Influence of the phase structure of signals on the effect of suppression of noise-concentrated interference used for data transmission in the infocommunication systems of automatic information systems of inland water transport

I A Sikarev, V V Sacharov, A A Chertkov, A V Garanin

Admiral Makarov State University of Maritime and Inland Shipping, 5/7 Dvinskaya St., St. Petersburg, 198035, Russian Federation
E-mail: kaf_electricautomatic@gumrf.ru, sikarev@yandex.ru

Abstract. The article proves the existence of the effect of noise-concentrated interference suppression in the purposeful formation of the phase structure of complex signals, an example of the choice of signals is given. It is shown that the coherent technique has, in comparison with incoherent additional resources, an increase in noise immunity under conditions of the effect of noise-centered interference.

1. Introduction

Under the conditions of the increase in traffic volume on the internal waterways (IW) of the Russian Federation, the enhancement of work reliability of information transmission systems becomes increasingly more crucial task. The important tool for ensuring accident-free process of navigation is application of the automatic information systems (AIS). In turn, ensuring electromagnetic security of radio channels of various applications allows to increase the quality of monitoring and management at the level of metasystem: Corporate river information systems, River information services, Shipping traffic Automated control systems (CRIS-RIS-STACS). The article considers the influence of spread-spectrum signals structure on the effect of noise-centered interference.

Nowadays experts pay much attention to the application of spread-spectrum signals in the systems of discrete message transmission against the noise-centered interference [1-5]. The considerable number of methods of power suppression and restriction of such interferences by means of various filters were investigated [1–4]. As a rule, the initial choice of spread-spectrum signals for all these methods is based only on mutual distinction of the energy spectrums of legitimate signals and the noise-concentrated interferences. Therefore, the primary focus is directed to identify the opportunities of interference suppression following from the properties of amplitude-frequency spectrum signals.

We analyze in this study the possibility of noise-concentrated interference suppression based on the use of harmonic constituent phase structure of legitimate signals.

2. The analysis of the concentrated interferences influence

Let us consider the class of binary systems of discrete information transmission where the legitimate transmitted signals can be presented in the following way:
\[
Z_r(t) = \sum_{K=K_{r0}}^{K_{r1}} A_K \cos(k\omega_r t + \varphi_K);
\]
\[t \in [0, T], r = 1, 2, \ldots \tag{1}\]

Where \(\omega_r = \frac{2\pi}{T}\), \(T\) – duration of signal element \(K_{r0} - K_{r1} + 1 = F_r\) – signal base \([5]\), and spread-spectrum signals \(- F_r T \gg 1\), \(F_r\) - conventional frequency band, occupied by a signal, and \(K_{ri}\) - is whole positive integers.

It is not too difficult to see that harmonical components, generating signal element \(Z_r(t)\), orthogonal on the interval \([0, T]\).

Hereafter we will consider as \(Z_r(t)\) is from (1) when \(r \neq l\) is either orthogonal in intense context, or opposite \([1]\).

Let us assume that concentrated interference is approximated by a quasi determinated stochastic process as:
\[
\mu_n \tilde{z}_n(t, \ell_0, \ell_n) = \mu_n A_n \cos(\omega_n t + \ell_n),
\]
\[t \in [0, T], \quad \tilde{Z}(t) = (\tilde{Z}(t), \tilde{Z}(t), \tilde{Z}(t)) \tag{2}\]

where the amplitude transmission coefficient \(\mu_n\) and initial phase \(\ell_n\) are random variables, according to the laws of probability distribution. In Rayleigh interference fading channels their one-dimensional densities are as follows:
\[
W_{\mu_n} = \frac{\mu_n e^{-\mu_n^2/2}}{\mu_n^2}, \quad \mu_n \gg 0 \tag{3}\]

The noise immunity analysis of various types of the single and diversity reception systems under simultaneously operating fluctuation noise and the concentrated interferences \([2-5]\) shows that probable errors of element-by-element reception are defined not only the energy ratio of the accepted legitimate signal to the spectral density of fluctuation noise, but significantly depend on the degree of a signal discrimination and the concentrated interference in time-and-frequency area. In case of channels with constant parameters or with the Rayleigh fading the use of the quasi determinated stochastic processes at approximation of legitimate signals and the concentrated interferences allows to enter a quantitative measure of discernability of \(z\)’s option of a signal and the concentrated interference in the form of the coefficient defined as functional \([2]\):
\[
g_r^2 = K_0 \left[ \int_{0}^{T} Z_r(t)Z_n^*(t)dt \right]^2. \tag{4}\]

Where \(Z_r(t)\) and \(Z_n^*(t)\) are analytical functions describing forms of a signal and an interference (2); \(K_0\) is a normalizing multiplier.
\[
Z_r(t) = Z_r(t) + j\tilde{Z}_r(t),
\]
\[
Z_n^*(t) = Z_n(t) + j\tilde{Z}_n(t), \tag{5}\]

Where \(\tilde{Z}_r(t)\) and \(\tilde{Z}_n(t)\) are functions, conjugate sensu Hilberd to \(Z_r(t)\) and \(Z_n(t)\); \(\mu_r\) is amplitude coefficient \(r\) signal variant transmission.
At the Rayleigh fading of signals and interferences \( \mu_r \) and \( \mu_n \) in (5) must be replaced with their quadratic means \( \sqrt{\mu_r^2} \) and \( \sqrt{\mu_n^2} \). \( P_r \) is a potency \( r \) signal variant, independent of harmonic initial phase values \( \varphi_k \) in (1):

\[
P_r = \mu_r^2 \sqrt{\frac{Z_r'^2(t)}{0}} dt,
\]

(6)

The known calculation examples of interference immunity of discrete information transmission systems allow to conclude that, reducing the value \( g_r^2 \) leads to diminishing probable errors [2-5].

Thus, we study \( g_r^2 \) versus characteristics of legitimate signal phase structure.

Having used complex formulation of signals \( Z_r(t) \) and the concentrated interference \( Z_n(t) \), according to (4) we obtain:

\[
g_r^2 = \frac{\sum_{K=K_{min}}^{K_{max}} A_K^2 \Omega_K^2}{\sum_{K=K_{min}}^{K_{max}} A_K^2} \frac{\sin \left( \frac{\Omega_K T}{2} \right)}{\Omega_K^2} \exp \left( j\left( \varphi_K + \frac{\Omega_K T}{2} \right) \right),
\]

(7)

where \( \Omega_K = (k\omega_0 - \omega_n) \) is frequency of interference disturbance with respect to \( k\omega_0 \).

When determining the character of amplitude values \( A_K \) in (1) we are based on the emergency of the concentrated interference equally probable in any frequencies on the band \( F_r \). Therefore, it is chosen as a necessary condition for suppressing concentrated interference:

\[
\mu_K A_K = \frac{(2P_r)^2}{F_r T} = \text{const}(k),
\]

(8)

Тогда соотношение (7) принимает следующий вид:

Then the formula (7) takes the following form:

\[
g_r^2 = \frac{\sum_{K=K_{min}}^{K_{max}} A_K^2 \Omega_K^2}{\sum_{K=K_{min}}^{K_{max}} A_K^2} \frac{\sin \left( \frac{\Omega_K T}{2} \right)}{\Omega_K^2} \exp \left( j\left( \varphi_K + \frac{\Omega_K T}{2} \right) \right),
\]

(9)

Where

\[
B_r = \frac{1}{F_r T} \frac{h_n^2}{h_r^2},
\]

\[
h_r^2 = \frac{P_r T}{\nu^2},
\]

(10)

Here \( h_r^2 \) and \( h_r^2 \) are consequently the ratio of accepted signal variant energy \( r \) and concentrated interference to white noise spectral density \( \nu^2 \), and \( P_n \) is the power of - concentrated interference:

\[
P_n = \frac{\mu_n^2 A_r^2}{2}.
\]

(11)

In practical applications it is often used \( \Delta \omega \) - frequency detuning of concentrated interference with regard to signal average frequency \( \frac{1}{2}(K_n + K_m)\omega \) instead of the value \( \Omega_k \). Thus we can write \( \omega_z = \frac{1}{2}(K_n + K_m)\omega_0 \pm \Delta \omega \), and after transformations the formula (9) becomes:
\[ g_{z}^{2} = B_{z} \cos^{2} \frac{\Delta \Omega T}{2} \left( \sum_{k=k_{0}}^{k_{0}+1} \frac{e^{ik \Delta \Omega T}}{\alpha_{k} \pm \Delta \Omega T} \right) \text{, для } F_T = 2i; \]  
(12)

\[ g_{r}^{2} = B_{r} \sin^{2} \frac{\Delta \Omega T}{2} \left( \sum_{k=k_{0}}^{k_{0}+1} \frac{e^{ik \Delta \Omega T}}{\alpha_{k} \pm \Delta \Omega T} \right) \text{, для } F_T = 2i - 1; \]  
(13)

Where \(i=1,2,3; \alpha_{r} = (k - \frac{K_{r} + K_{n}}{2})\pi \) and minus sign corresponds to mixing \( \omega_{n} > \frac{1}{2}(K_{r} + K_{n})\omega_{b} \).

From (12) and (13) it follows that for every fixed \( r \) the values of mutual distinction coefficients depend on the signal phase structure, defining by \( \{\theta_{i}\} \). Herewith, it is necessary to choose the range of initial phases for achieving the border of any value \( \Delta \Omega \), at any rate, on the interval of \( [0, \pi F_{r}^{'}, \pi F_{r}^{'}, \pi F_{r}^{'}, ... , \pi F_{r}^{'}]; \) for \( \{\theta_{j}\} \).

\[ \min \Delta \Omega \in [0, \pi F_{r}^{'}, \pi F_{r}^{'}, \pi F_{r}^{'}, ... , \pi F_{r}^{'}]; \]  
(14)

Surely, if the value of detuning interference frequency has been measured, then the objective function can be used instead of (14):

\[ \min \Delta \Omega 
\{\theta_{j}\}; \]  
(15)

However, the location of \( \{\theta_{j}\} \) on account of (14) or (15) is impossible owing to the following conditions of signals applicability (1). Firstly, for efficient using the linearity stock of a transceiver track of information transmission system it is strived to synthesize signals (1) with peak factor \( \left[ \frac{1}{2} \max \{\gamma \} \right] \) evenly minimal on \([0, \pi T] \).

Secondly, when performing a condition

\[ (K_{r} - K_{r}^{'}, + 1)\omega_{b} \ll \frac{K_{r} + K_{r}^{'}}{2} \omega_{b}; \]  
(18)

Which is always practically encountered for radio signal, a multitude \( \{\theta_{j}\} \); found from (17), provides simultaneously and minimum possible influence of time concentrated (impulse) interferences on the considered systems.

The arisen alternative in relation to solution for \( \{\theta_{j}\} \) from (14) and (17) can be overcome by the following way.

It is known that the solution of the task (17) has several stationary points 2. Let us assume that

\[ \Phi = \{\theta_{z}^{(q)}\}_{q=1,2,3,...,F_{r}} \]  
(19)

corresponding \( Q \) to the stationary points acceptable solutions sets as

\[ K\{\theta_{z}^{(q)}\} \leq K_{0}, \{\theta_{z}^{(q)}\} = \theta_{z}^{(q)} \in \{\theta_{z}^{(q)}\}, \theta_{z}^{(q)} \in \{\theta_{z}^{(q)}\}, \theta_{z}^{(q)} \in \{\theta_{z}^{(q)}\} \]  
(20)

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1 Some points are probably local minimum [6]. The issue about the global solution of L.I. Mandelstam’s problem is still open.

2 The objective function (14), made for frequency domain, can be called as a dual problem of L.I. Mandelstam
where \( K \) is a permissible value of a peak factor for a signal applicability (1).

Then minimization of the influence of the spectrum concentrated interference due to the change of signal phase structure (1) can be reached by choosing such \( \theta^{(s)} \), where there is:

\[
\min_{\Phi, \Delta \Omega \in [0, 2\pi F_T]} \left\{ \theta^{(s)}, \theta_{kr}^{(s)} \right\},
\]

either

\[
\min_{\Phi, \Delta \Omega \in [0, 2\pi F_T]} \left\{ \theta^{(s)}, \theta_{kr}^{(s)} \right\}.
\]

We believe that only function (22) satisfies the imposed restrictions. Changing the choice \( \{ \theta_{kr}^{(s)} \} \in \Phi_{cr} \), it is possible to minimize the influence of the concentrated interferences for various \( \Delta \Omega \in [0, 2\pi F_T] \). We will show it by means of the example, which is very important for practical applications. Let us consider the multitude of antipodal signals of the type (1), for which the condition is done (8) and

\[
K_T = K_i; K_m = K_r; F_T = FT, r = 1, 2;
\]

(23)

\[
\theta = \begin{cases} \theta_k, \quad r = 1 \\ \theta_k + \pi, \quad r = 2, K = K_i, K_i + 1, ..., K_i \end{cases}
\]

(24)

Let us suppose that \( \theta_k \) in (24) can accept only two values: null and \( \pi \), that is especially important for simplifying systems hardware implementation.

Then multitudes - \( \{ \theta_{kr}^{(s)} \} \in \Phi \) satisfying the condition (20) can be constructed, for example, as it is shown in the table 1, for case \( Q = 5, FT = 7, K \leq 2 \).

The given values \( \{ \theta_{kr}^{(s)} \} \) are determined experimentally by the combined stress generator, similarly described in [6].

The calculated values of mutual distinction standardized coefficient according to (13) with regard to (23) and (24):

\[
\hat{q}_{\theta}^{(s)}(\Delta \Omega, \{ \theta_{kr}^{(s)} \}) = q_{\theta}^{(s)}(\{ \theta_{kr}^{(s)} \}) \frac{h_{\hat{q}}}{h_{\tilde{q}}},
\]

(25)

show (Figure 1), that the solution of the problem (21) meaningless if

\[
\Delta \Omega = 0, \pm \omega_o, \pm 2\omega_o, \pm 3\omega_o,
\]

(26)

as in this case the congruence \( q_{\theta}^{(s)} = \frac{1}{F_T} \) is always valid.

In any other cases \( \Delta \Omega \epsilon [0, 2\pi F_T] \) the solution of considered problem makes sense and can lead to the essential reduction \( \hat{q}_{\theta}^{(s)} \).

To estimate the energy score, provided with the purposeful choice of multitude \( \{ \theta_{kr}^{(s)} \} \) we should address to the following examples. Let us assume that the discussed earlier signal processing with base \( FT = 7 \) is carried out by A. Kotelnikov’s receiver. Under unfading signals and fading according to the Rayleigh's law on solitary concentrated interference the probability of mistake of coherent antipodal signal can be calculated in formula [2]:

In any other the solution of the considered task makes sense and can lead to essential reduction.

At not fading signals and the hindrance fading under the Rayleigh law single the probability of an error of coherent reception of opposite signals can be calculated on a formula [2]:

\[
p = \frac{1}{2} \left[ 1 - \Phi \left( \frac{\sqrt{2}h_{\tilde{q}}}{\sqrt{1 + h_{\tilde{q}}^2}} \right) \right],
\]

(27)
where $\bar{g}_r^2$ is the average value of the mutual distinction coefficient received by replacement of $\mu_\Pi$ into (5) on $\sqrt{\mu^{(2)}_\Pi}$:

$$\Phi(x) = \frac{1}{\sqrt{\pi}} \int \exp(-\frac{x^2}{2}) \, dx$$

$\Phi(x)$ is Crump's function.

The formula (27) with regard to (10) and (25) can be put in to a form:

$$p = \frac{1}{2} \left[ 1 - \Phi \left( \sqrt{\frac{2h_{\Pi}}{1+h_{\Pi}^2 g_{r,0}^2}} \right) \right],$$

(28)

Where $h_{\Pi}^2 = \frac{P_{\Pi} T^{(2)}}{v_r}$, $P_{\Pi} = \frac{\mu^{(2)}_\Pi A_{\Pi}^2}{2}$

| $z_{qr}(t)$ | Code                   | $\delta_\theta$ | $\delta_r$ | $\delta_{\bar{g}}$ | $\delta_{\bar{g},g}$ | $\delta_{\bar{g},g}$ | $\delta_{\bar{g},g}$ | $\delta_{\bar{g},g}$ | $\delta_{\bar{g},g}$ | $\delta_{\bar{g},g}$ | $K$ |
|------------|------------------------|-----------------|-------------|---------------------|----------------------|----------------------|----------------------|----------------------|----------------------|----------------------|-----|
| $z_{l1}(t)$ | Quadratic residue | $\delta^{(1)}_1$  | 0            | 0                   | $\pi$                | $\pi$                | $\pi$                | $\pi$                | $\pi$                | $\pi$                | 1.91 |
| $z_{l1}(t)$ |                        | $\delta^{(1)}_2$ | $\pi$        | $\pi$               | 0                   | $\pi$                | 0                   | 0                   | 0                   | 1.91                |
| $z_{l2}(t)$ | Barker                | $\delta^{(1)}_3$ | 0            | 0                   | 0                   | $\pi$                | 0                   | $\pi$                | 0                   | 1.78                |
| $z_{l2}(t)$ |                        | $\delta^{(1)}_4$ | $\pi$        | $\pi$               | 0                   | 0                   | $\pi$                | 0                   | 0                   | 1.78                |
| $z_{l3}(t)$ | Huffman               | $\delta^{(1)}_5$ | 0            | 0                   | $\pi$               | $\pi$                | 0                   | $\pi$                | 0                   | 1.94                |
| $z_{l3}(t)$ |                        | $\delta^{(1)}_6$ | $\pi$        | $\pi$               | 0                   | $\pi$                | 0                   | $\pi$                | 0                   | 1.94                |
| $z_{l4}(t)$ | Random number 1       | $\delta^{(1)}_7$ | 0            | $\pi$               | 0                   | 0                   | $\pi$                | $\pi$                | $\pi$                | 1.80                |
| $z_{l4}(t)$ | version               | $\delta^{(1)}_8$ | $\pi$        | $\pi$               | 0                   | $\pi$                | 0                   | $\pi$                | $\pi$                | 1.80                |
| $z_{l5}(t)$ | Random number 2       | $\delta^{(1)}_9$ | 0            | $\pi$               | $\pi$               | 0                   | 0                   | $\pi$                | $\pi$                | 1.83                |
| $z_{l5}(t)$ | version               | $\delta^{(1)}_{10}$ | $\pi$     | $\pi$               | $\pi$               | 0                   | 0                   | $\pi$                | $\pi$                | 1.83                |

Let further the information is transmitted by signaks $z_{qr}(t)$. Let us suppose, that calculated frequency mismatch of the concentrated interference equals $\Delta \Omega = 0.5 \omega_k$. When $\bar{g}_r^2 \cong 0.46$ (Figure 1. See dotted graph) and $\bar{g}_r^2 \cong 8.8 \cdot 10^{-4}$ (Figure 1. See solid line) after signals changing.

![Figure 1](image.png)

**Figure 1.** The values dependence of mutual distinction coefficient on frequency mismatch under codes: random numerals (solid line), Huffman (dotted graph).
Let the receiving conditions be the following, \( h_t^2 = 10, \overline{h_t} = 10^3 \). Thus, error probability in the first case according to (28) will be \( p = 0.21 \), and in the second \( 6 \cdot 10^{-5} \). The energy score, given by the signals change will be approximately 16.5 dB. However it is clear that, such score cannot be always got, for example, it is impossible if the conditions (26) have been fulfilled.

To estimate the average energy score, provided with the signals change, we should address to the following example. Contrary to the previous case, let us assume that frequency mismatch \( \Delta \Omega \) can take up any values within the interval \([0, 4 \omega_0]\). It is obvious that some energy score will be observed only in those cases when \( \Delta \Omega \) value belongs to the parts \([0, \omega], (\omega, 2\omega), \ldots, (\omega_0, 4\omega_0 - \omega)\), where \( q^2 \geq \frac{1}{FT} \). Let \( \Delta \Omega \in [0, \omega] \) (Figure 1. See dotted graph). Thereafter, the average error rate \( p_{cr} = \frac{1}{M} \sum_{K=1}^{M} \max_{\Delta \Omega K} P_K \left( \overline{r}_{\omega}^{0} (\Delta \Omega) \right) \). (29)

Where \( M \) is the number of separation part \( \Delta \Omega K, K = 1, 2, \ldots, M \) within the interval \([0, \omega]\). Using signals \( z_{\omega}(t) \) agreeing with (29) we get \( p_{cr} = 0.22 \), when we change \( z_{\omega}(t) \) into \( z_{\omega}(t) \), which is an equivalent of the average energy score.

\[ D_{cr} = \frac{1}{M} \sum_{K=1}^{M} \max_{\Delta \Omega K} \left[ \frac{1 + \frac{h_t^2}{\overline{h_t}} \overline{g}_{\omega}^2 (\Delta \Omega)}{1 + \frac{h_t^2}{\overline{h_t}} \overline{g}_{\omega}^2 (\Delta \Omega)} \right] \approx 6.886, \]

Where intervals \( \Delta \Omega \in [\omega(i+1), \omega_i] \) and other variants of signals \( D_{cr} = 3 \sim 8 \Delta \). From the given examples it follows that accounting of the compound signals phase structure allows in a number of cases to suppress the concentrated interference. It is important that this process is carried out only by changing, \( \{q_{\omega}^*, \} \) without signal-carrier frequency modulation, although it is possible to use this or that cases combination for operating point position \( \Delta \Omega, \).

3. Conclusion

We should take into account, that, as it is followed from (12) and (13), such way of minimization \( g^2 \) it is possible only under coherent signal receipt, when random increment of initial phases harmonic signal constituents in channel can be measured and eliminated.

Furthermore, the use of considered noise suppression method requires, undoubtedly, feedback communication channel.

On the basis of the above information, we may conclude that in case of fluctuation noise of coherent and incoherent reception systems are about equal in the context of noise immunity. However, under the influence of narrowband concentrated interferences the coherent reception can be more noise immune, if we take into account signal phase structure at interference rejection.

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