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ASYMPTOTICALLY OPTIMAL ALGORITHM FOR PROCESSING SIDE RADIATION SIGNALS FROM MONITOR SCREENS ON LIQUID CRYSTAL STRUCTURES

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Abstract. *An asymptotically optimal compatible algorithm for detecting side radiation signals from the monitor screen on liquid crystal structures and estimating the duration of image immutability on the monitor screen is found, which will better intercept information from monitor screens. The structure of a special technical intelligence tool is justified as a maximum likelihood algorithm for a finite number of unknown quadrature amplitudes of the information leakage signal from the monitor screen on liquid crystal structures.*

Keywords: side electromagnetic radiation and guidance, video card signals, liquid crystal structures, spectra of signals

ASYMPTOTYCZNIE OPTYMALNY ALGORYTM PRZETWARZANIA SYGNAŁÓW PROMIENIOWANIA BOCZNEGO Z EKRANÓW MONITORÓW LCD

Streszczenie*. Znaleziono asymptotycznie optymalny wspólny algorytm wykrywania sygnałów promieniowania bocznego z ekranu monitora na strukturach ciekłokrystalicznych i szacowania czasu trwania niezmienności obrazu na ekranie monitora, który w najlepszy sposób przechwyci informacje z ekranów monitorów. Struktura specjalnego narzędzia wywiadu technicznego jest uzasadniona jako algorytm maksymalnego prawdopodobieństwa dla skończonej liczby nieznanych kwadraturowych amplitud sygnału wycieku informacji z ekranu monitora na strukturach ciekłokrystalicznych.*

Słowa kluczowe: boczne promieniowanie elektromagnetyczne i przesłuchy, sygnały z kart graficznych, struktury ciekłokrystaliczne, widma sygnałów

Introduction

Eighteen years have passed since the publication of Markus Kuhn's work, in which he first investigated the leakage of information from monitors on liquid crystal structures (LCS) [5]. This time was used by developed industrial countries to create special technical means of intelligence (STMI) capable of intercepting information at distances of tens to hundreds of meters [3, 6–8]. At the same time, most open publications on this topic are based on the desire to immediately describe devices for intercepting information, the leakage of which is caused by indirect electromagnetic radiation and interference (IEMR&I), without justifying their structure using the classical theory of optimal signal filtering.

The theory of optimal signal reception against the background of internal receiver noise states that the best signal detection is the one that is most consistent with the IEMR&I signal [9]. Under conditions of a priori uncertainty with respect to most parameters of the leakage signal, a similar signal receiver is an asymptotically Bayesian IEMR&I signal detector – a receiver, which approaches the optimal signal-to-noise ratio at the output of its linear part [10]. Such receivers use maximum likelihood algorithms (MLA), the essence of which is that unknown parameters of the received signal replace them with the most plausible estimates, in the case when the number of unknown parameters is finite.

1. Statement of the problem

We will set a goal to justify the structure of the STMI that implement the MLA. Let the image of the monitor screen on LCS of the computational facilities remain unchanged during the analysis time $T_a \in [T_{a\,\min}, T_{a\,\max}]$, $T_{a\,\min}, T_{a\,\max}$ – lower and upper limits of the analysis time. Then at the time interval $t \in [0, T_a]$, $T_a >> T_f$, T_f – the period of the monitor scan frames, the signal realisation is analysed

$$x(t) = \begin{cases} n(t), & \text{when the signal is not present} \\ n(t) + s(t, \mathbf{v}_0), & \text{when the signal is present} \end{cases} \quad (1)$$

where $n(t)$ – Gaussian process with zero mean and correlation function

$$B(t, \tau) = M\left[n(t)n(t+\tau)\right] \quad (2)$$

$\mathbf{v}_0$ – vector of actual values of IEMR&I signal parameters $s(t, \mathbf{v}_0)$. It is assumed that $s(t, \mathbf{v}_0)$ is a known function of time t and a vector n with – parameters $\mathbf{v}_0 \in \mathbf{\Theta}$, $\mathbf{\Theta}$ – parameter space, in which the intervals of each parameter are finite $\Theta_i \in [\Theta_{i1}, \Theta_{i2}], i = 1...n$, or $\mathbf{\Theta} \in [\mathbf{\Theta}_1, \mathbf{\Theta}_2]$; $\mathbf{\Theta}_1$ – vector of lower parameter values; $\mathbf{\Theta}_2$ – vector of upper parameter values.

The decision on the presence of a signal $s(t, \mathbf{v}_0)$ is made when the likelihood ratio function (LRF) is the absolute maximum

$$\sup_{\mathbf{v}\in\mathbf{\Theta}}\left[l(T_a, \mathbf{v})\right] \geq h \quad (3)$$

and about the fact that there is no signal – when $\sup_{\mathbf{v}\in\mathbf{\Theta}}\left[l(T_a, \mathbf{v})\right] < h$, where h – a certain detection threshold that depends on the optimality criterion,

$$\begin{gathered} l(T_a, \mathbf{v}) = \exp\left[L(T_a, \mathbf{v})\right] \\ L(T_a, \mathbf{v}) = \int_0^{T_a} x(t) V(t, \mathbf{v})\,\mathrm{d}t - \frac{1}{2}\int_0^{T_a} s(t, \mathbf{v}) V(t, \mathbf{v})\,\mathrm{d}t \end{gathered} \quad (4)$$

a $V(t, \mathbf{v})$ – solution of the integral equation:

$$\int_0^{T_a} B(t, \tau) V(\tau, \mathbf{v})\,\mathrm{d}\tau = s(t, \mathbf{v}), \qquad t \in [0, T_a] \quad (5)$$

Goal: find (4) by solving integral equation (5), and obtain MLA (3) for an arbitrary vector of unknown parameters $\mathbf{v}$ of IEMR&I signal and unknown time of unchanged image on the monitor screen $T_a \in [T_{a\,\min}, T_{a\,\max}]$.

2. Solution of the problem

Let us consider a specific signal of information leakage through IEMR&I in the form of a modulating voltage of one of the three colours of the RGB monitor on the LCS – $s(t, \mathbf{v}_0)$ (see Fig. 1).

If the image on the monitor is static, then it can be represented as the sum of voltages m – periodic i-th sequences of signals, for Fourier series coefficients:

$$\begin{aligned} s(t, \mathbf{v}_0) &= \\ &= \mathbf{1}(T_{a0} - t)\sum_{k=-\infty}^{\infty}\sum_{i=1}^{m}\frac{U_i}{\pi k}\sin\left(\frac{\pi k \tau_i}{T_f}\right)\cos\left[\frac{2\pi k}{T_f}\left[t - t_{di}\right]\right] \end{aligned} \quad (6)$$

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$\mathbf{1}(x)$ – single function, T_{a0} – true duration of the unchanged image on the monitor screen. As illustrated in Fig. 1 example $m = 3$

The zero harmonic is further excluded from consideration, since it does not propagate in space. Then (6) can be expressed in terms of amplitude quadratures:

$$a_{kc} = \sum_{i=1}^{m} \frac{2U_i}{\pi k} \sin\left(\frac{\pi k \tau_i}{T_f}\right) \cos\left(\frac{2\pi k t_{di}}{T_f}\right)$$

$$a_{ks} = \sum_{i=1}^{m} \frac{2U_i}{\pi k} \sin\left(\frac{\pi k \tau_i}{T_f}\right) \sin\left(\frac{2\pi k t_{di}}{T_f}\right)$$

in the following form:

$$s(t,\mathbf{v}) = \mathbf{1}(T_{a0} - t) \sum_{k=1}^{\infty} \left[a_{kc} \cos\left(\frac{2\pi kt}{T_f}\right) + a_{ks} \sin\left(\frac{2\pi kt}{T_f}\right) \right] \quad (7)$$

Since the periodic structure of the signal does not change over a period $t = [0, T_{a0}]$, each $a_{kc}(t)$ – and i $a_{ks}(t)$ – and amplitude quadrature with cyclic information leakage frequencies $2k\pi / T_f$ is constant: $a_{kc}(t) = \text{const1}$; $a_{ks}(t) = \text{const2}$, and change only when $t > T_{a0}$. Fig. 2 shows, for example, changes in time of the $a_{205c}(t)$-th, $a_{10023s}(t)$-th, and $a_{200045c}(t)$-th quadrature of amplitudes for three realisations of random time intervals T_a of changing static images on the monitor screen – $T_{a10}, T_{a20}, T_{a30}$.

As you can see, each k – and the quadrature amplitude is a sequence of rectangular pulses of unknown amplitude $a \in [0, a_{\max}]$ at intervals $T_{a10}, T_{a20}, T_{a30}, \ldots$, and substitutions of (7) in (5) for (2):

$$B(t,\tau) = \frac{N_0}{2} \delta(t-\tau)$$

where $\delta(\tau)$ – Delta function, N_0 – one-way spectral power density of white Gaussian noise (WGN), gives a solution to integral equation (4), for $t \in [0, T_a]$:

$$V(t,\mathbf{v}) = \frac{2}{N_0} \sum_{k=1}^{\infty} \left[a_{kc} \cos\left(\frac{2\pi kt}{T_f}\right) + a_{ks} \sin\left(\frac{2\pi kt}{T_f}\right) \right] \quad (8)$$

So, whatever the structure of the periodic (with a follow-up period T_f) signal $s(t,\mathbf{v})$, its energy is invested in quadrature amplitudes a_{kc} and a_{ks}, $k = 1, 2, .., \infty$:

$$\begin{aligned} E(\mathbf{v}) = \int_0^{T_{a0}} s^2(t,\mathbf{v})\,\mathrm{d}t = \frac{T_f}{2\pi} \sum_{k=1}^{\infty} \sum_{l=1}^{\infty} \frac{1}{k^2 - l^2} \times \\ \times \Bigg((a_{kc}a_{lc}k - a_{ks}a_{ls}l) \sin\left(\frac{2\pi k T_{a0}}{T_f}\right) \cos\left(\frac{2\pi l T_{a0}}{T_f}\right) + \\ + (a_{ks}a_{ls}k - a_{kc}a_{lc}l) \cos\left(\frac{2\pi k T_{a0}}{T_f}\right) \sin\left(\frac{2\pi l T_{a0}}{T_f}\right) - \\ - (a_{kc}a_{ls}k + a_{ks}a_{lc}l) \sin\left(\frac{2\pi k T_{a0}}{T_f}\right) \sin\left(\frac{2\pi l T_{a0}}{T_f}\right) - \\ - (a_{ks}a_{lc}k + a_{kc}a_{ls}l) \cos\left(\frac{2\pi k T_{a0}}{T_f}\right) \cos\left(\frac{2\pi l T_{a0}}{T_f}\right) + \\ + (a_{ks}a_{lc}k - a_{kc}a_{ls}l) \Bigg) \end{aligned} \quad (9)$$

Substituting (8) in (4) allows getting the LRF:

$$\begin{aligned} L(T_a,\mathbf{v}) = \frac{2}{N_0} \sum_{k=1}^{\infty} \int_0^{T_a} x(t) \Bigg[a_{kc} \cos\left(\frac{2\pi kt}{T_f}\right) + \\ + a_{ks} \sin\left(\frac{2\pi kt}{T_f}\right) \Bigg] \mathrm{d}t - \frac{E(\mathbf{v})}{N_0}, \end{aligned} \quad (10)$$

in which $E(\mathbf{v})$ – is set (9).

The convergence of the double row in (9) depends on the specific "image" on the monitor screen. But in the vast majority of cases, in (10) we can limit ourselves to the total number of information harmonics with frequencies k / T_f, k – harmonic number, $k = 1, 2, \ldots, K$, which reaches $K \approx 3.3 \cdot 10^7$, since for $T_f = 1/60$ Hz the upper frequency limit of IEMR&I – does not exceed 2 GHz, for most monitors on LCS of the computational facilities.

Such quantitative restriction of unknown parameters allows us to solve the problem of finding MLA for LRF, in which the vector of unknown signal parameters $\mathbf{v}$ is $2K$ – measurable:

$$\begin{aligned} L(T_a, a_{1c}, a_{1s}, a_{2c}, a_{2s}, .., a_{Kc}, a_{Ks}) = \frac{2}{N_0} \sum_{k=1}^{K} \int_0^{T_a} x(t) \cdot \\ \cdot \left[a_{kc} \cos\left(\frac{2\pi kt}{T_f}\right) + a_{ks} \sin\left(\frac{2\pi kt}{T_f}\right) \right] \mathrm{d}t - \\ - \frac{1}{N_0} \sum_{k=1}^{K} \int_0^{T_a} \left[a_{kc} \cos\left(\frac{2\pi kt}{T_f}\right) + a_{ks} \sin\left(\frac{2\pi kt}{T_f}\right) \right]^2 \mathrm{d}t \end{aligned} \quad (11)$$

The essence of MLA is that unknown $2K$ – quadrature amplitudes a_{kc}, a_{ks}, $k = 1, 2, \ldots, K$, replace them with the most plausible estimates – $\hat{a}_{kc}, \hat{a}_{ks}$, which are arguments of alternately solved equations:

$$\begin{aligned} \frac{\partial L(T_a, a_{1c}, a_{1s}, a_{2c}, a_{2s}, .., a_{Kc}, a_{Ks})}{\partial a_{kc}} = 0 \\ \frac{\partial L(T_a, a_{1c}, a_{1s}, a_{2c}, a_{2s}, .., a_{Kc}, a_{Ks})}{\partial a_{ks}} = 0 \end{aligned} \quad (12)$$

The arguments of solutions (12) for quadrature amplitudes will have the form:

$$\begin{aligned} \hat{a}_{kc} \approx \frac{2}{T_a} \int_0^{T_a} x(t) \cos\left(\frac{2\pi kt}{T_f}\right) \mathrm{d}t \\ \hat{a}_{ks} \approx \frac{2}{T_a} \int_0^{T_a} x(t) \sin\left(\frac{2\pi kt}{T_f}\right) \mathrm{d}t \end{aligned} \quad (13)$$

which are more accurate than $T_a >> T_f$ and then the signal-to-noise ratio at the output of the linear part of the STMI receiver is greater, and substituting (13) in (11) allows us to obtain LRF for MLA, in which the uncertainty with respect to quadrature amplitudes is overcome:

$$\begin{aligned} L(T_a) = \frac{4}{N_0 T_a} \sum_{k=1}^{K} \Bigg[\left(\int_0^{T_a} x(t) \cos\left(\frac{2\pi kt}{T_f}\right) \mathrm{d}t \right)^2 + \\ + \left(\int_0^{T_a} x(t) \sin\left(\frac{2\pi kt}{T_f}\right) \mathrm{d}t \right)^2 \Bigg] \end{aligned} \quad (14)$$

A compatible algorithm for detecting IEMR&I and estimating the time interval at which they do not change consists in comparing the absolute maximum of (14) with the detection threshold h, in which a decision is made to detect IEMR&I from the monitor screen when

$$\sup_{T_{a\,\min} \le T_a \le T_{a\,\max}} L(T_a) > h \quad (15)$$

and the decision that there is no IEMR&I signal – when

$$\sup_{T_{a\min}\le T_a\le T_{a\max}} L(T_a) \le h$$

A diagram of the asymptotically Bayesian compatible IEMR&I signal detection algorithm and image duration estimation is shown in Fig. 3.

It consists of K – energy storage channels k harmonics in quadratures, K – adders in processing channels from $T_{a\min}$ to $T_{a\max}$, maximum selection device (MSD) and a comparison scheme with the detection threshold h. Since estimate of the frame duration on the monitor screen $\hat{T}_{a0}$ is known, it is possible, by using (13), to obtain estimates of k spectral quadrature amplitudes (see Fig. 4).

Diagrams of Fig. 3 and Fig. 4 fully describe the possibilities of modern STMI with asymptotically optimal algorithms for joint detection of signals and evaluation of their informative parameters, except for the procedure for estimating the period of following the frame scan of the monitor on LCS, which precedes the detection of the IEMR&I signal from computational facilities. To reproduce a black-and-white image intercepted by the STMI from the screen of the monitor of computational facilities, it is enough to generate a signal (7) using amplitude estimates (13) and feed it to the monitor's video card (after mixing all RGB signals).

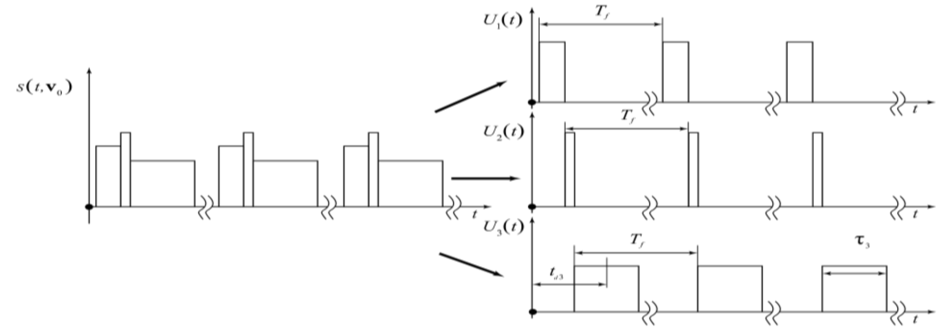

Fig. 1. Decomposition into elementary sequences of rectangular pulses of the information signal of the monitor on LCS

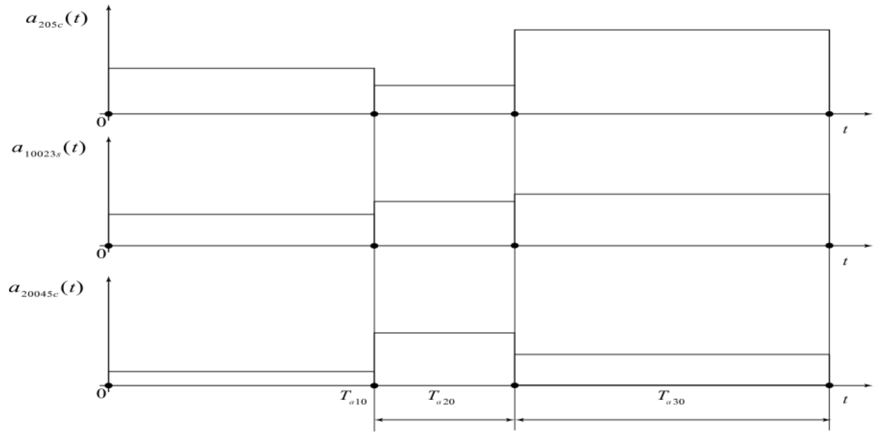

Fig. 2. Examples of changes in quadrature amplitudes over time

3. Further ways to solve the problem

The synthesis of STMI, which better intercepts static images from the monitor screen om LCS, is necessary to assess the potential capabilities of the enemy by "reading" information from the monitor screen. The better the IEMR&I signal detection quality indicators, for example, according to the Neumann-Pearson criterion: the greater the probability of correct signal detection

$$D = 1 - F_0\left(h, T_a/1\right) \tag{16}$$

in case of a fixed false alarm

$$1 - F_0\left(h, T_a/0\right) \tag{17}$$

the worse the information is protected. In (16) and (17) $F_0\left(x,T_a/0\right)$, $F_0\left(x,T_a/1\right)$ – distribution of absolute maxima (DAM) of the process (10), when the IEMR&I signal is present in the implementation $x(t)$ and when it is not, respectively.

However, each specific solution to the problem of analysing STMI quality indicators will depend on a specific "picture" on the monitor screen and a specific vector of parameters $\mathbf{v}_0 = \left(a_{1c0}, a_{1s0}, a_{2c0}, a_{2s0}, .., a_{Kc0}, a_{Ks0}\right)$, and all further tasks of analysing the quality of detection of IEMR&I signals of STMI are reduced to the search for DAM $F_0\left(x,T_a/0\right)$, $F_0\left(x,T_a/1\right)$ random process (10), found only for most discontinuous signals.

Since the process at the output of a linear system is limited by frequency K/T_f, its spectral power density at the output of a linear system when there is no IEMR&I signal at the input of the STMI, taking into account (1) and, will be equal to:

$$S_o\left(T_a, T_f, \omega\right) = \frac{N_0}{2} \times \\ \times \begin{cases} \left| \dfrac{\sin\left(\dfrac{\omega T_f}{2}\left(2\,\mathrm{int}\left[\dfrac{T_a}{2T_f}\right]+1\right)\right)}{\omega \sin\left(\dfrac{\omega T_f}{2}\right)} \right|, & 0 \le \omega \le 2\pi K/T_f \\ 0, & \omega > 2\pi K/T_f \end{cases} \tag{18}$$

where $\mathrm{int}[x]$ – integer part of a number x. The corresponding (18) correlation function presented by the Taylor series for small τ, and is equal to:

$$B\left(T_a, T_f, \tau\right) = \frac{1}{2\pi} \int_0^{2\pi K/T_f} S_o\left(T_a, T_f, \omega\right)\left(1 - \frac{\omega^2\tau^2}{2}\right) d\omega = \\ = \sigma^2\left(T_a, T_f\right) - \frac{\sigma^2\left(T_a, T_f\right)\omega_2\left(T_a, T_f\right)\tau^2}{2} \tag{19}$$

where the variance of the non-stationary process is equal to:

$$\sigma^2\left(T_a,T_f\right)=\frac{1}{2\pi}\int\limits_0^{2\pi K/T_f} S_o\left(T_a,T_f,\omega\right)\mathrm{d}\omega$$

and the second spectral moment of the process is equal to:

$$\omega_2\left(T_a,T_f\right)=\frac{\int\limits_0^{2\pi K/T_f} S_o\left(T_a,T_f,\omega\right)\omega^2\mathrm{d}\omega}{\int\limits_0^{2\pi K/T_f} S_o\left(T_a,T_f,\omega\right)\mathrm{d}\omega}$$

The correlation function of the process (19) corresponds to a differentiated in the mean square non-stationary process, for which the search for a DAM $F_0\left(x,T_a/0\right)$ and $F_0\left(x,T_a/1\right)$ has been a scientific problem until recently. Solution of the analysis problem for such processes, in cases where further spectral moments can be considered $\omega_4\left(T_a,T_f\right)$, $\omega_6\left(T_a,T_f\right)$, .., $\omega_{2n}\left(T_a,T_f\right)$ – infinite, is presented in the monograph [5]. However, the practice of applying the developed mathematical apparatus proves that even in the case of finite higher spectral moments, this does not significantly affect the results of the analysis. It is enough to fulfil condition $\omega_4\left(T_a,T_f\right)>>\omega_2^2\left(T_a,T_f\right)$ for everything to work satisfactorily [1–3].

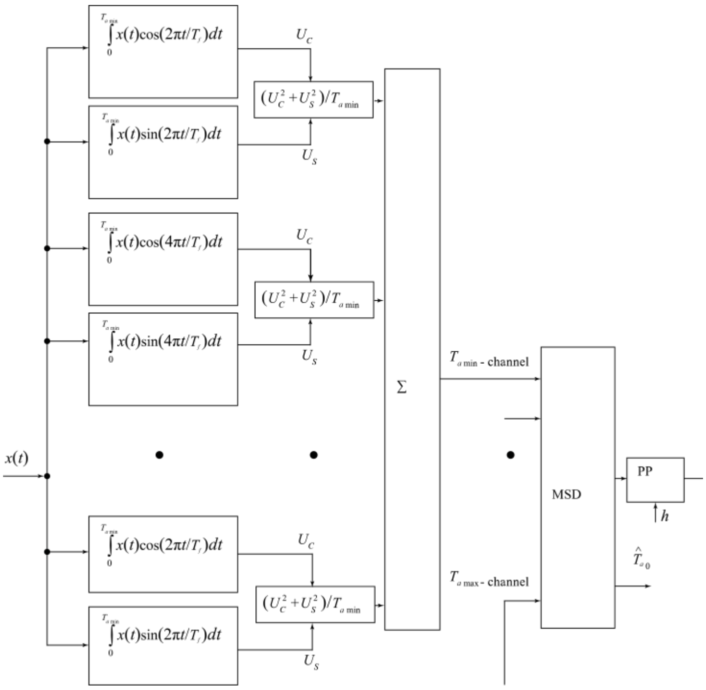

Fig. 3. Asymptotically Bayesian compatible algorithm for detecting IEMR&I and estimating the duration of a static image on a monitor screen

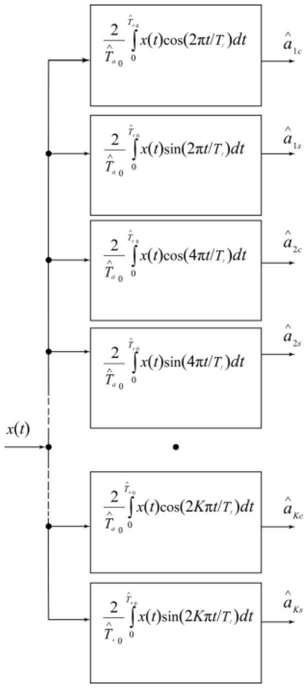

Fig. 4. Block diagram of the IEMR&I quadrature amplitude estimation device

4. Conclusions

1. Synthesis of the maximum likelihood algorithm in the form of asymptotically Bayesian detection of side electromagnetic radiation and interference signals is possible only when the number of unknown quadrature amplitudes of the leakage signal a_{kc}, a_{ks} is finite – $2K$.
2. The finite number of unknown quadrature amplitudes during the analysis of algorithms for detecting signals of adverse electromagnetic radiation from the monitor screen does not allow using the well-known apparatus of one-component Markov processes, suitable for breaking signals.
3. Further solution of the problem of analysing algorithms for detecting signals of side electromagnetic radiation and interference in a specialised enemy reconnaissance equipment requires finding distributions of absolute maxima of non-stationary processes differentiated in the mean square.

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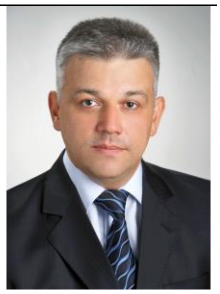

The Doctor of Science in Engineering and the Professor. He is the author of more than 300 publications, including 2 monographs, 140 articles in scientific specialized publications, 20 textbooks and training manuals, 20 utility model patents and 25 certificates of copyright registration for work. The author's scientific interests are in cryptographic and steganographic protection of information, technical protection of information and security of information systems.

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