Vestnik of Don State Technical University. 2018. Vol. 18, no. 4, pp. 385–391. ISSN 1992-5980 eISSN 1992-6006
Вестник Донского государственного технического университета. 2018. Т. 18, № 4. С. 385–391. ISSN 1992-5980 eISSN 1992-6006

МАШИНОСТРОЕНИЕ И МАШИНОВЕДЕНИЕ
MACHINE BUILDING AND MACHINE SCIENCE

УДК 621.391.3
https://doi.org/10.23947/1992-5980-2018-18-4-385-391

Linear-logical decision-making algorithm for signal processing[*]

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Линейно-логический алгоритм принятия решения при обработке сигналов[***]

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Introduction. Heuristic synthesis is used to improve the efficiency of reception and processing of discrete signals under aprior information pressure. The analysis of the decision-making algorithm for the linear-logical processing of discrete signals in case of the incomplete aprior data on their parameters is presented. The work objective is to develop and analyze the efficiency of the linear-logical algorithms.
Materials and Methods. New mathematical algorithms for the signal reception and processing, effective under conditions of a priori uncertainty, are proposed. They are based on the consideration of the structure of emissions and process exceedance in the signal processing channels.
Research Results. Linear-logical algorithms for processing discrete signals are developed. They are based on the consideration of one, two and more detailed characteristics of emissions or exceedance of random processes.
Discussion and Conclusion. The results obtained can be useful in the synthesis of algorithms and devices for the signal reception and processing. Algorithms and devices are implemented both in an analog form and in the form of algorithms for computers. The simulation programs for the signal processing under conditions of the considerable uncertainty of aprior information on the signals and the channels of their distribution are developed.

Введение. Для повышения эффективности приема и обработки дискретных сигналов в условиях дефицита априорных сведений применяют эвристический синтез. Представлен анализ алгоритма принятия решения при линейно-логической обработке дискретных сигналов в случае, если априорные данные об их параметрах неполны. Цель работы — построение и анализ эффективности линейно-логических алгоритмов.
Материалы и методы. Предложены эффективные в условиях априорной неопределенности математические алгоритмы приема и обработки сигналов. Они основаны на учете структуры выбросов и превышений процессов в каналах обработки.
Результаты исследования. Созданы линейно-логические алгоритмы обработки дискретных сигналов. Они основаны на учете одной, двух и более детальных характеристик выбросов или превышений случайных процессов.
Обсуждение и заключения. Полученные результаты могут быть полезны в процессе синтеза алгоритмов и устройств приема и обработки сигналов. Алгоритмы и устройства реализуемы как в аналоговом виде, так и в виде алгоритмов для ЭВМ. Созданы программы моделирования при обработке сигналов в условиях значительной априорной неопределенности информации о сигналах и о каналах их распространения.

Keywords: decision rules, heuristic synthesis, reception and processing of discrete signals, probability distribution densities, emissions and exceedance of random processes.

Ключевые слова: решающие правила, эвристический синтез, прием и обработка дискретных сигналов, плотности распределения вероятностей, выбросы и превышения случайных процессов.

For citation: V.S. Plaksienko. Linear-logical decision-making algorithm for signal processing. Vestnik of DSTU, 2018, vol. 18, no. 4, pp. 385-391. https://doi.org/10.23947/1992-5980-2018-18-4-385-391.

Образец для цитирования: Плаксиенко, В. С. Линейно-логический алгоритм принятия решения при обработке сигналов / В. С. Плаксиенко // Вестник Дон. гос. техн. ун-та. — 2018. — Т. 18, № 4. — С. 385-391. https://doi.org/10.23947/1992-5980-2018-18-4-385-391.

Introduction. Heuristic engineering synthesis of nonparametric decision rules is used to optimize signal processing under conditions of considerable a priori uncertainty. This procedure is based on the analysis of

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the emission parameters of random processes at the output of the demodulator of the receiver of discrete signals [1–7]. The emission theory is of considerable use in the engineering practice. However, the analysis of regularities and detailed characteristics of emissions is a complex analytical task even at a constant or slowly varying threshold. In the course of the analytical approach, relations are obtained that lead to nonconvergent series, which explains the absence of physically meaningful results.

At present and in the near future, the use of discrete multiposition signals is promising. They include discrete address systems, multiple telegraphy systems (frequency telegraphy, multiposition frequency telegraphy), and systems with D and E codes in which elementary parcels of T_c duration at one or different frequencies are transmitted serial/parallel in time [5, 8–10].

When receiving binary signals at the resolver input, two random processes occur, and the decision procedure is reduced to the problem of statistical hypothesis testing. It is necessary to determine which random process (of the compared ones) has more energy on the observation interval. In this case, the decision-making procedure can be reduced to comparing the difference signal value at the receiver output with a constant zero threshold. Hence, it is necessary to compare at least two random processes (at the best case, a random process from the output of the receiver of discrete signals at a slowly varying threshold is analyzed).

Statistical testing of hypotheses is reduced to the analysis of the mutual exceedance of two or more processes. The analytical presentation of this problem is cumbersome, and it does not provide engineering solutions [1, 11–15]. Heuristic synthesis and computer-based statistical modeling enable to obtain significant engineering applications.

When receiving multiposition signals, the following can be simplified:

- their spectra $S\,(f)$;
- amplitude-frequency characteristics (AFC) of the filters of K (f) receivers (Fig. 1).

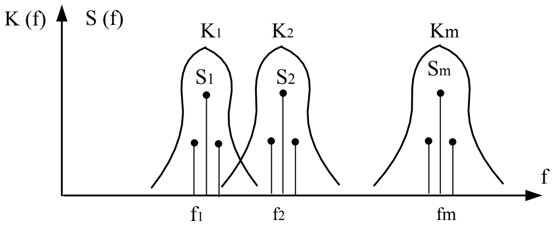


Fig. 1. Frequency response of filters

A linear receiver of multiposition signals should have:

- common intermediate frequency amplifier (IFA),
- general decision making circuit (DMC).

Sets of separation filters (see Fig. 1) and amplitude detectors (AD) are also required. The analysis of such receivers shows [1] the following: the greater the number of m signal locations, the lower their immunity. Requirements for the frequency response of filters (see Fig. 1) are quite rigid. AFC should not be overlapped to ensure frequency orthogonality. In this case, the noise at the filter outputs will be independent. There should be no overlapping regions between the AFC filters tuned to $f_{i,}$ frequencies (see Fig. 1). The AFC form should have a flat area in the neighborhood of the resonant frequency, so that the signal spectra are not distorted.

Some existing contradictions should be observed. Thus, narrowband filters limit the operating speed. In case of signal depression and the Doppler effect, the degradation of quality and even failure of communication may occur. Broadband filters lead to the interpenetration of the signals of the neighboring frequency channels, i.e. the orthogonality is violated, and, accordingly, the reception quality decreases.

The procedures at the filter outputs of the adjacent channels in the signal detection and processing systems are characterized by the statistical relationships that increase with extending the mutual overlapping of the signal spectra or AFC filters. A detailed examination of the frequency-sharing procedure shows that we can speak of pairwise dependent workflows in the frequency co-channels when processing multiposition signals in the case of the overlapping AFC filters. This is of particular importance when used to optimize the reception of multiposition signals of nonlinear or linear logic procedures [1, 11–14].

Research Objective. Under conditions of considerable prior uncertainty, the signal frequency is known with limited accuracy, and the range of variation of the elementary symbol durations can change up to a thousand times. Additional requirement is real-time operation. For simplicity, we will restrict ourselves to the case of processing binary signals.

Decision algorithm synthesis. In papers [1, 11–13], some features of processing discrete signals under conditions of a considerable prior uncertainty of the information about a symbol duration are considered. The problem can be solved through the linear procedures by parallelism of the decision algorithm. The problem becomes more involved through increasing the required accuracy and expanding the variation range of the elementary symbol duration.

Under such conditions, the use of the adaptive procedures requires significant amount of time to adapt; either it is almost unrealizable due to high prior uncertainty. Let us analyze the possibilities of the heuristic synthesis of the algorithm based on the statistical properties of the mutual exceedance of two or more random processes [1, 11–12].

Consider a broadband reception with integration or filtering after the detector, when $\Delta f_{\text{п}} T >> 1$ ($\Delta f_{\text{п}}$ is fп is the receiver bandwidth, T is the duration of the elementary symbol). In this case, the counts of the process at the resolver output can be considered near-normally distributed. The expectation and dispersion of this process are determined by the relations [4]:

$$\Delta M[x] = M[x_1] — M[x_2], \qquad D[x] = D[x_1] + D[x_2].$$

The probability of erroneous reception is calculated from the formula [1–3, 12]:

$$P = \frac{1}{2}[1 - \Phi(\alpha)].$$

Here $\Phi(\alpha) = \sqrt{\frac{2}{\pi}} \int_0^{\alpha} \exp(-\frac{x^2}{2}) dx$ is Kramp function; $\alpha = \frac{\Delta M}{\sqrt{D}} = \frac{h}{\sqrt{2 + 2\Delta f T / h^2}}$ is ratio of the constant component to the effective value of the variable; $h^2 = \frac{a^2}{2\nu^2}$ is ratio of the signal element energy to the noise spectral density, where a is the signal normalized amplitude, and ν^2 is the noise spectral density.

When processing discrete signals under these conditions, only non-parametric decision algorithms can be used. The statistical characteristics of emissions of random processes are interesting themselves: $t_{\text{П}}$ duration of the emissions (exceedance), $T_{\text{И}}$ duration of the intervals between emissions, ξ_m values of emission maxima, etc. [3]. The optimization decision algorithms can be based on one of the detailed characteristics, for example: the crossing threshold number during the observation period, the duration of the threshold crossing intervals, etc. It is necessary to determine the informative features of such detailed characteristics of the mutual exceedance of random processes. Technically realizable engineering metering data will optimize the algorithm for receiving and processing signals under the specified conditions.

In the context of energy, the greatest accuracy under the conditions of considerable prior uncertainty will be ensured by the consideration of $S_{\text{П}}$ areas of mutual exceedance (within the energy limit). However, to implement it in real time algorithmically and a fortiori technically is difficult.

The concept of emissions is a special case of the concept of mutual exceedance for two or more processes, including random ones. When processing binary signals, the problem of analyzing the emissions of the difference process with respect to the zero threshold is set. It is adequate to the task of analyzing the mutual exceedance of two envelope processes in the signal processing channels [3, 11].

To optimize the decision-making problem in real time, it is advisable to simultaneously consider two or more detailed characteristics of emissions, for example, the duration and exceedance value. The product of the duration by the level (amplitude) of the exceedance is an evaluation of the exceedance area (considering the shape factor of the exceedance) [11].

We use two detailed characteristics.

1. q relative level of excess:

$q = X_i(t) / X_j(t)$, where $X_i(t)$ and $X_j(t)$ are the analyzed processes.

2. Θ relative duration of excess:

$\Theta = t_{\text{П}} / \tau_{\text{К}}$, where $\tau_{\text{К}}$ is the correlation interval of the processes at the output of the linear part of the receiver determined by its passband.

To consider these characteristics in combination is not so hard technically.

Joint consideration of these characteristics is relatively not difficult. Совместный учет указанных характеристик технически сравнительно не труден

At the same time, its reliability is close to the indicators obtained allowing for $S_{\text{П}}$ areas of exceedance. Considering the meaning of the term “excess”, q should be greater than 1, therefore in a binary situation, when forming two-parameter distributions, q is determined by the relation [11]:

$$q = \begin{cases} \dfrac{x_1(t)}{x_2(t)}; & x_1(t) \geq x_2(t); \\ \dfrac{x_2(t)}{x_1(t)}; & x_2(t) \geq x_1(t). \end{cases} \tag{1}$$

This approach allows us to analyze the multiparameter distributions of mutual excesses of two or more random processes.

To improve the quality of decision-making, it is necessary to reduce the total number of mutual exceedance of processes. This follows from the analysis results of the two-dimensional laws of the mutual exceedance distribution of the signal-noise mixture envelope and noise envelope [11]. It is necessary to transform the processes in such a way that, without disturbing the likelihood ratio, to obtain the two-dimensional distribution forms, easily distinguished by the resolver [12].

Both problems are solved using a modified combined addition algorithm [1, 11, 14]:

$$\begin{aligned} X_{1\text{П}}(t) &= [X_1(t) - K\,X_{2\text{П}}(t)]\;1[X_1(t) - K\,X_2(t)], \\ X_{2\text{П}}(t) &= [X_2(t) - K\,X_{1\text{П}}(t)]\;1[X_2(t) - K\,X_1(t)], \end{aligned} \tag{2}$$

where K is a coefficient taking values from 0 to 1; 1 $[Z(t)]$ is a single step function, with 1 $[Z(t)] = 1$ for $Z(t) > 0$ and 1 $[Z(t)] = 0$ for $Z(t) < 0$.

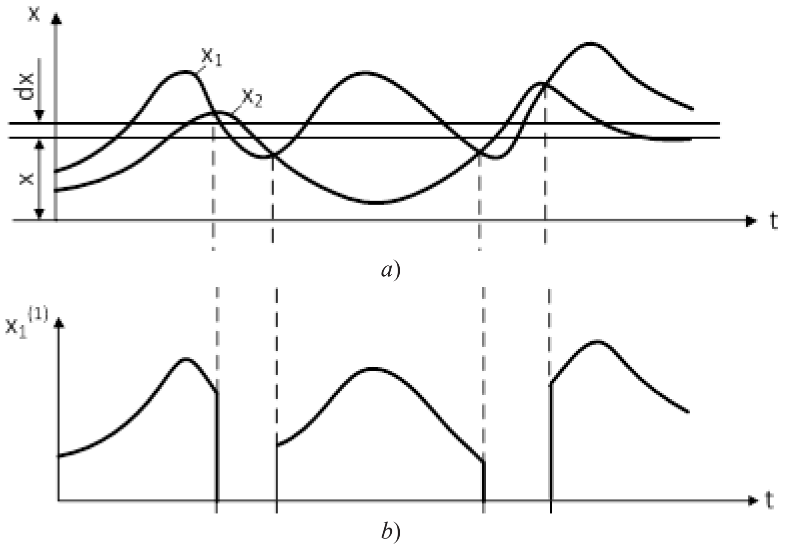
The spectra of the $X_{1\text{П}}(t)$ and $X_{2\text{П}}(t)$ processes formed after processing by the algorithm (2) are extended. They should be limited to the width of the spectra of the initial information processes $X_1(t)$ and $X_2(t)$.

The value of K determines the implemented modifications of the algorithm and devices of the combined addition. We are talking about the algorithm of mutual transformation, the method of combined addition, the cross-blocking system [1, 11].

When $K = 1$, only the fact of the process exceedance is taken into account of all the detailed characteristics of the exceedance. The auto-selection algorithm is implemented when the diversity technique is used [4], and the mutual conversion – under decision making [11].

When $K = 0.414$, both the fact that one process is exceeded by another, and the level of q excess are considered [4]. The combined addition is implemented in the diversity reception. When $1 > K > 0$, not only the fact of excess, but also q level of excess is taken into account. The modified method of combined addition is implemented under making decision.

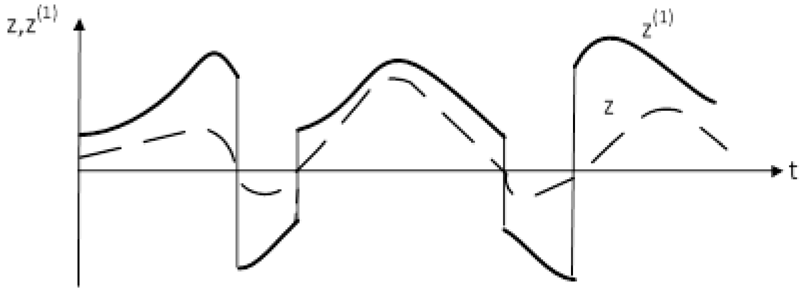
Linear-logical procedures implemented as a result of heuristic synthesis enable statistically to transform the original random processes. When $K = 1$ in (2), auto-selection of processes is realized in time. Temporally continuous processes (Fig. 2, *a*) turn into sequences of pulses with $X_1^{(1)}(t)$ and $X_2^{(1)}(t)$ random amplitudes (Fig. 2, *b* and 2, *c*).



a)

b)

c)



d)

Fig. 2. Combined addition at *K*=1

In Fig. 2, *d*, the difference processes are presented: $Z = X_1 - X_2$ without processing and $Z^{(1)} = x_1^{(1)} - x_2^{(1)}$ after processing according to rule (2).

Density of probability distribution of $X_1^{(1)}(t)$ and $X_2^{(1)}(t)$ processes:

$$W_1^{(1)}(x) = A_1\delta(x) + W_1(x)F_2(x) \tag{3}$$

$$W_2^{(1)}(x) = A_2\delta(x) + W_2(x)F_1(x). \tag{4}$$

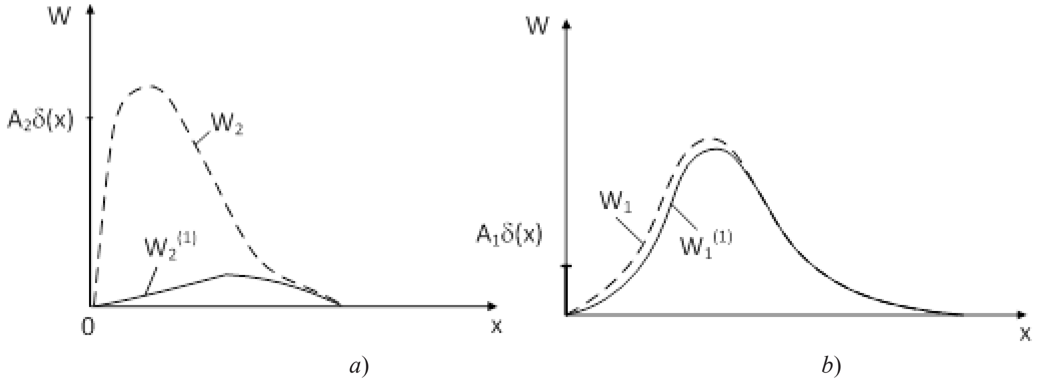
A_1 and A_2 coefficients are determined from the normalization condition:

$$A_1 = 1 - \int_0^\infty W_1(x)F_2(x)dx, \tag{5}$$

$$A_2 = 1 - \int_0^\infty W_2(x)F_1(x)dx\,, \tag{6}$$

where $F_1(x)$ and $F_2(x)$ are cumulative distribution functions.

From the consideration of Fig. 2, *a* - 2, *c,* it follows that $X_1^{(1)}(t)$ and $X_2^{(1)}(t)$ processes are equal to zero for some time. Therefore, their $W_1^{(1)}(x)$ and $W_2^{(1)}(x)$ probability distribution densities will contain $\delta(x)$ delta functions (Fig. 3).



a) *b*)

Fig. 3. Density of probability distribution of processes

Fig. 4 shows the probability distribution density of difference processes $W(z)$ without processing according to rule (2) (Fig. 4, *a*) and $W_1^{(1)}(Z)$ after processing (Fig. 4, *b*). Here, Δ is the erasing zone of the resolver.

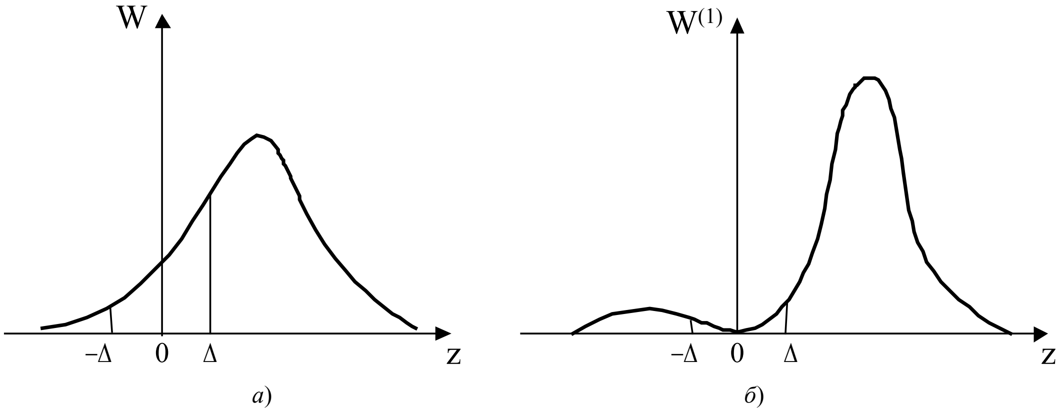


Fig. 4. Density of probability distribution of $Z(t)$, $Z^{(1)}(t)$ processes

In accordance with Fig. 2, *b* and 2, *c*, the processes after treatment according to rule (2) are impulsive. Their spectra will be broader than the spectra of the source processes. Thus, processing according to rule (2) does not lead to an increase in the quality of reception, but only improves the threshold properties [11–12, 16].

Their spectra will be broader than those of the source processes. Thus, processing according to rule (2) will not lead to an increase in the reception quality, but it will only improve the threshold properties [11–12, 16].

A full treatment procedure includes two operations:

- linear-logical operation according to rule (2) (it is pertinently non-linear, since there appear components in the spectrum that were not at the input);
- filtering.

Filtering considers the second parameter of Θ exceedance – relative duration. The expanded spectra of processes remain within the boundaries specified under the formation of $X_1(t)$ and $X_2(t)$ source processes (see Fig. 2, *a*).

Processing according to rule (2) can repeat depending on the variation range of the duration of the expected signals and reception conditions [12]. In this case, the values of *K* parameter are different, they are always less than 1, and increase in the subsequent processing cycles.

Problems of the automatic frequency control are solved more efficiently when using devices that implement linear-logical processing [14, 17–18]. Locking and retention bands are extended by low-end techniques. Certain parameter stability of the automatic frequency control under the additive interference is provided.

Research Results. The results of studying the algorithm (2) in case when signals are dependent are beyond the scope of this paper. However, the data already obtained have shown the algorithm efficiency up to the values of the cross-correlation coefficients of $\rho = 0.5–0.6$ processes. This is in good agreement with the results of solving the tasks of the diverted reception [2–4]. Algorithms of the modified combined addition of signals are effective both under the diversity technique, and in decision-making problems. Yet, the consideration of their implementation features is beyond the scope of the paper.

Thus, the optimization of the decision-making procedure for processing discrete signals under conditions of considerable prior uncertainty can be performed on the basis of non-parametric algorithms with the heuristic consideration of the detailed characteristics of mutual exceedance of random processes. More detailed characteristics complicate the algorithm. Still, it is this algorithm that provides greater invariance in terms of noise immunity under varying the duration of the expected signals. The synthesized algorithms can be implemented in the form of additional processing procedures on a computer, and technically – in the form of analog devices [14, 19].

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Received 27.09.2018
Submitted 27.09.2018
Scheduled in the issue 21.10.2018

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