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

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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.

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The noise immunity in data transmission over wireless channels subjeed 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

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

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 Δf 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 Δf 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 σ_n^2 within wide frequency band Δf_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

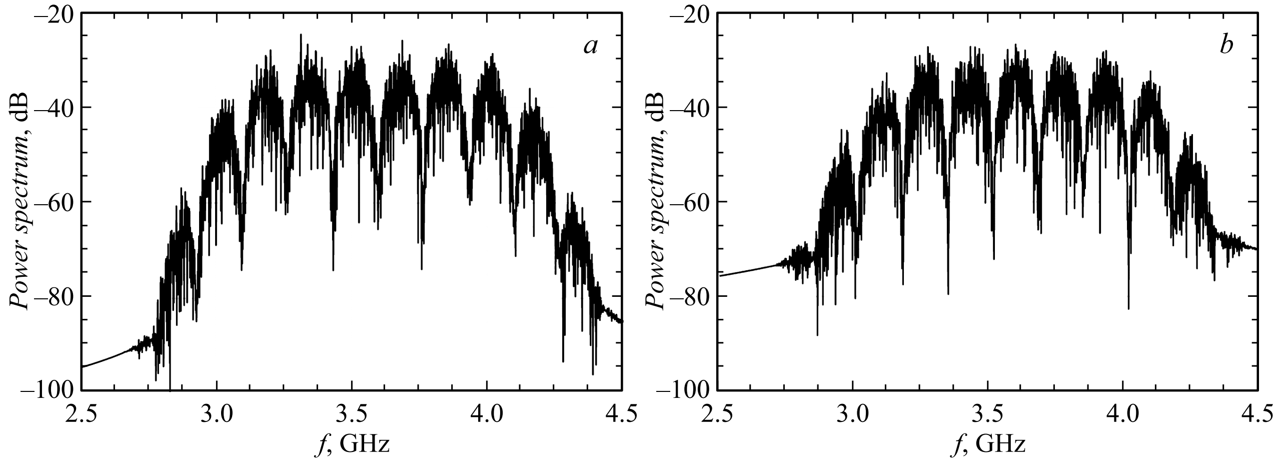

Figure 1. Shift of the interference pattern in the spectrum during transmission of positive $b_l = +1$ (*a*) and negative $b_l = -1$ (*b*) binary symbols.

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

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

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 $E(b_l) = b_l M\{\hat{k}_y(0)\} = b_1\sigma_y^2$, which depends on mean power σ_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

$$M\{\hat{E}(b_l)\} = \frac{1}{T_b} \int_{0}^{T_b} M\{r_l(t) r_l(t - T)\} dt = b_l\sigma_y^2 + b_l k_y(2T) + 2k_y(T) + k_n(T). \quad (8)$$

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:

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

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

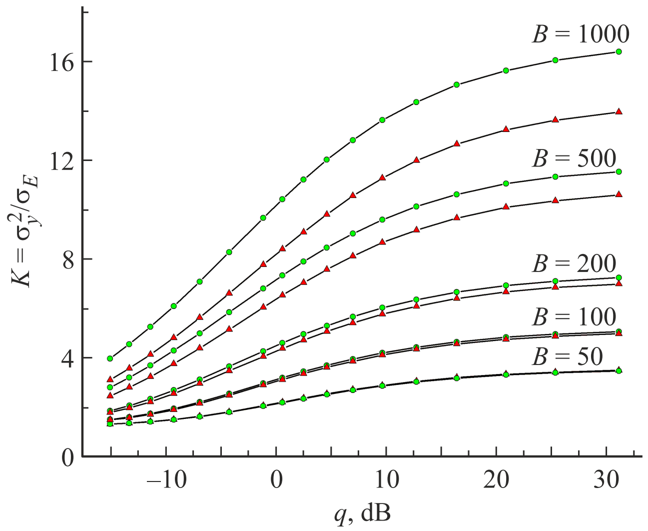

Figure 2. Noise characteristics $K(q)$ with different bases $B = \Delta f T_b$ for carrier signals with a rectangular spectrum (curves marked with triangles) and with a time window (curves marked with circles).

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 σ_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

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

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 σ_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.

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