Development of a mathematical model and analysis of the receiver for emergency alerts in a mine

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Abstract. The article presents the scientific and methodological approaches to the principles of construction and justification of the characteristics of a new sample of the SDV radio channel in underground mines to assess the required sensitivity of the receiving equipment and the maximum range of the channel. Based on the estimates obtained, as well as using radio engineering methods for calculating communication systems, the principles of noise reduction are formulated, coding and modulation systems are selected and justified. Mathematical modeling of noise reduction processes was carried out and algorithms and programs for the receiving and transmitting paths of a wireless data transmission system through rocks were developed. The paper presents the results of field observations of noise recorded in a working mine for the extraction of non-ferrous metals.

1. Introduction
One of the most important elements of safety and effective work in mines is the organization of telecommunication systems, both inside the mine, and ensuring uninterrupted communication of any part of the mine with the dispatcher on the surface. The lack of reliable emergency communications in emergency situations is one of the main problems of ensuring industrial safety in the event of accidents in mine workings or a rock shock phenomenon.

At present, modern mining enterprises have the following basic requirements for emergency communication systems:

- mine explosion safety for gas and dust. Gas accumulations and a suspension of coal dust in the workings are explosive, which requires meeting the conditions of intrinsic safety;
- providing mine personnel with reliable and high-quality communications over the entire length of the mine workings during regular operation and emergency situations;
- timely prompt notification of emergency situations of all mine personnel.

Currently, there is no universal solution on the market that fully meets all the requirements [1]. For this reason, several parallel operating systems are installed in the mines that satisfy the above requirements for the connection of mine workings with the surface.

This article is aimed at studying the effective reception of electromagnetic waves of the SDV range with frequency manipulation in underground mine workings to test the possibility of organizing a low-frequency emergency warning and personal call of miners. The analysis will be based on portable RFID tags for receiving individual and emergency call signals. The determination of the minimum sensitivity
The threshold of the RFID tag will be based on the calculated magnetic field strength at the measurement point and electromagnetic noise measurements at various points of the copper-zinc ore mine.

2. The study of methods for organizing general alerts in mines
For underground mines, as well as for metro tunnels, the most common warning and communication systems are automatic telephone exchanges with loudspeakers and fixed telephones connected to them, and WLAN networks that organize wireless microwave or Wi-Fi points in tunnels [2]. One of the most common communication methods in mines is the installation along the workings of long feeder lines that allow you to organize a duplex text and voice channel [3]. All presented data transmission systems work only in the line of sight or the coverage area of the access point and cable.

The authors of [4] conducted research on the modernization of ZigBee wireless communication technology based on the IEEE 802.15.4 standard. The presented network has a large capacity and a coverage area of 50-500 m in the line of sight and a transmission speed of 250 kbit/s. The authors also conducted studies at the zinc ore mine, evaluating the effect of bending of mine tunnel tunnels on the signal intensity of the transmitter at a frequency of 2.4 GHz. However, this system is not suitable for transmitting signals through rocks.

An alternative to wired and electromagnetic data transmission channels is a seismic channel [5], which includes a system of a seismic source capable of modulating elastic waves and a receiving group of seismic receivers connected to a stationary receiver. Such a channel is presented as an emergency data transmission system between mines and the surface in rocks with high electrical conductivity, but its design is possible only for stationary communication points.

Warning and data transmission systems covering large areas of mine production transmit a useful signal through the rock using an electromagnetic field (SDV range). For most TTE communication systems, a large-radius loop antenna or a magnetic coil is used to emit a useful signal [6, 7]. The receiver may be magnetically coupled to the transmitter using a similar receiving antenna or portable transmitter for individual use. Also, these systems can be used in TTE channels as a transmission path [8, 9]. As receivers, it is possible to design portable RFID tags that act as signaling devices for general and individual call of personnel.

3. Analysis of measured electromagnetic interference in mine workings
In the process of researching the optimal parameters of the RFID tag, electromagnetic interference studies were conducted at a copper-zinc ore mine. The measurements were carried out at several points in the mine production using special receiving devices in the form of a ferrite antenna (a 6000-turn copper coil with a ferrite core) (figure 1b) connected to the LTR-CEU1-4 L-CARD model ADC. The ADC is connected to a laptop, where the recording file is saved to disk for further analysis (figure 1a).

Figure 1. Block diagram and photo for recording electromagnetic interference from a receiving antenna: a - block diagram and photo of recording scheme, b - 3D model of a receiving ferrite antenna.
The registration of electromagnetic noise was carried out in a mine for the extraction of copper-zinc ores. The map of the mine is shown in figure 2, it has a depth of 850 m and a length of up to 5000 m. 11 points are located throughout the mine, where several measurements were made with a duration of 60 s.

![Figure 2. Layout of measurement points in the mine.](image)

Electromagnetic interference was recorded using a receiving antenna and ADC in the form of files on a laptop for further processing and use. The interference level at each measurement point is presented in table 1. The measurements are implemented in three modes: with a resonant capacitance (4 ADC channels); without resonant capacitance (4 ADC channels); signal at the output of the amplifier with a gain of 7500 (1 channel ADC). ADC channels have an individual resistance R: 1 channel - without resistance; 2 channel - 30 kOhm; 3 channel - 15 kOhm; Channel 4 - 11 kOhm.

**Table 1.** The measured level of electromagnetic interference in the mine.

| point number | antenna without resonant capacitance (voltage $U_N$, μV) | antenna with resonant capacitance (voltage $U_N$, μV) | amplifier output (voltage $U_N$, μV) |
|--------------|--------------------------------------------------------|------------------------------------------------------|------------------------------------|
|              | channel number                                        |                                                      |                                    |
| 1            | 0.023 0.023 0.023 0.017                                | 0.023 0.017 0.023 0.017                               | 1.7                                |
| 2            | 0.031 0.056 0.056 0.039                                | 0.056 0.063 0.1 0.044                                 | 0.31                               |
| 3            | 0.023 0.056 0.056 0.023                                | 0.023 0.023 0.023 0.023                               | 0.17                               |
| 4            | 0.031 0.039 0.039 0.039                                | 0.025 0.039 0.031 0.039                               | 0.1                                |
| 5            | 0.023 0.023 0.023 0.023                                | 0.023 0.023 0.023 0.023                               | 0.1                                |
| 6            | 0.056 0.056 0.056 0.056                                | 0.023 0.023 0.023 0.023                               | 0.1                                |
| 7            | 0.039 0.031 0.039 0.039                                | 0.012 0.023 0.023 0.023                               | 0.1                                |
| 8            | 0.031 0.028 0.028 0.025                                | 0.023 0.025 0.025 0.023                               | 10                                 |
| 9            | 0.1 0.031 0.031 0.031                                  | 0.1 0.023 0.023 0.023                                 | 10                                 |
| 10           | 0.1 0.031 0.031 0.031                                  | 0.1 0.023 0.023 0.023                                 | 10                                 |
The electromagnetic interference recorded in the mine has an intensity below a predetermined receiver sensitivity threshold of 5 μV. This creates a very favorable interference environment for registering a useful signal. Taking into account the intensity of the measured electromagnetic interference, it is possible to estimate the magnetic field radiated by the radiating antenna at the point of interference measurement to ensure a sufficient signal-to-noise ratio and achieve a BER bit error probability of no worse than $10^{-3}$ [10].

$$H = \frac{U_s}{\omega \mu_0 S_{\text{eff}}},$$

where $S_{\text{eff}} = \mu_{\text{core}} S_{\text{core}} n_{\text{rec}} = 6$ m² is the effective area of the receiving antenna; $\omega = 2\pi f$ is the angular frequency of the signal; $\mu_{\text{core}} = 80$ is magnetic permeability of the core; $S_{\text{core}}$ - core cross-sectional area; $\mu_0 = 4\pi \cdot 10^{-7}$ is magnetic constant; $n_{\text{rec}} = 6000$ is the number of turns of the receiving antenna; $U_s$ is the voltage of the useful signal at the input of the receiver, required to provide the necessary BER value.

The receiver sensitivity limit exceeds the level of measured interference by 40 dBV, corresponds to a voltage of $U_s = 5$ μV, respectively, the minimum required magnetic field strength at the antenna is $H = 1.05 \cdot 10^{-4}$ A/m.

4. Modeling of receiving RFID tags and processing FSK signals

The results of measurements of electromagnetic interference at the mine will be further used in the design of the receiving RFID tag for receiving a useful signal and its integration into the general telecommunication and dispatch network of the mine enterprise.

To analyze the efficiency of receiving a useful signal at noise measuring points, at a receiver sensitivity of 5 μV, a useful signal with FSK modulation ($f_1 = 966$ Hz, $f_2 = 984$ Hz) was modeled and summed up with noise recorded in the mine after amplification (gain 7500) (figure 3).

![Figure 3. Temporal realization and spectral characteristic of a mathematical model of signal and noise recorded in a mine.](image)

The spectral characteristic of the received signal at shows a signal-to-noise ratio of 50 dB, which ensures reliable reception of the useful signal.

To register a useful signal, a scheme of a compact individual receiver of FSK signals with automatic adjustment of the threshold of a resolver was developed (figure 4). This receiver is designed to register binary signals with FSK modulation. The input signal induced on the magnetic antenna, after preliminary amplification and filtering (gain 7500), the signal passes through the input band-pass filter
BPF₀ (center frequency \( f₀ = 1000 \text{ Hz}, \) frequency band \( ΔF = 120 \text{ Hz}, \) quality factor \( Q = 10 \)). The signal is fed to two band-pass filters BPF₁ (\( f₁ = 984 \text{ Hz}, \) frequency band \( ΔF = 9 \text{ Hz} \)) and BPF₂ (\( f₂ = 966 \text{ Hz}, \) frequency band \( ΔF = 9 \text{ Hz} \)) to isolate signals with modulation frequencies. After quadratic rectification (QR) of the filtered signals, they are summed and several integration steps are performed with the difference between the rectified signals being reset using the integrator block. Depending on the input parameters, a binary code sequence is generated in the decision device (DD).

![Figure 4. Functional diagram of a searchless FSK signal receiver (RFID tag).](image)

Figure 5 shows the processing of the sum of the simulated input signal and the electromagnetic noise (signal + noise) recorded at the output of the receiver amplifier recorded in the mine. After the primary filtering in BPF₀, the signal undergoes additional filtering in BPF₁ and BPF₂ to isolate the signals at the modulation frequencies. The signals after filtering go through the process of rectification in QR and summing. The resulting sum signal is integrated, after which you can get the bit sequence in the DD block.

![Figure 5. The signal conversion process in the FSK signal receiver.](image)
The receiver board with dimensions of $60 \times 30$ mm is shown in figure 6. The antenna of the receiving device is located on the device board and is implemented as a magnetic ferrite antenna 50 mm long with a winding of copper wire with 6000 turns. The output of the receiving RFID tag is connected to the lamp of the miner’s lamp. When an alarm or an individual call number is received, the receiver flashes a flashlight.

![Figure 6. 3D model of FSK signal receiver board with magnetic antenna.](image)

The technical characteristics of the developed receiving device are shown in table 2. These characteristics will ensure efficient reception of FSK signals in the presence of sufficient magnetic field intensity.

| Parameter name                             | Parameter value            |
|--------------------------------------------|----------------------------|
| supply voltage                             | 3.3 - 5 V                  |
| power supply undervoltage protection level  | 3B                         |
| current consumption                        | no more than 10 mA         |
| sensitivity                                | no worse than 5 uV         |
| pass-through gain                          | 7500                       |
| center frequency of the receiving amplifier | 1000 Hz                    |
| working frequency band of the amplifier of the receiving path | 80-200 Hz |
| output impedance of the receiving path amplifier | no more than 20 kOhm |
| bit ADC microcontroller                     | 12 bit                     |
| ADC sampling rate                          | 4800 Hz                    |
| microcontroller external clock frequency   | 16 MHz                     |

5. Conclusion

Measurements in the mine workings showed that the intensity of electromagnetic interference at the measurement points is below the receiver sensitivity threshold of 5 μV. This indicates an extremely favorable interference situation in the mine, which allows to achieve a large signal-to-noise ratio and bit error probabilities of no worse than $10^{-3}$. To ensure an acceptable level of BER, the minimum value of the magnetic field strength of the emitting antenna at the measurement point should provide a voltage of at least 5μV threshold, which corresponds to $H=1.05 \times 10^{-4}$ A/m, which is the minimum acceptable level of the magnetic field.

In the simulation, processing the useful FSK signal and the recorded noise in the receiver showed a signal-to-noise ratio of 50 dB. Also, a model of a bezososik receiver of general and individual warning signals with frequency telegraphy (FSK) in the form of a compact board with a magnetic antenna located on its body was also proposed.

Interference measurements have shown that the noise environment in the mine is favorable for receiving transmitter electromagnetic signals, however, the absorbing properties of the rocks and ores limit the TTE technology for transmitting the useful signal. The organization of a useful signal
transmission system remains a separate problem and requires an individual approach and analysis to ensure that the mine is fully covered by an emergency warning system.

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