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"EMC-ANALYZER" EXPERT SYSTEM: IMPROVEMENT OF IEMCAP MODELS

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Abstract: The paper presents an overview of the current state of the art in a system-level electromagnetic compatibility (EMC) analysis technology called the discrete nonlinear analysis (DNA) and implemented in the "EMC-Analyzer" expert system. This technology is a fundamental evolution of a linear discrete EMC analysis; the last one was developed in the framework of the Intrasystem Electromagnetic Compatibility Analysis Program (IEMCAP). The DNA technology provides the following capabilities: 1) to model the radio transmission and reception in an extremely severe (up to 100 000 of modulated signals) electromagnetic environment (EME); 2) to consider both the linear effects (gain, attenuation, filtering) and the nonlinear effects of various types (intermodulation, desensitization, cross-modulation, reciprocal mixing, amplitude-to-phase conversion) and high orders (up to the order 25 and higher) in one common simulation procedure; 3) to carry out the EMC analysis quickly (the DNA's computational advantage over traditional techniques grows rapidly with increasing EME complexity and with increasing order of the nonlinear effects); 4) to automatize the search of nonlinear interference sources.

Keywords: discrete nonlinear analysis, intermodulation, IEMCAP, EMC-Analyzer.

1. INTRODUCTION

The "EMC-Analyzer" expert system is a comprehensive and powerful software tool to solve EMC problems in various onboard and ground systems (aircraft, helicopter, missile, satellite, ship, car, airport, seaport, building roof, antenna tower, etc.) by taking into account various types of spurious couplings and nonlinear behavior of receivers [1]–[3].

"EMC-Analyzer" is a system-level tool based on the methodology of Intrasystem Electromagnetic Compatibility Analysis Program (IEMCAP) [4]. The original simulation technology implemented in "EMC-Analyzer" and called the discrete nonlinear analysis (DNA) is an important improvement over the nonlinear analysis methods of the IEMCAP [5].

The objective of this paper is to review the current state of the art in the DNA technology by summarizing the latest achievements in this field [13] – [15], [19] – [30], [34] – [36] and the experience of the DNA's software implementation [1] and practical application.

The paper is organized as follows. Section 2 discusses drawbacks of the traditional technique for the nonlinear EMC analysis. DNA principles are stated in Section 3. Then basic stages (Section 4), capabilities (Section 5), and restrictions (Section 6) of the DNA are considered. Applications of the DNA and a future prospect are given in Conclusion.

2. TRADITIONAL APPROACH TO NONLINEAR ANALYSIS OF EMC

Multi-level interference analysis methods, which intend sequential performing different stages, e.g., amplitude analysis, frequency analysis, detailed prediction, find a wide application in EMC analysis and design [6]. The biggest difficulties when using such methods are caused, as a rule, by analysis of a nonlinear interference in a receiver's front-end, especially by an analysis of intermodulation. These difficulties grow into problems when the receiver has to operate in a severe electromagnetic environment (EME), i.e., when a lot of interfering signals having different levels affect the receiver. Let us consider this in more details.

A traditional technique for the analysis of intermodulation in the receiver's front-end (variations and special cases of this technique are considered in [5] – [10]) intends sequential performing the following stages.

1) Spectrum discretization. A spectrum at the receiver input is approximated by a line model, i.e., by a sum of continuous-wave (CW) tones.

2) Frequency analysis. The purpose of this stage is to find potentially dangerous intermodulation products, the frequencies of which fall into a receiver passband and/or into spurious-response bands.

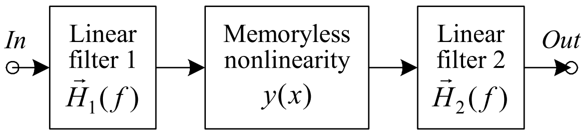

Figure 1. The Wiener–Hammerstein model.

3) Synthesis of a nonlinear model for the receiver's front-end. The Wiener–Hammerstein model (and its special cases) is a prevailing representation of the front-end. This model (ref. Fig. 1) takes into account the following properties: frequency selectivity of the receiver's input circuit (the 1st linear filter), nonlinearity of the front-end (the memoryless nonlinearity), and intermediate frequency (IF) selectivity (the 2nd linear filter). Parameters of the model can be extracted from the performance specification of the receiver or from measurements. The default values of the parameters can be set with the aid of statistical summaries of measured data [6].

4) Amplitude analysis. Amplitudes of all the potentially dangerous intermodulation products (ref. stage 2) are calculated using the front-end model (ref. stage 3) and the combinatorial formulas [9], [10]. Each of the amplitudes is then compared with the susceptibility threshold of desired or spurious receiving channel.

5) Analysis of the nonlinear interference's addition in desired and spurious receiving paths. Note that possible phase relationships between the intermodulation products should be taken into account at this stage.

The rapid growth of the 2nd and 4th stages' computational complexity with increasing the number of interfering signals at the receiver input and with increasing order of the nonlinear effects under analysis is a drawback of the traditional technique. Let us consider an example [7], p.1.11. When the input signal consists of two CW components, the 3rd degree nonlinearity generates 10 intermodulation products. With a 10 component input signal and a 5th degree nonlinearity, more than 18 000 intermodulation products will be generated!

Therefore, the traditional technique does not provide a required accuracy and a reasonable computational efficiency of the analysis in the most complicated situations when a large number (hundreds, thousands) of interfering signals having a wide range of levels must be taken into account, so the danger of high-order and multi-signal intermodulation should be considered.

The problem stated above can be solved using the DNA technology. This technology, which was proposed in [11], [12], allows taking into account all the fundamental types of nonlinear effects (intermodulation, desensitization, cross-modulation, reciprocal mixing, amplitude-to-phase conversion) in one common simulation procedure and keeps the computational efficiency at the level quite acceptable for applications.

As an example, consider the following situation. The EME is described by a discrete spectral model containing 1 million of CW components; the Wiener–Hammerstein model including a 15th-order polynomial nonlinearity is used to approximate the receiver's front-end. In this case, the analysis of unintended interference in the front-end with the aid of the DNA technology and PC Pentium-IV (3.2 GHz, 1 Gbyte RAM, Windows XP) takes about 25 seconds, note also that the dynamic range of the analysis (the ratio of the maximum and minimum amplitudes in the output spectrum of the receiver model) is 300 dB. Solving of the similar task by traditional techniques without additional simplifications in EME and receiver models is impossible even with the use of the most up-to-date computers.

3. DNA PRINCIPLES

The basic DNA principles can be reduced to the following.

1) Utilization of discrete models for the EME and for composite signals in the receiver's front-end.

2) Representation of the receiver block diagram as linear filters (matching networks) and memoryless nonlinearities (active elements) connected in series (or in parallel, or both).

3) Application of the efficient modeling methods for the linear and nonlinear transformations: linear filters are modeled in the frequency domain, memoryless nonlinearities are modeled in the time domain, the transition from the time domain to the frequency domain and vice versa is made with the use of the direct and inverse fast Fourier transform (FFT).

4) Use of polynomial models for the memoryless nonlinearities. These models ensure a controllable increase of a signal's bandwidth as a result of the nonlinear transformation and make it possible to achieve a high dynamic range (up to 300 dB) of the nonlinear analysis.

5) Utilization of a special polychotomous (in particular, a dichotomous [13]) search procedures for identification of nonlinear interference (intermodulation, etc.) sources.

6) Application of the Hilbert transform for calculating the quadrature component when modeling the amplitude-to-phase (AM–PM) conversion.

7) Use of digital signal processing (DSP) techniques (for example, matched filtering, correlation and spectrum analysis) to estimate distortions of the desired signal at the receiver model's points under study, as a rule, at the output of the model.

4. BASIC STAGES OF THE DNA

1) Frequency-domain discretization of the EME. A composite input signal (CIS), i.e., modulated signals' totality forming the EME at the receiver input, is represented as a sum of CW components, i.e., as a polyharmonic model [12], [14], [1]. The value of the frequency-sampling interval Δf should be set in view of the following circumstances:

a) when analyzing EMC with an accuracy to the carriers, the interval Δf should not exceed the smallest carrier frequency or the minimal difference of carrier frequencies in the CIS;

b) when analyzing EMC with the use of polyharmonic spectral models of separate signals in the CIS, the interval Δf should be less than the bandwidth of each of the input signals; for an adequate estimation of distortions of the desired signal having a spectrum in width D_f, it is expedient to choose Δf by a factor of ten less than D_f.

2) Behavioral modeling of the receiver. The receiver model is represented as the serial-parallel unidirectional (without feedbacks) structure containing blocks of two types – linear filters and memoryless nonlinearities. This representation makes it possible to process each of the blocks sequentially. Signal passage through a linear filter is simulated in the frequency domain using the complex transfer function of the filter [1], [12], [15], [16]. A memoryless nonlinearity is simulated in the time domain using the instantaneous transfer function (ITF) [1], [12], [15], [16]. The transition from the time domain to the frequency domain and vice versa is made with the use of the direct and inverse FFT [17], [18]. When modeling of the AM–PM conversion in the receiver elements (amplifiers, mixers, etc.) is required, the instantaneous quadrature algorithm [15], [19] can be utilized. When the composite spectrum at the IF output of the receiver is not enough for EMC estimation, modeling of the signal demodulation is performed with the aid of the quadrature algorithms [20], [21] based on the Hilbert transform or with the use of the algorithms developed in papers [22] – [24]. The latter algorithms are compatible with the DNA implementation in the "EMC-Analyzer" expert system [1].

3) Estimation of a receiver defeat by interference. Operational performance of the receiver is estimated using the signal at the receiver model output; when necessary, a type and a source(s) of interference are then identified (up to the separate estimation of performance degradation caused by each kind of linear/nonlinear effects) [12] – [14], [24], [25]. As the discrete (polyharmonic) models of composite signals are used in the DNA technology, modeling of a signal processing in the presence of interference (including an estimation of distortions of the desired signal) can be carried out with the use of standard DSP algorithms.

5. DNA CAPABILITIES

The DNA technology is a fundamental evolution of a well-known discrete EMC analysis technology developed in the framework of the IEMCAP [4], [6]. In the latter, a small number of frequency samples distributed equidistantly on a logarithmic frequency axis are used in combination with a limited list of fixed frequencies, and the analysis of intermodulation is performed by traditional techniques [5], [6].

The following may be considered among principal capabilities and advantages of the DNA.

1) A capability of radio reception modeling and EMC analysis in an extremely severe EME in which up to 10^4...10^5 signals are simultaneously present at the receiver input (the details are considered in Section 6).

2) Analysis of the nonlinear effects in the receiver can be performed using both the CW-type model (accuracy to the carrier) and a complicated spectral model for each of the input signals. In the latter case, the model can contain several groups of the spectral components to describe a modulation and spurious emissions of the transmitter (harmonics, subharmonics, broadband noise, etc.). Imaginative solution is to carry out a step-by-step modeling of the receiver by varying the frequency resolution [11], [12] – from analysis with accuracy to the carriers (low resolution) to analysis with accuracy to the line model of the modulation spectrum (high resolution), with an option to estimate the spectrum of the revealed interference by the use of the lowpass equivalent method (very high resolution).

3) A capability of utilizing high-order polynomial models to describe the ITFs of nonlinearities. Such models ensure adequate description of both the backed-off region with a mild nonlinearity, dangerous in terms of intermodulation emergence, and the saturation region having essential nonlinearity, hazardous in terms of desensitization. This makes it possible to consider both the linear effects (gain, attenuation, filtering) and the nonlinear effects of various types (intermodulation, desensitization, cross-modulation, reciprocal mixing, amplitude-to-phase conversion) and high orders (up to the order 25 and higher) in one common simulation procedure. Acceptable modeling errors can be reached by using polynomial models of degree from 11 to 29. Methods for synthesis of the high-order polynomials are treated in [26] – [30], [1].

4) A capability to represent the structure and characteristics of the receiver model (as well as its elements – amplifiers, mixers, etc.) at various levels of detail. This enables to perform EMC analysis of the required depth and details, to detect the emergence point and causes of a nonlinear interference in the receiver, as well as to determine the measures to be taken for its elimination. Such analysis is exceptionally important when designing complex co-site RF/microwave systems (on-board or ground-based), in the process of which a considerable part of the radio equipment to be further used in the system is developed.

5) All DNA stages are accomplished on the same (unified) methodology background utilizing a limited number of models and procedures – discrete (frequency-domain and time-domain) models of composite signals, discrete Fourier and Hilbert transforms, linear filtering in the frequency domain, memoryless nonlinear transformations in the time domain, and standard DSP algorithms (matched filtering, correlation and spectrum analysis, etc.). This feature facilitates a software implementation of the DNA substantially.

6) Ease of use the EME radiomonitoring data, which can be obtained with recording panoramic receivers or spectrum analyzers, for evaluating radio reception conditions from the EMC point of view.

7) A capability to extract the models of both the whole receiver and its elements (amplifiers, mixers, demodulators, etc.) from measurements [12], [15], [16], [19] – [23], [26] – [28], [31] – [35], [1].

6. DNA RESTRICTIONS

Application of the discrete models of composite signals in the frequency or time domain does not impose any fundamental restrictions on the number of samples being used. Theoretically, the frequency-sampling interval may be less than the band of long-term instability of reference generators (local oscillators) in the receiver, or it may be selected in a way providing adequate representation of modulation spectrum for the signals forming the EME; in these cases, the differences between discrete and analog EMC analysis may be neglected. In practice, the number of samples is, as a rule, limited by the computer RAM capacity or by the analysis time.

The restrictions caused by the growth in time of the FFT and other DNA procedures with increasing the number of samples are less significant since EMC analysis problems do not, as a rule, demand real-time solution. At present, the DNA of unintended interference in the receiver's front-end requires about 25 seconds of CPU time under the conditions given in Section 2 (note that the FFT length N_{SF} is equal to $2^{23} \approx 8 \cdot 10^6$ spectral samples).

The DNA restrictions caused by the limited RAM capacity are more important for applications, since storage of the samples array or of its part on a hard disc in the process of modeling is unacceptable in view of a drastic increase of time needed to perform the FFT. RAM sizes required to implement the DNA at different levels of detail are given in the Table I below. To compose the Table I, the following circumstances should be taken into account.

1) In case of EMC analysis with accuracy to the carriers, the minimal required number N_{SC} of complex-valued spectral samples is defined as the maximal (typical for the EME at the receiver input) ratio of the carrier frequency to the spectrum width, i.e., $N_{SC} = (f_C / \Delta f)_{\max}$; as a rule, the cases such as $N_{SC} \le 10^4 ... 10^5$ are of practical interest.

2) When using the polyharmonic models of separate input signals, the required number N_S of spectral samples must be increased with respect to N_{SC} to describe the modulation spectrum of each (or some) of the signals. Let N_{SM} be the number of spectral samples describing the modulation spectrum; the values $N_{SM} = 10 ... 10^3$ (and $N_{SM} = 1$ for analysis with accuracy to the carriers) are of practical interest. Therefore, $N_S = N_{SC} \cdot N_{SM} \le 10^4 ... 10^8$.

3) When performing the DNA, the frequency range, the upper boundary of which exceeds the tuning frequency of the receiver under analysis by several times, is of interest: in the simplest case, an excess by an octave is used $(N_E = 2)$; in more complicated cases, in which an analysis of the effects caused by local oscillator voltage harmonics is required, an excess by up to a decade is necessary $(N_E = 10)$.

4) For a memoryless polynomial nonlinearity of order K_P, the output signal bandwidth is K_P times greater than the input signal bandwidth. Thus, in order to avoid aliasing distortion in the frequency range under analysis $f \in [0; N_A \cdot \Delta f)$, $N_A = N_S \cdot N_E$, we must increase the number of spectral samples to $(K_P + 1)/2$ times N_A, e.g., the number of samples raises by a factor of ten if $K_P = 19$. Taking into account the previous items, we can express the number of spectral samples as

$$N_{S0} = N_{SC} \cdot N_{SM} \cdot N_E \cdot (K_P + 1)/2 . \tag{1}$$

5) Before the performing of the FFT, the array of the spectral samples is padded with zeros, so the array length increases to the nearest integral power of two.

6) One complex-valued spectral sample takes 16 bytes of RAM (double precision).

7) In practice, the size of the spectral samples' array should not exceed one quarter of the computer RAM capacity. Summarizing the last three items, we can calculate the RAM capacity W required to perform the DNA as follows:

$$W = 4 \cdot 16 \cdot 2^{Ceil[\log_2(N_{S0})]}, \tag{2}$$

where $Ceil(\cdot)$ represents the operator of rounding up to the nearest integer.

The RAM capacity available for Win32 applications is limited by 2 Gbytes, which corresponds to the 6th level of detail of the DNA (ref. Table I). 64-bit technologies of memory access (for example, EM64T, Intel Itanium) make it possible to increase the level of detail.

Note that the required RAM capacity can be half as large as in (2) if using a single-precision representation of the spectral samples (8 bytes per sample), but this will decrease the dynamic range of the DNA to 120 dB.

TABLE I. LEVELS OF DETAIL OF THE DNA

Level of detail	N_{SC}	N_{SM}	N_S	Frequency resolution of the DNA, Δf [Hz] (f_C is a carrier frequency of the desired signal)		N_E	K_P	N_{S0}	W [byte]
				f_C = 1 GHz	f_C = 10 GHz				
4	10^4	1	10^4	10^5	10^6	2	11	$1.2 \cdot 10^5$	8M
						10	19	10^6	64M
5	10^5	1	10^5	10^4	10^5	2	11	$1.2 \cdot 10^6$	128M
						10	19	10^7	1G
6	10^5	10	10^6	10^3	10^4	2	11	$1.2 \cdot 10^7$	1G
						10	19	10^8	8G
7	10^5	10^2	10^7	10^2	10^3	2	11	$1.2 \cdot 10^8$	8G
						10	19	10^9	64G
8	10^5	10^3	10^8	10	10^2	2	11	$1.2 \cdot 10^9$	128G
						10	19	10^{10}	1T

7. CONCLUSION

In spite of the fact that the DNA technology was proposed [11], [12] as an effective tool for analyzing the influence of interfering signals on a receiver operating in a severe EME, there are some other fields where the use of the DNA allows to perform an analysis at the higher quality level. Let us note the most important applications of the DNA.

1) Receiver analysis and design with the use of a real-world EME model.

2) Transmitter analysis and design taking into account EMC requirements and nonlinear effects.

3) Analysis and design of the active array antennas [36], [37].

4) EMC analysis and design of co-site radio-electronic equipment located, for example, on a ship, an aircraft, a car, or a building roof. For this type of situation, it is necessary to consider geometry of the object under analysis and a layout of the equipment.

5) EMC analysis and design of geographically-distributed systems. In this case, one must also take into consideration a geographical attributes (landform, buildings, etc.) of territory under analysis. The advanced solution of this problem is an integration of EMC analysis software with geographic information systems, such as “MAP-Info”.

At present, many typical problems in the above-listed fields can be solved using the DNA’s implementation in the “EMC-Analyzer” expert system [1].

In the future, it is expected the DNA efficiency to increase due to increasing the computer performance. If the progress in the computer engineering keeps the current pace (the RAM capacity of PCs has been enlarged by a factor of thousand over the last ten years), the RAM capacity will reach 1 Tbyte within the next ten years. This will enable to provide a representation of the spectra in such a fine details (ref. Section 6) that the boundary between the discrete and continuous (analog) EMC analysis will be nearly eliminated.

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