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Probability of Pulse Overlap as a Quantitative Indicator of Signal Environment Complexity

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Abstract
Introduction. Simultaneous operation of numerous sources of radio emission form complex signal environment. Different devices with the common name “wideband analyzers” (WBA) are widely used to analyze and to control such environment. There is currently a need for developing the quantitative characteristics of a complex signal environment, which will make it possible to predict the stability of the WBA operation.
Aim. The development of the indicator of the signal environment complexity, which will make possible the quantitative assessment of such environment.
Materials and methods. To provide the desired indicator, simulation and mathematical tools for random events description are used. All calculations are performed using MatLab.
Results. The principles of disturbances in the WBA receiver and algorithmic errors in the processing of overlapped signals are described. To quantify the “complexity” of the signal environment it is proposed to use the probability that pulses from several sources overlap in time. This allows one to compare signal environments with each other. The new analytical expression for estimating the pulse overlap probability is proposed. Functions of the pulse overlap probability from the complex signal environment parameters were obtained.
Conclusion. According to the comparative analysis of the calculations using proposed analytical expression and simulation, the new expression allows one to achieve the calculation speed up to 6 orders of magnitude higher with an error below 7% compared to the simulation. The high performance of the calculations using the proposed expression allows one to simulate the complex signal environment in dynamics more efficiently.

Keywords: complex signal environment, wideband signal analysis, pulse overlap probability, pulse sequences overlap, pulse trains overlap, signal environment analysis

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Introduction. Modern means of communication, navigation, radiolocation, and radio control solve a wider range of tasks in everyday life beginning with road traffic control and ending with the smart house [1–3]. The necessity of simultaneous operation of various radio-electronic devices has led to the expansion of the frequency range in use. In order to improve the electromagnetic compatibility (EMC), the number of the used signal types has also increased. However, even with all these measures having been taken, very often EMC is not reliably provided in practice. All these factors lead to the formation of a complex signal environment. Therefore, wideband analyzers (WBA) are used as practical means that help analyze and control the signal environment. Such devices must solve the problems of detection and discrimination of signals from various sources with parameters that overlap in time and frequency domains. For this purpose, it is necessary to measure the parameters of each received pulse, such as carrier frequency, pulse width, amplitude, time of arrival (TOA), and direction of arrival (DOA) [4, p. 317, 5].

Many sources use pulsed signals that often have a burst structure. Pulses from different sources inevitably overlap in time in the complex signal environment, which can disrupt the normal functioning of the WBA. Such overlaps affect the operation of both the analog and digital paths of these devices.

WBA receive path disturbances. WBA can be built based on a single-channel scanning superheterodyne receiver with a digital signal processing (DSP) device. The instantaneous signal reception and processing bandwidth of such receiver, as a rule, does not exceed 1 GHz. Pulses with the close carrier frequency overlapped in the receiver can cause interference in intermodulation receiving channels [6]. Moreover, mixers and amplifiers of the receiver fail to work properly in linear mode at the high input power. As a result, a wide ensemble of additional harmonics is formed at their output.

WBA also can be built according to a multi-channel scheme. In this case, digital analysis is performed either in all channels simultaneously or in one of the channels. At the same time, in order to increase the sensitivity of such system, the input wideband radio frequency amplifier common to all channels is routinely used. For the aforementioned reasons, even greater number of spurious harmonics appears in the amplifier. These harmonics go further to digital processing.

The third WBA implementation is based on the instantaneous digitization of a broad frequency band (up to 18 GHz) using monobit analog-to-digital converters (ADC) [7–10] or undersampling technology [11–13]. With this approach, the problems arising in the analog path are eliminated. However, with a strong input signal, harmonic components are similarly formed at the ADC output. Along with that, monobit ADCs rarely allow distinguishing time-overlapped signals. With regards to analyzers with undersampling, the problem of separating the pulse sequences folded to the first Nyquist zone from all the zones has to be solved. This is an even more difficult task than the pulse sequences deinterleaving in traditional DSP methods.

In all these cases, predicting the frequencies of spurious harmonics is virtually impossible, so they cannot be excluded from processing.

Another problem that arises in the complex signal environment is the reception of powerful out-of-band signals. In this case, in addition to the occurrence of the spurious harmonics in the reception band, a sensitive input amplifier can be damaged. Another effect is the decrease of sensitivity of the WBA due to the operation of the automatic gain control system (if it is used).

WBA DSP device disturbances. Even without the above described effects, the overlap of the pulses makes it difficult to measure their width, amplitude, and DOA. Therefore, a number of algorithms have been designed whose purpose is to eliminate these difficulties.

The algorithm described in [14] allows to detect and to measure the TOA, width, and amplitude of several time-overlapped pulses. This algorithm remains operational at low signal-to-noise ratios (SNR). However, signal detection in the WBA is performed in hard real-time conditions. Execution of the algorithm presented in [14] under such conditions, according to the authors, will require the WBA to be equipped with high-performance central processor unit and graphic accelerators for the implementation of parallel computing. Such equipment significantly increases the complexity, cost, power consumption, and the overall dimensions of the WBA.

If the time-overlapped pulses have close carrier frequencies, which is likely in conditions of high radio band load [15], their analysis in the frequency domain will also be significantly more difficult [5]. A literature review conducted by the authors of this paper could not identify works that would offer suitable for the WBA solutions to the problem of measuring the parameters of the pulses overlapped in both time and frequency domains. In [16, 17], this problem is solved with application to radars that operate in a narrow frequency band with a priori known information about the receiving signals. In [18], an algorithm is described for separating the overlapped in the time and frequency domains responses on the radar probing signal. This algorithm is based not on digital processing of the received signal, but on the beamforming in the radar antenna; it cannot be used in the WBA for the same reason as the previously mentioned ones.

One of the tasks of the broadband frequency analysis is to determine which of the received pulses belongs to a specific source. Omissions, as well as incorrect measurements of the parameters of the pulses can significantly complicate the operation of the algorithms that solve these problems. There are a few algorithms that take this factor into account. For example, the algorithm described in [19] allows determining the pulse repetition intervals (PRI) in four overlapped pulse sequences with an error below 2.5 %, even if 25 % of the pulses in these sequences were missed. However, the implementation of mathematical operations required by this algorithm in the modern real-time systems will be extremely difficult. The computational complexity of the algorithm described in [20] is lower, but, according to its authors, the performance of this algorithm rapidly degrades with the increasing proportion of the missed pulses. Thus, even at 5 % of the omissions, the algorithm incorrectly classifies more than 10 % of the pulses.

Considering the above discussion, it can be concluded that the pulse time-overlap in the input of the WBA receiver leads to negative consequences for both the analog receiver and the digital signal processing device. The effectiveness of the WBA functioning in the complex signal environment is significantly deteriorating. Therefore, there exists a need for a quantitative assessment of the signal environment "complexity". As the means of such an assessment, we propose the use of the probability of the time overlap of the pulses coming from several sources. The use of such quantitative indicator will make it possible to predict the stability of the WBA operation, as well as to compare various signal environments.

Determination of the pulse overlap probability. The probability that the pulses from n sources overlap in time is a function of these sources' signal parameters, i. e.

$P = f\left(\tau_1, \ldots, \tau_n, T_1, \ldots, T_n, \tau'_1, \ldots, \tau'_n, T'_1, \ldots, T'_n, \varphi_1, \ldots, \varphi_n\right),$

where n – the number of sources considered; τ_i – pulse width of the i-th source; T_i – PRI of the i-th source; τ'_i – pulse burst width of the i-th source radiated in the WBA direction; T'_i – pulse burst repetition interval of the i-th source radiated in the WBA direction; φ_i – the initial phase of the i-th source signal. The described signal structure is shown in Fig. 1.

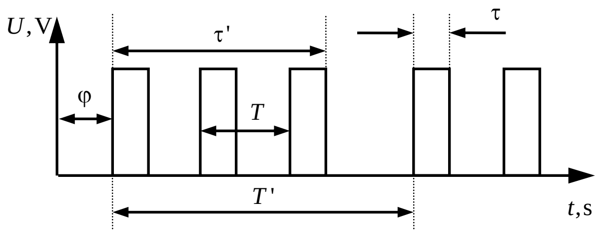

Fig. 1. Burst signal structure

The vectors of the sources' signal parameters $\left(\tau_i, T_i, \tau'_i, T'_i, \varphi_i\right)$ are independent, but the joint probability densities of the elements of these vectors are unknown. The nature of the functional dependence itself, which connects the probability P with the indicated parameters of the signals, is also unknown. This makes it impossible to determine the statistical characteristics of the probability P.

At the same time, the parameters of the signal are largely determined by the tasks solved by its source and by the underlying internal structure of that source [21]. Therefore, the radical changes in the signal parameters during the operation of its source in one mode are extremely unlikely. Consequently, the variances of the signal parameters within one mode of its source operation will be small. Taking this into account, it would be a reasonable assumption to replace each of the considered sources having the signal structure described by a random parameter vector $\left(\tau, T, \tau', T', \varphi\right)$ with the source having the signal structure described by a deterministic parameter vector $\left(\bar{\tau}, \bar{T}, \bar{\tau}', \bar{T}'\right)$ and a random initial phase φ. In doing so, the average values of the elements of the vector of random signal parameters can be used as the elements of the vector of deterministic parameters.

However, when predicting the potential signal environment, an accurate description of the signal in one or another mode of its source operation is usually unknown. Therefore, to provide the possibility to determine the probability P, it is useful to characterize the signal by its average duty cycle

$$\bar{R}_i = \frac{\bar{\tau}'_i}{\bar{T}'_i} \cdot \frac{\bar{\tau}_i}{\bar{T}_i}.$$

In the rest of this paper, for the convenience of writing the formulae, we omit the averaging signs of the parameters τ, T, τ', T', R_i, always implying the use of the averaged values of these parameters. The average duty cycle of the pulse sequences τ_i / T_i depends on the type and the operation mode of its source and can be estimated from the information contained in the reference literature or from the available data about a similar source.

If the pulses are emitted in bursts (for example, by radar), the average duty cycle of the pulse bursts' sequences τ'_i / T'_i depends on the scan pattern used by the radar. For example, in the case of a circular scan in the azimuthal plane, this value can be defined as $\alpha / \Delta\alpha$, where α is the radar antenna beamwidth and $\Delta\alpha$ is the width of the radar scan area in this plane.

Thus, the function of the pulse time-overlap probability P can be represented as

$$P = f\left(R_1, \ldots, R_n, \varphi_1, \ldots, \varphi_n\right).$$

Nevertheless, even with all the assumptions made, the problem of analytical determination of the probability P has not been significantly simplified. The probability density functions of the signal initial phases $W_{\varphi i}(x)$ are still unknown, as well as the nature of the function f. Moreover, the estimation of the statistical characteristics of the random vector of the signal initial phases $(\varphi_1, \varphi_2, ..., \varphi_n)$ is impossible, because these phases depend on the circumstances of the particular situation in which the signal sources are used, their relative position, the actions of the operators, as well as many other factors, accurate prediction of which is impossible.

We can conclude, therefore, that the analytical calculation of the probability P, when considering it as a function of random variables, is not possible. This leads to the need of finding another way to solve the problem at hand.

Methods. The first and the obvious way is to simulate the simultaneous operation of several signal sources multiple times with different values of the vector $\vec{\varphi}$, and then to average the results. In this case, the signals are replaced with periodic sequences of unipolar pulses having the same duty cycle. The initial phases φ_i of the signals vary from 0 to $(1/R_i)\tau_x$, where τ_x is any positive number assumed to be the same for all the sources under consideration and changing with a fixed step $\Delta\varphi$. In the process of the described simulation, the following sequence of actions should be implemented as an iterative procedure:

1. A certain specified combination of the signal initial phases is set.
2. A long-time simulation of their simultaneous operation is carried out, and the intervals of the pulse overlaps are determined.
3. The probability of the pulse overlap is determined, and the next specified combination of the signal initial phases is set.

After many iterations, the arithmetic average of the found probability values is calculated.

The time required to complete such simulation can be approximately calculated using the formula

$$T \approx t_0 n_\varphi^{-(N-1)}, \quad (1)$$

where n_φ is the number of variations of the signal initial phases, N is the number of considered sources, t_0 is the time spent on one simulation with the fixed combination of the initial phases. In order to correctly determine the desired probability, this time should significantly exceed the maximum PRI of the simulated pulse sequences defined above as $(1/R_i)\tau_x$. It can be seen from (1) that the simulation algorithm has the computational complexity $O\left(n_\varphi^N\right)$. It means that the time of the full simulation rapidly increases with the increasing of the considered signal environment complexity, as well as with the increasing of the required accuracy of the analysis. In addition, in cases where the signals with the low value of the average duty cycle R are considered, more simulation iterations and, hence, a smaller step of the initial phases' variation are required in order to achieve the required simulation accuracy. In other words, the simulation time is determined by the reciprocal of the smallest average signal duty cycle. These circumstances make it difficult to use the simulation for the analysis of the complex signal environment.

The second way to solve the described problem is to consider the desired probability as the probability of a random event. Most of the works using this method [22–25] consider the problem of pulse overlap in relation to the task of the signal interception. With this approach, periodically occurring conditions necessary for the interception are presented in the form of window functions. Examples of such conditions include the algorithm of space scanning by the antenna and the algorithm of frequency range scanning in a tunable receiver. Since in this paper the event of overlap of the pulses from N sources is defined as the overlap of any number of pulses from 2 to N, it is not possible to apply the results of the abovementioned works to the solution of the stated problem. However, the general approaches to the mathematical description of the pulse sequences are universal. Thus, the authors of the classical work in the field of signal interception analysis [22] interpret the average duty cycle R_i as the probability of detecting a pulse from the i-th source at a random moment in time at any point in this pulse duration. If we adopt this interpretation, the task of determining the probability of time-overlap of pulses from several sources can be formulated as the task of finding the probability of the random event that two or more from N possible events having the probabilities $R_i, i = \overline{1, N}$ will occur simultaneously.

In this case, the probability that there are no pulses in any of N sequences at a random moment in time can be determined as

$$P_0 = \prod_{i=1}^{N}(1 - R_i),$$

and the probability that there is a pulse in only one of N sequences at a random point in time is

$$P_1 = \sum_{i=1}^{N}\left[R_i \prod_{j \neq i}^{N}\left(1 - R_j\right)\right].$$

Therefore, the probability that there is no pulse overlap at a random time is equal to

$$Q = P_0 + P_1,$$

and the probability that there is an overlap of two or more pulses can be determined as

$$P = 1 - Q = 1 - \left(\prod_{i=1}^{N}\left(1 - R_i\right) + \sum_{i=1}^{N}\left[R_i \prod_{j \neq i}^{N}\left(1 - R_j\right)\right]\right). \quad (2)$$

Since not just one, but several samples of the received signal are used in its digital processing, the short-time pulse overlaps may not pose a threat to the accuracy of the results. In this case, when calculating the probability P, it is possible to limit the minimum allowable duration of the overlap τ_o by modifying the probabilities R_i as follows

$$R_i' = \frac{\tau_i'}{T_i'} \cdot \frac{\left(\tau_i - \tau_o\right)}{\overline{T_i}}.$$

The complexity of calculating the required probability by using (2) is $O\left(N^2\right)$.

Further in this paper, instead of the average signal duty cycle R, the average signal duty-off factor $S = 1/R$ is used, since it is more familiar to human perception. To determine the signal duty-off factors of the typical sources, a review of reference materials [1] of the International Telecommunication Union (ITU) was performed on the example of radars. These materials contain the characteristics of typical radars operating in the frequency range from 30 MHz to 36 GHz. The brief results of this review are presented in the table below.

Signals' duty-off factors of different type radars

№	Radar type	Signal duty-off factor
1	Target tracking	Tens…hundreds
2	Surveillance and target search	Hundreds…tens of thousands
3	Navigation	Thousands … hundreds of thousands

Cellular stations can be used as an example of telecommunication sources. Thus, the GSM standard implies the use of time and frequency division multiplexing. The frequency range allocated to the station is divided into 200 kHz sub-bands. Within each of these sub-bands, the time-division multiplexing is used by further subdividing the sub-band into 8 time slots [26, p. 27]. The best-case scenario for the WBA is the work in an extremely low populated area. If the cellular station serves one subscriber, it can be considered as a narrow-band source with $S = 8$. If there are 8 subscribers to serve, the signal received by the WBA in one GSM frequency channel will become continuous, i. e. $S = 1$. With the number of subscribers greater than 8, the station can utilize other frequency sub-bands and can be considered as several sources with signals' duty-off factors ranging from 1 to 8. When a cellular station is operating in data transmission mode in UMTS networks that implement code-division multiple access, many subscribers can use one frequency channel with a width of 5 MHz [26, p. 121]. With a large number of subscribers, e. g., in an urban area, each of such channels can be considered as a narrow-band source with continuous signal $S = 1$.

Results. To experimentally compare the time of calculating the pulse overlap probability by simulation and by the use of the analytical expression (2), this probability was calculated for a signal environment with three identical sources. The simulation was performed for various values of S; its results are presented in Fig. 2.

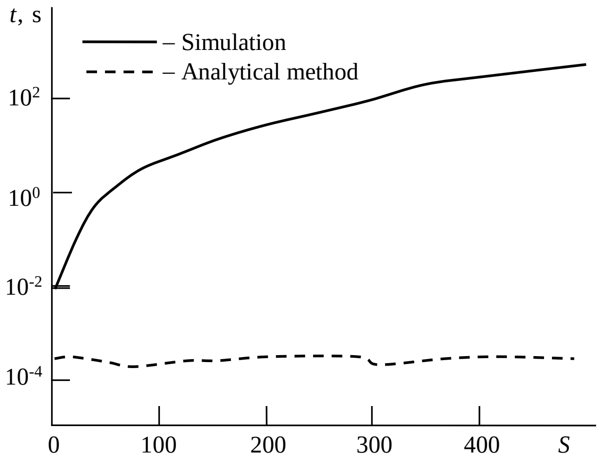

Fig. 2. Calculation time of the pulses from three sequences overlap probability as a function of their mean duty-off factor

Fig. 3 shows the relative deviation of the probability P_{sim} obtained in the simulation from the probability P_{an} calculated using (2) plotted against the value of S. The deviation is calculated as

$$\Delta P = \frac{P_{\text{sim}} - P_{\text{an}}}{P_{\text{an}}}.$$

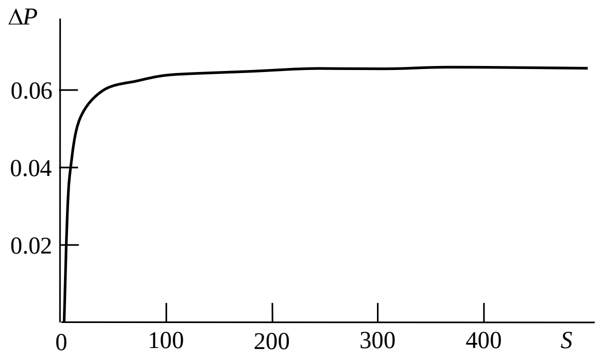

Fig. 3. Difference between analytical calculation of the pulses from three sequences overlap probability and its calculation by simulation as a function of the sequences mean duty-off factor

The dependencies of the pulse overlap probability presented in Fig. 4 and Fig. 5 are calculated using (2).

The probability of pulse time-overlap P is plotted against the number of signals' sources N in Fig. 4. These dependencies are obtained for different duty-off factors S of the pulse sequences.

Practice shows that in the complex signal environment most frequently from 10 to 100 of signals' sources are operating. Therefore, the individual dependencies were plotted against the range of the sources' number N, similar to those shown in Fig. 4. These dependencies are presented in Fig. 5.

Discussion. Fig. 2 shows that, when fixing the accuracy of calculation and the number of considered pulse sequences, an increase in these sequences' duty-off factors leads to a nonlinear increase of the simulation time. This is because with an increase of the signals' duty-off factors the desired probability decreases, and its estimating requires the accumulation of more data. Fig. 2 also shows that the analytical approach does not have this drawback, i. e., the time of calculation of the same probability remains constant with the increase of the considered signals' duty-off factors. To determine the probability of the pulse time-overlap even for three sources (with the signals' duty-off factors of several hundred), the simulation requires more than 100 seconds (All calculations described in the paper were performed in the MATLAB R2020a using the laptop with an Intel Core i5-8250U processor and 16 GB of random-access memory.). Accordingly, the use of this method in the analysis of the complex signal environment is extremely difficult. At the same time, Fig. 3 shows that the results obtained by using the proposed analytical expression differ from the simulation results by no more than 7 % for a wide range of the analyzed signals' duty-off factors.

Fig. 4 shows that the probability of the pulses' time-overlap strongly depends on their duty-off factors: for some duty-off factor values this probability does not exceed 1 % for almost any number of sources, and for some it tends toward 100 % even for the number of considered sources less than 10.

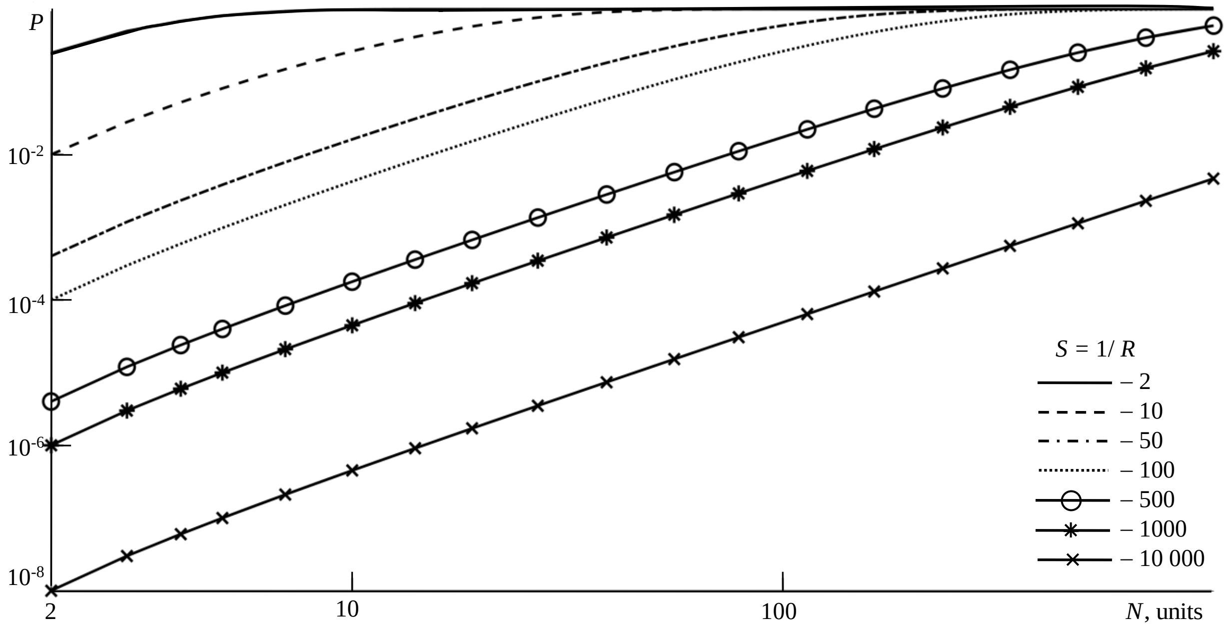

Fig. 4. Probability of the pulse overlap as a function of the pulse sequences number for different sequences duty-off factors, $N = 2\ldots1000$

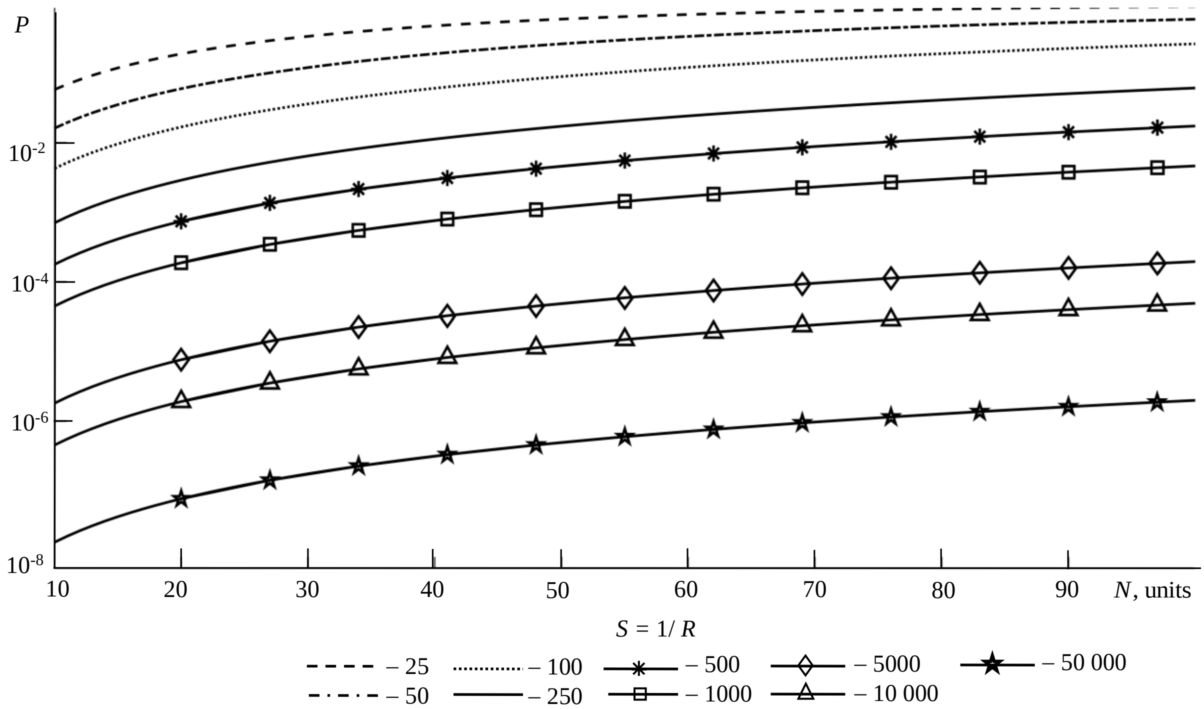

Fig. 5. Probability of the pulse overlap as a function of the pulse sequences number for different sequences duty-off factors, $N = 10\ldots100$

Fig. 5 shows that, if the complex signal environment is formed to a greater extent by the signals of the navigation radars, there is no threat to the stability of the WBA functioning. Even with 100 navigation radars located in the WBA coverage area, the probability of these radars' pulse time-overlap does not exceed 0.01 %. If the complex signal environment is formed by target tracking radars, the situation worsens significantly, i. e., even with 10 to 20 operating target tracking radars, the probability of their pulses' time-overlap can exceed 10 %.

Thus, due to the various effects in the complex signal environment, the number of false detections is significantly increasing, and the errors are occurring in determining the time and frequency parameters of the individual pulses. All this reduces the reliability of the signal types' determination and, accordingly, the classification of the signal sources. The quantitative indicator of a signal environment "complexity" proposed in this paper allows predicting the stability of various types of WBAs in a potential signal environment. Depending on the expected operating conditions, additional circuitry and algorithmic tools can be foreseen in the WBA design. This will improve the efficiency of the WBAs developed to date, especially of those that are based on new principles.

A comparative analysis of the calculations using proposed analytical expression and the simulation using real signals shows that the new expression allows one to achieve the computational speed of 2 to 6 orders of magnitude higher with an error below 7 %.

The authors' further plans include the development of more complex dynamic models of the complex signal environment that take into account the mutual motion of the signal sources and WBA carrier, the orientation of the antenna patterns, and the signal multipath propagation. The high performance of the calculations using the proposed expression will allow more efficient simulation of the complex signal environment in dynamics.

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