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RESEARCH ARTICLE

Digital technologies for signal radio vision and radio monitoring

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Abstract
Objectives. Radiophysical processes involving the electrodynamic formation of signal radio images diffusely scattered by the signature of small-sized objects or induced by the near field of radio devices are relevant for identifying radiogenomic (cumulant) features of objects in the microwave range in the development of neuroimaging ultra-short pulse (USP) signal radio vision systems, telemonitoring, and near-radio detection. The paper sets out to develop methods and algorithms for vector analysis of radio wave deformation of nonstationary fields forming a signal radio image based on radiophysical and topological characteristics of small-sized objects; to develop software and hardware for registration and neural network recognition of signal radio images, including methods for the synthesis and extraction of signal radiogenomes using digital twins of objects obtained through vector electrodynamic modeling; and to analyze signal radio images induced by elements of printed topology of electronic devices.
Methods. The study is based on statistical radiophysics methods, time-frequency approaches for wavelet transformation of USP radio images, numerical electrodynamic methods for creating digital twins of small-sized objects, as well as neural network authentication algorithms based on the cumulant theory of pole-genetic and resonant physically unclonable functions used in identifying signal radio images.
Results. The results of fundamental research on electrodynamic effects of vector-wave deformation of nonstationary fields of sub-nanosecond configuration are presented as a means of identifying and authenticating signal radio images. Neural network techniques for cumulant formation of radio genomes of signal radio images are proposed on the basis of pole-genetic and resonant functions.
Conclusions. A radiogenome, representing the unique authenticator of a radio image, is shown to be formed on the basis of physically unclonable functions determined by the structure and set of radiophysical parameters of the image. Cumulant features of signal radio images identified on the basis of pole-genetic and physically unclonable resonant functions of small-sized objects are revealed.

Keywords: signal radiovision, radiogenome, radio image, physically unclonable function, cumulant, pole-genetic functions

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НАУЧНАЯ СТАТЬЯ

Цифровые технологии сигнального радиовидения и радиомониторинга

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Резюме
Цели. Цель работы – разработка методов и алгоритмов векторного анализа радиоволновой деформации нестационарных полей, образующих сигнальное радиоизображение, определяемое радиофизическими и топологическими признаками малоразмерных объектов; создание программно-аппаратных средств регистрации и нейросетевого распознавания сигнальных радиоизображений, в т.ч. методов синтеза и экстракции сигнальных радиогеномов при помощи цифровых двойников объектов, полученных посредством векторного электродинамического моделирования; анализ сигнальных радиоизображений, наводимых элементами печатной топологии электронных устройств.
Методы. Использованы методы статистической радиофизики, частотно-временные методы вейвлет-преобразования финитных во времени сигнальных радиоизображений, численные методы электродинамики при создании цифровых двойников малоразмерных объектов, а также нейросетевые алгоритмы аутентификации, основанные на кумулянтной теории полюсно-генетических и резонансных физически неклонируемых функций (ФНФ), используемых при распознавании сигнальных радиоизображений.
Результаты. Приведены научные результаты фундаментальных исследований электродинамических эффектов векторно-волновой деформации нестационарных полей субнаносекундной конфигурации, представляющие интерес при распознавании и аутентификации сигнальных радиоизображений. Предложены нейросетевые методы кумулянтного формирования радиогеномов сигнальных радиоизображений на базе полюсно-генетических и резонансных функций.
Выводы. Показано, что радиогеном – уникальный аутентификатор радиоизображения – формируется в базисе ФНФ, определяемых структурой и набором радиофизических параметров объекта. Выявлены кумулянтные признаки распознавания сигнальных радиоизображений в базисе полюсно-генетических и резонансных ФНФ малоразмерных объектов.

Ключевые слова: сигнальное радиовидение, радиогеном, радиоизображение, физически неклонируемая функция, кумулянта, полюсно-генетические функции

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INTRODUCTION

Signal radio vision is a field of radiophysics that studies methods for forming, processing, and authenticating vector radio images of objects in the superhigh frequency (SHF) range, which result from the diffuse scattering by the object signature of an ultra-short pulse (USP) object or USP induced by electronic devices during transients on their components and distributed topology reactivities [1, 2]. Signal radio vision technology is based on the electrodynamic effect of vector-wave deformation of nonstationary fields of subnanosecond configuration. For ultra-wideband radio monitoring tasks, this can be used to obtain not only a vector radio image in the form of a signal radio profile (SRP) but also information about the radiophysical parameters of the irradiated object, including synthesizing a time-spectral radiogenome or unique authenticator on the basis of physical unclonable functions (PUF) [1–9]. Indeed, radiometric authenticators of objects (including radioelectronic devices) determined by the parametric distribution of reference element characteristics and inhomogeneities composing their structure (signature, topology, architecture, etc.) are hidden in wave deformations (dispersive, dissipative, polarization, time-frequency, and phase-dynamic) of the electromagnetic field scattered or induced into the USP space [10–14]. In order to identify radiogenomic features of small-sized objects in the SHF range, a neural network approach for authenticating radio images via cumulants on the basis of pole-genetic and resonant PUF synthesized using digital twin technology (numerical methods of electrodynamic modeling) [3, 10] is proposed.

On the basis of previously published research results in the field of signal radio imaging, including those presented in [1, 2, and 12], it can be shown that authenticators of different objects defined by the PUF reference basis are hidden in wave deformations of the USP field. Due to the quasi-identical envelopes of wave profiles of signal radio images of dissimilar objects, restrictions are imposed on their identification by means of USP envelopes. As a consequence, it becomes relevant to practically implement radio wave technologies of subnanosecond resolution.

1. FORMATION AND AUTHENTICATION OF SIGNAL RADIO IMAGES DIFFUSELY SCATTERED BY SIGNATURE OF SMALL-SIZED OBJECTS

The time-frequency authentication of signal radio images is determined on the basis of a priori research data on electrodynamic features of the radio wave processes of non-stationary fields, which are scattered on the impedance inhomogeneities of an irradiated object. This involves the development of adaptive algorithms for analyzing USP based on singular-statistical methods for obtaining reference frames (radiogenomes) in the time profiles of signal radio images, forming the most complete representation of the object structure in the SHF range (Fig. 1) [1, 2, and 9].

Neural network algorithms have been developed on the basis of cumulant theory of pole-genetic and resonant functions for finding and identifying reference frames in a radio signal image, which can be achieved by experimentally synthesizing specified impulse responses (IR) or using digital twin technology [1, 2, 9]. A neural network used for identifying signal radio images with an ultra-precise ConvNet architecture consisting of three layers is based on an Intel Neural Compute Stick 2 16-core USB computing module (Intel Corporation, USA), which uses backpropagation while training to minimize error probability when identifying the signature of a small-sized object.

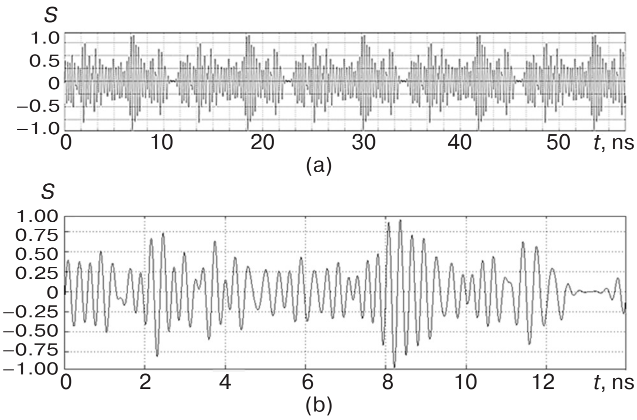


Fig. 1. Reduced signal radio image of a small-size UAV object: (a) USP periodicity on the equivalent time interval; (b) reference frame of the signal radio image. *S* is scale reduced to the USP power maximum (dimensionless); *t* is equivalent time of stroboscopic transformation

Analyzing the time-frequency distribution of diffusely scattered USP implies a preliminary wavelet transformation of the complete radio response, whose signal radio image concentrates the signature radio genome of the small-sized object's equivalent inhomogeneity, which is formed by its instantaneous effective scattering area (ESA). This influences the nature of the spectral formant superposition produced by the electrodynamic process of wave deformations of the nonstationary field *E*,*H*-components [1–10]. In this case, decomposition of the signal radio response of the object in the coordinated mode can also be achieved by discrete formation of the USP power spectral density function in time [10]. This provides a unique opportunity to create a library of signal radio genomes of small-sized objects of the "unmanned aerial vehicle" (UAV) type by specified signatures for generating a priori information about USP radio images [1, 2, and 10]. Indeed, in case of USP diffuse scattering by a small-sized object with dynamic ESA, the wavelet transform at the time set by a given windowed frame function permits the radiophysical behavior of USP wave deformations $s(t)$ to be localized and even identified when interacting with the signature. Thus, the functional character of the USP signal change $y(t)$ is shown to be completely determined by IR properties $h(t)$ of the propagation medium and the family of local IR of the object, as follows:

$$y(t) = H\left[s(t)\right] = \int_{-\infty}^{\infty} s(\tau)h(t-\tau)d\tau,$$

where H is the USP wave deformation operator determined by radiophysical and topological properties of the object signature.

At the same time, the singular-statistical evaluation of radio image reproducibility shows that the beat interference generation conditioned by multipath copies of $y(t)$ significantly affects ambiguity when identifying pole-genetic functions of the radiogenome [3]. At the same time, wavelet cepstral postprocessing of the form

$$C(q) = \frac{1}{2\pi}\int_{-\omega_{\text{bdry}}}^{+\omega_{\text{bdry}}} \ln\left[S(\omega)\right]^2 \mathrm{e}^{j\omega q_{\text{t}}}\, d\omega,$$

which is the most effective approach when decomposing signal radio images by pole-genetic functions, can be used to compensate for the impact of Rician interference [1, 2]. Here, $S(\omega)$ is USP amplitude spectrum $s(t)$; $\pm\omega_{\text{bdry}}$ is boundary frequencies of integration; $\ln\left[S(\omega)\right]^2$ is logospectrum; and q_{t} is cepstral time variable.

Considering the case when the radio image of an object can be represented by the difference in its intrinsic IR of the same signature shifted by the USP duration, the radio genome of the small-sized object is defined by complex basis of intrinsic resonant frequencies ω_m, $m = 1, 2, ..., N$, while the evaluation of the small-sized object IR is reduced to finding its pole functions

$$Q_m(\omega) = \frac{\dot{C}_m^*}{\omega + \dot{q}_m^*} - \frac{\dot{C}_m}{\omega - \dot{q}_m}, \dot{q}_m = \omega_m + j\gamma_m,$$

concentrated in the frequency-to-time mapping (FTM) of the scattered USP radio response. Here, it is assumed that each of basic functions $Q_m(\omega)$ with complex amplitude $\dot{C}_m$ contains pole cumulant $\dot{q}_m$ with frequency ω_m and dissipation coefficient γ_m set as a priori information when constructing a recurrent neural network for identifying signal radio images.

The vector radio images of the baseline signatures of the radiogenome of small-sized UAV-type objects and their corresponding pole functions at signal-to-noise ratio (SNR) equal to 12 dB shown in Fig. 2 include those used to determine the functional relationship between the change of the object signature in time and its radiogenome [1, 2–8, and 10].

The object signature PUFs (reference identifiers) can also be resonant frequencies (resonant cumulants) characterizing the set of reference elements and object signature inhomogeneities forming the superposition of resonators.

The nature of the PUF distribution comprises two elements, a "forced" component due to the influence of polarization, field strength distribution rate, direction

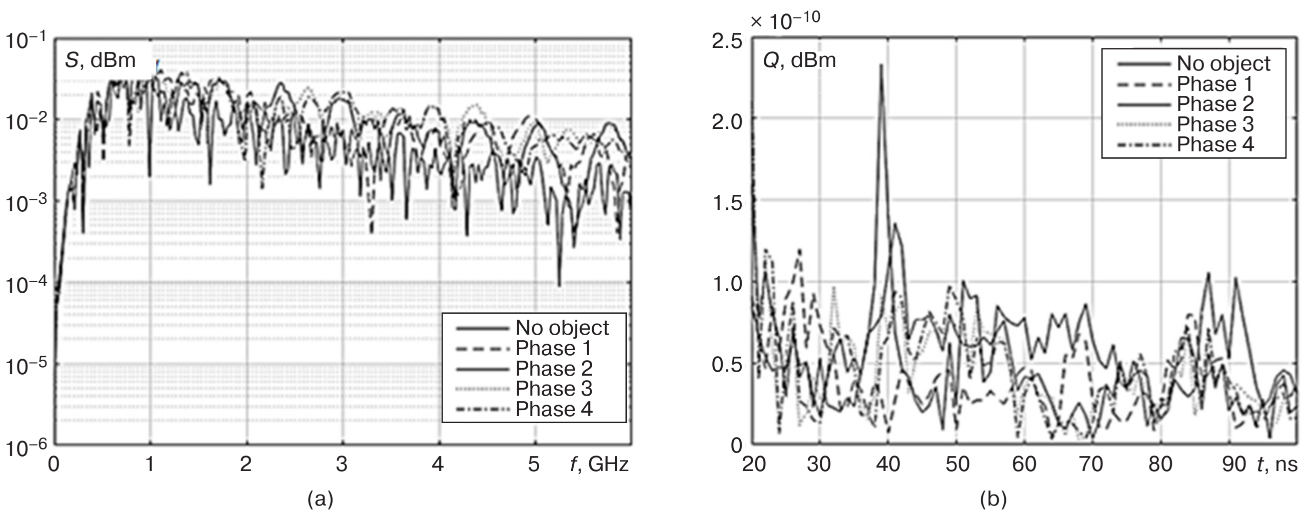


Fig. 2. UAV vector radio images (a) and their corresponding pole functions (b) obtained at periodic time phases of 10 ns; f is linear frequency ($\omega = 2\pi f$)

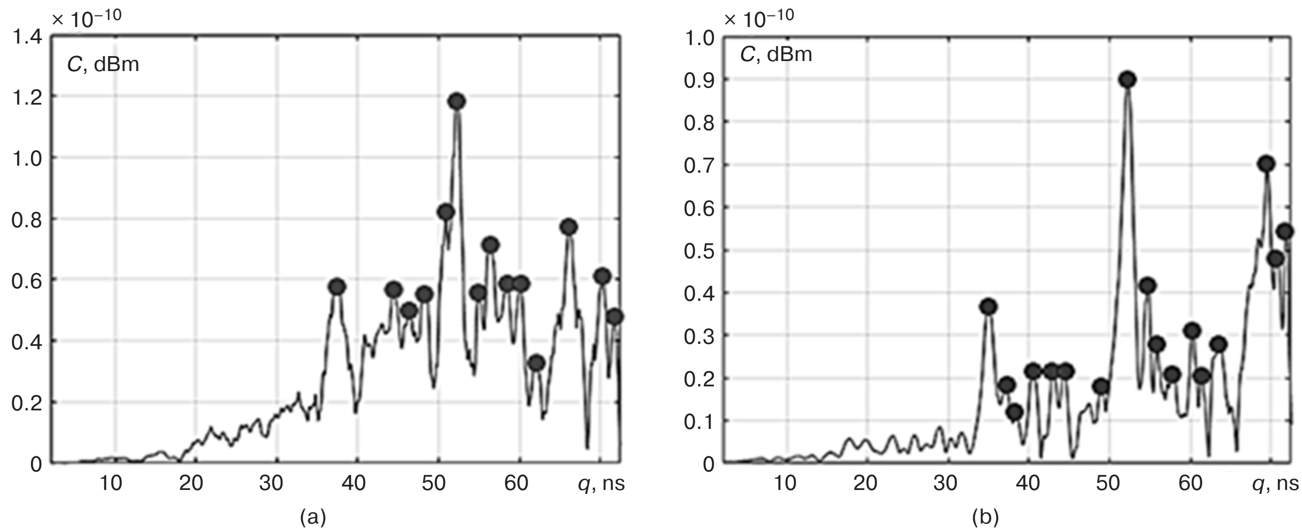


Fig. 3. Cepstral representation of the resonant components of the UAV signal radio image for two orthogonal signatures of a small-sized object: (a) angular position at 0°, (b) angular position at 90°

and conditions of the USP propagation medium, etc., and a "mode" component associated with USP diffuse scattering on resonant and selective structures of the object signature. Thus, in order to extract the mode component on the basis of a priori information on resonant frequencies obtained, for example, when irradiating a digital twin (electrodynamic model) of a small-sized object, a discriminative (anti-resonant) signal $d_e(t)$ of finite duration T_e fitted to the radio image compensates for resonances in scattered USP $s(t)$, at which convolution

$$\chi(t) = d_e s(t) = \int_0^{T_e} d_e(\tau) s(t-\tau) d\tau$$

for $t \geq T_e$ tends to zero.

Figure 3 shows cepstral functions $C(q)$ of resonant cumulants and the mode component comprising the radio genome of the UAV signal radio image [7, 10], whose vector radio image of pole functions is shown in Fig. 2.

According to published research, at SNR equal to 12 dB and a discriminative difference of 10 dB between scattered USP and reference PUF, the reproducibility of radio image identification by resonant responses may reach 0.95. In other words, since the singularization of radio images of small-sized objects in a given basis of resonant frequencies (radiogenomic features) used as cumulants of the neural network does not require a priori information about the complete time-spectral function of the object radio image, the probability of identifying object radio images by reference identifiers can be increased [9, 7, 10–12].

2. FORMING AND MONITORING SIGNAL RADIO IMAGES INDUCED BY PRINTING TOPOLOGY ELEMENTS OF ELECTRONIC DEVICES

Signal processes on reactive components of electronic devices (ED) are generally accompanied by the energy redistribution between capacitive and inductive elements (hereinafter referred to as accumulators) determined for a multiparameter system by stochastically oscillating electromagnetic radiation induced into space, forming SRP or a unique ED radiometric image. In this case, parasitic reactivities in conducting lines distributed as electronic circuit parameters that include interlayer topology elements can result in signal distortions related to the steepness of signal edges and impedance over-reflections [11]. This typically results in a lowered maximum frequency of digital devices or reduced capacity of microcircuit power outputs. At the same time, the supply line in the ED printing module topology accumulates electric and magnetic energy, combining inductances, capacitances, and ohmic losses whose values depend on the line topology and material properties. When analyzing SRP formation in the ED module with radiating circuit architecture (topology), the relationship between consumer loads and accumulators should be taken into account. These interrelations are determined by the values of roots of the secular equation set up for the ED radiating circuit architecture. The radiation in the ED fragment topology results in the energy redistribution between reactive accumulators. The general solution of this equation is the oscillation free component (U_{fr}) with complex-conjugate roots $\dot{p}_{1,2} = -\delta \pm j\omega$. The ED node usually comprises a group of components forming the electrical circuit architecture. The total operating field of an electronic circuit node is a superposition of emissions of input and output circuits constituting it. At time instants corresponding to the arrival of an actuating pulse (supply voltage, mode switching, or clocking), these components emit free damped oscillations described by the following expression:

$$U(t)=\sum_{i=1}^{N}U_{\text{fr}i}(t)=\sum_{i=1}^{N}U_{0i}\mathrm{e}^{-\delta_i(t-t_{0i})}\sin\left[2\pi f_i\left(t-t_{0i}\right)\right],$$

here, N is the number of components; $U_{\text{fr}i}$ is the reduced value of the free component of ith oscillation; U_{0i} is the reduced amplitude of the first half-wave of ith oscillation; δ_i s the damping factor of ith oscillation; t is the current time; t_{0i} is the radiation time of ith oscillation; and f_i is the frequency of ith oscillation.

The ED SRP decomposition with decomposition into formant components is shown in Fig. 4.

Analyzing the curves shown in Fig. 4b, it can be seen that signal parameters of SRP N-formant components carry information about the electronic node [12–15]. The number of sources of damped oscillations can be obtained from the N value to estimate whether all node elements of interest participate in radiation. Since not all emitters participate in the SRP formation, fewer emitters than in the reference SRP (received from a functioning original ED) means that ED malfunction (or unoriginality) has been detected. A number of emitters exceeding the reference value indicates incorrect measurement or that interference occurred during measurement. The amplitude of the first half-wave of oscillations U_{0i} (Fig. 4b) depends on the radiation power of the considered node components. The power of this radiation is proportional to the voltage drop across the emitter and inversely proportional to double the wave impedance of emitter Z [16]. Since the wave impedance of the emitter does not depend on electrical characteristics of the investigated radioelectronic node, the reduced amplitude of the first half-wave of the oscillation can be used to estimate the electrical potential at the emitter. The oscillation the damping factor δ determined by inductance and ohmic resistance shows the energy dissipation rate. While parasitic and concentrated inductances are not significantly dependent on changes in external factors, the equivalent ohmic resistance significantly depends on temperature. The biggest changes are in specific resistances of supply conductors ρ and conducting regions of semiconductor devices $\frac{d\rho}{dT}=\alpha_\rho\rho,$ where α_ρ is the temperature coefficient of conductor specific resistance (for copper, $\alpha_\rho = 4.1 \cdot 10^{-3}$ 1/K). Thus, the damping factor essentially indicates the temperature difference between the radiating node and the temperature at which the SRP reference measurement has been taken.

At equivalent capacitance values of the order of tens picofarads and equivalent ohmic resistances measured in tenths of 1 ohm, oscillation frequency f contains information about the quality of gate dielectrics of metal-oxide-semiconductor structures or modes of operation of p-n-junctions of ED radiating radioelectronic nodes. Here, oscillation frequencies are informative provided that there is a reference signal with previously extracted parameters. In this case, the radiation start time t_0 reflects the transmission rate of the disturbing influence and characterizes the response rate of the node. By comparing the measured value of this parameter with the reference value, the conclusion can be made about the change in the responsiveness of the considered ED components.

The physically unclonable function obtained by registering the electrical component of the electromagnetic radiation of ED electronic components defines physical parameters of the item taking into

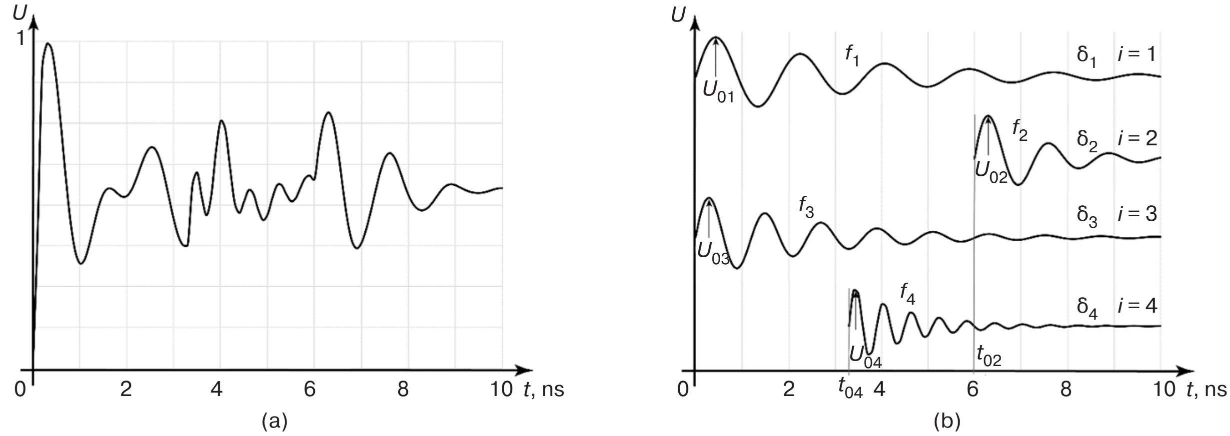


Fig. 4. SRP time representation:
(a) superposition of radiations, (b) SRP components

account the scatter of technological tolerances on component parameters. Reconstruction and analysis of this PUF by cross-correlation with the reference accepted by ED manufacturer, as well as comparison of the parameters obtained by the complex PUF decomposition allow evaluating the originality of the radioelectronic item remotely [17].

For recording SRP in laboratory research, sensitive ultrabroadband antennas, oscilloscopes with memory (or data transmission) function, and low-noise power preamplifiers providing a bandwidth of several gigahertz can be used. The detail of SRP research and the possibility of estimating the device radiometric characteristics depend on the bandwidth and sampling frequency. Due to its flexibility, the software-defined radio system for receiving and processing SRP opens up new opportunities in fields of nondestructive testing (NDT) and determining ED authenticity [18].

The total operating field in digital ED is emitted while applying the supply voltage to generate signals for controlling internal and external periphery at changes of power consumption mode. In the case of analog circuits, SRP is emitted only at the moment of supply voltage application.

In order to obtain the damping factor and the elementary radiation phase, the windowed Fourier transform is used. This method can be used to obtain the spectrum of damped oscillations with corresponding bias for each discrete quantity. For visualizing data in the form of samples, a three-dimensional dependence of the reduced value of signal energy X on frequency f and window position t is plotted (Fig. 5).

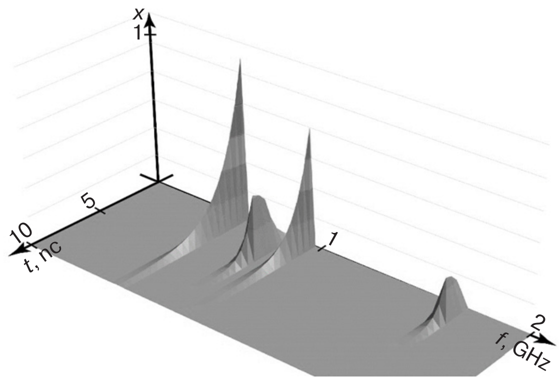
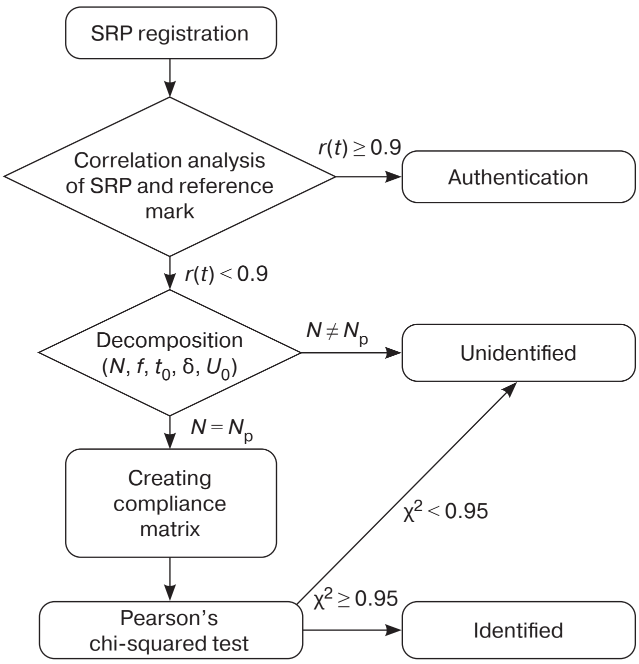


Fig. 5. SRP three-dimensional spectrum

When the amplitude value reduced to frequency increases or does not change with increasing time, the absence of radiation at this readout is indicated. A decrease in amplitude indicates the presence of radiation induction. The starting point of radiation is defined by the moment of transition from increasing amplitude to decay (peak point). The damping of the reduced energy value corresponds to the dumped oscillation law with the same factors $X_i = X_{0i}e^{-\delta_i t}$, where X_{0i} is the amplitude spectrum of ith oscillation at the start point. Correct SRP decomposition with parameter extraction is possible at SNR more than 18 dB.

For ED authentication, the compliance matrix is created (Fig. 6), where “1” stands for the transmitter parameter falling within the confidence interval determined by simulation results or experimental data.



Parameters \ Emitters	1	2	3	4
f	1	1	1	0
δ	1	0	1	1
t_0	1	1	1	1
U_0	1	1	0	1

Fig. 6. Architectural algorithmics of ED authentication by SRP. N_p is the number of desired emitters, while $r(t)$ is the correlation between the received SPR and the reference mark

Taking into account that during ED authentication the sample of SRP parameters is expected to fall into the confidence interval (Fig. 6) determined for each emitter experimentally, the Pearson's chi-squared test may be determined, as follows:

$$\chi^2 = \sum_{j=1}^{k} \frac{(u_j - e_j)^2}{e_j},$$

where u_j is the observed frequency of the feature in jth group and e_j is the theoretical frequency of the feature in jth group.

The analysis based on the experimental data show that for $\chi^2 \geq 0.95$, the ED authentication reliability is determined to be at least 95% [19, 20].

CONCLUSIONS

The radiogenome formed on the basis of PUF determined by the structure and the set of radiophysical parameters of the object serves as a unique radio image authenticator to obtain information about radiophysical parameters of both irradiated and radiating SRP of the object. Radiometric authenticators of objects including ED determined by parametric distribution of characteristics of reference elements and inhomogeneities constituting their structure (signature, topology, architecture, etc.) are hidden in wave deformations (dispersive, dissipative, polarization, frequency-time, and phase-dynamic ones) of the electromagnetic field scattered or induced into the USP space. The vector-wave deformation of nonstationary fields of subnanosecond configuration can be used to identify and authenticate objects according to signal radio images or so-called radio genomes on the basis of synthesized pole-genetic and resonant PUFs using neural network algorithms. The extraction of SRP parameters using floating "window" provides new opportunities in identifying ED radio-physical parameters, including the development of new SHF technologies for signal radio vision, telemonitoring, and short-range radio detection. Further development of signal radio vision technology will involve creating an algorithm for identifying radio wave images based on vector analysis, as well as the adaptation and emulation of a neural network for identifying signal radio images with ultra-precise ConvNet architecture on a single-board module, and the formation and extraction of a database of radiogenomes of small-sized objects and ED in order to create a prototype of an autonomous neuroimaging hardware and software system for short-range radio detection.

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Authors' contributions

M.S. Kostin—formulation of the problem, conducting the experiment, analyzing the results obtained, formulating conclusions, and writing the text of the article.

K.A. Boikov—conducting the experiment, analyzing the results, formulating conclusions, and writing the text of the article.

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