Surface Electromagnetic Wave-Based Wireless Communication System for Mines

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Abstract. The paper discusses the advantages and shortcomings of resonance and single-frequency single-wire induction communication systems for mines. The issues of creating a magnetic induction communication system based on the twin transmission line (the MIKON-Tel queuing system) and the prospects for using small antennas to arrange two-way communication channels through the rock have been considered. The possibility of creating a multichannel queuing system for subscribers, which operates in a wide frequency band using a twin induction transmission line and small ferrite resonator antennas, is shown. The antenna designs used for magnetic induction communication in mines have been considered. High level of radio frequency signals has experimentally been proven when using a twin line and small antennas. The specific signal attenuation along the route in the coal mine was 4 dB/km. The results obtained prove the fundamental possibility of designing multichannel induction communication systems with a guaranteed communication range of over 4 km from the base station.

1. Introduction
The issue of reliable and feasible wireless communication for underground mining enterprises (mines) still remains unresolved. Attempts to use communication standards originally developed for material media with a low electromagnetic wave attenuation decrement in mines are not feasible due to insufficient communication reliability and the impossibility of improving the mining safety with their help.

An important parameter of any communication system is the guaranteed operating distance between two correspondents. The guaranteed distance determines both economic indicators and the costs of further operation and vulnerability in emergencies.

A simple implementation of known standards and technical solutions in wireless communication does not ensure the guaranteed communication ranges attainable on the Earth's surface. In fact, the average line-of-sight distance in the mine is 100-200 m. Also, vehicles can move in the mines, which are non-radio transparent screens and additionally weaken the useful signal.

2. Relevance
Almost all currently known wireless communication solutions for mines come down to the application of one or another VHF wireless data transmission standard with the short intervals of arrangement of base stations connected to the switching center by fiber optic or HF cables or wireless serial
connection of base stations [1]. Also, a solution of a VHF radiating cable communication system is used, which also requires installing a lot of signal repeaters-amplifiers connected to an expensive radiating cable [2].

Herewith, since the 80s-90s of the last century, induction coupling in the medium-wave frequency band has not been properly developed. The induction or one-dimensional surface wave communication range in the mine is up to several kilometers. But these induction systems had disadvantages such as bulky antennas inconvenient for subscribers and a single-channel dispatch mode. To develop induction communication systems, two problems had to be solved: creating small antennas for use as part of subscriber transceivers and developing the principles of multichannel communication that allowed serving many subscribers.

The examples of the current state-of-the-art in induction systems are the American development under the US patent No. 4777652 [3] and the Russian VEBR system [4]. Figure 1 shows the magnetic antennas used in the form of vests for a miner in the American development.

![Figure 1. Induction Communication Antenna as a Miner’s Vest.](image-url)

Such a flexible antenna on the human body is not an optimal option since a flexible design will be an unstable oscillatory circuit with constantly changing inductance parameters.

The VEBR system also uses a flexible magnetic antenna in the form of a belt on the human body.

In the American system, a one-dimensional surface wave is excited in a single-wire line using a transmitter-cable matching device in the form of an opening toroidal magnetic core with a winding, through which the excited cable is passed. A feature of such matching devices is that they operate in a resonant mode and are narrowband, which limits the development of multichannel induction communication systems in mines.

Thus, the current state-of-the-art of single-wire induction mine communication systems ensures the maximum operating distance in the mine of about 1...3 km for all systems; the technique is single-frequency and requires inconvenient and bulky antenna systems.
3. **Research objective**
To ensure feasible technical activity and safety and monitor the personnel actions in mines, a communication system with the below properties is required:
- at least 3 km guaranteed distance of two-way data transmission from the miner to the base station (the length of the haulage roadway and airway to the cut face),
- the ability to ensure communication with miners and equipment in the face,
- simple installation and maintenance of the communication lines,
- the possibility to search for miners under the rock-falls,
- survivability of individual system segments in the case of an accident and guaranteed provision of emergency two-way communication channels with the surface in the case of any mine segment isolation.

4. **Developing a specialized mine communication system**
The communication channel bandwidth of several kHz of the induction communication systems allows transmitting voice messages, control commands, and telemetry data to almost any mine equipment, except for the video surveillance systems. The high operating distance at a low radio transmitter power of 1...5 W and the independence of the communication range from the subscriber’s line-of-sight conditions makes the induction systems promising, provided that below two technical problems are solved:
- creating and using a small antenna that can be placed in the battery unit of the miner's lantern,
- developing a solution for multichannel inductive communication.

These two tasks turned out to be related.

The disadvantage of the previous generation of induction systems based on a single wire is the uneven coverage of the mine section with a useful signal. The amplitude of the magnetic field of a single conductor laid along the mine side rapidly decreases to 30 dB at the opposite side of the opening. Figure 2 shows the dependence of the magnetic field of the signal in the single-wire and twin lines in the mine section plane. The magnetic field of a single current-carrying conductor is determined by the formula:

$$ B = \frac{\mu H I}{2\pi r}, $$

where $\mu$ is the magnetic permeability, H,
I is the current induced in the conductor, A,
$ r $ is the distance from the conductor to the receiving point, m.

![Figure 2. Distribution of the Amplitude of the Magnetic Field of the Single-Wire (1) and Twin (2) Transmission Lines in a Plane Perpendicular to the Direction of a 5 m Wide Mine Opening.](image-url)
The big practical disadvantage of single-wire induction lines is that the second wire for this system is the ground one, and any conductive objects in the mine such as metal supports, meshes, and even puddles and water spills lead to losses. The location of a single-wire line near grounded pipes or in water may cause significant losses. In such a situation, a capacitive coupling of the line with the ‘obstacle’ is formed, and the single-wire line current drains to the ground. When passing such an ‘obstacle’, the signal loss may exceed 10 dB.

The only disadvantage of a twin system is that it is twice as expensive as a single-wire one, and the advantages are:
- the possibility to match the transmitter with the line in a wide frequency range,
- a more uniform useful signal distribution in the mine section,
- low specific radio-frequency signal attenuation along the twin line,
- a high line impedance of 600-800 Ohm and low ohmic losses.

Due to these advantages, the most simple and optimal technical solution is the use of a twin induction line in the development of a promising mine communication system.

Small antennas are a key issue for any low-frequency radio system. The developers proposed a resonant magnetic transceiver antenna with a ferrite core and a linear dimension of 10 cm max. and a transmitter power of 1 W max. so that the antenna’s ferrite core does not saturate. Accordingly, the operating distance in the mine would be determined by the maximum transmitter power of 1 W, the ability of such an antenna to induce a signal in a twin line, and the linear signal attenuation, which was to be verified in the experiment.

To implement transport communication channels in the standard mode, multichannel base stations of the induction system are connected to Ethernet points, and the switching center is installed in the mine office on the surface.

Communication with miners and equipment in the face can be provided by installing an additional mobile base station at the face, connected to the main base stations via a transport channel in the MW band and to a single-wire induction line, whose function is performed by the face lighting cable, through a matching device.

In the case of an accident, emergency wireless communication channels between the base stations and the surface should be arranged so that even the system segments cut off from the rest of the mine by the accident can transmit control commands to miners and equipment, and the ‘surface’ get real-time data on the accident. The bandwidth requirements for these communication channels can be much lower. The very fact of the possibility of exchanging critical data is important to eliminate the accident and rescue the personnel.

As the experience of using Russian low-frequency mobile transmitters for the mine rescue and speleological communications FERRA L1 [5] at a frequency of 1 MHz and a power of 5 W has shown, small antennas can transmit radio-frequency signals horizontally through the rock to a distance of 700-1,000 meters. The top-down mode is especially difficult for transmission through the rock since the signal passes through several rock layers with different conductivity and dielectric constant, which leads to high losses. Also, the mine is often reinforced with metal mesh. This leads to screening the resonant antenna’s near-zone electric field. If an electric antenna is used in a mine, it allows only induction coupling along the cables, and the radio wave cannot form and expand beyond the opening screened by a metal mesh. In the same way, electric antennas do not allow communicating from the ground surface with any objects in the subway which is a concrete structure with shielding steel reinforcement. When developing high-quality resonant magnetic antennas, the field of which is much less screened, the tuning capacitor breakdown problem arises, due to which the known solutions apply expensive vacuum or dielectric capacitors and have large weight and size characteristics [6]. Therefore, to solve the issue of arranging communication channels within 0.1-1 MHz through the rock under the conditions of partial shielding with metal meshes, a small antenna named ‘Spiral’ has been developed [7], which has both electric and magnetic field components and does not require a variable capacitor for resonance tuning.
5. Practical implementation and experimental testing the solutions
As part of the study, a field experiment was performed in the Polysaevskaya coal mine in the Kemerovo region. A 3 km twin line was installed. The line wires were laid along the mine sides.

The experiment objective was to get data on the specific radio-frequency signal attenuation when laying a twin line in a coal mine and determine the level of the radio-frequency signal induced by the twin transmission line in a small resonant magnetic ferrite antenna. This size of the small antenna was chosen as acceptable to arrange subscriber terminals for miners. The antenna was made on a ferrite core with a magnetic permeability of 400 and had the dimensions of 10x10x100 mm. FERRA L1 radio stations with a power of 1 W at a frequency of 1 MHz were used as transceivers. The stationary radio station was connected to the twin line through a step-up transformer.

In the coal mine, the average attenuation of the specific radio-frequency signal along the route equal to only 4 dB/km was got with the twin line at a frequency of 1 MHz. The irregularity of covering the mine section with the twin line magnetic field was 15-18 dB, which coincided with the theoretical data.

The level of the radio-frequency signal from the generation center (at the minimum signal point) transmitted from a subscriber with a small ferrite antenna at a distance of 3 km to a stationary radio station connected to the twin line was about 70 μV.

At the Malyshevsky mine in the Sverdlovsk Region, Spiral antennas were tested using FERRA L1 radio stations for emergency communication at a frequency of 1 MHz and a signal power of 5 W. The antennas ensured reliable reception and transmission of SMS messages from a depth of 150 m. Communication with a subway station in Omsk was also tested. The Spiral antenna provided voice communication with a shielded reinforced concrete object in the ‘subway-surface’ mode.

The antenna size of 1...1.5 m allows conveniently using it in the mines, e.g., placing it next to the collective rescue point (CRP) in the rock space. The efficiency of such antennas measured by the calorimetric technique ranges from only a few to twenty percent, and the figure of merit can reach 500-700 units. The antenna has a high electrical resistance. The maximum tested signal level fed to the antenna was equal to 100 W.

Based on the data obtained, a technical task was set to develop a specialized multichannel induction communication, navigation, telematic system [8] with small communication terminals for miners and base stations serving up to 4 physical directions (mine openings) via 24 digital communication channels simultaneously.

Based on the experiments and calculations, to ensure guaranteed voice communication and meet the requirements of industry regulatory documents for monitoring the subscriber conditions and his immediate environment in the coal mine, at a distance of up to 4.5 km from the base station, a signal power of 0.1-1 W was chosen for the subscriber terminals with a data transmission rate of up to 6 kbps and 0.1 W per channel for a base station with a maximum power of up to 10 W.

The MIKON-Tel system ensures:
- the possibility of providing communication with the moving face,
- arranging independent transport channels between the base stations in the case of an emergency and the lack of Ethernet signal,
- the possibility of providing the emergency low-speed two-way mine-surface communication channels to arrange the communication of mine segments cut off, e.g., by a rock fall.

To ensure communication with miners and equipment in the face, a special device has been developed for connecting to single-wire lines [9, 10], which, along with a portable base station (BS), is installed at the end of the roadway, and the BS is connected to the lighting network in the face using a matching device. In contrast to the American solution [3], our device operating principle is based on capacitive coupling with a transmission line instead of an inductive one. This greatly improved the operational capabilities of the communication device. Under the mine conditions, it can be very difficult to open the magnetic core of the matching device and pass the excited cables through it. In the modern solution, to excite the line, a small 5-10 m piece of wire coming out of the matching and
connection device is laid next to it. Such a device is easy to install, carry to another place, and dismantle.

6. Conclusion

Induction coupling in mines uses one-dimensional surface electromagnetic waves (SEW). Radio systems using two-dimensional SEW are known [11]. They are used for communication and location over the sea surface. Here, the surface radio wave spreads at the interface between the two media, and its attenuation is up to 3 dB per octave without considering the electromagnetic energy dissipation. This is its main difference from a bulk radio wave, the attenuation of which in free space is 6 dB per octave.

One-dimensional SEW is ideal for signal propagation in mines and tunnels, which are one-dimensional objects. In the absence of electromagnetic energy dissipation, one-dimensional SEW does not weaken during its propagation. With a one-dimensional SEW, electromagnetic energy will dissipate in dispersive media—supports, puddles, and other conductive obstacles. However, it has been experimentally established that when using a twin SEW line, such an attenuation of the radio-frequency signal is minimal and equal to only 4 dB/km for coal mines. This value of the specific radio-frequency signal attenuation turned out to be less than in most radio frequency cables. When using twin SEW lines in dry mines (e.g., potash ones), the specific radio-frequency signal attenuation associated with energy dissipation will be even less, and the area served by a single base station larger.

At a base station signal power of 0.1 W and a specific attenuation of 4 dB/km, base stations connected directly to the linear waveguides will confidently receive each other's signals at a distance of even over 20 km. This property allows making the communication system independent of Ethernet transport channels and arranging the transport channels in the MW electromagnetic wave band using the phenomenon of surface propagation of radio waves.

A particularly important characteristic of the mine communication systems is their survivability and the ability to provide two-way data transmission channels in an emergency, when some lines and cables are destroyed, and the system integrity is violated.

Figure 3 shows the structure of a prospective mine communication induction network with an ability of two-way communication through rocks.

![Figure 3. The Mine Induction Communication Network Structure.](image-url)
Along with technical parameters, one of the most important indicators is the telecommunications system cost. A preliminary economic assessment of the induction system based on one-dimensional SEW has been performed in comparison with the well-known VHF communication standards used in the mining industry. The comparison is given in Table 1. The radiating cable system indicators were taken as 100 %.

Table 1. Economic Comparison of the Mine Radio Communication Systems.

| System/Cost     | Cost of 1 km of Underground Equipment, % | The Entire System, % |
|-----------------|------------------------------------------|----------------------|
| Radiating cable | 100                                      | 100                  |
| Wi-Fi           | 178                                      | 155                  |
| Nordic          | 88                                       | 83                   |
| ZigBee          | 54                                       | 60                   |
| NanoLOC         | 47                                       | 54                   |
| Inductive MIKON-Tel | 18                           | 33                   |

In conclusion, it can be noted that a communication system with a twin SEW line is optimal for mining enterprises to arrange the production control in terms of economic indicators and survivability in an emergency. Soon, a Russian equipment will be created and produced on the mass scales for the underground navigation and communication subsystem, ensuring remote, automated, and automatic control over, e.g., fire and rescue robotic vehicles and complexes at mining enterprises.

7. References
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