STUDY OF HF BROADBAND DIGITAL RADIO LINE SIGNALS COHERENT RECEPTION DEVICE NOISE IMMUNITY

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ABSTRACT

This article presents the results of testing a software model of a wideband digital voice radio signal receiving device using an ionospheric channel model. This model was used to develop scientifically based recommendations for the application of a coherent algorithm in a digital voice radio signal receiving device and to compare its noise immunity with the prototype software model. During modem testing, scientifically based recommendations were developed for the application of an optimal filtering algorithm in real-world conditions. These recommendations consist of restarting the optimal filter upon receiving a new radiogram and setting the Doppler spreading value used in the optimal filter synthesis to 2 Hz under conditions of a priori uncertainty regarding the Doppler spreading value in the channel. The results of the study showed that the device, which differs from the known ones by the use of a coherent processing algorithm with optimal filtering of the coefficients of a multipath ionospheric channel and operating taking into account the recommendations presented in this work for the conditions of a priori uncertainty about the dynamics of changes in the state of the channel, makes it possible to increase the noise immunity of a wideband radio line for transmitting voice messages, which is quantitatively expressed in a decrease in the proportion of unreceived radiograms by 31 percent compared to the prototype when processing broadcast recordings.

KEYWORDS: *HF communication, voice transmission, Kalman filter, ionospheric channel*.

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Introduction

Decameter-wave radio communication is one method for constructing operational communications systems, along with backup communications and high-power broadcasting systems. For operational communications systems, the ability to reuse frequency resources (due to the congestion of the decameter range in general, and the presence of a significant number of users in relative proximity in particular) and ensuring the confidentiality of information transmission (which can be ensured, in addition to cryptographic protection methods, by operating with complex signals in a wide frequency band) are important.

The use of an alphabet of orthogonal wideband phase-shift keyed signals, in conjunction with modern non-binary error-correcting coding algorithms and speech compression algorithms, enables the implementation of wideband voice radio links with increased noise immunity to meet these requirements. The main challenges in constructing decameter-wave radio links are predicting the state of the ionospheric channel, as well as assessing and compensating for the distortions it introduces into the useful signal under conditions of multipath propagation. The use of wideband signals allows for the detection, separation, and summation of multipath signal components, implementing the principles of optimal coherent diversity reception to improve the link's noise immunity [1,2]. However, coherent diversity reception requires assessing and tracking changes (filtering) in the values of the complex channel coefficients for each multipath component during radiogram reception under the a priori uncertainty that arises when using an alphabet of orthogonal wideband phase-shift keyed signals.

This paper examines the testing of a software model of a device using an ionospheric channel model to develop scientifically based recommendations for the application of a coherent reception algorithm using channel transmission coefficient estimates refined by an optimal filtering algorithm in a digital voice radio signal receiving device and a comparison of noise immunity with the prototype software model.

Description of the hf range digital voice radio link signal receiving device operation

Figures 1 and 2 show the block diagrams of devices for receiving digital voice radio line signals with incoherent signal processing for each of the received beams (prototype) and coherent processing with optimal filtering of channel coefficients using the algorithm described in [3] (proposed device). When receiving a radiogram before demodulating symbols with useful information, it is necessary to solve the problems of detection and estimation of signal parameters. In [4, 5], an algorithm for detecting a wideband signal with simultaneous estimation of many of its parameters was developed, including the delay and frequency shift of the signal, as well as the slope of the dispersion characteristic (DC) of the ionospheric channel, which characterizes the degree of dispersion distortion of the signal. The prototype modem implements a reception algorithm that includes the above-mentioned principle of signal detection with independent estimation of the signal parameters for each multipath component during multipath signal propagation. Frequency shift compensation is implemented by multiplying the received signal samples by a complex harmonic signal with a frequency equal to $-\hat{f}_d$. Compensation for the ionospheric channel dispersion distortions is implemented in accordance with [6] and is applied to the signal samples after the frequency shift has been eliminated. The dispersion distortion compensator uses the DH slope value estimated during detection. Next, the decision statistics are calculated as correlation sums of the received samples and the samples of the ensemble sequences, taking into account the initial delay of the radiogram for each of the beams. For the matrix of decision statistics, the posterior probabilities of receiving each of the code block symbols are calculated as [7]:

$$P\left(c_k / \mathbf{y}_1, \mathbf{y}_2, ..., \mathbf{y}_{N_p}\right) = \frac{1}{\sum_{l=1}^{2^m}\left(\frac{\left|\dot{y}_l\right|^2}{\left|\dot{y}_k\right|^2}\right)^{\frac{1-N_p}{2}} I_{N_p-1}\left(\sqrt{\frac{\left|\dot{y}_l\right|^2}{\sigma_{ш}^2}\frac{E_s^2\sum_{j=1}^{N_p}\left|\dot{h}_j\right|^2}{\sigma_{ш}^2}}\right)\left[I_{N_p-1}\left(\sqrt{\frac{\left|\dot{y}_k\right|^2}{\sigma_{ш}^2}\frac{E_s^2\sum_{j=1}^{N_p}\left|\dot{h}_j\right|^2}{\sigma_{ш}^2}}\right)\right]^{-1}}, \quad (1)$$

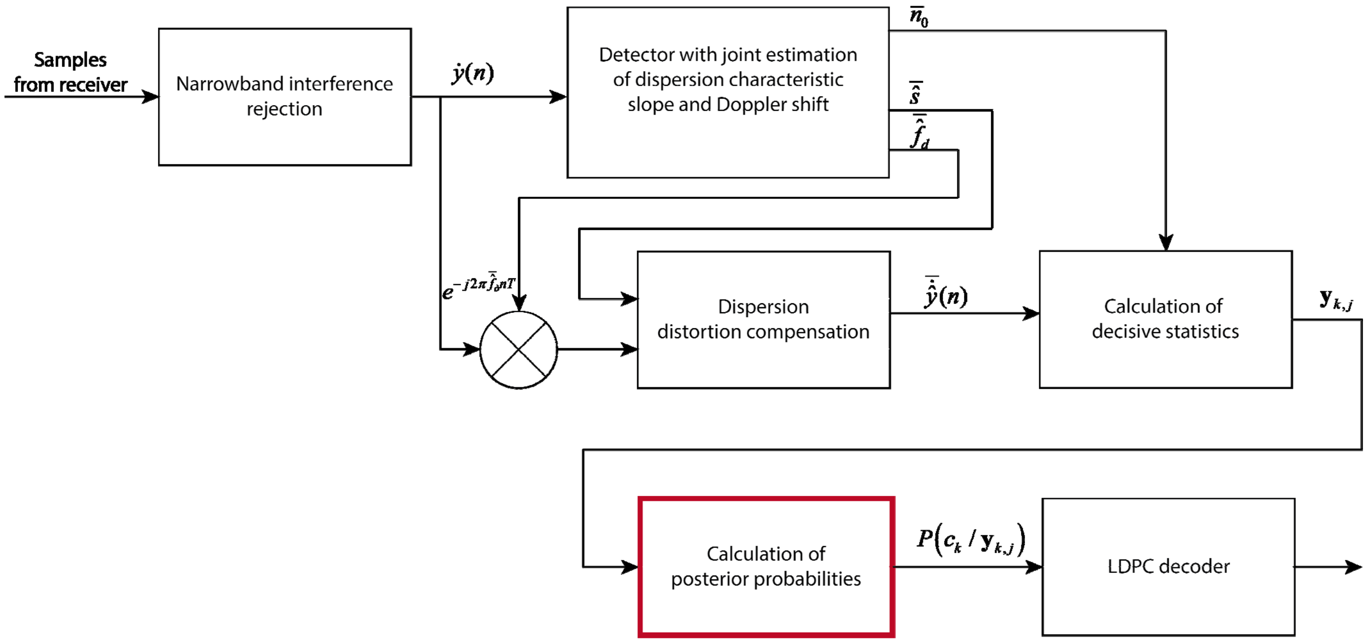
where c_k is the expected received symbol, $k = 1,...,M$, M is the number of orthogonal signals in the alphabet used, $\left|\dot{y}_k\right|^2 = \sum_{j=1}^{N_p}\left|\dot{y}_{k,j}\right|^2$ and $\left|\dot{y}_l\right|^2 = \sum_{j=1}^{N_p}\left|\dot{y}_{l,j}\right|^2$ are the correlator responses for the j-th diversity branch, is the number of diversity branches (N_p is the number of multipath components), $I_{N_p-1}(x)$ is the modified Bessel function of the first kind, order $N_p - 1$, $\left|\dot{y}_l\right|^2$ and $\left|\dot{y}_k\right|^2$ are the results of square summation of the correlator responses over all diversity branches.

Thus, expression (1) implements the quadratic beam summation scheme in the channel. The calculated posterior probabilities are fed to the LDPC decoder, which extracts the payload bits.

The coherent reception scheme shown in Figure 2 differs from the incoherent one in terms of calculating the posterior probabilities and estimating the coefficients. Estimates of the channel coefficients are required for coherent beam summation and calculating the posterior probabilities from the real part of the combined decision statistics. For this purpose, the Kalman filter is fed with complex values $\dot{y}_{k,j}$ of the correlation sums and the values of the correlation sums $\mathbf{y}_{pr}$ for the preamble sequences, calculated at the signal detection stage. Based on these values, in accordance with the algorithm described in [3], refined estimates of the channel coefficients $\hat{h}_{k,j}$ are calculated. The calculation of the posterior probabilities, taking into account $\hat{h}_{k,j}$, is implemented as follows [8]:

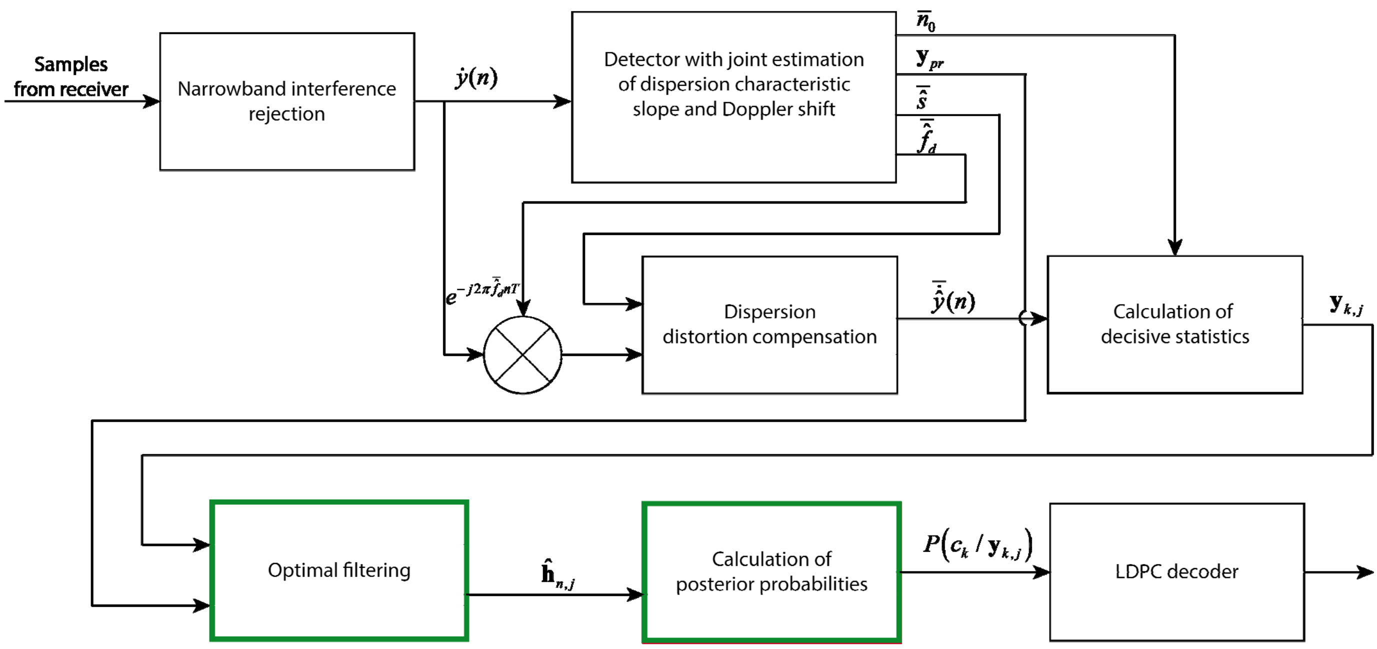
$$P\left(c_k / \mathbf{y}_1, \mathbf{y}_2, ..., \mathbf{y}_{N_p}\right) = \frac{1}{\sum_{l=1}^{2^m} e^{\sum_{j=1}^{N_p}\frac{E_s \operatorname{Re}\left(\left(\dot{y}_{l,j} - \dot{y}_{k,j}\right)\hat{h}_{k,j}^*\right)}{\sigma_{ш}^2}}}. \quad (2)$$

After that, similar to the algorithm with non-coherent reception, the payload bits are calculated as a result of decoding the LDPC code.



$$P\left(c_k / \mathbf{y}_{k,j}\right)=\frac{1}{\sum_{l=1}^{2^m}\left(\left(\frac{|\dot{y}_l|^2}{|\dot{y}_k|^2}\right)^{1/2-N_r/2}\frac{I_{N_r-1}\left(\sqrt{|\dot{y}_l|^2 E_s^2\sum_{j=1}^{N_r}\frac{|h_j|^2}{\sigma_n^2}}\right)}{I_{N_r-1}\left(\sqrt{|\dot{y}_k|^2 E_s^2\sum_{j=1}^{N_r}\frac{|h_j|^2}{\sigma_n^2}}\right)}\right)}$$

Figure 1. Block diagram of a device for non-coherent reception of a digital voice radio link signal in the HF range.



$$\hat{\mathbf{h}}_{k,j}=\hat{\mathbf{h}}_{k,j}^{-}+\mathbf{K}_{k,j}\left(\mathbf{y}_{k,j}-\hat{\mathbf{y}}_{k,j}^{-}\right)$$

$$P\left(c_k / \mathbf{y}_{k,j}\right)=\frac{1}{\sum_{l=1}^{2^m}\left(e^{\frac{\sum_{j=1}^{N_r} E_s \mathrm{Re}\left(\left(\dot{y}_{l,j}-\dot{y}_{k,j}\right)\hat{\mathbf{h}}_{k,j}^{*}\right)}{\sigma_n^2}}\right)}$$

Figure 2. Block diagram of a device for coherent reception of signals from a digital voice radio link in the HF range.

Assessment of the gain from using an optimal filtering algorithm as part of a digital voice radio link signal receiver

In the receiving device, each radiogram is detected and received independently. Therefore, it is impossible to guarantee the continuity of symbols received from adjacent radiograms, and it is impossible to correctly take into account the information contained in the Kalman filter memory when processing a new radiogram. Consequently, it is necessary to restart the optimal filter when receiving a new radiogram.

To evaluate the noise immunity gain achieved by using the developed algorithm for optimal filtering of the channel gain under ionospheric propagation conditions in the HF range, taking into account the limitations imposed by the implementation of the receiving algorithm, a numerical experiment was conducted using the developed software model of a device for demodulating signals from a wideband digital voice radio line, as well as a software model of the prototype modem. The receiving device for which the model was developed differs from that implemented in the prototype modem by the addition of a module for optimal filtering of channel coefficient estimates and refined estimates when calculating the posterior probabilities of receiving code block symbols using a coherent scheme in accordance with expression (2). Figure 3 shows the diagram of the simulation experiment carried out to compare the reception algorithms, where device 02-01 is a modulator that generates complex readings of the quadratures of radiograms, device 01-02 is an AWGN generator with a given dispersion, device 02-02 is a Watterson channel simulator corresponding to the model described in section 1.1.2, device 04-02 is an adder, devices 03-04 and 03-05 are a module for calculating the signal power to noise power ratio and a display module, devices 04-04 and 04-05 are a counter for the number of transmitted radiograms and a display module, devices 01-07 and 01-08 are a demodulator with quadratic addition of beams, the structural diagram of which is shown in Figure 1 and a statistics display module, devices 03-07 and 03-08 are a demodulator with an estimate and optimal filtering of the channel transmission coefficients and coherent addition rays, the structural diagram of which is shown in Figure 2 and the statistics display module.

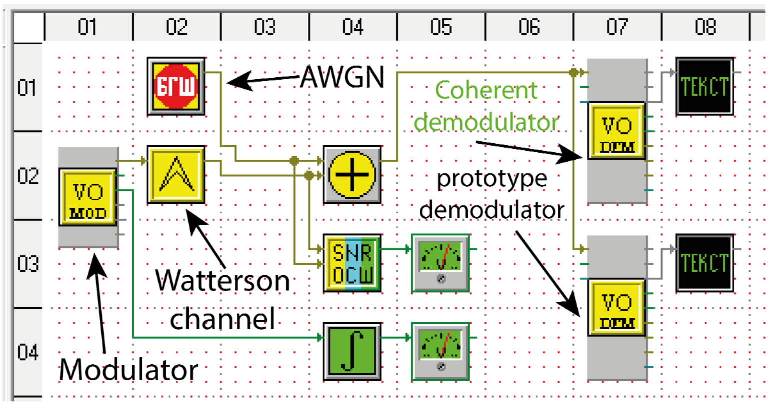


Figure 3. Experimental setup in “Spectr 2” environment.

The detection algorithm implements a combined estimate of the delay, Doppler frequency shift, and dispersion slope. As shown in [9], the coherence interval of these parameter estimates is 3-5 seconds, which is significantly longer than the duration of the radiogram used. Thus, up to the quality of the estimate, the influence of these parameters can be assumed to be compensated and will not be considered further.

Figures 4–6 show the dependences of the code block decoding probabilities for the algorithm with incoherent quadratic addition and with coherent addition and optimal filtering of the channel transmission coefficient. These dependences demonstrate a gain in noise immunity from 1.4 dB to 2.4 dB with a decoding probability of 0.95.

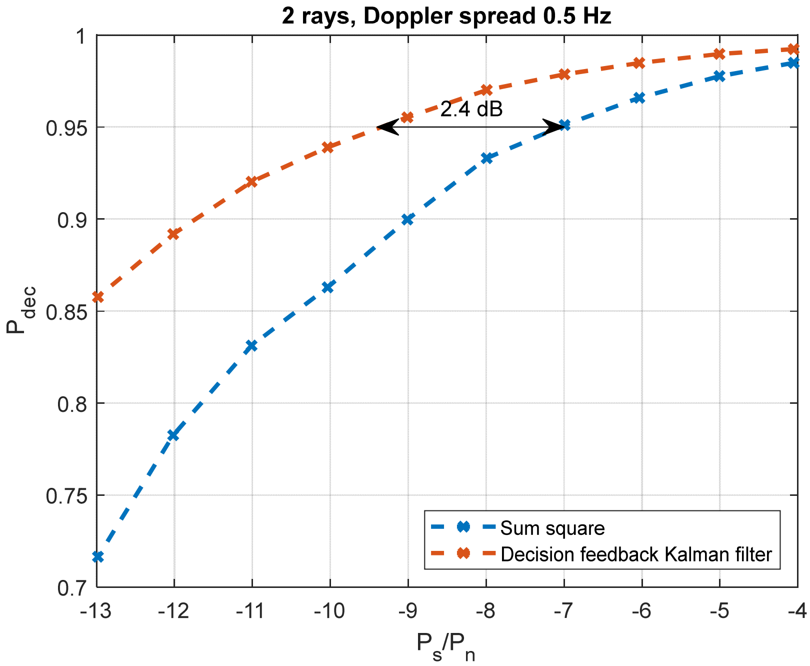


Figure 4. Dependence of the code block decoding probability on the SNR with Doppler spread 0.5 Hz.

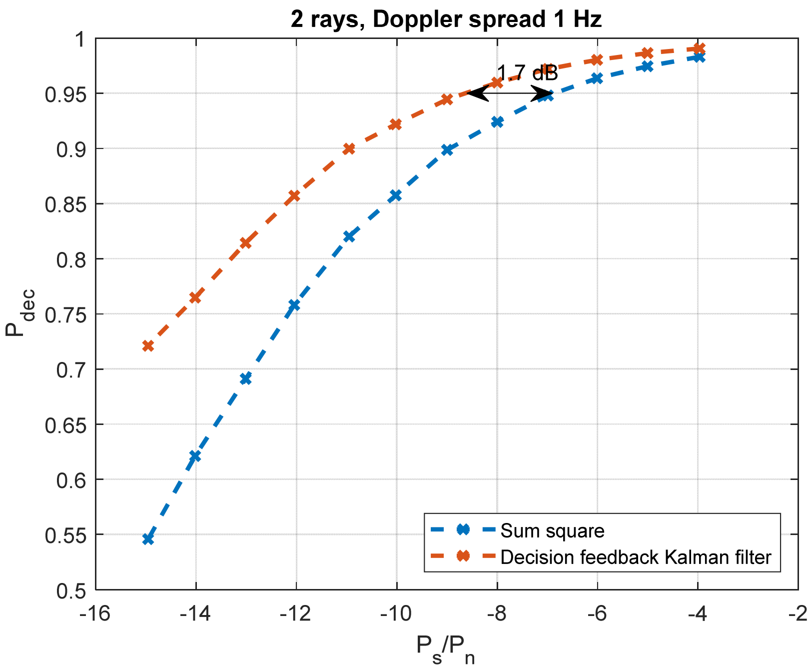


Figure 5. Dependence of the code block decoding probability on the SNR with Doppler spread 1 Hz.

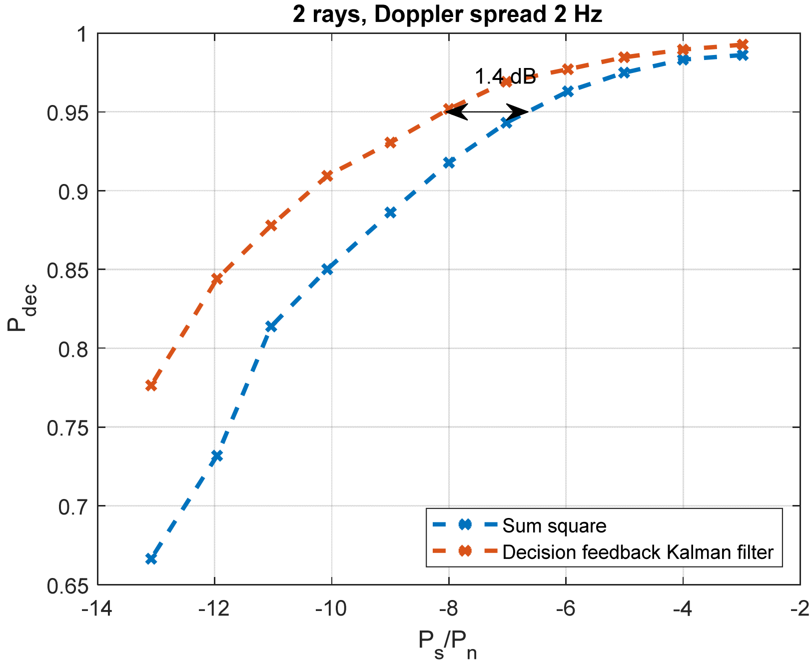


Figure 6. Dependence of the code block decoding probability on the SNR with Doppler spread 2 Hz.

Figures 7–9 show the dependences of the joint probability of detection and decoding of a radiogram for modems with non-coherent quadratic addition and with coherent addition and optimal filtering of the channel transmission coefficient. These dependences show a gain in noise immunity from 0.6 dB to 0.7 dB with a decoding probability of 0.95, depending on the magnitude of the Doppler spread in the channel.

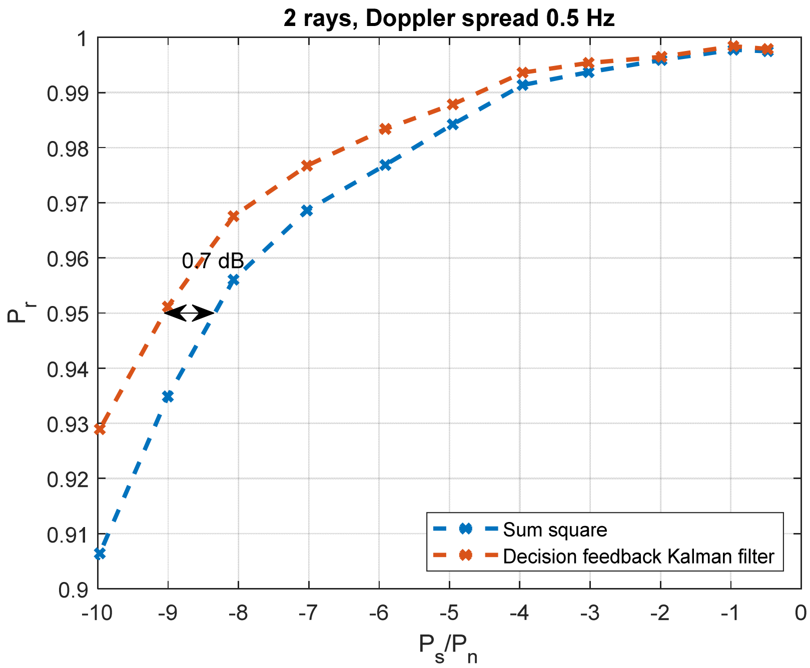


Figure 7. Dependence of the radiogram receiving probability on the SNR with Doppler spread 0.5 Hz.

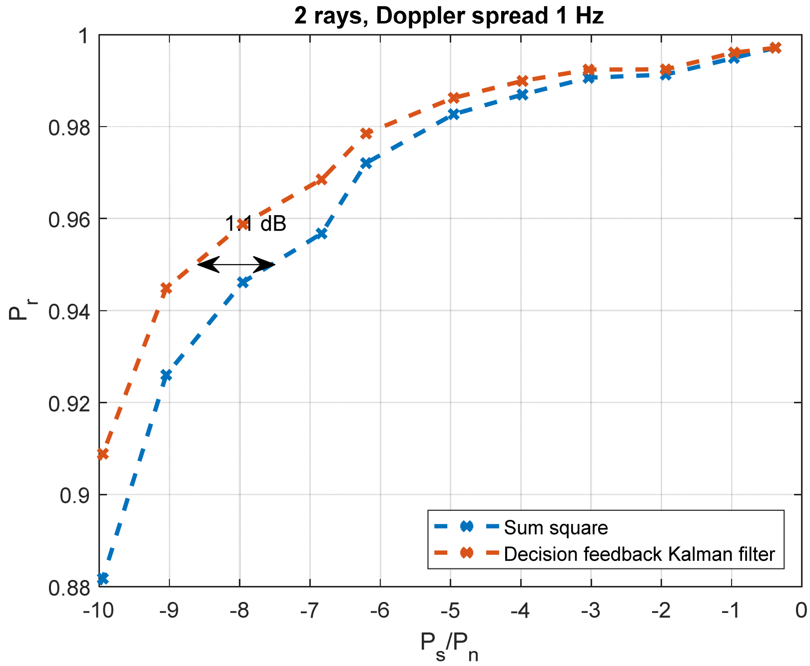


Figure 8. Dependence of the radiogram receiving probability on the SNR with Doppler spread 1 Hz.

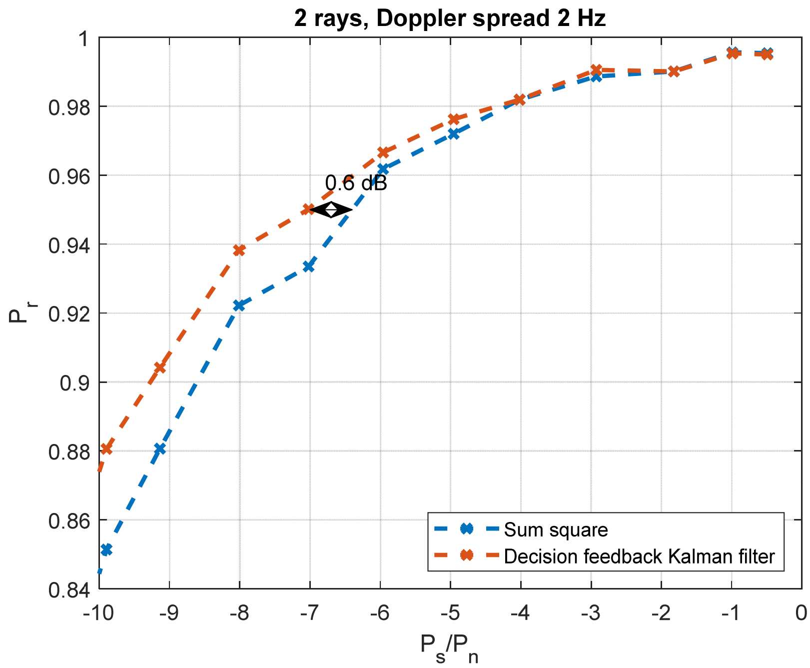


Figure 9. Dependence of the radiogram receiving probability on the SNR with Doppler spread 2 Hz.

Assessment of the dependence of noise immunity on the accuracy of doppler spread determination

Since the demodulation algorithm under consideration does not involve Doppler spread estimation, it is proposed to estimate the dependence of noise immunity on the difference between the specified and actual Doppler broadening values. The scheme of this experiment is shown in Figure 10. In this scheme, devices 02-01, 01-02, 02-02, 02-04, 03-04, 04-04 are similar to the devices from the scheme in Figure 3.

Devices 01-07, 03-07, 05-07 are demodulators with a coherent beam combining algorithm and optimal filtering based on a Kalman filter tuned to fading with a Doppler spread of 0.5, 1.0 and 2.0 Hz, respectively.

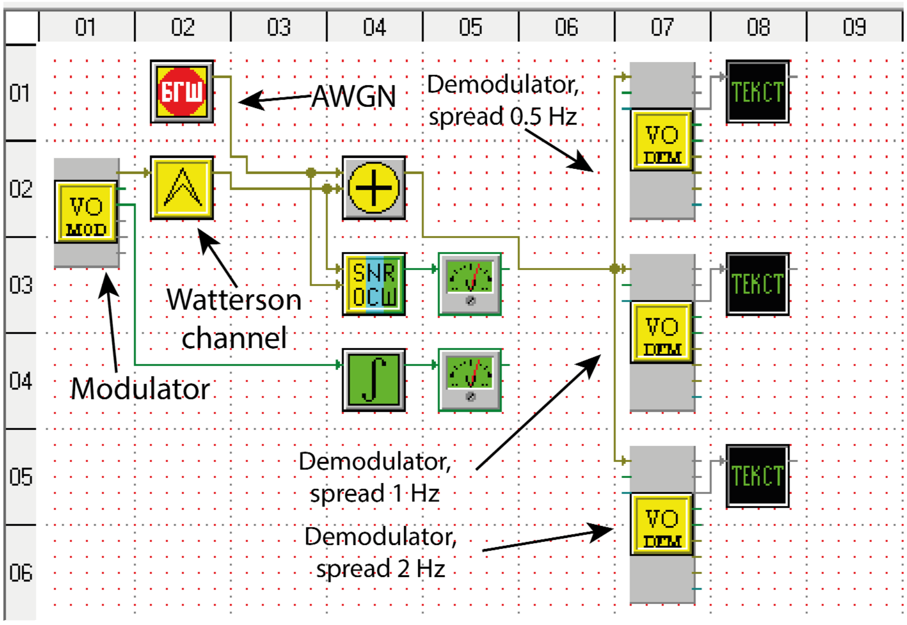


Figure 10. Experimental design for determining the effect of error in Doppler spread estimate on noise immunity.

Figures 11–13 show the dependences of the code block decoding probability on the SNR for Doppler spreading in the 0.5, 1, and 2 Hz channels. According to these dependences, for a Doppler spread of about 2 Hz, the Kalman filter tuned for a Doppler spread of 0.5 Hz is inferior to the filter for 2 Hz by about 2 dB. However, for smaller Doppler spreads, the difference between the algorithms is close to zero, which suggests the possibility of using the optimal filter for Doppler spreads smaller than that for which it was synthesized without a noticeable deterioration in noise immunity.

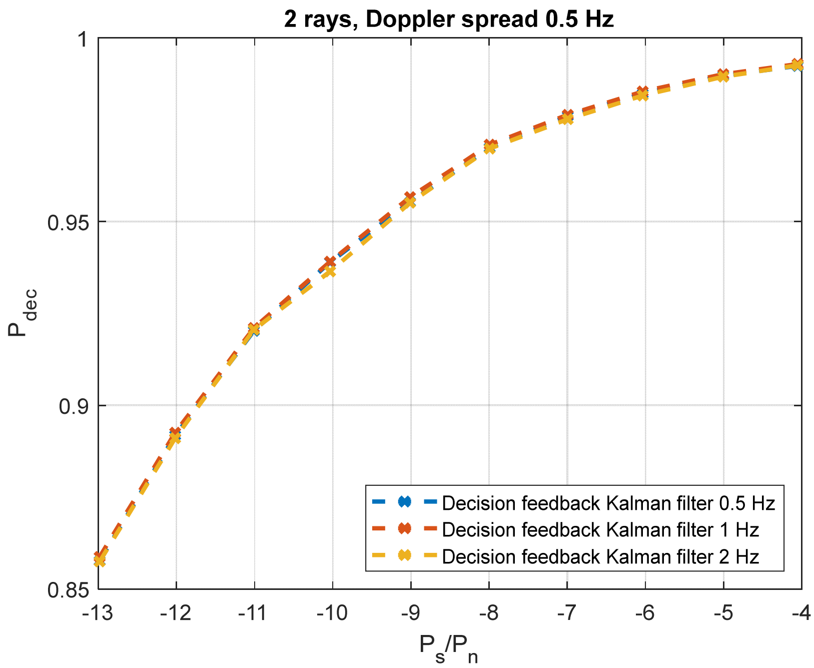


Figure 11. Dependence of the code block decoding probability on the SNR with Doppler spread 0.5 Hz

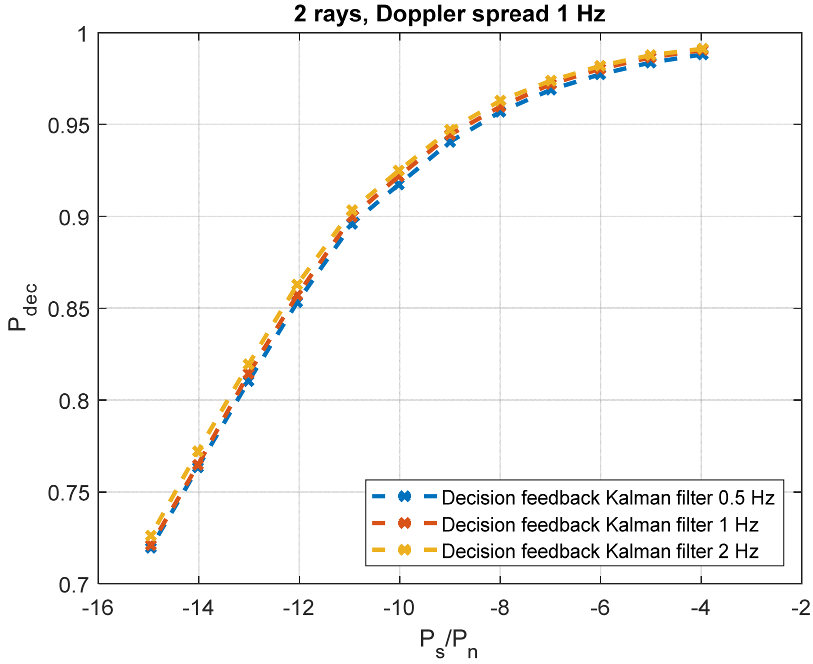


Figure 12. Dependence of the code block decoding probability on the SNR with Doppler spread 1 Hz

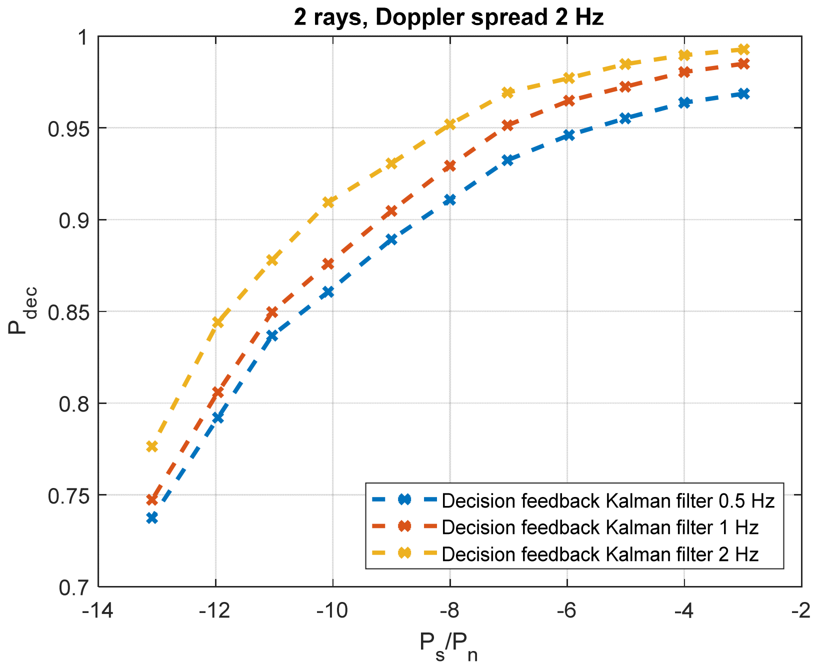


Figure 13. Dependence of the code block decoding probability on the SNR with Doppler spread 2 Hz

Results of processing air recordings

In order to experimentally confirm the effect of using coherent processing of decision statistics from received signal beams, signal recordings received during full-scale prototype tests were reprocessed as described in [7]. To solve this problem, a device for receiving digital voice radio line signals was developed that implements the developed algorithm. It includes software that allows processing signal recordings in the format used during testing so that the radiogram reception algorithm corresponds to that shown in Figure 2 and described above. Figure 14 shows the graphical interface of the recording processing software module. In the payload of each radiogram, in addition to the vocoder data blocks, one byte is allocated for service information about the radiogram number. This number increases monotonically from 0 to 255, after which it resets to 0. This allows, under the assumption that no more than 255 unreceived radiograms were transmitted between the two closest correctly demodulated radiograms, to determine the estimate of the proportion of correctly received radiograms as:

$$\hat{P}_r = \frac{N_{dec}}{\sum_{n=1}^{N_{dec}-1} (i_n - i_{n-1})}. \qquad (3)$$

where N_{dec} is the number of correctly decoded blocks during a communication session, i_n is the number of the radiogram transmitted as part of the useful message for the n-th decoded parcel.

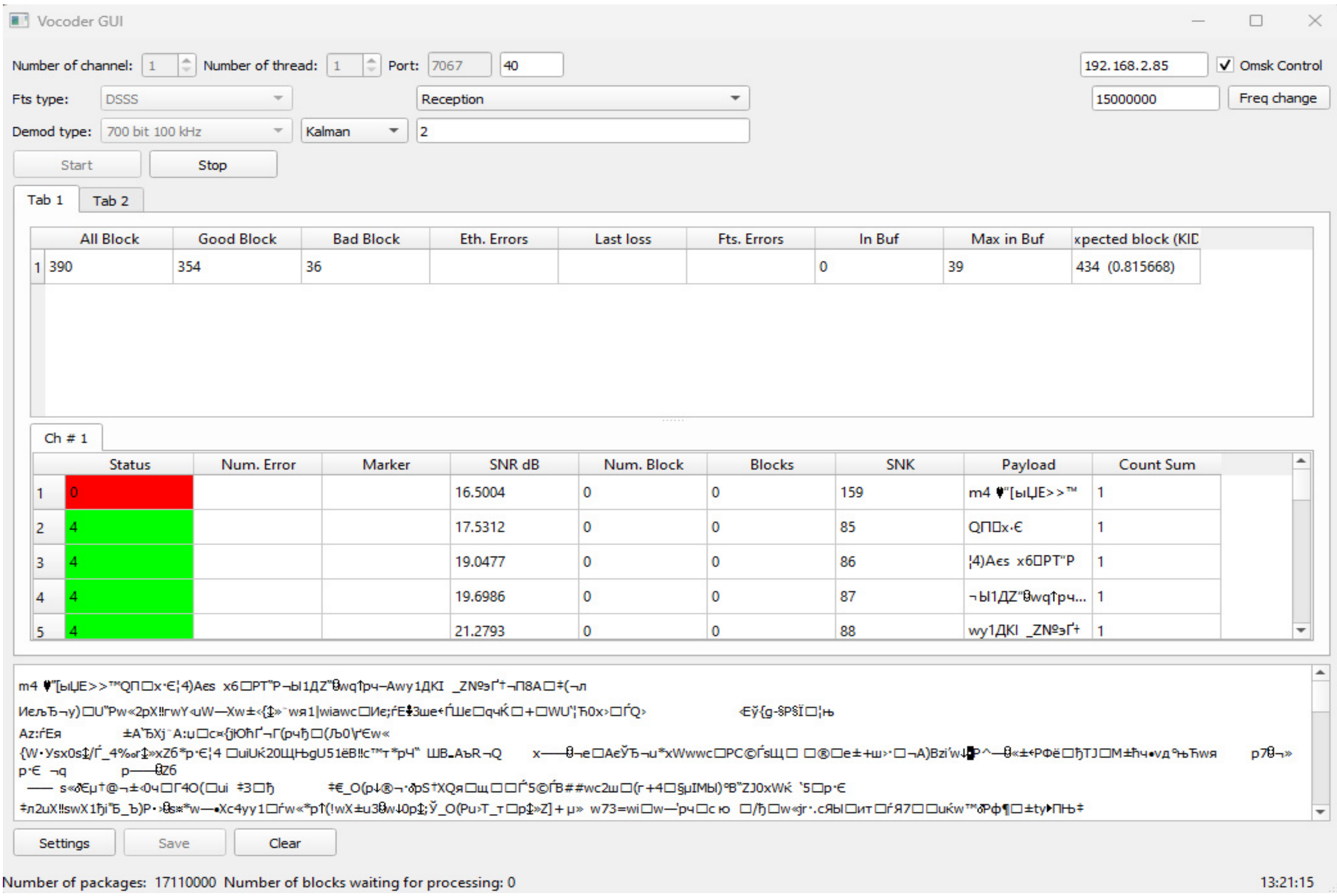


Figure 14. Record processing module interface.

Figure 15 compares the estimated reception probabilities for processing using an algorithm with non-coherent quadratic beam combining and one with coherent beam combining with optimal filtering. For the processed records, the developed algorithm demonstrated noise immunity either similar to or better than the non-coherent algorithm, with up to a twofold increase in the number of correctly received radiograms. On average, across all processed records, the decoding error probability decreased by 1.92 times (48%), resulting in a 1.45-fold (31%) decrease in the reception error probability.

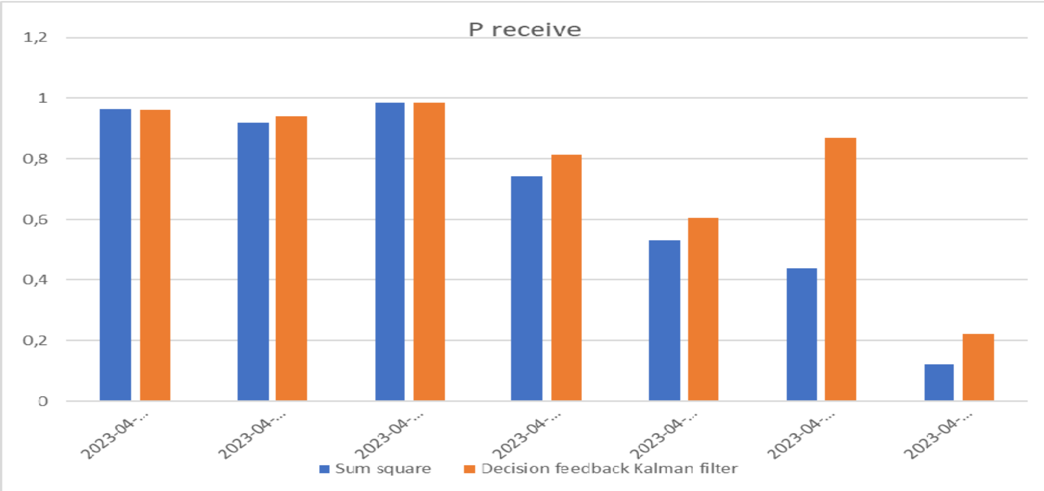


Figure 15. Comparison of reception probabilities for non-coherent reception and coherent reception with optimal filtering.

Conclusion

This paper presents a software model of a digital voice radio line signal reception device implementing the reception algorithm synthesized in Section 3. The developed model implements the Kalman filter operation using MP estimates of the channel coefficients obtained from preamble symbols, as well as information symbols selected in accordance with hard decisions during preliminary processing with quadratic addition. To eliminate uncertainty regarding the channel noise variance, this variance was estimated using decision statistics for non-information positions. A numerical experiment was conducted to test and compare the noise immunity of the radio link using the developed reception algorithm and the prototype radio link. The experiment results showed an energy gain in decoding probability from 1.4 to 2.4 dB with a Doppler spread of 0.5 to 2 Hz, respectively, for the developed model using an optimal filter calculated for the true value of the Doppler spread. It was also shown that, under conditions of a priori uncertainty regarding the fading rate in the ionospheric channel (Doppler spread values in the range of up to 2 Hz), the parameters of the optimal channel multiplier filtering algorithm calculated for a Doppler spread of 2.0 Hz should be used. This will allow processing wideband signals in the Doppler spread range from 0.5 Hz to 2 Hz with losses not exceeding 0.1 dB relative to precisely tuned optimal filtering algorithms.

The results of processing recordings from full-scale tests of the prototype radio link using the developed reception algorithm are presented. It was shown that the use of this algorithm reduced the probability of decoding errors in the code block by 1.92 times (48%), and the probability of radiogram reception errors by 1.45 times (31%).

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