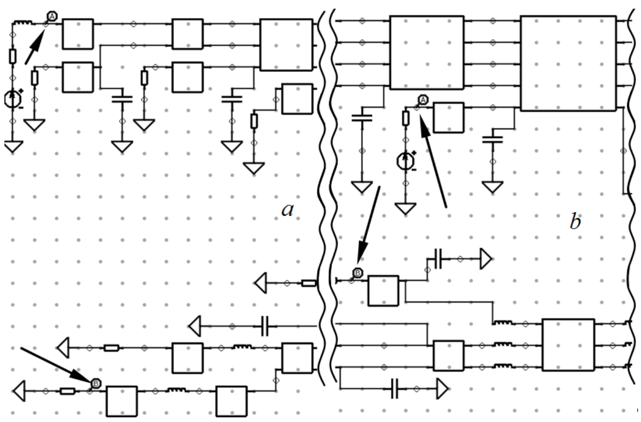

Fig. 4. A and B points for one (*a*) and two (*b*) generators.

C. Excitation Parameters

In this paper three types of ultrashort pulses, each with amplitude of 1 V are chosen as excitations. Waveforms of each pulse are presented in Fig. 5. 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. Each pulse was successively fed to each generator. In case with two generators, pulses on the both were the same.

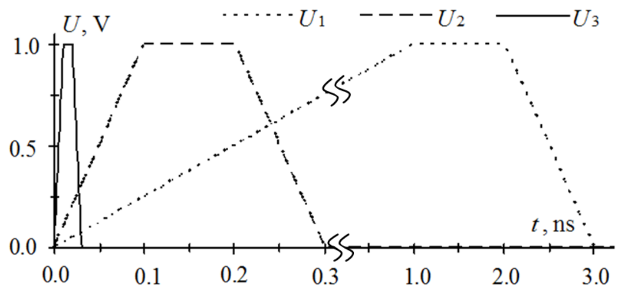

Fig. 5. Excitation pulse waveforms.

D. Optimization Parameters

GAs, the most popular EAs, 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 [11]. 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 to exclude the blind search. GA was launched with the parameters: the number of chromosomes in population – 5; the number of populations – 50; mutation coefficient – 0.1; crossover coefficient – 0.5. The whole duration of the ultrashort pulse was optimized in the range from 3 ns to 30 ps. Fitness function maximized the voltage peak value in the given node of PCB bus of autonomous navigation system. Therefore the aim was to seek such duration of ultrashort pulse with which the voltage peak value in the node V34 (showed by the arrows in Figs. 1, 2) of the PCB bus will be the greatest.

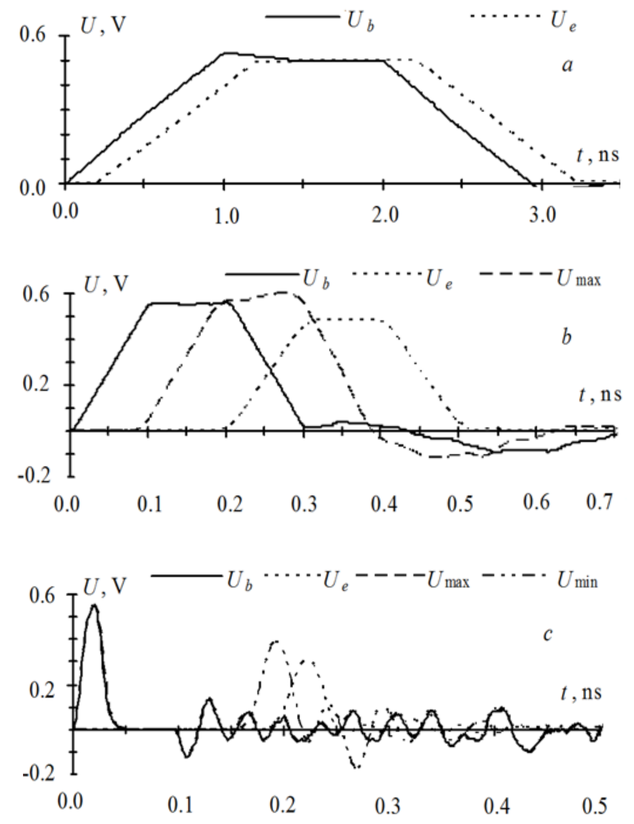

Fig. 6. Signal waveforms obtained in case 1 under the excitations U_1 (*a*), U_2 (*b*) and U_3 (*c*).

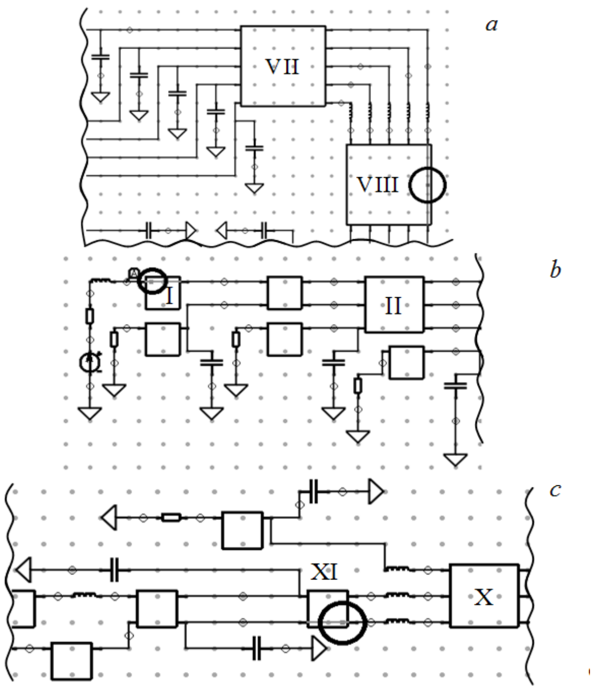

Fig. 7. Locations of maximums (*a* and *b*) for signals from Fig. 6 *b* and *c* respectively and also location of minimum (*c*) for signal from Fig. 6 *c*.

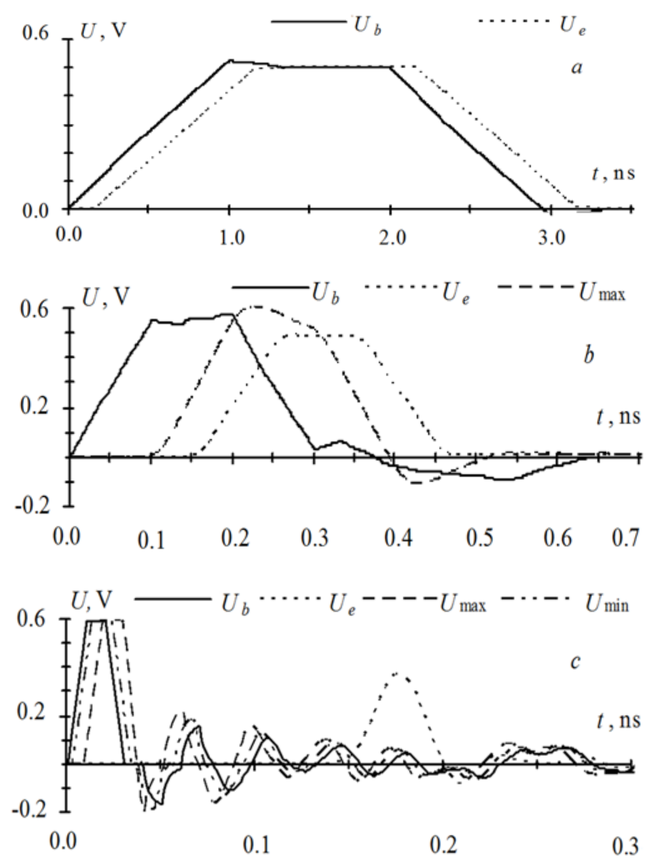

Fig. 8. Signal waveforms obtained in case 2 under the excitations U_1 (*a*), U_2 (*b*) and U_3 (*c*).

IV. Simulation Results

In case with one and two generators, 20 voltage waveforms were calculated in the each segments along each conductor of each transmission line section from Fig. 3. But only waveforms at the conductor beginning (U_b) and end (U_e) and also with voltage maximum (U_{max}) and minimum (U_{min}) values, appearing under each excitation, are presented.

Let us consider the first case with one generator connected to the first conductor. Signal waveforms along investigated conductor are presented in Fig. 6 and locations of these signals peak values are shown by circles in Fig. 7. Under the excitation U_1, signal maximum coincides with signal waveform in node, and minimums – under the excitations U_1 and U_2. Therefore their waveforms and locations are not shown in Figs. 6, 7. Simulation results for the second case are presented in Fig. 8 and peak values locations are shown by circles in Fig. 9.

Voltage peak values and numbers of segments with theirs locations are summarized in Table I. Table II shows the results of GAs operation – revealed duration of ultrashort pulse that is generating the greatest voltage in the node V34 of PCB. The waveforms for the last line of Table II with the highest voltage maximum value (0.58 V) are shown in Fig. 10.

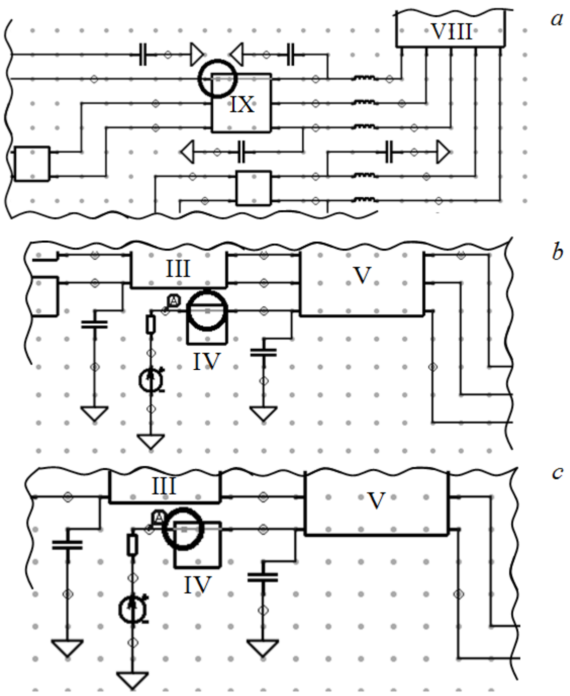

Fig. 9. Locations of maximums (*a* and *b*) for signals from Fig. 8 *b* and *c* respectively and also location of minimum (*c*) for signal from Fig. 8 *c*.

V. Discussion of Results

Let us consider the excitation (U_1). The waveforms presented in Fig. 6 *a* are revealed for the case with one generator, but peak levels and locations coincide with waveforms on the conductor's ends. The situation of the case with two generators is the same for the first one due to fact that revealed waveforms which are presented in Fig. 8 *a* also coincide with signals on the conductor's ends and are located in the diagram nodes.

Let us consider the U_2 and U_3 excitations which can be relegated to high-speed or interfering signals because its durations are shorter. In case with one voltage generator under the U_2 excitation, voltage maximum is 0.59 V (Fig. 6 *b*) that is by 18% higher than the steady level of 0.5 V. The maximum is localized in the segment 10 (Table I) in one of the transmission line sections (VIII) with five conductors that are located on another layer (Fig. 7 *a*). Under the U_3 excitation, not only voltage maximum of 0.552 V that is by 10% exceeding the 0.5 V level is revealed but also minimum of -0.18 V (Fig. 6 *c*) or -36% of 0.5 V lower the level of zero. Moreover, they are localized in the absolutely different places as we can see from Table I and Fig. 7 *b* and *c*.

In case with two generators voltage maximum of 0.6 V (Fig. 8 *b*) by 20% exceeding the 0.5 V level is revealed for U_2 excitation. It is localized in the segment 17 (Table I) in transmission line with three conductors which is located in the second half of PCB bus of autonomous navigation system. Two peak values are revealed for U_3 excitation: maximum of 0.593 V by 18% exceeding the 0.5 V level and minimum of -0.2 V or -40% of 0.5 V lower the level of zero. Both values are localized in the same transmission line section which is the nearest to voltage generator (Fig. 9 *b* and *c*). There are differences in number of segments: the minimum value is localized in the segment 5 and the maximum one is in the segment 11.

Let us consider both cases for U_3 excitation. Except for the appearance of peak values, multiple reflections are observed. The decrease of signal amplitude in the output of the line is observed. It is 0.3 V in Fig. 6 *c* and 0.4 V in Fig. 8 *c* that is by 40 and 20% lower the 0.5 V level.

It is seen from Table II that the greatest voltage value is 0.58 V that exceeds the 0.5 V level by 16%. The value is revealed when the whole duration of ultrashort pulse is near 0.13 ns.

TABLE I
Voltage Peak Values and Its Localization Parameters

Generators number	Excitation	Figure	U_{max} Value, V	U_{max} Segment, Figure	U_{min} Value, V	U_{min} Segment, Figure
1	U_1	6 *a*	0.530	1	-0.05	1
1	U_2	6 *b*	0.597	10 (7 *a*)	-0.11	20
1	U_3	6 *c*	0.552	5 (7 *b*)	-0.18	3 (7 *c*)
2	U_1	8 *a*	0.540	1	-0.05	1
2	U_2	8 *b*	0.604	17 (9 *a*)	-0.12	20
2	U_3	8 *c*	0.593	11 (9 *b*)	-0.20	15 (9 *c*)

TABLE II
Results of GA Operation

The number of populations	Duration of ultrashort pulse, ns	U_{max}, V
5	1.936584	0.530
25	1.913967	0.537
50	0.128297	0.580

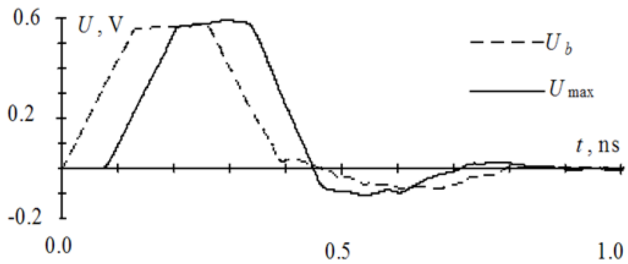

Fig. 10. Signal waveforms obtained for the last line of Table II.

VI. Conclusion

The investigation shows specific aspects of peak values appearance and localization of ultrashort pulses with different durations. For instance, the greatest maximum value (about

0.6 V) is observed under the U_2 excitation in both cases as we can see from Table I. However, if the amplitudes behave alike for both cases, then we can't say the same about its locations: they are located in different transmission line sections and segments along these lines (i.e. in different places of PCB). Inference should be drawn that for complex investigation of PCB, it is useful to consider not only useful but interfering signals because in such case stronger changes of signal waveform and amplitude are observed. It will allow increasing of radio electronic equipment efficiency and failure reliability.

This paper considers only three duration variants of one excitation, but it is easy to consider any other excitation, for example, electrostatic discharge, Gaussian pulse, etc. Also, we present only the results for active conductors, whereas more comprehensive processes will be observed in passive conductors because of crosstalk which should also be considered in detail. The results of GAs usage showed the ability to discard the blind search and to solve more complex optimization tasks, for example, the influence of ultrashort pulse durations from a number of excitation sources on the voltage peak values along active lines of the whole PCB. More complex investigation of active and passive lines is possible later. 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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