

01.5;11

## Fluctuation Analysis of Digital Communications Based on the Spectral Interference of Noise Random Signals

© V.I. Kalinin, O.A. Byshevski-Konopko

Fryazino Branch, Kotel'nikov Institute of Radio Engineering and Electronics, Russian Academy of Sciences, Fryazino, Moscow oblast, Russia  
E-mail: val.kalinin@mail.ru

Received May 18, 2023

Revised May 27, 2024

Accepted May 27, 2024

The fluctuation analysis of correlation estimations was performed for the transmission of information using a relative method based on noise chaotic signals with spectrum modulation. Asymptotic limitation of correlation effect due to the intra-system interference has been found. The possibility to reduce fluctuations in correlation estimates and to increase the noise immunity during information transmission based on ultra-wideband noise chaotic signals with time windows is shown.

**Keywords:** noise communications, correlation estimation, fluctuation analysis.

DOI: 10.61011/TPL.2024.09.59158.19631

The noise immunity in data transmission over wireless channels subjected to interference and multipath propagation is enhanced using the methods of spectrum expansion (Spread Spectrum) [1], space-time signal processing [2], and noise-resistant encoding [3]. Data transmission with the use of the transmitted reference technique and ultra-wideband noise chaotic signals is noted for data security and radiation covertness in channels [4–7]. Random changes in the energy of noise carrier signals in the data flow cause fluctuations of the correlation effect with a trend synchronous with the transmission rate [5,6]. Detrended fluctuation analysis (DFA) algorithms are used [8,9] to eliminate trends in the analysis of random and chaotic processes. In the present study, we propose a new approach to reducing correlation fluctuations and eliminating trends in a noise system based on incoherent interference of delayed noise signals during data insertion. Demodulation and data reconstruction are produced in result of autocorrelation processing of ultra-wideband incoherent signals.

Digital data are transmitted using the Transmitted Reference method based on continuous noise signals with spectral modulation [5,6]. Chaotic noise signals with a flat spectrum from the source in the transmitter are fed to the input of a bandpass filter with  $\Delta f = 1000$  MHz and mean frequency  $f_0 = 3600$  MHz. Noise signal  $y(t)$  at the bandpass filter output is split into data and reference channels. In the data channel, carrier signal  $y(t)$  is delayed by  $T = 6$  ns, which exceeds coherence time  $\tau_c \approx 1/\Delta f = 1$  ns. The delayed signal is multiplied by opposite values  $b_l = \pm 1$  of data bits following with period  $T_b$  and is fed in the form of  $b_l y(t - T)$  to one of the adder inputs. Reference signal  $y(t)$  is fed to the other input. The linear adder superposes the delayed data signal and the reference signal, which are incoherent:

$$z_l(t) = y(t) + b_l y(t - T). \quad (1)$$

Incoherent signals (1) interfere under the conditions

$$T \gg \tau_c, \quad T\Delta f \gg 1. \quad (2)$$

The power spectrum of sum signal  $z_l(t)$  is modulated by a periodic function of the form

$$\hat{S}_z(f, b_l) = 2\hat{S}_y(f) [1 + \cos(2\pi f T + \pi(1 - b_l)/2)]. \quad (3)$$

Here,  $\hat{S}_z(f, b_l)$  and  $\hat{S}_y(f)$  are random estimates of spectra for sum  $z_l(t)$  and reference  $y(t)$  noise signals. Frequency band  $\Delta f$  of the noise signal accommodates many periods  $F_m = 1/T$  of spectral modulation. The fine interference pattern in spectrum (3) is shown in Figs. 1, *a, b* for total noise signal (1) entering the communication line.

It follows from the comparison of spectra shown in Figs. 1, *a, b* that spectral modulation is shifted by half a period ( $F_m/2 = 1/2T = 83.33$  MHz) in transmission of opposite symbols  $b_l = \pm 1$ .

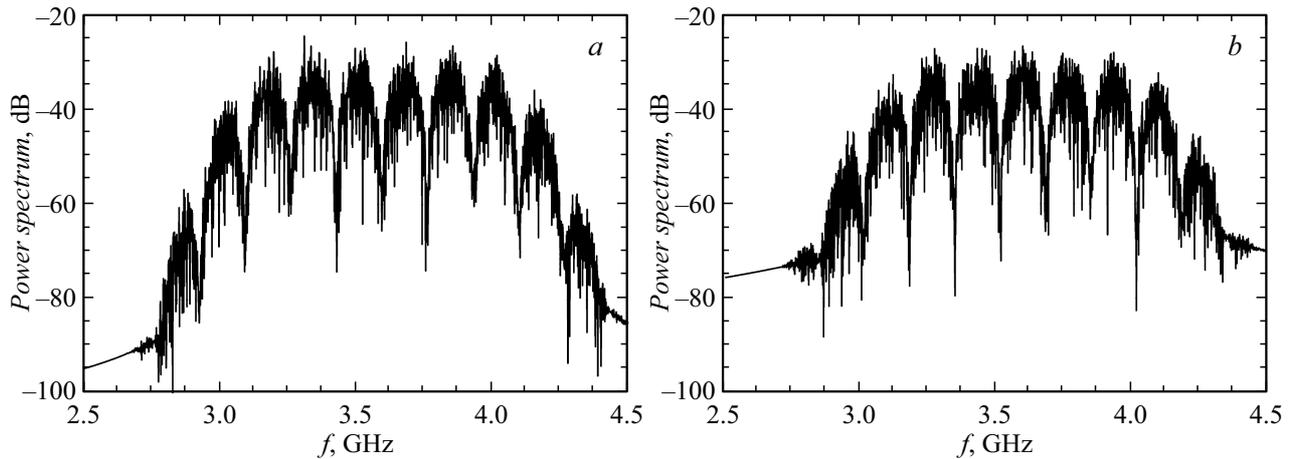
As a result of spectral modulation (3), frequency band  $F_b \approx 1/T_b$  for data symbols  $b_l$  is expanded to the band  $\Delta f$  of total signal (1).

Product  $B = \Delta f T_b$  determines the base of transmitted signals, on the value of which depends the intensity of fluctuations in correlation estimates. Transmitted signal power  $z_l(t)$  may be set equal to  $\sigma_z^2 \approx 2\sigma_y^2$  under condition (2) of interference of incoherent noise signals [5,6].

The total signal  $z_l(t)$  enters the communication channel with additive Gaussian white noise  $n(t)$  and is fed to the receiver input in the form

$$r_l(t) = z_l(t) + n(t) = [y(t) + b_l y(t - T)] + n(t). \quad (4)$$

We consider noise  $n(t)$  with mean power  $\sigma_n^2$  within wide frequency band  $\Delta f_n$ . If condition (2) is satisfied, the signal-to-noise ratio at the receiver input may be set equal to  $q = \sigma_z^2/\sigma_n^2 \approx 2\sigma_y^2/\sigma_n^2$ . Autocorrelation processing of



**Figure 1.** Shift of the interference pattern in the spectrum during transmission of positive  $b_l = +1$  (a) and negative  $b_l = -1$  (b) binary symbols.

incoming signal (4) is performed in the receiver within the duration of each bit  $T_b$ . Delay  $T$  in the receiver correlator corresponds to data signal delay  $b_l y(t - T)$ .

The  $\hat{E}(b_l)$  correlation estimate at the integrator output in the receiver is defined as

$$\hat{E}(b_l, T) = \frac{1}{T_b} \int_{t_l}^{t_l+T_b} r_l(t)r_l(t-T)dt. \quad (5)$$

Here,  $t_l = (l-1)T_b$  is the initial moment of time at the arrival of bit  $b_l$  with number  $l$ . Statistical estimate (5) for received signal (4) is calculated as

$$\begin{aligned} \hat{E}(b_l, T) = & b_l(\hat{k}_y(0) + \hat{k}_y(2T)) + 2\hat{k}_y(T) + \hat{k}_n(T) \\ & + b_l\hat{k}_{yn}(0) + 2\hat{k}_{yn}(T) + b_l\hat{k}_{yn}(2T). \end{aligned} \quad (6)$$

Here,  $\hat{k}_y$  and  $\hat{k}_n$  are random estimates within the  $b_l$  bit time for the correlation functions of carrier signal  $y(t)$  and noise  $n(t)$ . The useful effect at the receiver output depends on the first term  $b_l\hat{k}_y(0) = b_l\hat{\sigma}_y^2$  in formula (6). The true magnitude of the correlation effect is determined by the expected value of estimate  $E(b_l) = b_l M\{\hat{k}_y(0)\} = b_l\sigma_y^2$ , which depends on mean power  $\sigma_y^2$  of carrier noise signal  $y(t)$  with a sign change synchronous with the  $b_l$  bit sequence. Self-jamming is specified by the sum of estimates (6) in the form

$$\hat{\Psi}_y(b_l, T) = b_l[\hat{k}_y(0) - \sigma_y^2] + b_l\hat{k}_y(2T) + 2\hat{k}_y(T). \quad (7)$$

Intra-system jamming (7) is specified by the relative fluctuations of power  $b_l(\hat{\sigma}_y^2(b_l) - \sigma_y^2)$  of the carrier noise signal summed with the fluctuations of estimates  $b_l\hat{k}_y(2T)$  and  $2\hat{k}_y(T)$ . Intra-system jamming (7) with a non-zero mean leads to random variation and non-stationary shift of correlation effect (6). Intra-system jamming (7) has a masking effect on the receiver throughout the entire communication session.

Fluctuations of random estimates (6) lead to errors in the recovery of transmitted data at the receiver [5,6]. Type I errors arise due to the random spread of the  $\hat{E}(b_l)$  values measured in different samples  $r_l(t)$  of received signals within time  $T_b$  of each bit  $b_l$ . Type II errors are systematic and manifest themselves as a non-stationary shift of correlation effect (6) synchronous with the  $b_l$  bit rate.

The mean value of estimate (6) in a bit stream is specified by expectation

$$\begin{aligned} M\{\hat{E}(b_l)\} = & \frac{1}{T_b} \int_0^{T_b} M\{r_l(t)r_l(t-T)\}dt \\ = & b_l\sigma_y^2 + b_lk_y(2T) + 2k_y(T) + k_n(T). \end{aligned} \quad (8)$$

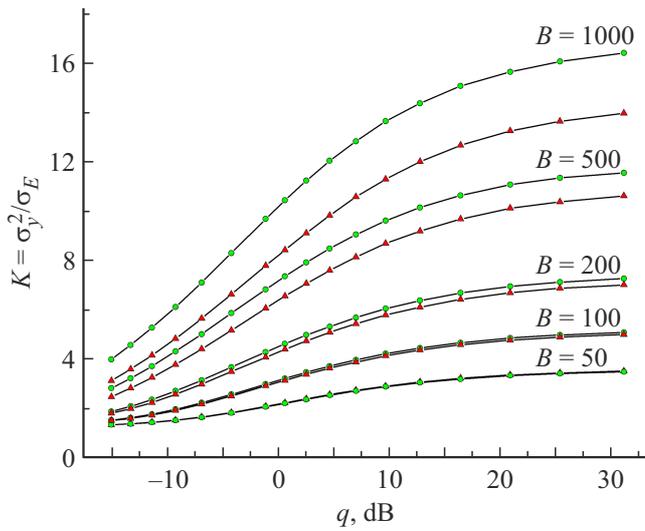
Here, the first term  $b_l\sigma_y^2$  characterizes true magnitude  $E(b_l)$  of the correlation effect. The remaining terms in (8) characterize the fixed shift of estimate (6) with respect to the true  $E(b_l)$  value. Relation (8) holds true under the condition of statistical independence between carrier signal  $y(t)$  and external noise  $n(t)$ . Then the  $\hat{k}_{yn}(\tau)$  components with shift  $\tau = 0, T, 2T$  in formula (6) are zeroed out upon averaging.

The shift of correlation estimate (6) in a  $b_l$  bit stream is set by mean value (8) minus the  $E(b_l) = b_l\sigma_y^2$  true value:

$$\Delta E(b_l) = M\{\hat{E}(b_l)\} - b_l\sigma_y^2 = b_lk_y(2T) + 2k_y(T) + k_n(T). \quad (9)$$

The process of recovery of transmitted data in the receiver depends on non-stationary shift  $\Delta E(b_l)$ , which varies in time synchronously with a  $b_l = \pm 1$  bit stream. If condition  $T \gg \tau_c$  (2) for noise carrier signal  $y(t)$  and similar condition  $T \gg \tau_n$  for external noise  $n(t)$  are satisfied, a small non-stationary shift (9) may be neglected in the estimation of correlation effect (6).

Numerical modeling of a noise system with different data transmission rates  $C = 1/T_b$  was performed with the use



**Figure 2.** Noise characteristics  $K(q)$  with different bases  $B = \Delta f T_b$  for carrier signals with a rectangular spectrum (curves marked with triangles) and with a time window (curves marked with circles).

of ultra-wideband noise carrier signals of two types: with a rectangular spectrum and with a time window in the form of a four-term Blackman–Harris function [1]. External noise is matched with carrier signals within the  $\Delta f = 1000$  MHz frequency band. Carrier signals  $y(t)$  and noise  $n(t)$  are reproduced by discrete samples  $y(k)$  and  $n(k)$ , which follow over time  $t(k) = kd$  with step  $d = 0.035$  ns shorter than coherence time  $\tau_c = 1$  ns. Correlation estimate  $\hat{E}(b_l)$  is calculated similar to integral (5) as a sum by averaging over discrete  $r_l(k)$  samples over the length of each bit  $b_l$ .

Mean deviation  $\sigma_E$  of correlation estimates  $\hat{E}(b_l)$  from true values  $E(b_l) = b_l \sigma_y^2$  in a binary  $b_l = \pm 1$  bit stream is determined by averaging over the ensemble as

$$\sigma_E = \left[ \frac{1}{N} \sum_{l=1}^N [\hat{E}(b_l) - b_l \sigma_y^2]^2 \right]^{1/2}. \quad (10)$$

The number of  $b_l = \pm 1$  bits equally probable in sign is  $N = 10^6$ . The ratio of the absolute true value of estimates in the form of modulus  $|E(b_l)| = \sigma_y^2$  to mean deviation  $\sigma_E$  specifies noise immunity  $K(q) = \sigma_y^2 / \sigma_E$  of a communication system [1,4]. Figure 2 presents five families of noise characteristics  $K(q)$  plotted as dependences on signal-to-noise ratio  $q$  in a communication channel with different bases  $B = \Delta f T_b = 50, 100, 200, 500,$  and  $1000$ .

As the base of carrier signals increases from  $B = 50$  to  $1000$ , noise immunity  $K(q)$  of the system improves. Ratio  $K(q)$  at the receiver output increases smoothly with ratio  $q$  [dB] in a communication channel, reaching an asymptotic saturation level at each signal base  $B$ . Noise characteristics  $K(q)$  are limited by intra-system jamming (7) at zero external noise in the channel. It follows from the comparison of characteristics in Fig. 2 that the use

of carrier noise signals with time windows leads to an increase in the  $K(q) = \sigma_y^2 / \sigma_E$  ratio at the receiver output, which is indicative of improvement of the noise immunity of the communication system. At low base  $B < 100$ , signals with time windows provide no benefit. Fluctuation analysis of non-stationary correlation characteristics is of interest for increasing the noise immunity of wireless data transmission systems with spread spectrum based on noise chaotic signals.

### Conflict of interest

The authors declare that they have no conflict of interest.

### References

- [1] K. Feher, *Wireless digital communications: modulation and spread spectrum applications* (Prentice Hall, Upper Saddle River, N.J., 1995).
- [2] V.R. Anpilogov, V.V. Denisenko, B.A. Levitan, V.N. Kozlov, A.M. Shitikov, A.V. Shishlov, *J. Commun. Technol. Electron.*, **68** (8), 819 (2023). DOI: 10.1134/S1064226923080016
- [3] L.E. Nazarov, A.S. Zudilin, V.I. Kaevitser, I.V. Smolyaninov, *J. Commun. Technol. Electron.*, **66** (1), 56 (2021). DOI: 10.1134/S106422692101006X
- [4] M.R. Bloch, *IEEE Trans. Inform. Theory*, **62** (5), 2334 (2016). DOI: 10.1109/TIT.2016.2530089
- [5] V.I. Kalinin, V.V. Chapurskii, *J. Commun. Technol. Electron.*, **60** (10), 1072 (2015). DOI: 10.1134/S1064226915100046
- [6] V.I. Kalinin, *Tech. Phys. Lett.*, **44** (24), 45 (2018). DOI: 10.21883/PJTF.2018.24.47029.17301  
[V.I. Kalinin, *Tech. Phys. Lett.*, **44** (12), 1139 (2018). DOI: 10.1134/S1063785018120465].
- [7] A.S. Dmitriev, T.I. Mokhseni, M.M. Petrosyan, *Tech. Phys. Lett.*, **48** (18), 10 (2022). DOI: 10.21883/PJTF.2022.18.53391.19312  
[A.S. Dmitriev, T.I. Mokhseni, M.M. Petrosyan, *Tech. Phys. Lett.*, **48** (9), 48 (2022). DOI: 10.21883/TPL.2022.09.55082.19312].
- [8] K. Kiyono, Y. Tsujimoto, *Physica A*, **462**, 807 (2016). DOI: 10.1016/j.physa.2016.06.129
- [9] O.N. Pavlova, A.N. Pavlov, *Tech. Phys. Lett.*, **47**, 463 (2021). DOI: 10.1134/S1063785021050126

Translated by D.Safin