Selection of the optimal configuration of a signal transmission system through a rock depending on the mine geological structure

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Abstract. The article gives numerical estimates of a wireless warning system model and individual call of personnel in mines using a low-frequency electromagnetic field (ULR-range) with account for low-resistivity ore reserves. The presence of such deposits is represented by the main problem of the implementation of TTE (Through-the-Earth) communication due to the large size and strong shielding properties, which are also evaluated. The article shows numerical estimates for two long dipole antenna configuration models (symmetric and asymmetric). The comparison provides an assessment of the benefits of different antenna installation options to neutralize the shielding properties of the deposits.

1. Introduction
With the closed method of mining, mine tunnels have a complex and branched structure depending on the structure of the mineral deposits. Due to the specifics of mine production, underground horizons undergo a constant structural change in the form of laying new workings and preserving spent workings. These conditions do not allow the installation of emergency warning systems and individual calls to mine personnel (mine automatic telephone exchanges, radio stations, feeder lines, etc.) in all mine workings, which makes it impossible to install wired warning systems throughout the mine territory. In this case, to cover most of the mine field without using an extensive and complex ATS (automatic telephone station) or WLAN network, it is possible to use wireless data transmission systems through subsurface rock (TTE) using a low frequency electromagnetic field. The article discusses various types of radiating antennas in accordance with the topology of the mine workings, as well as the location, electrodynamic properties, size, and shape of mineral deposits.

2. Analysis of research and TTE communication methods for mines
TTE data transmission methods can conveniently be divided into frequency ranges and methods of radiation as well as reception of a useful signal.

Among the VLF data transmission systems, near-field magnetic communication is distinguished, operating in the frequency band of 30–100 kHz. This type of signal transmission uses magnetic coils or loops connected to a transmitter on the surface of the earth to transmit a signal and in a mining to receive a signal as well. The coil can be located in free space or wound around a column in a tunnel, which is suitable for control stations. The large size of the receiver and antenna does not allow the employment of the device for personal use. According to the studies of the developers [1-3, 4], with a transmitter power of 7–10 kW, the device reaches a signal transmission range of 300 m through the rock mass,
however, the study does not take into account the presence of ore bodies that absorb an electromagnetic field.

In studies in the field of wireless data transmission systems of the VLF range through rocks (Through-the-Earth Communications), the results of works published in one of the articles [5] are of interest. A group of scientists carried out modelling and analysis of the propagation of EM signals in the frequency band of 400 Hz – 9 kHz in the presence of metal structures in the form of rails. They proved that TTE signals interact with long conductors of artificial origin, which allows them to be re-emitted through these structures, increasing the range of the TTE communication system. A wide range of scientific research and scientific and technological developments in the field of wireless mine communication systems operating in various ranges (from 300 Hz to 10 MHz) and presented in the scholarly press confirms the significance of this research area.

The authors of this article previously performed analysis and experimental studies of TTE communications using a long dipole antenna [6, 7]. The article provides an analysis of the propagation of currents and the magnetic field of a transmitting grounded dipole antenna in a homogeneous medium and experimental data. The dependence of the useful signal level on the frequency during its propagation through rocks was experimentally confirmed. The model parameters shown by the authors of this article will be used to create a computational model of a TTE communication system with the presence of an ore body for various configurations of a radiating antenna.

The authors of the article [8] conducted a study of the propagation of natural EM fields in rocks and their interaction with micro seismic vibrations of the earth. The data of the article indicate that the electromagnetic field strength of the earth is too low to be considered as interference in calculating the voltage at the receiver.

3. Theoretical analysis of the attenuation of EM waves in rocks dependence on their frequency

The main parameter of rocks that affects the propagation of EM fields is the electrical conductivity $\sigma$. This property to a greater extent affects the damping parameter $\alpha$, which also depends on the signal frequency and the electrophysical properties of the medium [1]. The attenuation parameter indicates the degree of decrease in field strength in the medium during propagation (figure 1):

$$\alpha = \omega \sqrt{\frac{\mu'\varepsilon'}{2}} \left(\sqrt{1 + \text{tg}^2 \delta} - 1\right),$$

where $\mu'$ and $\varepsilon'$ - the relative magnetic and dielectric constant of the medium; $\omega=2\pi f$ is the angular frequency of electromagnetic waves; $\text{tg}\delta=\sigma/\omega\varepsilon$ is the dielectric loss tangent; $\sigma$ is the electrical conductivity of the medium.

![Figure 1](image)

**Figure 1.** Dependence of the attenuation parameter on electrical conductivity for various frequencies of the EM field. Frequency step - 100 Hz.

It is worth considering that for $\text{tg}\delta<1$, $\alpha\rightarrow0$, and in the case of $\text{tg}\delta>1$, $\alpha = \sqrt{\frac{\sigma\omega\mu}{2}}$ [2].
The geology of non-ferrous metal mines is characterized by a different structure of the host rocks (solid, porphyritic), with crystalline inclusions, pores, cracks, and faults. Such rock-forming minerals, subject to a low pore moisture content, have an incredibly low electrical conductivity \( \sigma = 10^{3-12} \text{ c/m} \). Ore bodies are made up of one or more types of ore minerals found in the rocks in the form of streaks and inclusions that increase the electrical conductivity of the rocks. Most pure ore minerals (galena, pyrite, chalcopyrite, etc.) have high electrical conductivity in the range \( \sigma = 1-10^5 \text{ c/m} \), however, in ore deposits, these minerals are presented in the form of grains and veins, which makes the resistance parameter difficult to calculate and requiring direct measurement [1]. Due to the strong frequency dependence of the parameter \( \alpha \), the most suitable is the frequency in the region of 1 kHz, because further frequency lowering also lowers the voltage at the receiving antenna. Table 1 shows the electrophysical properties of some host rocks and ore minerals, the electrical conductivity of rocks and minerals differs by 5–7 orders of magnitude, which increases the absorption of EM waves and currents J.

Table 1. Electrodynamical properties of ores and host rocks.

| Name             | Grade of ore                    | \( \sigma \) (См/м) | Type of magnetic permeability | \( \varepsilon' \) |
|------------------|---------------------------------|---------------------|-------------------------------|-----------------|
| Orebody essential minerals |                               |                     |                               |                 |
| pyrite           | Iron                            | \( 10^2-10 \)       | paramagnetic                  | 33.7            |
| sphalerite       | Zinc 0.41–7.07%                | \( 10^7-10^5 \)     |                               | 7.8             |
| galena           | Lead 0.14–2.09%                | \( 10^3-10^7 \)     | diamagnetic                   | 81              |
| chalcopyrite     | Copper 0.52–2.09%              | \( 10^3-10 \)       |                               | 7.8             |
| Host rocks       |                                 |                     |                               |                 |
| aleurolite       |                                 | \( 1-4\times10^2 \) |                               | 4.9             |
| malm rock        |                                 | \( 10-10^4 \)       |                               | 12              |
| andesite porphyry|                                 | \( 5\times10^5 \)   |                               | 6.8             |
| basalt porphyry  |                                 | \( 10^4-10^7 \)     |                               | 4.5             |
| gabbro           |                                 | \( 4\times10^6 \)   |                               | 11              |
| diorite          |                                 | \( 10^3-10^7 \)     | diamagnetic                   | 6.2             |
| plagiogranite    |                                 | \( 10^3-10^6 \)     |                               | 21.3            |

The form of ore deposits is of great importance in the design and installation of TTE warning systems because they affect the location of mine workings and mine horizons, as well as the propagation of EM fields. Deposits in the form of lenses with different thicknesses (pay of zone) have strong shielding properties, depending on the electrophysical properties of the medium, the geometry of the deposit, and the signal frequency. Thus, the ore body creates a “blind zone” in the occurrence area, where the signal level is below the receiver sensitivity threshold or is absent.

4. Communication system performance analysis for two antenna configurations

To cover most of the mine workings, the use of a long dipole antenna in the form of a cable of length \( l \) with current \( J \) and with grounding at the ends is proposed. This type of emitter allows you to transmit a signal over a large area underground. To neutralize the “blind spots” in the mine field, two main configurations of transmitting antennas can be used: symmetric (figure 2a), where the grounding is installed at the same \( z \) level, and asymmetric (figure 2b), where the grounding is installed at different depth levels.
Figure 2. Installation options for a long dipole antenna: a – symmetric, b – asymmetric.

Let us consider the behaviour of the electric field of grounding and the magnetic field of the cable itself for these models. The main parameter of the effectiveness of the method will be the voltage $U$ at the input of the receiver induced on the magnetic antenna of the receiving RFID tag at point $M(x_3, z_3)$ and its comparison with the sensitivity threshold. The signal source is ground 1 (0, 0) and ground 2 ($x_1$, $z_1$). If there is a deposit at point $S(x_2, z_2)$, it will be represented as a sphere with the properties of the ore body and radius $R$ comparable with the volume of the ore body. Field registration is performed on the antenna in the form of a copper coil wound on a ferrite core. The system parameters for the calculation are shown in table 2.

| Name of parameter            | Value       | Name of parameter                | Value       |
|------------------------------|-------------|----------------------------------|-------------|
| Transmitter                  |             | Medium parameter                 |             |
| Maximum power                | 5 kW        | Host rocks conductivity, $\sigma_1$ | $10^{-3}$ Cm/m |
| Driving voltage, $U_{ll}$    | 380 V       | Ore-shoot conductivity, $\sigma_2$ | 10 Cm/m     |
| Frequency, $f$               | 700–5000 Hz | Ore-shoot amount, $R$            | 50 m        |
| Antenna current, $J$         | 16 A        | Distance along $x$              | 1000 m      |
| Antenna length, $l$          | 1500 m      | Distance along $z$              | 500 m       |
| Receiver with loop-coupled antenna |          | Receiving point coordinate      | 600 m, 450 m |
|                             |             | Deposit coordinate $S(x_2,z_2)$  | 600 m, 300 m |
| Working voltage stress       | 3.7 V       |                                  |             |
| Response                     | 5 mkV       |                                  |             |
| Antenna thread               | ferrite ($\mu=100$) |                                |             |
| Antenna geometrical dimensions | $48\times4$ mm |                              |             |
| Turning number, $n$          | 6000        |                                  |             |

The electric field of the antenna grounding points at point $M$ under the condition of homogeneous enclosing rocks is calculated through equation [2] (figure 3):

$$E_x = \frac{J}{\sigma_1 2 \pi} \left( \frac{x_2 + x_1 - x_3}{r_1^3} + \frac{x_1 - x_3}{r_2^3} \right) e^{-\sigma_1 r_1} e^{-\sigma_1 r_2},$$  \hspace{1cm} (2)

where $J$ – the antenna current; $\sigma_1$=$10^{-3}$ Cm/m – the electrical conductivity of the host rocks; $x_1$ – the distance from 0 to ground point 1 along the $x$ axis; $x_3$ – distance from 0 to the measurement point along the $x$ axis; $r_1$, $r_2$ – distance between grounding points and accurate measurement.

The distance between the ground and the measuring point is calculated from the formula:

$$r_1 = \sqrt{(x_0 - x_3)^2 + (z_0 - z_3)^2}, \quad r_2 = \sqrt{(x_1 - x_3)^2 + (z_1 - z_3)^2}, \hspace{1cm} (3)$$
Figure 3. The dependence of the antenna grounding electric field strength on the distance: a - for a symmetric antenna configuration, b - for an asymmetric antenna configuration.

From figure 3 it can be judged that the maxima of the electric field are observed in the area of the antenna earth ground, which exponentially decrease in a uniform rock environment \( (\sigma_1=10^{-3} \text{ Cm/m}) \). For the symmetric model in figure 2a, the field sources are located at the same depth; therefore, the field strength decreases with depth \( z \). In this case, the deposit at point \( S \) shields the receiving antenna at point \( M \). The asymmetric model (figure 2 b) gives an advantage if part of the cable is grounded deeper than the deposit, because between ground 2 and measuring point \( M \) there are no shielding obstacles in the form of deposits. The magnetic field in the region of point \( M \) in this case has a strength \( H_x=1.17\times10^{-2} \text{ A/m} \).

The electric field with the presence of deposits is calculated by a two-stage method. At the location of the deposit \( S(x_2, z_2) \), it is necessary to calculate the electric field strength \( E_x \) radiated by the antenna ground \[2\].

\[
E_x = \frac{J}{\sigma_2 2\pi} \left( \frac{x_2 \pm x_1 - x_2}{r_1^2} \right) \cdot e^{-\alpha_1 h} \cdot e^{-\alpha_2 z},
\]

\[
r_1 = \sqrt{(x_0 - x_2)^2 + (z_0 - z_2)^2}, \quad r_2 = \sqrt{(x_1 - x_2)^2 + (z_1 - z_2)^2},
\]

For the asymmetric model, the electric field strength at the point \( S \) is \( 35.12 \text{ V/m} \), for the asymmetric model - \( 67.5 \text{ V/m} \).

To determine the secondary electric and magnetic field emitted by the host, the dipole moment of the host is determined \[2\]:

\[
P = -2\pi \cdot E_x \cdot e^{-\alpha_2 R} \cdot K_{2m} \cdot R^3, \]

\[
K_{2m} = \frac{\rho_2 - \rho_1}{2\rho_2 + \rho_1},
\]

where \( R \) is the radius of the sphere from the ore body; \( K_r \) is the reflection coefficient; \( \alpha_2 \) is the attenuation coefficient of the EM field for a sphere from an ore body; \( \rho_1, \rho_2 \) is electrical resistivity of the host rock and ore body, respectively.

The dipole moment of the ore deposit for the symmetric model is \( P=6.4\times10^{-3} \), for the asymmetric model - \( P=1.2\times10^{-4} \).

Since the sphere has an electrical conductivity exceeding the \( \sigma_1 \) parameter of the host rocks by \( 3 \sim 5 \) orders of magnitude, the main contribution to the attenuation \( \alpha_2 \) is made precisely by the parameter \( \sigma_2 \).
and the radius of the sphere $R$, which correlates with the size of the ore deposit located between the emitter and the measurement point. The intensity of the magnetic and electric fields at the measuring point $M$ is determined by the formulas [2]:

$$
H_M^x = \frac{P}{4\pi r_3^2} e^{-\alpha_1 r_3}, \quad E_M^y = \frac{2\rho P}{4\pi r_3^3} e^{-\alpha_1 r_3},
$$

$$
r_3 = \sqrt{(x_2-x_3)^2 + (z_2-z_3)^2}.
$$

The calculation of the voltage at the output of the antenna at the measurement point is made according to the formula [9]:

$$
U_j = \omega \cdot \mu_0 \cdot H_e \cdot S_{ef},
$$

where $S_{ef} = \mu_e \cdot S_{sec} \cdot n_r = 4 \text{ m}^2$ is the effective area of the receiving antenna; $\mu_e$ - magnetic permeability of the core; $S_{sec}$ - the cross-sectional area of the core; $\mu_0 = 4\pi \cdot 10^{-7} \text{ Gm/m}$ - magnetic constant; $n_r$ - the number of turns of the receiving antenna; $H_e$ is the magnetic field strength.

The magnetic field emitted by the deposit under the influence of the grounding field for the symmetric model $H_e = 1.7 \cdot 10^{-10} \text{ A/m}$, for the asymmetric model $H_e = 3.2 \cdot 10^{-10} \text{ A/m}$.

In addition to the EM grounding field, the field of the cable itself with a current $J$ forming the transmitting antenna is induced on the RFID antenna. In the first case, a radiating antenna with a length of 1500 m is located on the surface of the earth (Fig. 2a), in the second case, the antenna has a bend at the transition point between the shaft of the mine and the beginning of the mine and in the mine workings (figure 2b), in the calculation, each cable is divided into 2 sections (vertical 500 m and horizontal 1000 m), the field of which is calculated at the measurement point and added to the grounding field. The magnetic of each part of the cable and the voltage at the output of the receiving antenna is calculated using the formulas [10] (Fig. 4):

$$
H_1^y = \frac{J}{2\pi r_{k1}} e^{-\alpha_1 r_{k1}}, \quad H_2^y = \frac{J}{2\pi r_{k2}} e^{-\alpha_1 r_{k2}},
$$

$$
U_1 = \omega \cdot \mu_0 \cdot H_1^y \cdot S_{ef1}, \quad U_2 = \omega \cdot \mu_0 \cdot H_2^y \cdot S_{ef2},
$$

where $r_{k1}, r_{k2}$ – is the distance between the cable with current and the measurement point $M$.

Figure 4. Dependence of the magnetic field strength $H_y$ on depth $z$. a - for a symmetric model, b - magnetic field strength of two cable parts for an asymmetric model.
The total magnetic field of the grounding and the antenna cable and the voltage at the receiving antenna of the RFID tag for the symmetric model are $H=2.061 \cdot 10^{-10}$ A/m, $U=8.17 \cdot 10^{-12}$ V. The voltage level of the RFID input is much lower than its sensitivity limit of 5 µV, which does not allow to register a useful signal with these system parameters. For a symmetrical antenna configuration, the RFID tag at point $M$ is located in the “blind zone” of the system, which is also shown in Fig. 2.

For an asymmetric model with specified system parameters, $H=9.95 \cdot 10^{-3}$ A/m, $U=3.9 \cdot 10^{-3}$ V. The voltage at the input of the RFID tag is above the sensitivity threshold, which ensures reliable reception of the transmitter information signal. This is due to the fact that with an asymmetric configuration of the transmitting antenna, the RF tag at point $M$ remains open for the second part of the cable and grounding 2, due to which the magnetic field of this part of the transmitting antenna undergoes only attenuation in the host rocks.

5. Conclusion
Calculations of the voltage on the RFID tag at point $M$ show that the installation of TTE-communication systems of the type presented must be carried out individually for each type of mine to consider the shielding properties of ore deposits. In this model, the asymmetric model is the most suitable, since it allowed to avoid “blind spots” that lower the overall signal-to-noise ratio. This shows the need for individual consideration of the topology of the mine workings and the location of ore deposits when planning the installation of TTE wireless data transmission systems. This will partially or completely neutralize the effect of ore bodies on the electromagnetic field of the radiating antenna.

In addition to the location of the deposits, it is necessary to consider their mineral composition, which determines their electrophysical properties and the attenuation parameter. In addition to changing the topology of the emitting antenna, the shielding properties of the ores with a small deposit size can be overcome by standard methods of dealing with a low signal to noise ratio. These methods include lowering the operating frequency of the channel, provided that the voltage gain in equation (9) is overcome by standard methods of dealing with a low signal-to-noise ratio. These methods include lowering the operating frequency of the channel, provided that the voltage gain in equation (9) is obtained, the selection of effective modulation methods (BPSK), increase the signal accumulation time and transmitter power.

Acknowledgements
The reported study was supported by grant of the Russian Science Foundation (project No. 18-79-00137), also the paper was funded by RFBR, the Government of Krasnoyarsk Krai and enterprise of Krasnoyarsk Krai according to the research project № 18-47-242017.

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