Multi-Variant Discrete Analysis of EMC of On-Board Radio Equipment with Use of Worst-Case Models

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***Abstract* — The technology for step-by-step computer diagnostics of EMC of radio equipment contained in a complex on-board system is developed. At the first stage, all potentially dangerous paths of interference propagation are identified with the use of the broadband analytical worst-case model developed within IEMCAP program; the model allows to calculate spurious couplings between antennas of radio equipment. At the second stage, refined worst-case models for the elements of potentially-dangerous interference propagation paths identified before (i.e., numerical models of frequency characteristics of spurious couplings, numerical or analytical models of emission spectra and susceptibility characteristics of the equipment) are developed; then EMC diagnostics is performed on the basis of the refined models. The final stage of the diagnostics is discrete nonlinear analysis of EMC, which is made with the help of the high order nonlinearity models and radio receivers' selectivity models; these models are obtained on the basis of the results of double-frequency testing of the receivers. The use of the developed technology makes it possible to achieve high computational efficiency of EMC diagnostics; this is demonstrated by way of the example of EMC diagnostics for on-board system containing a set of HF, VHF, and UHF radio stations installed on the small-sized mobile object.**

Keywords— EMC diagnostics, systems engineering and theory, worst-case models, electromagnetic coupling, intermodulation

I. Introduction

Wireless equipment of various radio services (fixed and mobile communication, navigation, radar, etc.) might operate unreliably when being installed on a small-sized object. This problem may be even more serious if the object is located within industrial zone where radio transmitters of different services are distributed with high terrestrial density. In this situation, the problem of ensuring the operation of wireless equipment in severe electromagnetic environment (EME) is rather complicated: it is necessary to provide both intrasystem and intersystem EMC of this equipment. The degree of EME severity is defined by a number of characteristics, such as the dynamic range of undesired signals at the input of each on-board radio receiver and the quantity of these signals. In these conditions, the most difficult problem is analyzing both the danger of nonlinear interference (intermodulation, desensitization, cross-modulation, etc.) and simultaneous effect of linear and nonlinear interference in radio receivers.

In many cases of EMC diagnostics of complex systems, a multi-variant analysis of intrasystem and intersystem EMC is required, i.e., the analysis of EMC must be performed for different locations and operation modes of on-board radio equipment, for different implementations of protective measures, for different characteristics of external EME, etc. For example, the analysis of various antenna locations on the mobile object body is intended to ensure the choice of the location variant with the smallest spurious electromagnetic (EM) couplings between the antennas and with the smallest influence of the changes in electrical characteristics of the soil (on which the object is situated) on intrasystem EMC. In practice, it is required to analyze dozens or even hundreds of variants of the system implementation and application, so the decrease in the duration of EMC diagnostics of each variant is an issue of particular importance.

When detecting and identifying linear and nonlinear radio interference, it is advisable to focus on pessimistic EMC estimates, which allow errors of the first kind ("false alarm") but exclude errors of the second kind ("erroneous undetection"). The price of the second-kind errors is many times higher since they have to be eliminated at subsequent stages of the system life cycle (otherwise the user must reconcile himself to the deterioration of the system performance due to the presence of interference in real operating conditions).

These features determine the reasonability of using the following methods and tools for EMC diagnostics: computationally efficient technologies and algorithms of discrete nonlinear EMC analysis [1, 2, 3], highly informative method of double-frequency experimental analysis of a radio receiver susceptibility to interference through its antenna input [4, 5, 6]; worst-case models for spurious EM couplings, emission spectra of radio transmitters, and frequency characteristics of the radio receiver susceptibility [7, 8]. The use of these modern methods and tools provides the ability of multi-variant computer diagnostics of the danger of linear and nonlinear radio interference, as well as the ability of detailed pessimistic analysis of EMC of an on-board system operating in the most severe EME. Earlier, the effectiveness of these technologies in diagnosing and solving EMC problems of radio equipment of complex stationary ground-based objects was demonstrated in [9].

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The objective of this work is a practical assessment of the effectiveness of using the above mentioned methods and tools for EMC diagnostics in the design of a vehicle equipped with a set of wireless equipment operating in HF, VHF, and UHF bands.

II. Description of Mobile Object and Its Radio Equipment

When developing a complex on-board system installed on a mobile object, the following is used as the initial data for designing and optimizing the EMC of this system: parameters of the object's body, characteristics of the antennas, emission spectra of radio transmitters, characteristics of frequency selectivity and front-end nonlinearity of radio receivers.

The analyzed system is a mobile control and communication system implemented on the board of a specialized vehicle capable of operating in swampy terrain of moderate and high latitudes in a hard climate for geological exploration and mining. A three-dimensional model of this vehicle is shown in Fig. 1. The main characteristics of radio stations used in different quantities and combinations in the analyzed variants of the on-board system are given in Table I. The types of antennas proposed for the use in this system are given in Table II.

Table I. Main Characteristics of Radio Stations Used in Designing the On-Board System

Characteristic	**Type 1**	**Type 2**	**Type 3**	**Type 4**
Frequency range, MHz	7.0-30	30-470	30-50	146-174
Radiated power, W	20-125	20-65	4-65	2-40
Rx Bandwidth, kHz	7.0	18.0	12.0	10.0
Rx Sensitivity, μV	1.0	0.5	0.5	0.35
Image channel selectivity, dB	80	80	80	60
Rx selectivity wrt other spurious responses, dB	80	80	80	70
Rx dynamic range for IM, dB	60	60	60	65

Table II. Types of Antennas Used in the Analyzed On-Board System

Type of Antenna	**Frequency Range, MHz**
1. Dipole antenna (2.9 m)	30-108
2. Dipole antenna (4.2 m)	2-80
3. Discone antenna (1.0 m)	100-470
4. Dipole antenna (1.35 m)	130-180
5. NVIS antenna	1.5-12

Based on the expected conditions of the application of the analyzed mobile control and communication system, the EMC analysis was performed for the following situations:

1. Operation of a single mobile object in an open area far away from other sources of radio interference. In this situation, the EME at the input of each radio receiver is mainly formed by the radiated emissions of the on-board radio equipment.

2. Operation of the on-board system in an extractive industry zone characterized by a high spatial density and high activity of use of HF, VHF, and UHF wireless equipment belonging to various radio services. In this case, the EME at the input of each radio receiver is created by radiations of not only the on-board transmitters but also a multitude of transmitters located in the extractive industry zone.

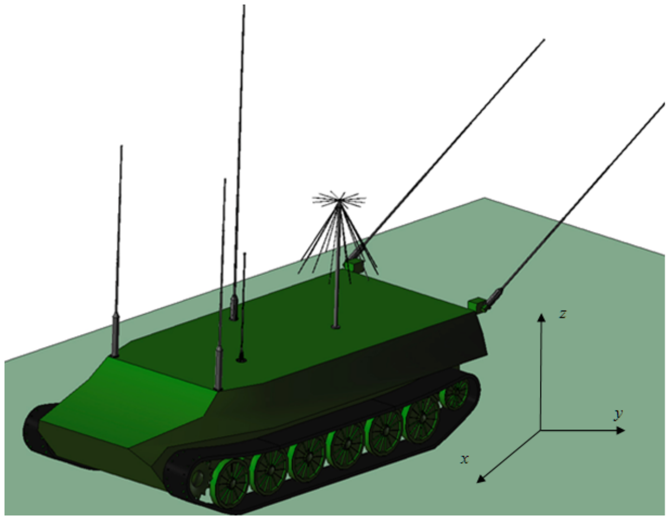

Figure 1. Three-dimensional model of the analyzed on-board control and communication system (one of the variants for placing antennas of radio communication equipment on the vehicle body is shown)

III. Technology for Analysis of EMC of On-Board Radio Equipment

The developed technology for multi-variant discrete analysis of EMC of on-board radio equipment operating in a complex EME includes the following main stages.

1. Discrete linear analysis of EMC with the use of simplified broadband worst-case models. This stage of analysis includes the following steps:

1.1. To develop a three-dimensional model of the vehicle (several variants of antenna location should be considered). At this step, it is necessary to evaluate all characteristics of the vehicle body and surrounding objects which may affect spurious EM couplings between the on-board antennas (e.g., the material of vehicle body, soil conductivity, parameters of antenna location on the vehicle body, as well as the type, size, and matching conditions of the antennas).

1.2. To develop simplified worst-case models for all variants of on-board system implementation, including the following models:

1.2.1. Models of antenna radiation patterns (which are needed to analyze the influence of external EME).

1.2.2. IEMCAP models of spurious EM couplings between the on-board antennas [7, 8].

1.2.3. Models of main and spurious emission spectra of each transmitter; these models must be defined in the wide frequency range [fmin/K, K*fmax], where [fmin, fmax] is the operating frequency range of the radio station, K = 2…10.

1.2.4. Models of frequency-dependent susceptibility of each radio receiver; these models must also be defined in the wide frequency range and they must account for the main channel, adjacent channel, and spurious responses of each receiver.

1.2.5. Models of frequency selectivity of input/output filters and feeder elements (cables, combiners, etc.).

The examples of such models are presented in Fig. 2 for the case of K = 10.

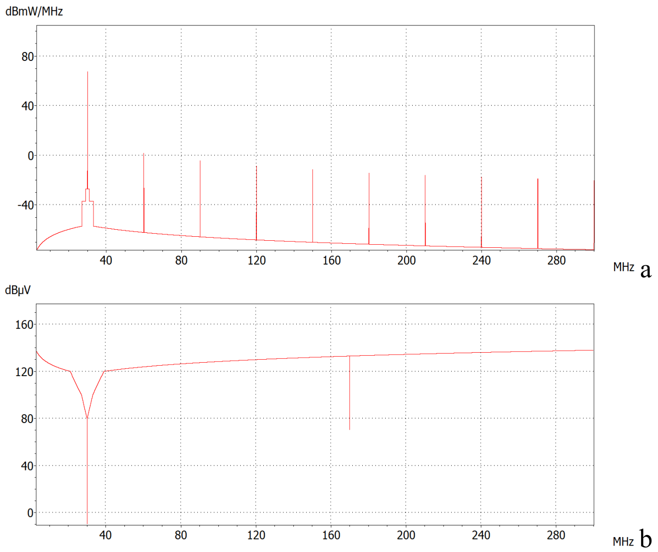

Figure 2. Worst-case models of EMC characteristics for type 1 radio station tuned at 30 MHz: (a) transmitter emission spectrum (b) receiver susceptibility

1.3. To perform the discrete linear modeling of EMC for each variant of location of on-board system antennas on the vehicle body. As a result, the initial worst-case estimation of danger of interference produced in radio receivers (via main and adjacent channels, and also via spurious responses) by main and spurious emissions of on-board system transmitters as well as by components of external EME is obtained.

1.4. To select the best variants of system implementation for the further analysis, i.e., to choose one or several variants for which the danger of interference in the radio receivers is minimal (that is, for which the interference margin values are minimized).

2. Discrete linear analysis of EMC with the use of detailed worst-case models. This stage of analysis includes the following steps:

2.1. To refine the models of potentially dangerous spurious EM couplings (i.e., those spurious couplings that cause interference identified at step 1.3 as dangerous).

2.1.1. By the use of numerical methods of computational electromagnetics (FDTD, MoM, FEM), to calculate S-matrix elements that characterize amplitude-to-frequency characteristics (AFCs) of spurious couplings between antennas; this calculation is performed for each selected variant of location of the antennas on the vehicle body. During these calculations, small variations in positions of the antennas are carried out, and the soil conductivity at vehicle location place is varied substantially. The calculations are performed in the relatively narrow frequency range in which the spurious couplings are identified as potentially dangerous.

2.1.2. To develop numerical worst-case models which envelop the calculated AFCs of the spurious couplings. An example of the numerical worst-case model of spurious coupling between antennas of type 4 and type 5 (ref. Table II) is given in Fig. 3. The blue solid line and the blue dashed line in Fig. 3 show the AFCs of S-matrix element S_{45} for maximal ($\sigma = \infty$) and minimal ($\sigma = 0$) values of the soil conductivity σ, correspondingly; positions of the antennas are fixed. The other blue lines show similar AFCs calculated for slightly changed positions of the antennas: the case of $\sigma = \infty$ is displayed by the dash-dot line and the case of $\sigma = 0$ is given by the dotted line. The pink line represents the mathematical envelope of the four above-mentioned AFCs, this envelope is constructed by the use of the technique developed in [9]. The red line represents the worst-case envelope constructed by connecting local maxima of the mathematical envelope as follows: the maxima the values of which are not less than the values of two adjacent maxima are connected.

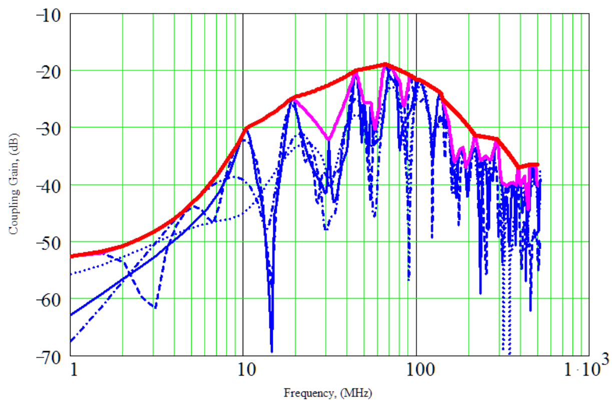

Figure 3. Amplitude-to-frequency characteristic of spurious coupling between antennas of type 4 and type 5: numerical solutions of Maxwell equations are shown as blue lines, their mathematical envelope is displayed by pink line, and worst-case envelope is given as red line

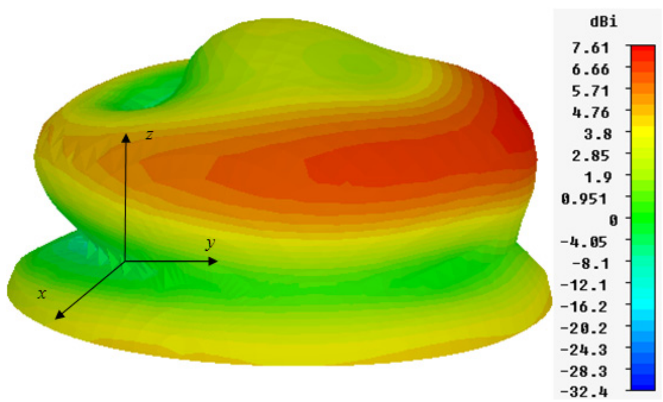

Figure 4. Radiation pattern of type 2 antenna at 50 MHz for one of variants of its location on the vehicle body, calculated by FDTD method for minimal value of soil conductivity

2.2. To refine radiation patterns of the antennas (taking into account the peculiarities of their construction, their location on the vehicle body, and soil conductivity) by the use of numerical methods of computational electromagnetics. This makes it possible to analyze the influence of external EME on the system more objectively. An example of the refined model of the radiation pattern is given in Fig. 4 for the following situation: the antenna of type 2 (ref. Table II) is located on the vehicle body so as to provide its minimal coupling to the other antennas.

2.3. To refine the discrete models of spectra for the emissions that cause potentially dangerous interference (e.g., by introducing discrete models of the desired signal modulation spectra, by more accurate representation of spurious and noise emission spectra, by the use of measured spectra).

2.4. To refine the models of frequency-dependent susceptibility characteristics of radio receivers, for example, on the basis of measurement results.

2.5. To perform the discrete linear modeling of EMC. As a result, the refined estimation of danger of the interference detected at step 1.3 (including the quantitative estimation in the form of integral interference margin values) is obtained for the system implementation variants selected at step 1.4 and for different operating frequencies of on-board radio stations.

2.6. To apply technical measures in order to protect the system from linear interference predicted at step 2.5 (e.g., to connect additional filters to radio-frequency terminals of the radio stations). To repeat step 2.5.

2.7. To select the system implementation variants providing the absence of linear interference in order to perform the further analysis of these variants.

3. Discrete nonlinear analysis of EMC. This stage makes it possible to detect and eliminate nonlinear interference arising in the radio receivers and includes the following steps:

3.1. To select radio receivers for which it is necessary to perform the analysis of nonlinear interference. For this purpose, the potential danger of nonlinear interference in each radio receiver is estimated as follows: if the levels of the radio receiver input signals exceed the threshold of the receiver susceptibility to intermodulation (this threshold is the lowest one from the thresholds of susceptibility to different nonlinear effects), then the analysis of nonlinear interference is necessary for this receiver.

3.2. To synthesize the nonlinear behavioral model [1, 2, 10] for each of the radio receivers selected at step 3.1. This model describes the frequency selectivity and front-end nonlinearity of a radio receiver. Peculiarities of the receiver's structure, components, and frequency conversion parameters should be considered in order to synthesize the model.

The most adequate model of the receiver may be obtained on the basis of its testing with the use of Automated Double-Frequency Test Technique [4, 5, 6]. Such tests allow to find and identify all linear and nonlinear channels that could produce interference in the radio receiver via antenna input (this is achieved by analysis of the receiver's 3D double-frequency characteristics and their color maps called double-frequency diagrams, the example of such characteristic and diagram is given in Figs. 5 and 6), to measure the parameters of these channels, and to measure the receiver front-end nonlinearity parameters in a very accurate way.

Based on results of these tests, the components of the receiver's behavioral model are synthesized: the models of input and main frequency selectivity [10], as well as the polynomial model of the front-end nonlinearity [2, 3].

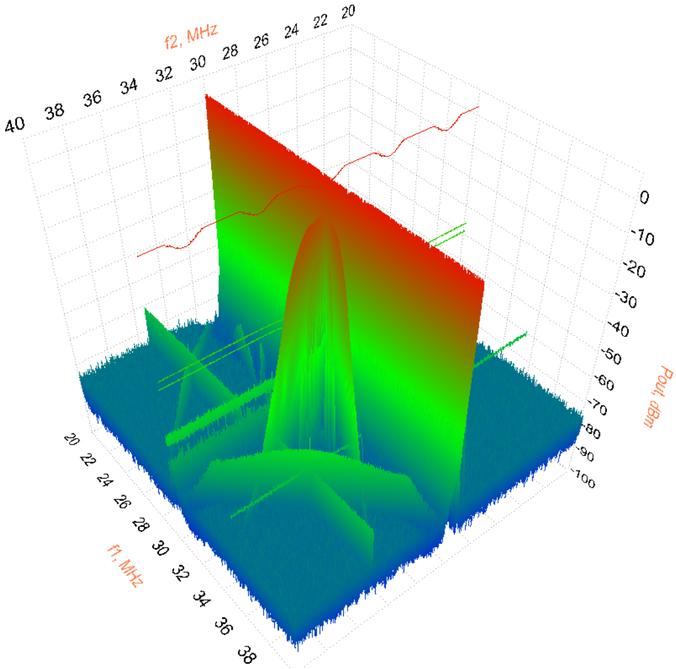

Figure 5. 3D plot of double-frequency characteristic measured for receiver of type 3 radio station; the receiver is tuned at 30 MHz

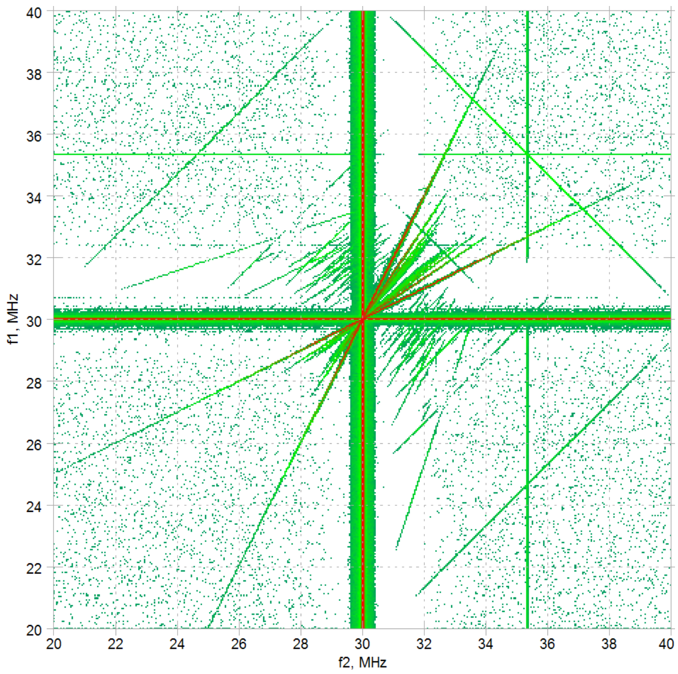

Figure 6. Double-frequency diagram which is a color-map plot of the double-frequency characteristic shown in Fig. 5, the display threshold level is -75 dBm (3 dB over the internal noise level of the receiver)

3.3. To perform the discrete nonlinear modeling of radio receivers' operation in the given EME (formed as a sum of external undesired signals and signals of on-board transmitters). The simulation is performed according to the technique [1, 2, 8] for each variant of the on-board antenna location on the vehicle body. Fig. 7 represents an example of intermediate results of the modeling: total signal spectra at various test points of the receiver's behavioral model for type 1 radio station. The final result is a set of situations in which the danger of nonlinear interference is confirmed.

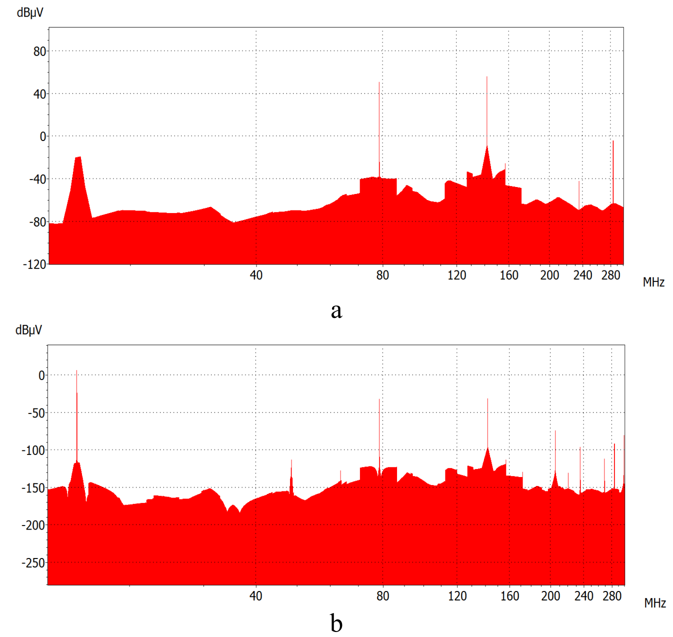

Figure 7. Spectra at test points of nonlinear model of type 1 radio station receiver tuned at 15 MHz: (a) at the output of receiver input filter model (b) at the output of the nonlinear model (intermodulation interference is identified)

3.4. To select the most preferable variant of antenna location on the vehicle body and, if necessary, to develop additional protective measures for the selected variant in order to prevent nonlinear interference in the on-board receivers.

IV. The Results of Mobile-Object Radio Equipment EMC Diagnostics

Computer diagnostics of intrasystem EMC for variants of on-board system implementation was performed under the following conditions:

1. at three levels of radiation power of transmitters (minimum, medium, and maximum);

2. with the use at least three operating frequencies for each radio station (near the lower bound, in the middle, and near the upper bound of the operating frequency range);

3. all possible variants of antennas (intended for on-the-move operation) were examined for each operating frequency.

The main results of the EMC diagnostics of the on-board system are as follows:

1. As a result of linear EMC simulation, variants of on-board system implementation for which the joint operation of specified radio stations is impossible are detected, and the operating conditions for each radio station without interference via the main, adjacent, and spurious channels of reception are determined.

2. As a result of the non-linear behavior simulation of radio receivers of the on-board system under the conditions listed above, and also taking into account external EME, cases of 3-rd and 5-th order intermodulation interference in the on-board receivers were detected and identified (see Fig. 7). It was also found that the traditional measures for providing EMC (the determination of bands and operating frequencies of specified radio stations, the use of which excludes the danger of intermodulation interference; the limitation of the radiated power of on-board transmitters; the use of attenuators at the inputs of receivers; the use of additional frequency filters, etc.) do not completely exclude the possibility of intermodulation interference in the examined on-board system. Therefore, it is suggested to use specialized software for the automated assignment of operating frequencies of the onboard radio equipment; in case of simultaneous operation of radio stations, this software will allow to exclude combinations of operating frequencies in which the on-board receivers can be affected by both linear and nonlinear interference.

3. The most reasonable variant of location of antennas on the vehicle body is chosen, which minimizes the danger of interference in radio receivers of the on-board system.

As a result of practical application of the developed technology intended for computer diagnostics of EMC in the process of complex on-board system engineering, the following features of this technology are defined:

1. The refinement of the worst-case models of radio transmitters' spectra and radio receivers' susceptibility characteristics, as a rule, allows to reduce significantly (by 10 ... 30 dB in the considered example of on-board system) the level of linear EMC analysis pessimism and to keep the practical absence of errors of the 2-nd kind (erroneous undetection of interference).

2. The procedure for pessimistic frequency discretization of spectra and susceptibility characteristics (this procedure is developed in [7] and improved in [8], it is based on the following rule: the value of a spectrum at a discrete frequency is chosen as the maximum value within the discretization interval, and the minimum value is chosen in susceptibility discretization procedure) is the reason for an additional increase in the number of errors of the 1st type and for overestimation of the integrated interference margin observed with a decrease in the number of frequency samples. This effect is insignificant if 10^6 samples are used; the overestimation is 0.3-1.7 dB (≈ 1 dB on the average) for 10^5 samples, and it increases sharply with the further decrease in the number of samples, e.g., the overestimation is 1.7-11.6 dB (≈ 7 dB on the average) for 10^4 samples.

3. The developed technology for computer diagnostics of EMC provides the ability of analysis of simultaneous linear and nonlinear interference of all kinds in the receiver, including the analysis of situation in which several nonlinear effects (intermodulation, desensitization, reciprocal mixing, cross-modulation, etc.) occur simultaneously in the receiver. This type of EMC analysis is much more detailed and

objective than the conventional analysis based on separate consideration of various types of interference. Another reason for increasing the accuracy of EMC analysis is the use of a complex EME model (in which the signals are represented not with accuracy to the carrier but in the form of discrete models of modulation spectra containing from several dozens to hundreds of spectral components) in process of the nonlinear modeling of radio receivers.

4. The developed technology provides the ability to create and continuously refine the on-board system model as the information about the characteristics of its radio equipment and the results of its operation is accumulated. This makes it possible to implement continuous support of the solution of the accompanying problems with intersystem and intrasystem EMC as the external operating conditions (i.e., EME) and the composition of on-board radio equipment are changed.

5. The main advantage of the developed technology of EMC diagnostics is the extremely high computational efficiency of discrete linear and nonlinear EMC analysis performed with high accuracy of representation of emission spectra, frequency responses of spurious couplings, susceptibility characteristics of radio receivers, and front-end nonlinearity of radio receivers (i.e., with high-order polynomial models of the nonlinearity). Table III shows the results of estimating the time required for performing the procedures of linear EMC analysis of one of the on-board system implementation variants; these estimations are made for different numbers of frequency samples in the spectra and susceptibility models by the use of a PC with AMD Phenom II 3.0 GHz processor and 12 GB RAM. Table IV shows the results of estimating the time required for performing the discrete nonlinear modeling of the impact of the complicated EME on a radio receiver represented by a behavioral model of "Filter–Nonlinearity–Filter" type (which is the sequence of an input filter, a nonlinear element, and an output filter of main selectivity); these estimations are made for different numbers of spectral components in the EME model and for various orders of polynomial approximation of the receiver front-end nonlinearity characteristic.

TABLE III. TIME NEEDED TO PERFORM PROCEDURES OF DISCRETE LINEAR ANALYSIS OF EMC

Procedure	**Number of frequency samples**		
	10000	**100000**	**1000000**
Computation of one spurious coupling between two antennas	< 1 s	< 1 s	7 s
Discrete linear analysis of EMC of on-board system (26 spurious couplings of "antenna-to-antenna" type)	2 s	12 s	101 s

TABLE IV. TIME NEEDED TO PERFORM PROCEDURES OF DISCRETE NONLINEAR ANALYSIS OF EMC

Number of frequency samples	**100000**		**1000000**	
Order of polynomial	**15**	**25**	**15**	**25**
One nonlinear transformation	< 1 s	2 s	5 s	11 s
Discrete nonlinear analysis of EMC of one receiver	2 s	2 s	9 s	14 s

V. CONCLUSION

The results of the multi-variant iterative discrete linear and nonlinear EMC analysis of the on-board system radio equipment (a set of HF, VHF, and UHF radio stations) with the use of worst-case models of spurious EM couplings, antenna patterns, transmitter emission spectra, and receiver (susceptibility and nonlinearity) characteristics confirmed the high efficiency of the developed EMC diagnostics technology and showed good agreement to the results of pilot tests. In particular, the full cycle of linear and nonlinear modeling of EMC for one variant of antenna positions with the use of an ordinary PC (described in Section IV), 10^6 discrete spectral components in the models of spectra and susceptibility characteristics, and 15…25-th-order polynomial models of receiver front-end nonlinearity took no more than 1 hour (including the computer time for calculations and output of the calculation results, but excluding the operator time for initial data acquisition and input, development of model, and analysis of the calculation results). This allowed to analyze more than 10 variants of antenna location on the vehicle body in a very limited time.

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