İSTANBUL UNIVERSITY CERRAHPAŞA

ORIGINAL ARTICLE
Electrica 2025; 25: 1-8

Compact Antenna for Through-the-Earth Mine Communication

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Cite this article as: A. K. Tiwary, R. S. Singh and V. R. Gupta, "Compact antenna for through-the-earth mine communication," *Electrica*, 25, 0144, 2025. doi: 10.5152/electrica.2025.23144.

WHAT IS ALREADY KNOWN ON THIS TOPIC?

- *This research paper addresses the various challenges of underground mine communication systems, specifically through-the-earth (TTE) communication, which uses radio signals to transmit information between the surface and underground sites. It also references various models that aim to better understand and improve electromagnetic field propagation in mine environments.*

WHAT DOES THIS STUDY ADD ON THIS TOPIC?

- *The proposed Archimedean spiral antenna offers a promising solution for TTE communication in deep mines by combining size reduction with improved performance, making it a practical alternative to conventional loop antennas.*

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Received: February 2, 2024
Revision Requested: March 26, 2024
Last Revision Received: November 24, 2024
Accepted: December 13, 2024
Publication Date: January 22, 2025

DOI: 10.5152/electrica.2025.23144

ABSTRACT

This research paper presents a planar Archimedean spiral antenna design for through-the-earth (TTE) mine communication. A study has been conducted to analyze the effect of factors such as depth, radial distance, loop antenna current, loop antenna radius, and conductivity of earth on TTE communication. The larger the radius of the loop antenna, the lower the frequency, the decrease in radial distance from the loop, and the increase in depth leads to a stronger magnetic field. As the loop current increases, signal strength increases. Lower conductivity allows a more extended range. Based on the study, the Archimedean spiral antenna is proposed to offer improved magnetic field strength over the conventional loop antenna while maintaining a lower thickness profile. The results demonstrate that the antenna size can be decreased without sacrificing performance by switching from a traditional loop antenna to a planar Archimedean spiral antenna. The suggested antenna offers a 50% size reduction compared to the standard single-turn loop antenna. Additionally, comparisons between the reported measured findings and the simulated outcomes are made.

Index Terms— Loop antenna, magnetic field, mine, skin depth, through-the-earth (TTE)

I. INTRODUCTION

Due to the presence of toxic, explosive gases and hazardous situations that endanger the safety of the workers, underground mines are challenging workplaces. Therefore, it becomes necessary to provide a reliable communication system connecting different underground sites to the surface to rescue the underground coal miners in an accident. Through-the-earth (TTE) communication systems, in which the radio signal passes directly through the mine, establish a link between the surface and the underground mine using soil as a propagation medium. In these systems, the radio signal travels straight through the mine. The skin depth, which measures the penetration depth, is defined by

$$Skin\ depth\ (\delta) = \frac{1}{\sqrt{\pi f \mu \sigma}} \tag{1}$$

where μ and σ are the permeability and conductivity of the material, respectively. Equation (1) demonstrates that the skin depth is inversely related to the square root of the material's frequency, conductivity, and permeability. This implies that at higher frequencies and/or higher conductivities, the skin depth will be smaller, and the electromagnetic field will be concentrated closer to the surface of the earth. Additionally, the earth's conductivity causes radio frequency (RF) signals to propagate with significant attenuation. To overcome the attenuation, frequencies below 10 KHz are employed with magnetic induction transmission [1].

Since the transmission is done at a lower frequency, there is a trade-off between the transmission rate and the range. Signal strength and battery power cannot be increased above a certain threshold because doing so may ignite a methane–air mixture, resulting in an explosion and fire hazard. Low-frequency antennas are electrically small and have very low radiation efficiency. Their size is increased to achieve greater radiation efficiency. However, the designer must not compromise their portability and must design the antenna considering the geometry of the mine.

The signal's power is diminished by the sixth power of the distance and a cubic meter of distance as it moves through space [2]. The infrastructure of the mine and the type of overburden vary from location to location depending on the type of mine. Mines with the higher conductivity will offer a lower range. The transmission line, motors, lightning, and generators produce low-frequency noises that interfere with TTE communication. A signal can be identified from these disturbances and received better by ensuring the signal level is higher than the noise level. The noise source's impact can be reduced by using filters, amplifiers, and digital processing methods. The most used microstrip patch antennas and dielectric resonator antennas [3-7] are not suitable due to the electrical behavior of the earth and the lower operating frequency.

Through-the-earth systems can be divided into two groups: magnetic induction-based systems and electric field-based systems. While an electric field system employs a pair of electrodes to broadcast and receive an electric field signal via earth, a magnetic induction system uses a couple of loops. Both the surface and the underground environments of the mine are dominated by the 60 Hz frequency and its harmonics from the nearby power plant and mining equipment. However, this effect is less pronounced in the underground [8]. Thus, the horizontal TTE offers more range due to less underground noise.

Various research related to undermined communication is presented in references [8-19] out of which few are purely related to TTE communication. Several authors have reported various models that predict the magnetic and electric field behavior inside a mine. Wait et al. developed deterministic models [12] using a loop antenna to estimate the magnetic field at every point in space within an underground environment. Wait and Durkin, in their work, proposed a few homogeneous layers between the transmitter and receiver to analyze electromagnetic propagation [12, 13], whereas Yan et al. [14] reported a more general and complicated model to characterize the propagation medium as multi-layer soil with diverse electric conductivity for each horizontal stratum. This model is complex and provides computational challenges.

This paper considers a homogeneous single-layer soil model with an apparent or equivalent conductivity of 0.01 and permeability of 1.0 for the design. The magnetic field has been evaluated using a loop antenna with the simulation software CST. The proposed Archimedean spiral structure is used under similar conditions in place of a single loop. Improved performance is observed in the proposed structure with the same dimensions as the single loop. The reduced size of 50% of the Archimedean spiral structure gives the same performance as that of a single-loop antenna.

II. LOOP ANTENNA FOR THROUGH-THE-EARTH

A loop antenna with a radius of 20 m is used as a reference. The transmission of signals between the downlink and uplink loops is based on Faraday's law of electromagnetic induction. The radiated magnetic fields of a small circular loop antenna [15] carrying a current of I_o amp in spherical coordinates are given by (2) and (3), respectively.

$$H_r = \frac{jM\omega\mu cos\theta}{2\pi\eta r^2}\left[1+\frac{1}{jkr}\right]e^{-jkr} \tag{2}$$

$$H_\theta = -\frac{kM\omega\mu sin\theta}{4\pi\eta r^2}\left[1+\frac{1}{jkr}-\frac{1}{\left(kr^2\right)}\right]e^{-jkr} \tag{3}$$

$$M = NAI \tag{4}$$

Where M is the magnetic moment. Here, A and N are the area and number of turns of the loop, respectively, η is the intrinsic impedance in air, μ is the magnetic permeability, ω is the angular frequency, and k is the wavenumber.

A. Downlink Scenario

Fig. 1(a) illustrates the downlink scenario in TTE communication. Two-loop antennas are utilized to establish communication, one positioned slightly above ground level and the other inside the mine. Downlink communication is easier because it is convenient to position the antenna with a larger radius at ground level.

A loop antenna with a radius of 20 m and a current of 100 A is used for the downlink system. The earth is modeled, assuming it to be homogeneous with a conductivity of 0.01 and a permeability of 1.0, respectively [13, 14]. For simulating the downlink situation, a single-turn loop, as shown in Fig. 1(b), is kept at a height (h) 2 m above the homogeneous half-earth shown in Fig. 1(a). The magnetic field variation with respect to radius and loop current at different depths (d) is shown in Figs. 2 and 3, respectively. The effect of conductivity on magnetic field strength is shown in Fig. 4.

1) Magnetic Field with Varying Depth for Different Loop Radii

Fig. 2 depicts that the loop antenna with a larger radius provides a stronger magnetic field. The greater magnetic moment in a loop with a bigger radius leads to a stronger magnetic field and a wider operating range. Therefore, low-frequency antennas must be large to obtain higher radiation efficiency. It is also possible to employ

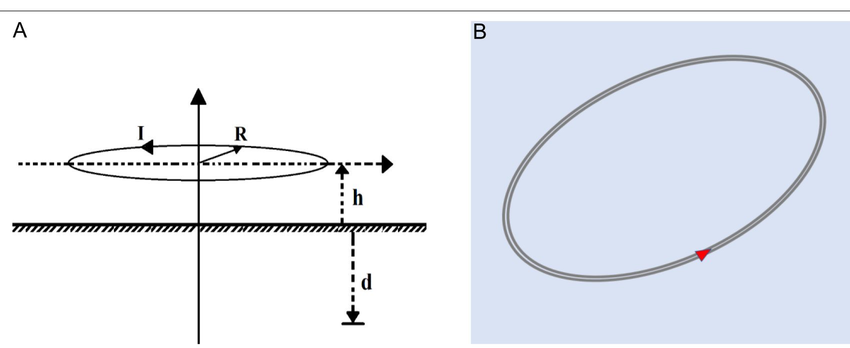

Fig. 1. (a). Downlink scenario. (b). Single-turn loop antenna.

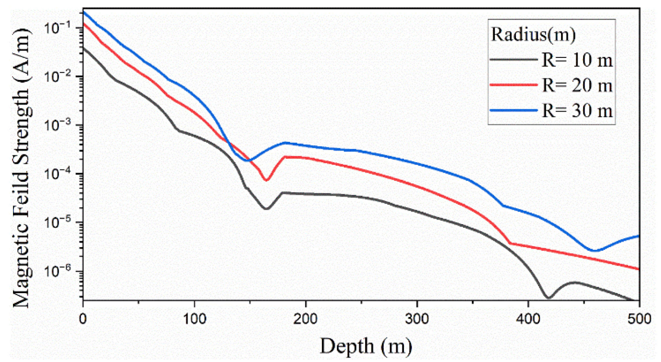

Fig. 2. Magnetic field with varying depth for different loop radii.

a loop antenna with a smaller radius and more turns inside the mine, together with a ferrite core, to produce stronger magnetic moments [16].

2) Magnetic Field with Varying Depth for Different Loop Currents

In Fig. 3, the magnetic field strength is shown as a function of depth for currents ranging from 20 A to 100 A while keeping the radius constant at 20 m. According to Fig. 3, it can be seen that when the loop current rises, the signal strength increases as well, leading to deeper penetration of the signal into the earth. Due to their electrically small size, low-frequency antennas require a larger current to maintain a strong enough magnetic field. The range, quality, and reliability of the communication will improve as the current increases. However, the underground transceiver power is limited for safety concerns due to the harsh conditions inside the mine, resulting in a shorter range. Lowering the subsurface antenna's frequency can compensate for the decreased range. There is no such restriction for the antenna above the ground. High-powered antennas mounted above the ground can operate at a higher frequency and data rate.

3) Magnetic Field with Depth for the Different Values of Conductivities

The magnetic field strength is depicted in Fig. 4 at a frequency of 3 KHz for four different conductivities and depths. The curve, which shows the lower conductivity, exhibits no signal attenuation and passes through the earth, allowing for a more extended range. In contrast, the graph's higher conductivity is shown by a curve that exhibits significant attenuation of the signal, indicating that the magnetic field is swiftly absorbed as it travels through the earth's layers. The rock's chemical composition, soil type, moisture level, concentration of dissolved salts, and temperature are some of the variables that determine the earth's conductivity. The skin depth of the mine reduces as conductivity rises, suggesting that the signal is absorbed more quickly and has reduced penetration into the earth.

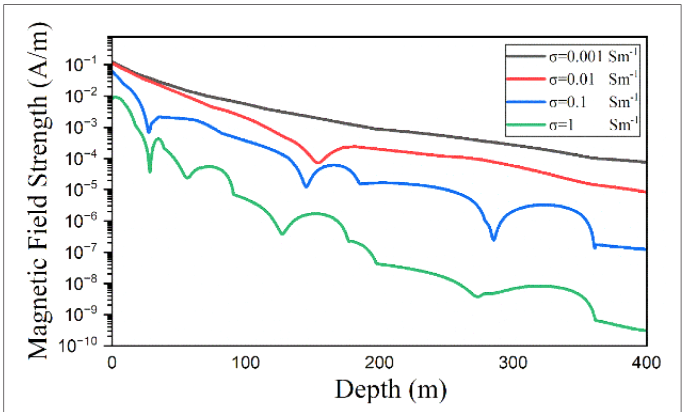

Fig. 4. Magnetic field along the depth (axis of a loop) at 3 KHz in a downlink scenario.

4) Magnetic Field Along the Radial Direction with Varying Depth

Variation in the magnetic field at a constant frequency of 3 KHz with radial distance at various depths in the downlink scenario is shown in Fig. 5, with the zero of the X-axis indicating the center of the loop. The graph shows that the magnetic field strength decreases as the radial distance from the loop increases and decreases as the depth increases. The maximum coupling between a receiver and transmitter can be achieved when they are aligned along the same axis. More generally, to optimize signal exchange between a receiver and transmitter, it is best to orient the receiver such that it faces the direction of the strongest magnetic flux emitted by the transmitter [17].

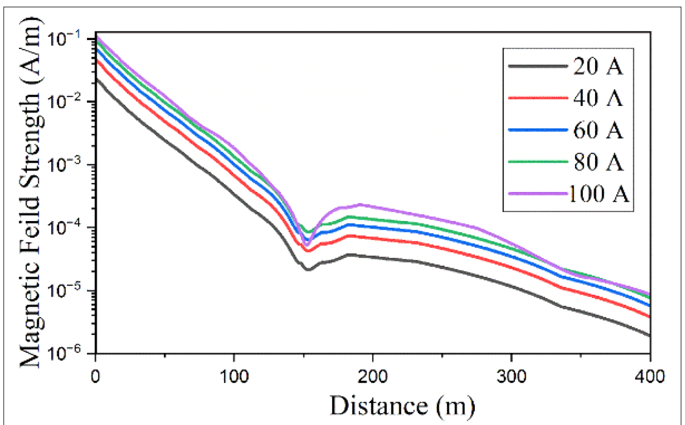

Fig. 3. Magnetic field with varying depth for different loop currents.

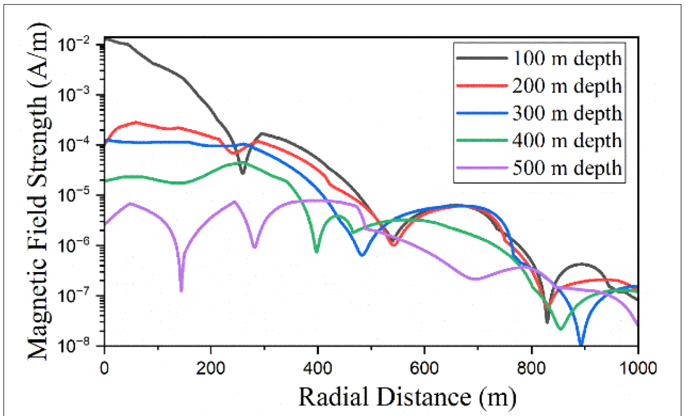

Fig. 5. Variation in the magnetic field with radial distance at different depths in a downlink scenario.

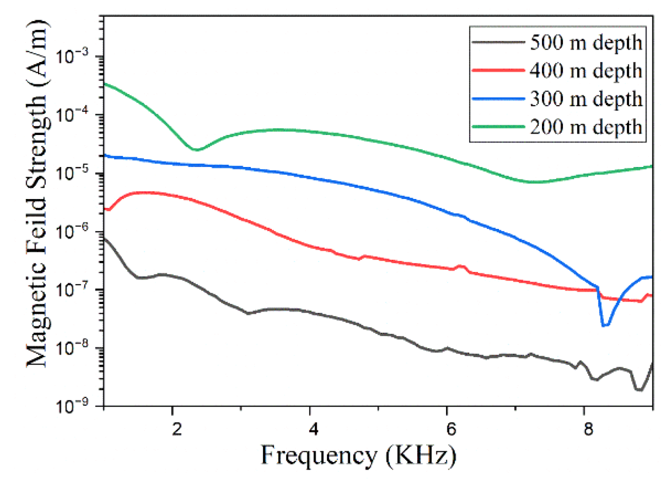

Fig. 6. Variation of magnetic field strength at the loop axis as a function of frequency.

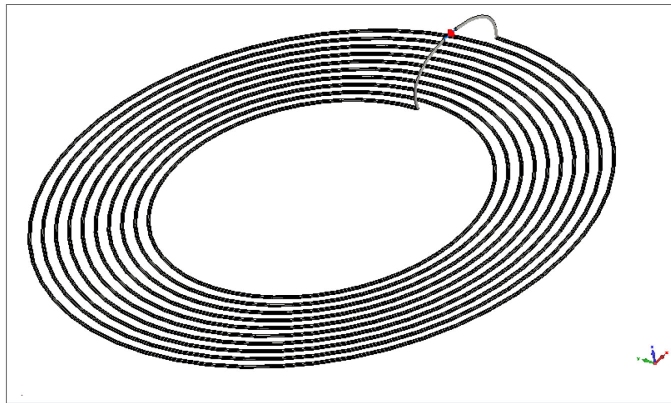

Fig. 8. A planar Archimedean spiral loop antenna.

5) Magnetic Field at a Depth as a Function of the Frequency

The frequency-dependent magnetic field versus frequency is plotted for different depths, as shown in Fig. 6. As a function of frequency, the magnetic field decreases with the increase in frequency. This is because the skin depth is inversely proportional to the signal frequency. The skin depth decreases as the signal frequency increases, implying that the signal is absorbed more quickly, resulting in lower penetration into the earth. The increased range of the TTE transmission can be achieved by lowering the frequency of the signal since the lower frequency signal offers less attenuation but at the cost of a lower signal transmission rate.

6) Verification of Simulated Data with the Measured Result

It was not possible to fabricate the designed antenna due to the limited fabrication and measurement facilities. However, to verify the accuracy and reliability of our simulated work, a comparison was made with the measured reported work by the U.S. Bureau of Mines [13], as shown in Fig. 7. The graph shows the normalized magnetic field for the reported work and simulated work for conductivity 0.01 and permeability 1 for the single loop in the downlink case at 660 Hz. It can be seen from the graph that the simulated result is in good agreement with the reported measured result.

B. Compact Loop Antenna for Through-the-Earth

An Archimedean spiral loop antenna, shown in Fig. 8, is considered, with an inner radius of 5 m, an outer radius of 20 m, and a current of 100 A. The simulated magnetic field as a function of depth is plotted for different separations (*t*) between consecutive turns of the loop, as shown in Fig. 9. The simulation results show that increasing the separation between turns leads to a decrease in the magnetic field strength at a given depth. The irregularities observed in the plot can be attributed to the effects of self-coupling between the turns of the loop and the half-homogeneous earth. The regularity of the plot at 0.4 m suggests that this distance may be a good choice for minimizing self-coupling. Hence, the proposed planar Archimedean spiral is designed with a loop of 37 turns by keeping the outer radius of 20 m, the inner radius of 5 m, and the spacing between loops of 0.4 m. The performance of the proposed antenna is compared with the single-turn loop under similar conditions. That is, the current applied is 100 A, and the conductivity and permeability of the earth are 0.01 and 1, respectively.

The magnetic field at a constant frequency of 3 KHz with radial distance at depths of 200 m and along the axial direction (varying depth) is compared with a single-loop antenna in Figs. 10 and 11, respectively.

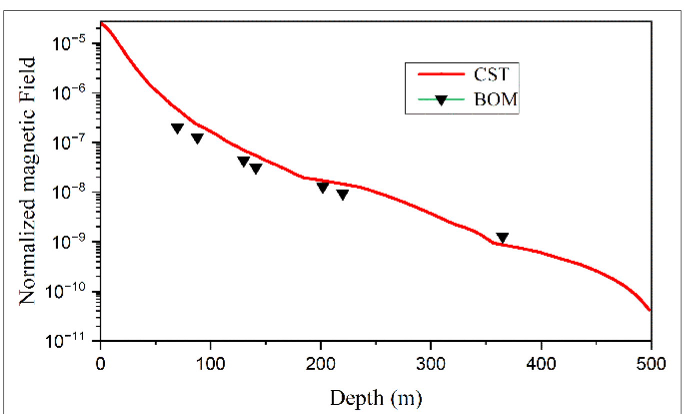

Fig. 7. Normalized field versus depth at 0.01 conductivity values (CST) and Bureau of mines measurements (data points).

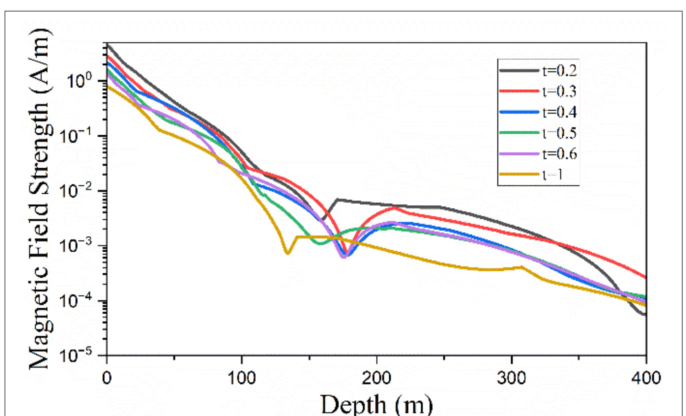

Fig. 9. Magnetic field as function depth for different consecutive turn separations.

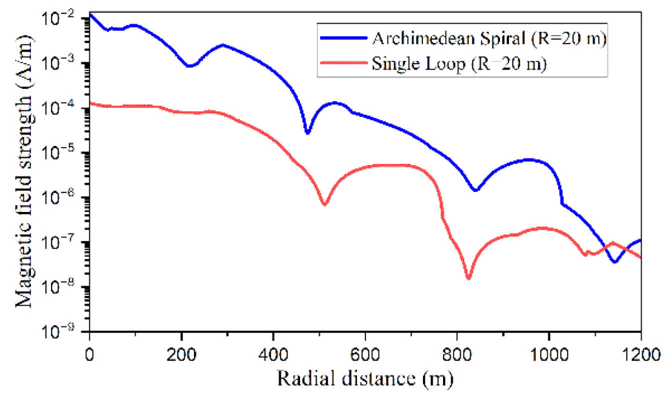

Fig. 10. Magnetic field along the radial direction at the depth of 200 m at 3 KHz.

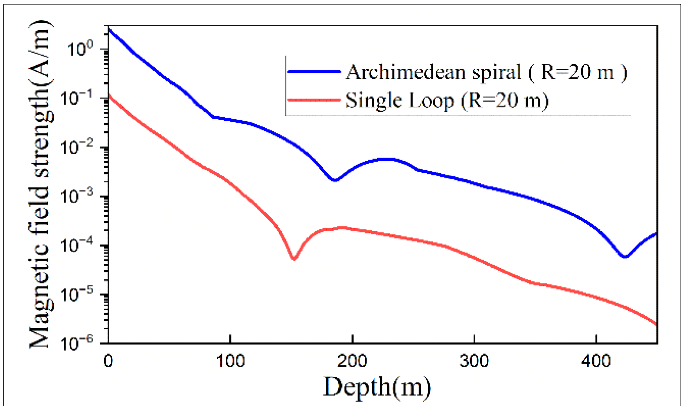

Fig. 11. Magnetic field along the axial direction (varying depth) at 3 KHz.

In both cases, the improvement in magnetic field strength can be observed. A comparative plot of the magnetic field as a function of frequency at a depth of 200 m is compared with a single loop, as shown in Fig. 12. The improved magnetic field strength can be observed at all the frequencies for the Archimedean spiral antenna compared to the single-loop antenna. The performance of the proposed antenna is also compared in Table I with the single-turn loop under similar conditions.

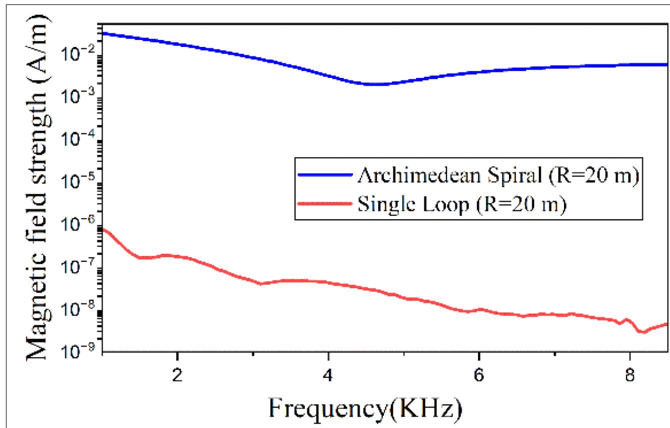

Fig. 12. Simulated magnetic field versus frequency at a depth of 200 m.

The increased axial and radial fields for the proposed structure will increase the range of signal penetration. This will be useful for establishing communication in the case of a deeper mine. It will also increase the reliability and quality of the communication.

Next, the size of the proposed structure can be reduced with performance equivalent to the single-turn antenna. A planar Archimedean spiral loop configuration with an inner radius of 5 m, a distance between consecutive turns of 0.4 m and a number of turns equal to 10 results in performance comparable to that of a single turn in the basic loop configuration as shown in Figs. 13 and 14. This enables a significant reduction in antenna size—by half—while still maintaining a planar configuration.

Finally, the proposed antenna is compared with some of the reported antennas in Table II.

III. CONCLUSION

This antenna will be useful for establishing communication in the deeper mine. Alternatively, the Archimedean spiral antenna, designed with a radius of 10 m, half that of the single-turn loop, indicating a significant size reduction, performs comparably to the single-turn loop of a 20 m radius. Thus, the proposed antenna offers a size reduction of 50% compared to the conventional single-turn

TABLE I. COMPARISON OF SINGLE-LOOP ANTENNA WITH PROPOSED ARCHIMEDEAN SPIRAL ANTENNA

Parameter	Simple Loop Antenna	Archimedean Spiral Antenna	Reduced Size Archimedean Spiral Antenna
Dimension	20 m radius	20 m outer radius, 5 m inner radius, 0.4 m separation	10 m outer and 5 m inner radius and 0.4 m separation
Drive current (A)	100	100	100
Radial field strength at 200 m depth (normalized)	10-4 A/m	102 times the simple loop at depth 200 m decreases as we move away from the centre at 3 KHz	Equivalent to the simple loop
Axial field strength (normalized)	$3.16 \times 10^{0-1-2-3}$ A/m	Average 102 times the simple loop at 3 KHz	Equivalent to the simple loop
Relative magnetic field strength versus frequency (normalized)	$10^{0-1-2-3-4-5-6-7}$A/m (mean)	Average 104 times the simple loop at 200 m depth at a frequency from 1 to 8 KHz	Equivalent to the simple loop

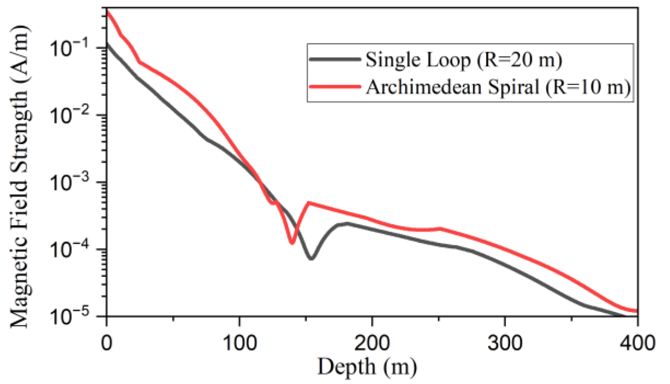

Fig. 13. Simulated magnetic field at varying depth at 3 KHz.

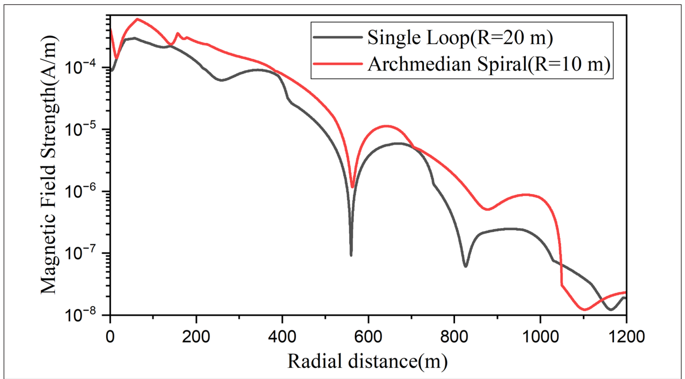

Fig. 14. Simulated magnetic field in the radial direction at a depth of 200 m for 3 KHz.

TABLE II. COMPARISON OF PROPOSED ANTENNA WITH REPORTED ANTENNAS

Ref.	Configuration	Size	Frequency of Operation	Conductivity of Ground	Field Strength
[14]	Single-loop antenna	Radius = 20 m, diameter of wire = 0.01 m	3030 Hz	0.01 S/m	10–4 A/m at 200 m
[16]	Ground rods used as electrodes	Length = 60 m, diameter = 1.58 cm	3030 Hz	0.01 S/m	−71.2 dBV (330 Hz) at 365m
[19]	Helical antennas designed for normal-mode radiation	Circumference = 0.701 m, 5.7° pitch, 30 turns diameter of wire=NA	2.9–3 MHz	High dielectric constant environments considered	10–2 V/m at 91.5 m
Proposed Antenna	Archimedean spiral antenna using magnetic radiation	Outer radius = 10 m, inner radius = 5 m, spacing 0.4 m, diameter of wire = 0.01 m	3 KHz	0.01 S/m	10–4 A/m at 200m

loop antenna and is a promising alternative for TTE communications. The number of turns can be varied based on the depth of communication.

Peer-review: Externally peer-reviewed.

Author Contributions: Concept – A.K.T., V.R.G.; Design – R.S.S., A.K.T.; Supervision – A.K.T., V.R.G.; Data Collection and/or Processing – R.S.S., A.K.T.; Analysis and/or Interpretation – A.K.T., R.S.S., V.R.G.; Literature Review – A.K.T., R.S.S., V.R.G.; Writing – A.K.T., R.S.S., V.R.G.; Critical Review – A.K.T., R.S.S., V.R.G.

Declaration of Interests: The authors have no conflict of interest to declare.

Funding: The authors declared that this study has received no financial support.

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