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STATISTICAL SIMULATION OF SIGNAL-TO-NOISE RATIO ESTIMATION

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ABSTRACT

The research addresses an urgent issue of operational control of the signal-to-noise ratio in radio-electronic systems. The proposed signal-to-noise ratio estimation technique is based on the maximum likehood estimation of the signal amplitude when observed against the white Gaussian noise. The paper presents block diagrams of sumilation in Simulink, which implement the proposed technique, in particular, a module for calculating the maximum likehood estimation of the signal amplitude, which involves quadrature heterodyning of the input signal, accumulation of the readings of the obtained components in the observation interval, and calculation of the square root of the sum of squares of in-phase and quadrature correlations. The statistical simulation (1,000 tests) was performed to verify the accuracy of the proposed technique. It was established that the mean-squared deviation of the signal-to-noise ratio estimation error is approximately 0.1 dB in the case of unlimited (by width) input and reference signals. With requirements to signal width reduced, or with sign approximation of input and reference signals, the mean-squared deviation of the signal-to-noise ratio estimation error does not exceed 0.2 dB. The results obtained confirm high accuracy and feasibility of the proposed estimator. The materials of this paper can be of use in the operative quality control of space communication channels.

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INTRODUCTION

A challenging area in the practice of operating radio-electronic systems is the estimation of a current value of the signal-to-noise ratio (SNR). In particular, such estimation is important for assessing the noise immunity of communication systems, including space communication systems, where high-precision SNR measurements within short periods of time are crucial to maintain contact with the spacecraft [1].

Many studies have been published on techniques of SNR estimation [3, 4, 5, 7-15, 17, 20, 22, 23, 24, 25]. Thus, it was proposed to estimate the SNR, based on the measurements of signal power and noise power; at that, mean-squared deviation (MSD) of the noise can be estimated quite accurately at the no-signal condition. Further, when receiving the additive mixture, the desired SNR is found as the ratio of the signal amplitude to the MSD of the noise [2]. Another possible estimator is based on the analysis of spikes in the envelope of additive mixture [3, 4, 5]. The weakness of this technique is the need to select a threshold level for counting the spikes.

This study aimed to develop a SNR estimation technique using the maximum likelihood estimation of the signal amplitude and to study its accuracy by statistical simulation. Subsequently, this paper proposes such a SNR estimator that employs the maximum likelihood estimation of the signal amplitude and the noise variance obtained by rejecting a continuous wanted signal, which is expected to provide high-precision measurements.

MATERIALS AND METHODS

To determine the SNR, it is necessary to estimate the amplitude. There have been various approaches to such estimations [6, 16, 18, 19, 21]. For the purposes of study, it was decided to choose the maximum likelihood estimation of signal amplitude [6, 18] as a methodological basis for the SNR estimation, because this algorithm is universally applicable in terms of the type of signal modulation. Estimation of the additive noise variance became possible due to the use of a band-rejection filter, which eliminated the wanted signal.

Consider the observation model and the amplitude estimation algorithm. The additive mixture of narrow-band signal and noise can be phrased as:

$$y(t) = A_m s(t, \varphi_\xi) + n(t, \sigma_n^2) = A_m \cos(2\pi f_0 t + \varphi_\xi) + n(t, \sigma_n^2) \tag{1}$$

where A_m is the signal amplitude, f_0 is the signal frequency, φ_ξ is the random initial phase of the signal, and σ_n^2 is the noise variance. The SNR to be estimated can be presented as [23]:

$$q_y = \frac{\sigma_s}{\sigma_n} = \frac{A_m / \sqrt{2}}{\sqrt{\sigma_n^2}} \tag{2}$$

where σ_s and σ_n are the mean-squared values of signal and noise, respectively, that are calculated as MSD for a sample of corresponding processes over an observation interval. As can be seen from Eq. (2), to determine the SNR, it is necessary to estimate signal amplitude A_m and MSD of noise σ_n (unless its value is already known).

The expression for the maximum likelihood estimation of the signal amplitude takes the following form [6,18]:

$$\hat{A}_m = \sqrt{z_1^2 + z_2^2} \tag{3}$$

In Eq. (3), z_1 and z_2 are scalar values formed by in-phase and quadrature correlated channels over observation interval T:

$$\begin{aligned} z_1 &= \int_0^T y(t)\cos(2\pi f_0 t)\,dt \\ z_2 &= \int_0^T y(t)\sin(2\pi f_0 t)\,dt \end{aligned} \tag{4}$$

Figure 1 shows a block diagram of the module for signal amplitude estimation ‘A_est_module’, implemented in the MatLAB–Simulink system, using Eqs. (3) and (4) above.

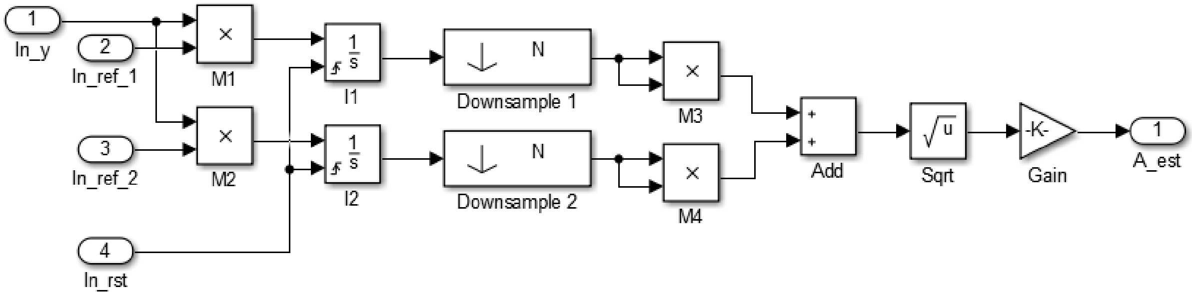

Fig.1. Module for signal amplitude estimation

Figure 2 shows an example of the block diagram of the project, by which the module for signal amplitude estimation ‘A_est_module’ was debugged, using the available tools of the MatLAB–Simulink system. The project implemented generation of the additive mixture as given in Eq. (1), formation of the reference harmonic signals for Eq. (4), formation of an auxiliary signal for resetting the integrators in the implementation of Eq. (4), and the operations provided by Eq. (3). The BSF module (band-rejection filter) eliminated the wanted signal in order to estimate MSD of noise σ_n .

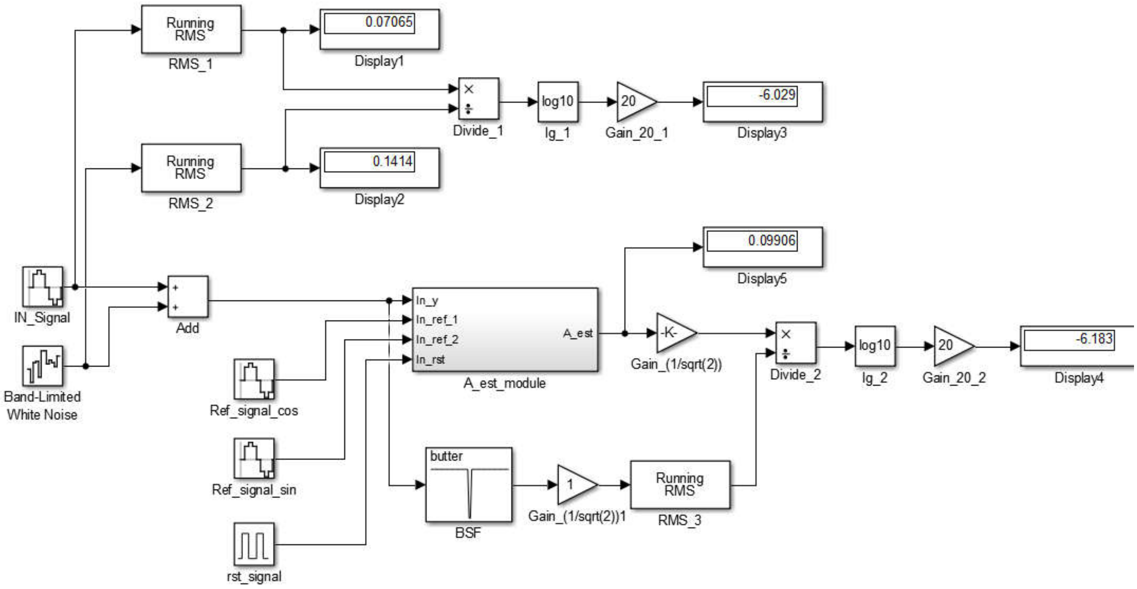

Fig.2. Module for SNR estimation

RESULTS

To verify the accuracy of the proposed SNR estimator, using the module for signal amplitude estimation, there was developed a script that ensured a multiple launch of the project (Figure

2). Besides, for each launch, a random value (uniform law) of the initial signal phase $\varphi_\xi \in [0;\, 2\pi)$ was set and the independent implementation of noise $n(t)$ was generated. At each launch (for each i-th statistical test), the SNR was calculated at the input $Q_i = 20\lg(q_y) = 20\lg(A_m / \sigma_n \sqrt{2})$ and at the output $\hat{Q}_i = 20\lg(\hat{A}_m / \hat{\sigma}_n \sqrt{2})$ of the algorithm; random error $e_i = | Q_i - \hat{Q}_i |$, its mathematical expectation $\langle e \rangle$ and MSD σ_e were calculated. There were conducted 1,000 tests. Statistical simulation was performed at the signal frequency $f_0 = 8\,kHz$, sampling interval $T_s = 10^{-7}\,sec$, and observation interval $T = 1/800\,sec$.

Figure 3 shows dependencies of the mathematical expectation of the SNR estimation error (dB) on the normalized amplitude of the input signal ($A_m / A_{m\max}$). Figure 4 shows dependencies of the MSD of the SNR estimation error (dB) on the normalized amplitude of the input signal ($A_m / A_{m\max}$). In Figures 3 and 4, blue curves denote the dependencies in the case of unlimited width of the input mixture, as given in Eq. (1), and reference signals. Red curves denote the dependencies in the case of using the sign approximation of the mixture, as given in Eq. (1), and reference quadrature harmonic signals, as given in Eq. (4).

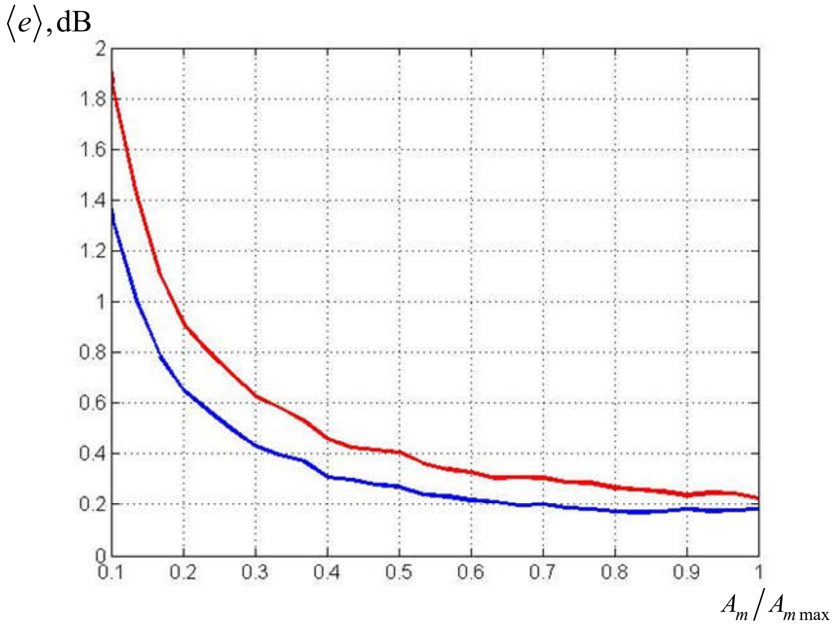

Fig.3. Dependency of the mathematical expectation of the SNR estimation error on the normalized amplitude of the input signal

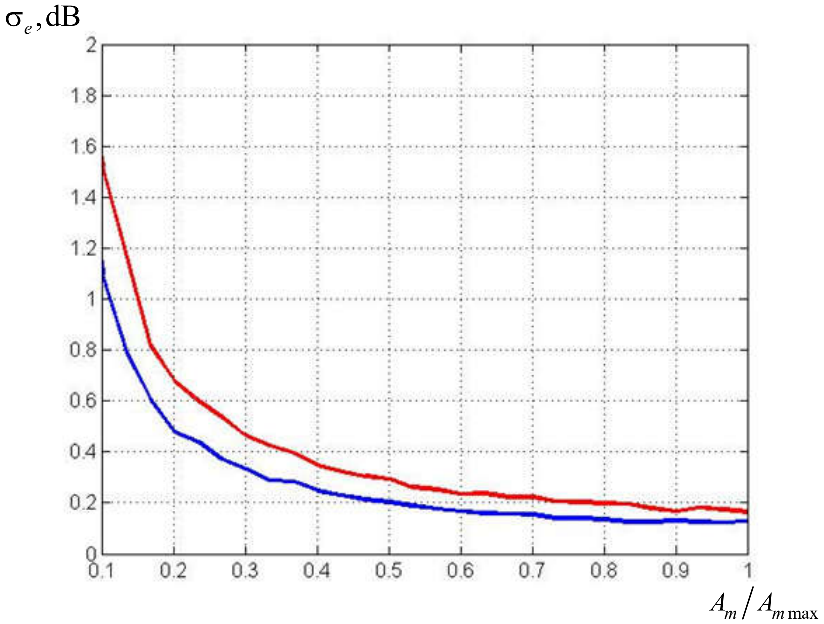

Fig.4. Dependency of the MSD of the SNR estimation error on the normalized amplitude of the input signal

DISCUSSION

As follows from Figure 3, for the most favorable conditions considered $(A_m / A_{m\max}) = 1$, the mathematical expectation of the SNR estimation error is $\langle e \rangle \approx 0.18\,\mathrm{dB}$. As follows from Figure 4, at the maximum signal amplitude considered — at the SNR $Q \approx -7\,\mathrm{dB}$, the MSD of the SNR estimation error is approximately 0.1 dB. When the requirements to the width of the input sample and the reference signals are reduced, the MSD of the SNR estimation error does not exceed 0.2 dB.

CONCLUSION

The developed SNR estimator has a relatively simple implementation and enables high-precision SNR measurements with the MSD of estimation error of approximately 0.1 dB. This allows using the estimator for various radio-engineering systems. Based on the results of such measurements (in the event that the required SNR is not provided), there can follow a possibility to increase it.

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