A complex method for preventing collisions between mining equipment and personnel in mine conditions

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Abstract. The article provides an analysis of low-frequency and high-frequency methods for determining the distance between mobile equipment and personnel for the purpose of preventing collisions in difficult mine conditions. The authors assessed the influence of the geology of mine workings, the earth's surface and transport on the electromagnetic field of the VLF, LF and C range. From the analysis, a combined design solution was derived for determining the distance in surface and underground mining conditions. The proposed methods for registering the proximity of objects compensate for each other's vulnerabilities and make it possible to implement an integrated approach to preventing collisions of mining equipment with personnel.

1 Introduction

With the development of mining industries, the use of large-sized mobile equipment for mining, transportation and personnel transportation is also expanding. Despite technological advances in the mining industry, the industry remains a high-risk area with a high likelihood of accidents involving mining machines [1, 2]. These factors lead to an increase in the number of unintentional interactions between people and machines [3]. From this we can conclude that workers in some cases are not able to recognize a dangerous situation and assess the risks when moving around the mine and approaching mining equipment.

In many countries with developed mining industries, fatal accidents involving transport and mining machines occur in 16–48% [4]. The most common cause of injury to personnel is the impact of a piece of mining machinery on a vehicle (18%). Research [5, 6] shows that mining equipment is the main source of injuries in this industrial sector. The most common traumatic incidents involving equipment and personnel are:

- collision due to reverse movement of equipment;
- collision with the front side of the car;
- loss of control of mobile equipment;
- collision with other mining equipment.

With the development of Industrie 4.0 technologies, there is a decrease in accidents when introducing technologies into mining production. This made it possible to include in the mine

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infrastructure systems for wireless communication with personnel, positioning and tracking the path of equipment and workers, etc. This variability creates a need for a portable solution for collision avoidance in both surface and underground mines.

There are many devices available in the industry that are capable of identifying people, vehicles and their proximity on the surface. However, they have their own specific framework in conditions of limited mine space [7–11].

UWB (Ultra-Wide Band) technology is based on the Time-of-Flight (ToF) measurement algorithm and has low power consumption. Thanks to the wide frequency band, the UWB module is capable of transmitting short pulses, which makes the channel resistant to the multipath effect, however, in the absence of line of sight, it is possible to use only signals reflected from walls due to the operating frequency in the C-band. This remains an ongoing problem, leading to distance error, which is an important problem when approaching less than 15 m in a curved or obstructed environment.

Measuring the power or amplitude of a signal on an RSSI receiving device can be combined with signals based on low-frequency magnetic fields in the VLF and LF ranges, which are more resistant to reflection and absorption by rocks.

In the conditions of rocks with an electrical conductivity of 0.001÷0.1 S/m [12], the absorption and reflection of high-frequency EM waves from walls and their scattering remain relevant. If the person with the radio module is positioned outside the line of sight, such as an obstacle or turning into an adjacent tunnel, it may lead to loss of signal or incorrect data exchange between the mining equipment module and the miner module.

As an additional support for the proximity detection system at close range (< 30 m), it is proposed to use low-frequency magnetic fields (VLF and LF ranges), which are more resistant to the influence of rocks composing the walls and roof of tunnels. The authors assess the propagation of high-frequency and low-frequency electromagnetic waves in mine workings with the influence of freight transport using computational modeling methods.

2 Materials and methods

All methods for determining the proximity of vehicles to each other and to workers in underground mines are influenced by the rock and the metal body of the vehicle. Rocks are classified into several groups according to their burial depths and petrophysical properties [12]. The petrophysical properties of rocks are mainly divided into values of specific electrical conductivity σ in the range of 10^{-4}÷10^{-1} S/m, relative dielectric constant εr in the range of 2÷30. The relative magnetic permeability for most rocks is equal to 1, except for iron-containing and magnetic minerals [13].

Mobile types of equipment in mines mainly include transport for miners and load-and-haul vehicles for transporting rock. Thus, the bulk of mining dump trucks for mines have the following dimensions: length - from 6 m, width - from 1.5 m, height - from 2 m. The maximum speed is from 20 km/h. Most mining equipment and vehicles must move freely through a tunnel with a cross section of 4x4 m with an overall machine width of 2.7 m.

It is necessary to assess the influence of the walls of underground mines on the electromagnetic field of the C-band, as well as the VLF and LF range. When EM waves fall on an uneven surface, they are reflected in different directions, which creates a scattering effect, in which the intensity of the reflected wave is less than when reflected from a perfectly flat surface. Modeling using the finite element method allows us to determine the effect of turned mine walls on electromagnetic waves in high frequency ranges. This will make it possible to track the influence of electrical conductivity and dielectric constant of rocks on the propagation of EM waves in the workings [14]. To simplify the analysis, a two-dimensional case is considered. To analyze the propagation of high-frequency EM waves in a medium with complex geometry, a numerical solution of the equation is necessary:

$$\mu^{-1}\nabla \times (\nabla \times \boldsymbol{E}) - k_0^2\left(\varepsilon_r - \frac{i\sigma}{\omega\varepsilon_0}\right)\boldsymbol{E} = 0, \tag{1}$$

where $k_0 = \omega\sqrt{\varepsilon_0\mu_0} = \frac{\omega}{c_0}$ – wave number for air; μ_0 – magnetic constant; σ – electrical conductivity; $\nabla = \left\{\frac{\partial}{\partial x}, \frac{\partial}{\partial y}, \frac{\partial}{\partial z}\right\}$ – obla operator; E – electric field strength vector; ε_r – relative dielectric constant; ε_0 – dielectric constant; c_0 – speed of light; ω – angular frequency of EM field.

To describe the incidence of an electromagnetic wave on the boundary of a metal vehicle body, the transition boundary condition equations are used, designed to calculate the influence of thin shells:

$$\begin{cases} \boldsymbol{J}_{s1} = \dfrac{(Z_S E_{t1} - Z_T E_{t2})}{Z_S^2 - Z_T^2} \\ \boldsymbol{J}_{s2} = \dfrac{(Z_S E_{t2} - Z_T E_{t1})}{Z_S^2 - Z_T^2} \end{cases} \tag{2}$$

$$\begin{cases} Z_S = \dfrac{-i\omega\mu}{k}\dfrac{1}{tg(kd)} \\ Z_T = \dfrac{-i\omega\mu}{k}\dfrac{1}{sin(kd)} \end{cases} \tag{3}$$

where the indices indicate 2 sides of the thin layer; d – the layer thickness; $k = \omega\sqrt{\left(\varepsilon + \frac{\sigma}{i\omega}\right)\mu}$ – wave number for continuum; $\varepsilon=\varepsilon_0\varepsilon_r$ – absolute dielectric constant; $\mu=\mu_0\mu_r$ – absolute magnetic permeability; μ_r – relative magnetic permeability, μ_0 – magnetic constant; Z – medium impedance; J – surface current.

To simulate the propagation of a high-frequency electromagnetic field, a two-dimensional model of a mine working was created with a radiator in the form of a compact electric dipole installed on the front of the truck cabin. The dimensions of the model are indicated in the diagram (Fig. 1). The thin shells representing the walls of the machine have the properties of 3 mm thick steel. The rock is assigned the value \ μ=1, σ=[0.001; 0.01; 0.1] S/m, ε=5. The width of the mine opening is 4 m, the boundaries are smooth, there is a turn at an angle of 90º. The properties of the body of a miner located in the path of propagation of the EM field do not change: μ=1, σ=0.66 S/m, ε=60 [15]. The current flowing in the dipole I_0=0.05 mA, the study was carried out for frequencies f= [2.2 GHz; 6.5 GHz].

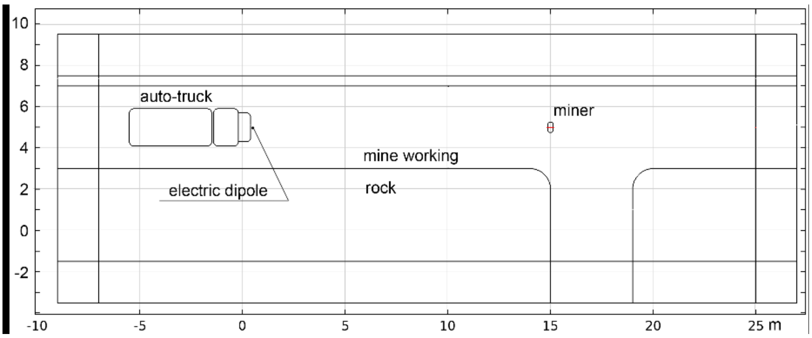
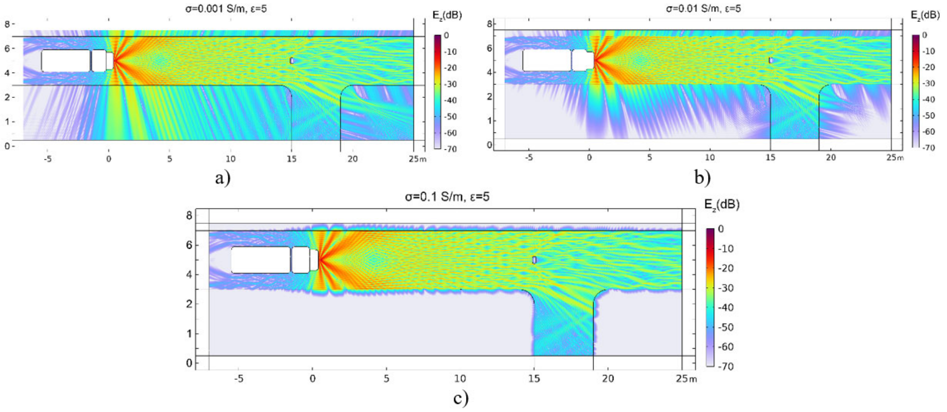


Fig. 1. Mine model diagram.

Figure 2 shows the distribution of the vertical component of the electric field E_z in the model at a frequency of 2.2 GHz. As the parameter σ increases, the depth of penetration of EM waves into the rock decreases. Thus, at σ = 0.001 S/m (host rocks), the level of E_z, refracted by the tunnel boundary, drops by 20–35 dB (Fig. 2 a). An increase in the electrical conductivity of rocks increases their absorption properties; with an increase in σ to 0.1 S/m, EM waves do not penetrate into the continuous medium and are almost completely attenuated at a depth of 20 cm (Fig. 2 c). Electrical conductivity within the range of 0.001÷0.1 S/m does not affect the refraction angle, nor does it affect the energy parameters of the reflected wave since this parameter depends on the dielectric constant of the medium. Interference minima and maxima are observed in the tunnel due to the superposition of waves due to their re-reflection from the walls and the phenomenon of multipath. There is also a reflection of the wave front from the front of the steel cabin, which causes the radiation energy to be directed directly in front of the vehicle. The rear of the vehicle remains in the blind spot, which requires the installation of at least two transmitting antennas - on the front and rear of the vehicle. After the wave passes through the human body, the amplitude E_z decreases at a distance of 0.2–1 m and stabilizes under the influence of diffraction and the superposition of waves reflected from the walls of the excavation.



a) b) c)

Fig. 2. Distribution of the electric component of the EM field in a mine working with fixed ε and varying electrical conductivity for a frequency of 2.2 GHz: a – σ=0.001 S/m; b – σ=0.01 S/m; c – σ=0.1 S/m.

The characteristics of reflected waves at the boundaries of the air and rock are calculated through an equation describing the impedance of the medium bordering the air:

$$\sqrt{\frac{\mu_0\mu_r}{\varepsilon_0\varepsilon_r-\frac{i\sigma}{\omega}}}n \times H + E - (n \cdot E)n = (n \cdot E_S)n - E_S. \tag{4}$$

where H – magnetic field vector; n – surface normal vector.

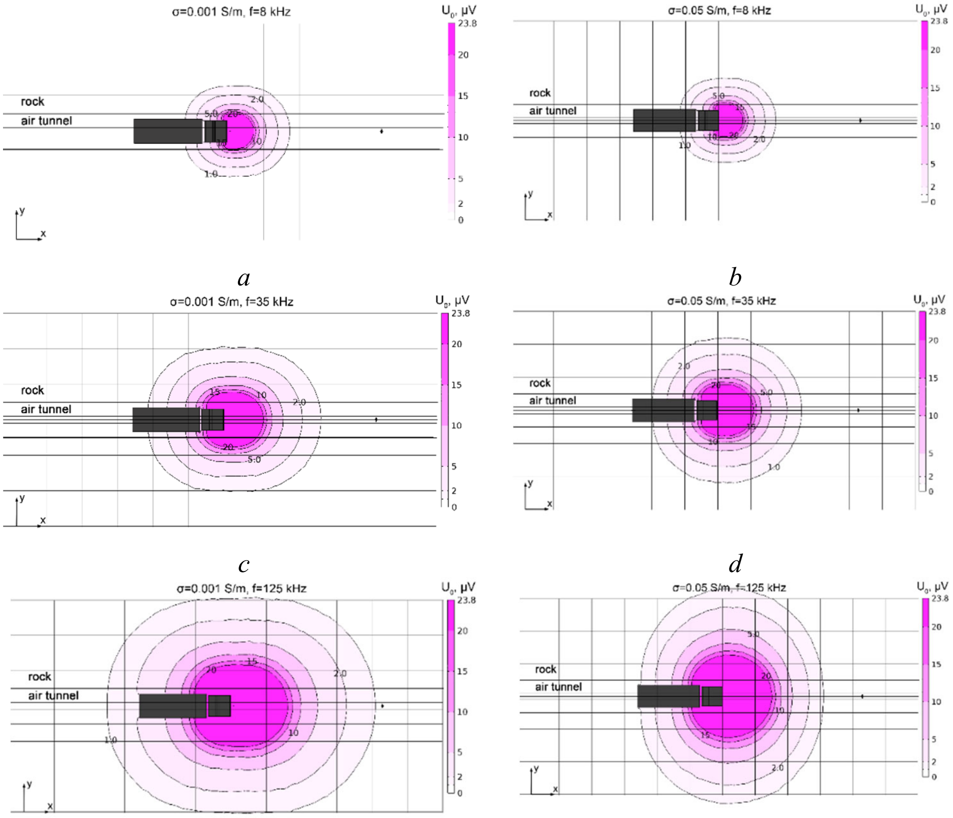
The value of the complex refractive index is determined as:

$$N = \sqrt{\frac{\mu\varepsilon_c}{\mu_1\varepsilon_1}}, \tag{5}$$

where μ_1 and ε_1 - magnetic and dielectric permeability of rocks; μ and ε_c - magnetic and dielectric constants of air.

To analyze the influence of rocks on the low-frequency magnetic field, a model of a rock section with an air tunnel of 5 × 5 m and a freight transport with a steel body with dimensions of 12 × 4.3 × 3.5 m was designed. A model of a magnetic beacon based on the ferrite core (magnetic permeability μ=700, number of turns n=10). The electrical conductivity of rocks varies in the range from 10^{-3} S/m to 0.05 S/m, the studied frequencies are 8, 35, 125 kHz, the current supplied to the magnetic antenna is 1 A.

At a frequency of 8 kHz in the considered conductivity range, the distortion of the signal level is insignificant and the error is less than 1 m (Fig. 3 a b). At a frequency of 35 kHz, with an increase in electrical conductivity to 0.05 S/m, a distortion of the magnetic field diagram is observed, the error reaches 1 m at a distance of 15 m (Fig. 3 b c). At a frequency of 125 kHz, with an increase in electrical conductivity to 0.05 S/m, the diagram shortens along the axis of the transmitting antenna (X-axis), the error reaches 5 m at a distance of 20 m (Fig. 3 d-f).



a *b*

c *d*

e *f*

Fig. 3. Distribution of the signal level when the magnetic antenna is located on the vehicle: a – XY plane, f=8 kHz, σ=0.001 S/m; b – XY plane, f=8 kHz, σ=0.05 S/m; c – XY plane, f=35 kHz, σ=0.001 S/m; d – XY plane, f=35 kHz, σ=0.05 S/m; d – XY plane, f=125 kHz, σ=0.001 S/m; e – XY plane, f=125 kHz, σ=0.05 S/m

3 Results and discussion

Based on calculated data, a comprehensive method for preventing vehicle collisions and collisions with personnel has been formed, combining high-frequency and low-frequency methods for determining the distance between the base station (beacon) and wearable tags for miners. The VLF/LF-band transport transponder is connected to transmitting antennas (installed outside the vehicle body in an amount of 2 to 4), thus providing the excitation of modulated electromagnetic fields penetrating through rocks (Fig. 4). The signal is received and decoded by a personal receiver, thereby allowing the determination of the distance from self-propelled equipment to personnel and the direction of approach. Using the high-frequency ToF algorithm, a distance of more than 30 m is determined, and service data and distance information registered on the worker's personal tag are also transmitted through this channel. At distances less than 30 m, the RSSI algorithm is used in conjunction with a low-frequency magnetic field, which is more resistant to rock influences for obstacles and turns. The amplitude of the envelope of the magnetic beacons on the machine is registered in the miner's personal tag. Based on the distance data, a decision is made to alert the worker about dangerous proximity using a sound signal and vibration. Also, distance information is transmitted via a 2.4 GHz return channel to the vehicle.

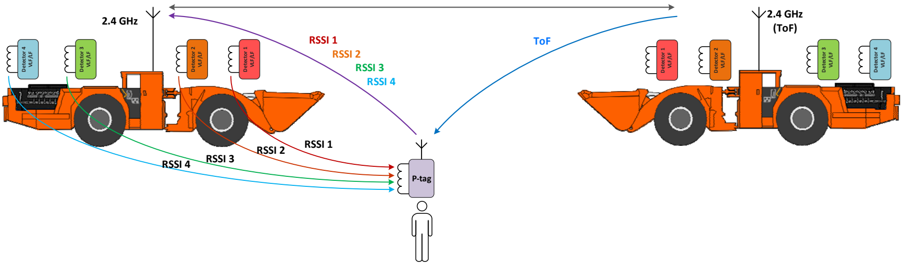


Fig. 4. System hardware structure.

A completed sample of transmitter equipment must be a modular device, which includes transmitting antennas, a control and data processing module, and a driver display module. The system assumes the following functions: control of transmission of signals from transmitting antennas; synchronization between transmitting antennas; collection of telemetric data; informing the driver about approaching personnel; light and sound indication of approach; indication of proximity and distance to personnel.

Operating functions of tags (must be included in software):

- measuring the distance in the "red" zone on the surface between UWB radio modules in point-to-point mode should be carried out using one of the ToF methods - TWR (Two-Way Ranging) with a guaranteed accuracy of measuring the distance between 2 devices no worse than 1 m;
- measurement of the distance in the "red" zone underground between detectors is carried out in the VLF range in the "point-to-point" mode and must be carried out using the RSSI method with a guaranteed accuracy of measuring the distance between 2 devices no worse than 1 m;
- organization of measuring the distance between all UWB radio modules within the radio visibility between them according to the "each with each" scheme:
- availability of software and hardware and interfaces for the future implementation of data transfer to the server.

4 Conclusion

A study of the propagation of low-frequency (VLF-, LF-band) and high-frequency electromagnetic (S-, C-band) waves in mine workings shows the need to combine these methods in such difficult conditions. These methods of registering the proximity of objects compensate for each other's vulnerabilities and make it possible to implement an integrated approach to preventing collisions of mining equipment with personnel. So, for long distances of 30-50 m, subject to direct visibility and small bends of the tunnel, it is possible to use the high-frequency range with appropriate distance determination protocols; this channel is also necessary for the exchange of data between workers and transport. The low-frequency method is resistant to the influence of rocks and makes it possible to recognize a moving vehicle outside the line of sight, which is important for the complex structure of mountain tunnels.

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