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To cite this article: D S Kudinov *et al* 2019 *IOP Conf. Ser.: Mater. Sci. Eng.* **537** 052013

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Evaluation of the possibility of wireless data transmission over rocks for automating an alarm system in mines using low-frequency electromagnetic waves and radio tags

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Abstract. The paper discusses the possibility of organizing a wireless data transmission channel in place of different kinds of mines for signalling and emergency communication using electromagnetic waves in the VLF propagation (300 Hz - 3 kHz). The paper gives theoretical estimates of the efficiency of propagation of electromagnetic waves in rocks and minerals with different values of electrical conductivity. The dependence of the depth of penetration on frequency is also studied. A review of the existing technical solutions to this problem is given. An analytical and numerical analysis of the current density in the rock and the magnetic field created by it using a radiating long cable is given. Reception of a signal with an informational message is carried out with the help of an individual radio tag informing personnel both in conditions of the mine's normal operation and in emergency situations. Comparative evaluations of the efficiency of using radio tags with different configurations of a receiving antenna in mine conditions at a depth of up to 800 m are given.

1. Introduction

Working in mines is connected with the risk of explosions and rock falls. Under these conditions, reliable communication is an important part of emergency response. As an alarm and emergency channel for transferring messages from the command post on the surface to any part of the mine, the most suitable is the wireless method of transmitting information. Information transfer systems between mine workings (horizons) use fully or partially wired methods of implementing a communication channel, which increases the risk of a channel breakage in emergency situations [1–4].

Wireless communication methods for mines can be conventionally divided into low-frequency, which use extended antenna-feeder devices for signal transmission, and high-frequency VHF-range, which are composed of wired communication lines in the form of a radiating cable laid along tunnels [1–4]. Recently, magnetic inductive or near-field magnetic coupling (BPM) has been identified as a separate type of communication in the frequency range of 30–100 kHz, which reaches the depth of transmission through the mountain massif to 300 m with a transmitter power of about 7–10 kW [5–8]. A large range of scientific studies presented in the scientific press confirms the importance of this field of research.

The fundamental problem of signal transmission through continuous mediums with high electrical conductivity arises when solving a number of applied problems associated with the organization of emergency communication channels in case of emergency situations, as well as permanent signalling



channels in underground mines. For wireless transmission of signals through rocks, the use of low-frequency electromagnetic waves is possible. The paper will investigate the magnetic component of the electromagnetic field in the frequency range of 300 Hz - 3 kHz (very low frequencies) in propagation media with several values of electrical conductivity corresponding to host rocks, several types of coal and metal ores. To transmit a signal at such a frequency, it is proposed to use an antenna in the form of a long grounded cable on the surface of a minefield. To receive the signal, it is planned to use a special radio tag with a magnetic antenna of two configurations (4000 and 8000 turns). This tag is designed to signal the mineworker about an emergency or the need to contact the dispatcher via other communication channels.

2. Methods and materials

2.1. Justification of the use of a radiating antenna in the form of a grounded cable line and the calculation of its magnetic field

When implementing a wireless mine communication channel, as one of the options, the use of a long grounded cable as a radiating antenna is evaluated. This type of emitter covers a large space of a minefield and half-space underground, and also allows emitting a signal at a low frequency. Let us analyze the magnetic field of the antenna in the form of a straight cable with L length and J current, which is located on the border of the half space along the x axis: the electrical conductivity of the half space is σ_1 , air - σ_2 . The cable is connected to current source and grounded at the ends. It is necessary to determine the magnetic field at z_l depth at M point (figure 1).

At low frequency, the field can be represented as the sum of the fields of two opposite charges located at the ground points. In the work of M. Zhdanov [10], a relation was obtained for calculating the current density in a conducting half-space. The current density in the coordinate system shown in figure 6, has three components j_x, j_y, j_z . Let us analyse the problem in x, z plane:

$$\vec{j}_x = \frac{\vec{J}}{2\pi} \left[\frac{x}{(x^2 + y^2 + z^2)^{3/2}} + \frac{(L-x)}{((L-x)^2 + y^2 + z^2)^{3/2}} \right], \quad (1)$$

$$\vec{j}_z = \frac{\vec{J}}{2\pi} \left[\frac{z}{(x^2 + y^2 + z^2)^{3/2}} - \frac{z}{((L-x)^2 + y^2 + z^2)^{3/2}} \right], \quad (2)$$

where \vec{J} is cable current.

The magnetic field at M point is represented as the sum of the fields created by the main current of the antenna \vec{J} and the elementary currents flowing in a half space, which has two components \vec{j}_x and \vec{j}_z . To determine the field created by the components \vec{j}_x , we will divide the entire area $z>0$ into elementary areas located at a distance Δz from each other, through which current \vec{J}_{xi} flows through an equivalent conductor with electrical conductivity σ_2 and diameter d . To determine the field created by the components, we divide the entire region $x>a$ into elementary areas located at a distance Δx from each other, through which current flows through an equivalent conductor with electrical conductivity σ_2 and diameter d (figure 1).

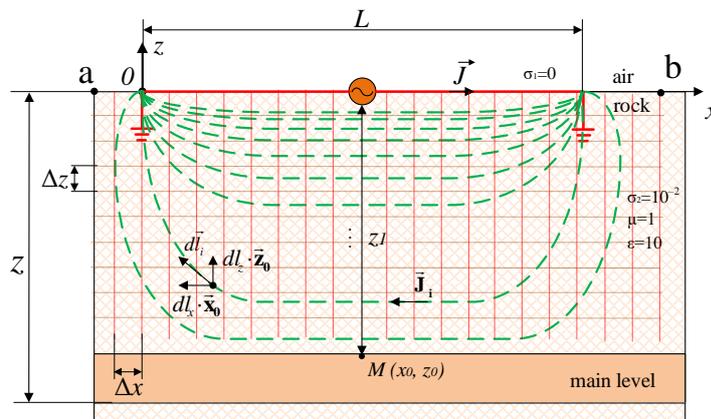


Figure 1. The distribution pattern of the density of currents in the rock for a grounded cable. The coordinates of the ground point are $x=0$ и $x=L$.

The magnetic field at M point created by \vec{J}_{xi} components will have the following components:

$$\vec{H}^x = \vec{H}_0 - \sum_{i=1}^{\kappa_1} \vec{H}_i^x + \sum_{i=\kappa_1+1}^{\kappa_2} \vec{H}_i^x, \quad (3)$$

where \vec{H}_0 the field created by \vec{J} current flowing between the grounds on the half-space surface.

The second component is the sum of the magnetic fields created by the elementary currents from a to b located above M observation point. The total number of such elementary currents is κ_1 , therefore, $\Delta z \cdot \kappa_1 \leq z_l$.

The third component determines the contribution of elementary currents located below M observation point. The total number of such elementary currents is κ , therefore, $\Delta z \cdot \kappa_2 \leq z_l + z$, where z is the total depth of the studied space.

The magnetic field at M point created by \vec{J}_{zi} components will have the following component:

$$\vec{H}^z = \sum_{i=1}^{\kappa_3} \vec{H}_i^z, \quad (4)$$

which is the sum of the magnetic fields created by the elementary currents \vec{J}_{zi} flowing from 0 to z .

The magnetic field of the current element is determined by the law of Bio-Savar:

$$\vec{H}_i = \frac{1}{2\pi} \int_{l_i} \frac{J_i \cdot [d\vec{l}_i \cdot \vec{l}_r]}{r_i^2} \cdot e^{-\alpha r_i}, \quad (5)$$

where $d\vec{l}_i$ – current element length J_i ; \vec{l}_r – ort of vector radius r_i ; r_i – distance from current element to point M ; l_i – current line (figure 1); $\alpha = \omega \sqrt{\frac{\mu' \epsilon'}{2} (\sqrt{1 + tg^2 \delta} - 1)}$ – damping rate; $\omega = 2\pi f$ – electromagnetic frequency; $\mu' = \mu / \mu_0$ – relative magnetic permeability; $\epsilon' = \epsilon / \epsilon_0$ – relative dielectric constant; μ , ϵ – absolute magnetic and dielectric constant; μ_0 , ϵ_0 – magnetic and dielectric constant of vacuum; $tg \delta$ – dielectric loss tangent.

2.2. Technical implementation of the receiver and the radio tag antenna

To register the signal in the mine, it is proposed to use a radio tag in the form of a receiver with FSK or PSK modulation (figure 2 and 3) and a magnetic antenna connected to it (figure 4). This type of antenna allows for a compact size to form a large effective area S_{eff} with small overall dimensions, due to the use

of a ferrite core and a winding with a large number of turns. This receiver registers the signal transmitted by the source, processes it and transmits information to a transistor switch connected to the light source of the shaft luminaire.

The work of the receiving device is shown in figure 2. The receiver is powered from the IP power source in the form of a rechargeable battery of the head shaft lamp. The signal in the form of a magnetic field is recorded using a ferrite antenna, and is fed to a regenerative amplifier of the receiving path with an integrated band-pass filter. If necessary, narrowing the bandwidth and increasing the gain of the receiving-amplifier path provides for the introduction of signal regeneration by introducing additional feedback. From the output of the receiving-amplifying path, the signal is fed directly to the input of the microcontroller's ADC, in which it is digitized, further digital filtering and detection using software algorithms in the MP microprocessor. The external reference clock is formed by a transistor cascade, in the positive feedback circuit of which a crystal oscillator is included. Switching the light sources of the head lamp is carried out through a transistor switch.

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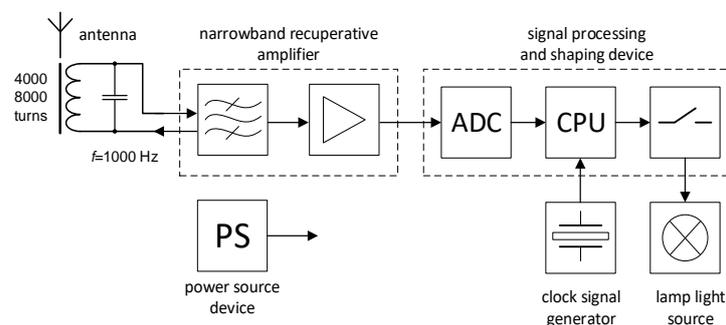


Figure 2. RFID tag for receiving messages.

The ferrite antenna of the receiving radio tag is fixed on the device board, which is connected to the miner's lamp (figure 3).



Figure 3. Radio tag card with antenna.

The antenna of the receiving device is implemented in the form of a ferrite core 49 mm long with a winding of copper wire containing 4000 or 8000 turns (figure 4).

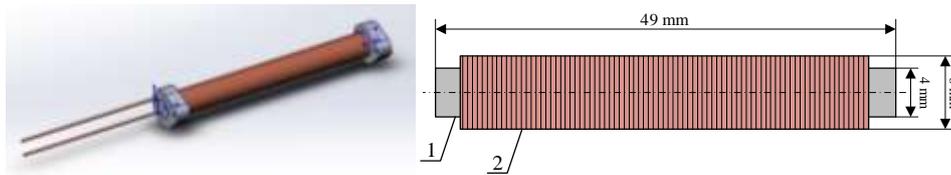


Figure 4. Receiving magnetic antenna: 1 - ferrite core; 2 - copper wire winding.

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

$$U = \omega \cdot \mu_0 \cdot H \cdot S_{eff}, \quad (6)$$

where $S_{eff} = \mu_{cor} \cdot S_{sec} \cdot n_{per}$ – receiving antenna effective area; μ_{cor} – magnetic permeability of the core depends on the magnetic permeability of the core material μ' , its length l and sectional area S_{sec} ; $\mu_0 = 4\pi \cdot 10^{-7}$ GN/m – vacuum permeability; n_{per} – the number of turns of the receiving antenna; H – magnetic field strength.

3. Results and discussions

3.1 Analysis of current density at the point of measurement

To analyse the nature of the distribution of currents in a half-space, it is necessary to set some parameters of the radiating antenna and medium. In the area of mines where coal and non-ferrous metals are mined, the average electrical conductivity of the medium is $\sigma = 10^{-2}$ S/m and the relative permittivity $\epsilon' = 10$. For the evaluation of the communication channel by the attenuation parameter, the transmitter frequency $f = 1$ kHz was chosen, which is not limited by the antenna size in the case of using a grounded cable on the surface of a mine field. The length of the grounded cable line is $L = 1500$ m. The antenna current is $J = 1$ A.

The structure of the streamline is determined by the expressions (1, 2) and has a complex configuration. Figure 5 shows three-dimensional structures of the current density distribution j_x (a) and j_z (b) at a depth of $z = 500$ – 800 m. The red line indicates the length of a grounded cable with current. The main difference in the behaviour of j_x and j_z current components is that the j_z component has a value of 0 under the centre of the current \vec{J} .

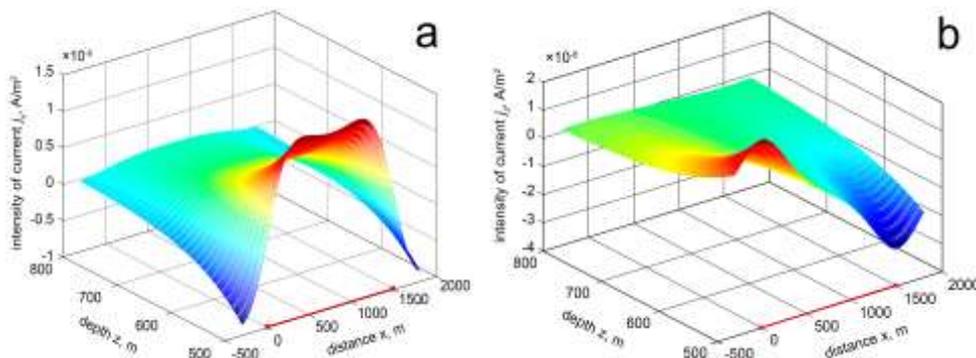


Figure 5. The current density distribution in the rock at a depth of $z = 500$ – 800 m: a – j_x ; b – j_z .

3.2. Numerical estimates

To assess the effectiveness of the communication channel, it is necessary to calculate the EMF at the output of the receiving antenna with the specified parameters at a depth of $z = 800$ m. We determine the magnetic field at point M (x_0, z_0) created by the currents J_x and J_z and also the antenna current \vec{J} , from which the total magnetic field is defined as:

$$H^x = -7,23 \cdot 10^{-7} \text{ A/m},$$

$$\begin{aligned}
 H^z &= -2,67 \cdot 10^{-8} \text{ A/m}, \\
 H_0 &= 6 \cdot 10^{-7} \text{ A/m}, \\
 H &= H_0 + H^x + H^z = -1,49 \cdot 10^{-7} \text{ A/m}.
 \end{aligned}$$

To register the signal in the task, a magnetic antenna is used with the following parameters:

Core length of the receiving antenna $l_s = 49 \cdot 10^{-3}$ m;

The diameter of the cross section of the core $d_s = 4 \cdot 10^{-3}$ m;

The cross-sectional area of the core $S_{sec} = 12,5 \cdot 10^{-6}$ m²;

$\mu_{cor} = 80$ – the magnetic permeability of the core is calculated from the magnetic permeability of the core material $\mu' = 700$ and relation of its length l to the section diameter d_s ;

The number of turns of the receiving antenna $n_{per} = 4000, 8000$.

The effective area of the receiving antenna S_{eff} constitutes 4.02 m² for 4000 turns and 8.04 m² for 8000 turns.

EMF at the output of the receiving magnetic antenna from the expression (6) at the cable current $J = 1$ A, $U = 4.73 \cdot 10^{-9}$ B for 4000 turns and $U = 9.45 \cdot 10^{-9}$ B for 8000 turns.

For current in the transmitting antenna $J = 15$ A, EMF at the output of the receiving magnetic antenna $U = 7.09 \cdot 10^{-8}$ B for 4000 turns and $U = 1.4 \cdot 10^{-7}$ B for 8000 turns.

4. Conclusion

Automation of a wireless security and alarm system using the presented antenna type and individual RFID tags is possible at a depth of up to 800 m. At a large depth of the radio tag, as well as in rocks with a high absorption coefficient of EM waves, to increase the signal level at the output of the receiving magnetic antenna, it is necessary to increase its effective area and increase the current level in the radiating antenna. In addition, it is possible to use noise-resistant methods of signal modulation and message coding. An analysis of the magnetic field shows that the currents flowing in the rock make the largest contribution to the total field, and not the current of the radiating antenna.

Acknowledgments

The work was supported by a grant from the Russian Science Foundation (project No. 18-79-00137).

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