Advanced MF antennas for underground communications

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Abstract. The paper considers the features of underground radio communication at medium frequency (MF) range. The perspective and most effective antenna solutions at MF range are presented. The characteristics of the antennas are given: the reflection coefficient, the dependence of the input impedance. Antennas are matched with voltage standing wave ratio (VSWR) less than 1.2. Attention is focused on some features of the operation of these antennas. The results of comparative tests of antennas are presented.

1. Introduction

Underground mine workings are horizontal or inclined tunnels with an average diameter of 3 to 20 m, located under the surface of the earth at a depth of tens and hundreds of meters. They often have multiple horizons. For interaction between personnel, transmission of information about the work performed and the condition of the equipment, as well as in the event of emergency situations, it is necessary to organize communication channels. The search for possible options for their implementation was carried out over several decades in various ranges; reviews of these works are presented in [1-8].

Communication equipment inside mines can be divided into several categories according to the principle of physical implementation of the communication channel:

- wire communication systems,
- leaky feeders at very high (VHF) - ultra high (UHF) frequencies ranges,
- through-the-air radio communication at VHF-UHF ranges,
- communication through monofilar waveguide lines at MF range,
- systems for the transmission of alerts and text messages at extremely low (ELF) - very low (VLF) frequency bands,
- other systems at the research stage (optical systems, etc.).

Wired communication channels include wired telephone or video communication, Ethernet communication over twisted pair, coaxial, optical lines. Such systems make it possible to organize a reliable communication channel from a stationary point, but limit the mobility of personnel.

Another type of wire communication is channels with a VHF-UHF leaky feeder, in which a special feeder with technological radiating gaps is used. Due to radiation along the entire length, it is necessary to install amplifiers in the line every 300-500 m. Due to their disadvantages: complexity of maintenance, low energy efficiency, small coverage of the face, these systems have lost their promise in comparison with other solutions.
In wireless radio communication VHF-UHF tunnels are used as hollow waveguides with different tilt angles, different transverse dimensions, bends, inhomogeneities, including stationary equipment, moving vehicles. The communication channel at the indicated frequencies is mainly organized at line-of-sight distances. Because of this, a large number of multiple reflections occurs, which requires the use of directional antennas and frequent repeaters.

Since mining operations are associated with the likelihood of emergencies, such as roof collapse, fires, explosions, the stability of communication in such situations is of great importance, which means increased requirements for the quality of communication. The rupture of the supply feeders in an accident leads to the inoperability of equipment in the cut off section of the mine. Thus, wire communication, emitting feeders, VHF-microwave systems cannot ensure reliability and safety in emergency situations.

The ELF-VLF bands have been selected to provide emergency through-the-earth communications (TTE) in emergency situations. Such systems make it possible to provide communication to a depth of several tens, hundreds, and even thousands of meters, depending on the geophysical features of the rock mass. The possibility of deep communication through the rock is associated with less attenuation of the signals of low-frequency fields in natural environments compared to a high-frequency field (Figure 1). At the moment, two types of TTE communication are being developed and used: based on magnetic antennas (see [9-11]) and electrode antennas (see [12-13]). Magnetic communication allows a high-quality organization of the channel from surface to underground: the antenna on the surface is rarely limited in size and input power, while magnetic sensors of high sensitivity can be used for reception at the bottom. The bottom-up channel is much more difficult to organize due to the limitations on the input power and the size of the loop antenna placement. At the same time, placing a loop antenna on a large perimeter is also associated with the likelihood of breaking its canvas. To ensure sufficient efficiency, electrode antennas require the location of the electrodes at a distance of several tens of meters from each other, which is also associated with the likelihood of breakage, and their use is not allowed in coal mines.

![Figure 1. TTE-communications at different points.](image)

The development of communication systems at frequency range 100 kHz ÷ 10 MHz is promising. Radio waves at these frequencies travel hundreds of meters through rocks. A communication channel based monofilar (or bifilar) line can also be implemented, in which a traveling wave is excited and received by a contact or contactless method (Figure 2). For this, both special stationary equipment and portable radio stations can be used. The first works in this direction were carried out in 1970-80 [2, 14-16]. The connection between subscribers, depending on the distribution conditions, reaches several kilometers. In this case, both specially laid conductors and “random” conductors - wire communication cables, equipment power cables, metal pipes - can be used as a line, and their own functional purpose does not change. This effect allows for extremely efficient communication even on different horizons, in which the same cable is laid.
In equipment for organizing wireless radio communication at MF range in mines and pits, one of the key elements is a small-sized antenna, the efficiency of which largely determines the quality and range of radio communication. Progress in the field of digital technologies makes it possible to minimize the size of radio stations, however, the problem of reducing the efficiency of antenna equipment with a decrease in size at the indicated frequencies remains open [17]. The peculiarities of the arrangement of underground objects impose restrictions on the dimensions of the antenna equipment. The optimal dimensions for portable devices are less than 0.5 m, for stationary ones - no more than 1.5 m. Thus, the antennas used have ultra-small wave sizes.

The purpose of this work is to present the characteristics of the most effective and promising MF antennas for underground radio communications.

2. Antenna characteristics.
In this work, the characteristics of several antennas are presented (we will conditionally denote by numbers):
- Ant1: portable electric antenna Ferra, designed according to a patent for invention [18], center resonance frequency $f_R = 1$ MHz, has electromechanical control with automatic regulation at the range of 950÷1050 kHz with SWR <1.2;
- Ant2: portable electric antenna Ferra, designed according to a patent for invention [18], center resonance frequency $f_R = 1.9$ MHz, has electromechanical control with automatic regulation at the range of 1900÷2000 kHz with SWR <1.2;
- Ant3: experimental model of a portable antenna, designed according to a patent for invention [19] with a maximum size of 0.45 m, $f_R = 1$ MHz, adjustable at the range of 950÷1050 kHz with SWR <1.2;
- Ant4: experimental model of a portable antenna, designed according to a patent for invention [19] with a maximum size of 0.45 m, $f_R = 1.9$ MHz, adjustable at the range of 1900÷2000 kHz with SWR <1.2;
- Ant5: experimental model of a stationary antenna, designed according to a patent for invention [19] with a maximum size of 1.2 m, $f_R = 1$ MHz, adjustable at the range of 950÷1050 kHz with SWR <1.2.

Figure 3-a shows Ant1, the dimensions of which are 550 × 35 mm, excluding the cable length, Ant2, with dimensions of 490 × 35 mm. Figure 3-b shows Ant3 and Ant4 with dimensions 450 × 370 mm. Figure 3-c shows Ant5 with dimensions 1200 × 1200 (1500) × 15 mm.

Ant1 and Ant2 are commercially available antennas; like radio stations Ferra, they have two versions: standard and explosion-proof. Ant3-Ant5 - promising solutions for resonant helical antennas.

Figure 4-a and 4-b shows the dependences of the modulus of the reflection coefficient $|p(f)|$ for Ant1, Ant3, Ant5 and Ant2, Ant4, respectively. Figure 5 shows the measured dependences of the components of the input impedance of the antennas at the region of ± 50 kHz on the resonance frequency $f_R$: $R (f)$, $X (f)$, $Z (f)$. It can be seen from the graphs that some antennas have a slight displacement of reactance to the inductive (Figure 5-b,c,e) or capacitive (Figure 5-a,d) region. This offset is insignificant, and the antenna tuning should be considered good.
Figure 3. MF antennas appearance.

Figure 4. The reflection coefficients of the antennas.

Figure 5. The input impedance of the antennas.
3. Experiments results

The structure of the rock in which the excavation is laid can vary depending on the geography and depth of passage of the earth strata. It can be marl, limestone, clayey rocks with varying degrees of moisture, which are characterized by different values of the dielectric constant $\varepsilon'$, ranging from units to several tens. The nature of this rock determines the depth and range of communication in the mine. The communication range confirmed by the protocols in the transmission mode of digital signals with PSK31 modulation in the BKPRU-2 potash mine is 1200 m through the rock without metal guides (Figure 3) with Ferra radio stations and Ant1 antennas at both ends of the radio link at a transmission power of 5 W. The antennas have been tested under various conditions. In this case, voice communication over metal monofilar lines was provided up to 3 km (Figure 6).

![Figure 6. Non-filar technique of communications.](image)

The mine workings are often reinforced with metal mesh. This leads to screening of the electric field in near-zone of the resonant antennas. Since Ant1-Ant2 are electric type antennas, in such mine workings only induction coupling along the cables is possible, and the radio wave cannot form and go beyond the workings bounded by a metal mesh. In the same way, being on the surface of the earth, using Ant1-Ant2 it is impossible to communicate with objects in the gallery which is a concrete structure with shielding iron reinforcement. When developing high-quality resonant magnetic antennas, the field of which is much less screened, the problem of tuning capacitor breakdown arises, which is why the known solutions have expensive vacuum or dielectric capacitors and large weight and size characteristics [17, 20]. Therefore, Ant3-Ant5 were developed, which have both electric and magnetic field components, which do not require a reactive element for tuning into resonance. The antennas were tested in Omsk metro tunnels and at the Malyshovsky mine. For the first time, positive results were obtained on communication with underground objects from the surface through the rock in the mode of transmitting digital PSK31 modulation signals. Ant3-Ant5 have greater weight and size characteristics than Ant1-Ant2, so the optimal use of this solution is in stationary or portable equipment. Table 1 shows the characteristics of the tested antennas.

![Table 1. Antennas characteristics](image)

| Antennas | VSWR at the resonance frequency | Relative bandwidth $f/\Delta f$ for VSWR = 2 | Quality $Q_A$ from $|p(f)| = 0.5$ |
|----------|--------------------------------|---------------------------------|---------------------------------|
| Ant1     | 1.05                          | 60                              | 20                              |
| Ant2     | 1.07                          | 70                              | 23                              |
| Ant3     | 1.04                          | 357                             | 128                             |
| Ant4     | 1.04                          | 470                             | 150                             |
| Ant5     | 1.1                           | 476                             | 146                             |

At the moment, antennas are known on the market in the form of a flexible conductive harness that is worn on the user. Such a device is proposed in the patent [21]. In this way, a loop antenna is obtained, the disadvantages of which are the constant detuning of the resonant frequency from the operating frequency and high losses in the human body directly adjacent to the antenna. Comparative tests have shown that their effectiveness is more than an order of magnitude lower.
4. Conclusion
Among the antennas considered, the serially produced Ant1-Ant2 are the best solutions for organizing communication of mobile users inside an underground facility, for example, for mine rescuers. Ant3-Ant5 is perspective solutions and it’s optimal for stationary use, for organizing a two-way TTE communication channel. The organization of such a channel is especially relevant for communication with points (cameras) of collective rescue of personnel in the event of an emergency.

Thus, the results of the development of antenna technology at MF range make it possible to solve the problem of two-way communication with underground facilities, which is necessary in emergency situations.

References:
[1] Murphy J N and Parkinson H D 1978 Underground mine communications Proc. IEEE 66 26-50
[2] Ranjan A, Sahu H B and Misra P 2015 Wave propagation model for wireless communication in underground mines 2015 IEEE Bombay Section Symposium (IBSS)
[3] Einicke G, Dekker D, Hainsworth D. 1997 A review of underground communications systems Technology Exchange Workshop in Coal Mine Productivity Underground Mining Methods and Communic. Systems, NEWCASTLE, 3rd & 4th December
[4] Yarkan S, Guzelgoz S, Arslan H, Murphy R 2009 Underground mine communications: a survey IEEE Commun. Surveys & Tutorials 11 125- 42
[5] Forooshani A E, Bashir S, Michelson D G, Noghanian S 2013 A survey of wireless communications and propagation modeling in underground mines IEEE Commun. Surveys & Tutorials 15 1524-45
[6] Patri A, Nayak A, Jayanthu D S 2013 Wireless communication systems for underground mines – a critical appraisal Internat. Journal Engin. Trends Technology (IJETT) 4 3149-53
[7] Hrovat A, Kandus G, Javornik T 2014 A survey of radio propagation modeling for tunnels IEEE Commun. Surveys & Tutorials 16 658-69
[8] Mulenga S, Besa B, Mazimba C 2020 Mines safety and accident communication system for underground mine OSF Preprints doi:10.31219/osf.io/bv9qr
[9] Jong E C, Schafrik S J, Gilliland E S 2016 A preliminary evaluation of a through-the-earth (TTE) communications system at an underground coal mine in Eastern Kentucky Mining Engineering 68 52-57
[10] Carreno J P, Silva L S, Almeida Nevis S O, Aguayo L, Braga A J, Barreto A N and Uzeda Garcia L G 2016 Through-the-earth (TTE) communications for underground mines Journal Commun. Informat. Systems 31 164-76
[11] Liu Y, Wang Q, Liu X, An Z, Pan R and Liu J 2020 Research on intrinsic-safe through-the-earth radio communication system technology with large depth 12th Internat. Conference on Commun. Software and Networks (ICCSN) 124-28
[12] Yan L, Zhou Ch, Reyes M, Whisner B and Damiano N 2020 Mathematical modeling and measurement of electric fields of electrode-based through-the-earth (TTE) communication Radio Scince 52, 731–42 doi:10.1002/2016RS006242
[13] Hao J, Mou Y and Yan B 2017 Impact of rods configuration on electrodes impedance of through-the-earth communication system International Journal of Hybrid Information Technology 10 101-10
[14] Dobroski H Jr, Stolarczyk L G 1973 A Whole-Mine Medium-Frequency Radio Communication System (Bureau of Mines U.S. Department of the Interior) 124-36
[15] Lagas R L, Curtis D A, Foulkes J D, Rothery J L 1977 Transmit Antennas for Portable VLF to MF Wireless Mine Communications (USBM Contract Final Report (H0346045) Task C, Task Order No. 1)
[16] Kenneth Sacks H, Chufo R L 1978 Medium-frequency propagation in coal mines Proc. of the Fourth WVU Conference on Coal Mine Electrotechnology, Aldridge-MD 27-1-12
[17] Hansen R C 2006 *Electrically Small, Superdirective, and Superconducting Antennas* (Wiley-Interscience)
[18] Fedosov D V, Khorvat V N, Korneev D A. Patent RU 2488927 H01Q9/18 *Tunable Resonant Antenna with Matching Device* 2013-07
[19] Fedosov D V, Kolesnikov A V, Nikolaev A V Patent RU 2680674 H01Q9/04 *Resonant Spiral Antenna* 2018-03
[20] Rothammel K and Krishke A 2011 *Encyclopedia of Antennas* (Moscow: DKM Press)
[21] Stolarczyk L G, Raton N M Patent US 4777652A *Radio communication systems for underground mines* 1982-07-27.