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Study on the Propagation Law of Magnetic Induction Signals for Wireless Communication in Underground Structures

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ABSTRACT: Despite advancements in electromagnetic wave-based communication, challenges such as high attenuation, medium variability, and large antenna requirements persist. Magnetic induction (MI) communication has emerged as a promising alternative, offering stable transmission characteristics and reduced near-field path loss. While previous studies have explored MI waveguide models and relay coil applications, experimental validation of through-the-ground MI transmission, particularly in homogeneous media, remains limited.This study investigates magnetic signal propagation in uniform underground environments through numerical simulations and experimental validation. A finite element model was developed using COMSOL to simulate magnetic signal transmission, focusing on coil geometry and medium properties. Experimental validation was conducted using a custom-built outdoor platform, where mutual inductance coils were employed to measure signal transmission in both air and soil. Key parameters, including coil spacing and medium permeability, were analyzed to evaluate path loss.Results demonstrate excellent agreement between simulations and experiments, confirming that soil's air-like permeability results in minimal path loss over short distances. The study highlights permeability as the dominant factor in signal attenuation, with soil moisture and composition showing negligible effects. These findings validate the theoretical framework for MI transmission in homogeneous media and provide practical insights for optimizing MI-based communication systems in applications such as agricultural monitoring and underground utility networks. Future work should focus on long-distance transmission and the impact of enhanced power levels to further refine system performance in real-world scenarios.

KEY WORDS: Magnetic Induction; Signal Propagation; Underground Communication; Path Loss; Steel fabric.

1 INTRODUCTION

Despite advancements in electromagnetic wave-based communication, challenges such as high attenuation, medium variability, and large antenna requirements persist[1]. Magnetic induction (MI)-based communication has emerged as a promising alternative, demonstrating stable transmission characteristics and reduced near-field path loss [2][3]. Early studies proposed MI waveguide transmission models with relay coils to extend communication range, successfully applied in underground pipeline monitoring [4].

Subsequent research expanded MI communication models, exploring interactions with underground conductive structures [5] and developing adaptive environmental sensing networks. Studies have improved MI transmission devices by analyzing coil behavior and optimizing system parameters [6]. More recent advancements include rotating permanent magnet pair (RPMP) antenna arrays for extremely low-frequency transmission [7] and tightly wound helix-toroidal coils for underground structural monitoring[8][9].

While significant progress has been made, gaps remain in experimental validation of through-the-ground MI transmission, particularly regarding the impact of soil eddy currents and complex underground conductive structures like rebar networks. To address these gaps, this study develops a detailed finite element model of rebar mesh, analyzing key parameters such as spacing, influence range, and diameter on MI signal path loss. Comparative experiments through soil and air further validate that soil's impact on MI transmission is minimal over short distances. This work highlights the need for expanded long-distance testing with enhanced transmission power to better understand soil's effect in practical scenarios.

2 METHODS

To investigate the propagation law of magnetic signals in underground structures, this study conducted a comparative analysis between numerical simulations and experimental investigations.

The research consists of two phases: (1) numerical simulation of signal transmission in homogeneous media, and (2) experimental validation of signal transmission in homogeneous media of signal transmission in homogeneous media.

2.1 numerical simulation

Firstly, this study performs parametric modeling of the magnetic signal transmission process based on COMSOL finite element software, establishes a magnetic induction signal simulation platform, and conducts multi-parameter analysis of the propagation characteristics of the magnetic signal.

First, a numerical simulation of magnetic signal propagation through a uniform medium is performed:

The coil domain consists of two concentric ring geometries: the primary coil and the secondary coil. These are controlled by the parameters: the Inner radius r_2, the Outer radius r_1, the

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number of turns *N*, and the coil center-to-center distance *d*. The medium domain is a spherical region through which the signal is transmitted, and it is controlled by the parameter: region radius *R*.

The coil domain material is copper, while the material of the medium domain is the propagation medium (soil/air). The material parameters include relative permeability, relative permittivity, and electrical conductivity.

An excitation voltage $V_0=sin(\omega t)$ is applied to the primary coil, where $\omega=2\pi f$, $f=50Hz$. The geometric center of the coil set is placed at the center of the simulation domain, as shown in Figure 1 Numerical Model of Magnetic Signal for Mutual Inductance Coils.

Based on the equipment in the reference experimental platform, the model parameters are set as Table 1 Simulation parameter value table:

Table 1 Simulation parameter value table

Parameter	Value	Description
r_1	12cm	Outer radius
r_2	1cm	Inner radius
N	500	Number of coil turns
d	40cm	distance between coils
R	5m	Radius of the medium domain
mu	1	Relative permeability of the medium

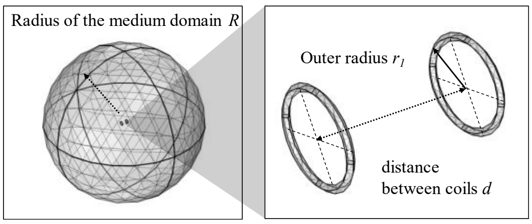

Figure 1 Numerical Model of Magnetic Signal for Mutual Inductance Coils

2.2 *experimental validation*

To investigate the propagation characteristics of magnetic signals in underground environments, validate the conclusions from theoretical and numerical simulations, and prepare for subsequent performance verification of magnetic signal equipment, an outdoor experimental platform for magnetic induction signal transmission was constructed, as shown in Figure 2.

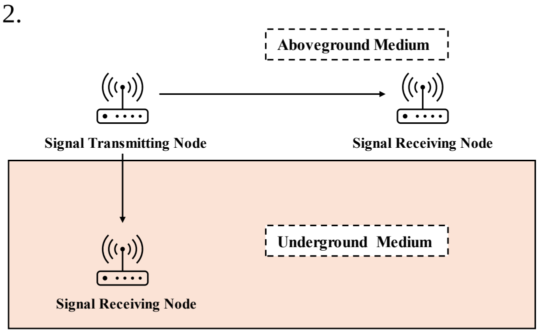

Figure 2 Schematic Diagram of Outdoor Transmission Experiment for Magnetic Induction Signal Using Mutual Inductance Coils

The equipment used in this platform includes

(1) Coil 1: Diameter 24 cm, 500 turns
(2) Coil 2: Diameter 24 cm, 500 turns
(3) Signal Generator (RIGOL-DG2052)
(4) Regulated Power Supply (ZHAOXIN-PS-23005D)
(5) Oscilloscope (Tektronix-TBS 2000 SERIE)

Figure 3 Outdoor Transmission Experiment Platform for Magnetic Induction Signal Using Mutual Inductance Coils

First, we connect the signal generator to the primary coil as the signal transmission node and the oscilloscope to the secondary coil as the signal receiving node, placing them in an interference-free open field (as shown in Figure 3 Outdoor Transmission Experiment Platform for Magnetic Induction Signal Using Mutual Inductance Coils). The two coils are fixed on a flat surface using mounting devices, ensuring that the coil axes are aligned and the coil planes are parallel. The distance between the coils is measured before each experiment.

The signal generator is used to apply a *10V* excitation to the transmitting coil (left side of Figure 3), which induces a current in the receiving coil that is captured by the oscilloscope.

By varying the coil spacing and recording the peak-to-peak voltage on the oscilloscope, the results can be calculated and visualized as shown in the figure.

To verify that the magnetic signal does not experience additional path loss when passing through soil, we conducted an underground experiment similar to the above-ground magnetic induction signal transmission experiment.

In the underground experiment, the excitation of the coil and the reception of the magnetic signal were the same as in the above-ground experiment. Here, we mainly describe the control of the transmission distance and coil attitude during the experiment.

First, a 31 cm deep pit was dug in the open field, and the bottom surface was leveled. The receiving coil was placed at the center of the pit, and a 1 cm thick layer of soil was added to ensure the receiving coil was just covered by the soil (with the receiving coil's small diameter of 1 cm). Then, a 10 cm thick layer of soil was added, and the surface was leveled again. The transmitting coil was placed at the center of the pit, excitation was applied to the transmitting coil, and the peak-to-peak value from the oscilloscope was recorded. This procedure was repeated for depths of 10 cm, 20 cm, and 30 cm to measure the magnetic signal path loss, as shown in Table 2 Path Loss Above and Below Ground with 10V Transmission Signal.

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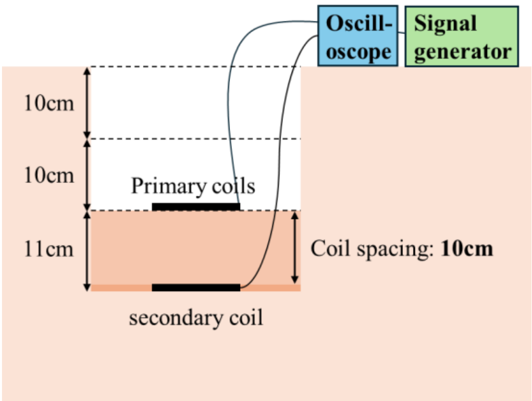

Figure 4 Schematic of the mutual inductance coil magnetic induction signal through-ground transmission experiment

An alternating signal generates a sinusoidal alternating magnetic field through the primary coil. The change in the magnetic field induces an electromotive force in the secondary coil, which in turn generates the corresponding induced signal. The voltage signal at the receiving end is recorded at different distances, and by combining the coil resistance, the induced power of the signal can be calculated, which allows for the calculation of magnetic signal transmission loss. The above-ground experiment is shown in Figure 4 Schematic of the mutual inductance coil magnetic induction signal through-ground transmission experiment.

3 RESULTS AND ANALYSIS

3.1 Propagation in Homogeneous Media

First, a trial calculation is performed under the conditions of a coil spacing *d=50cm* and a uniform medium. The path loss is *44.16dB*, which is in good agreement with the theoretical value. The model performs well, producing the simulation cloud maps shown in Figure 5, Figure 6 Magnetic induction strength contour plot between coils

Next, the coil spacing *d* is scanned in the range of *20cm-200cm* with a step size of *10cm*, keeping all other parameters constant. The path loss is calculated for the model and compared with experimental values (see Figure 8).

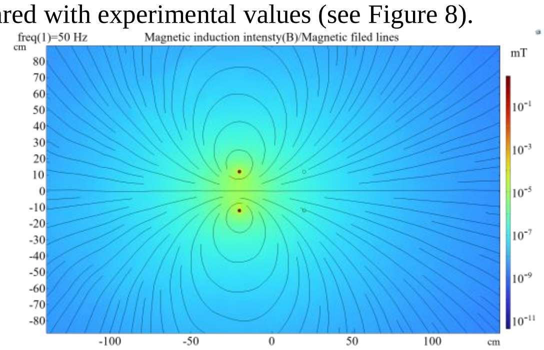

Figure 5 Magnetic induction strength contour plot of the coils cross-section

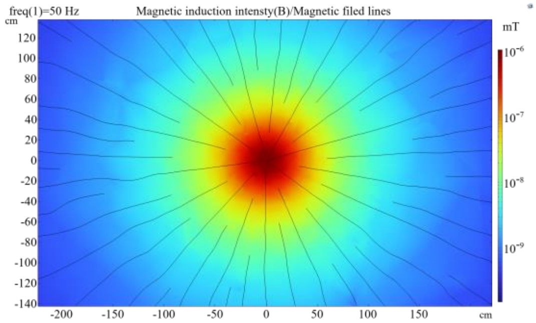

Figure 6 Magnetic induction strength contour plot between coils

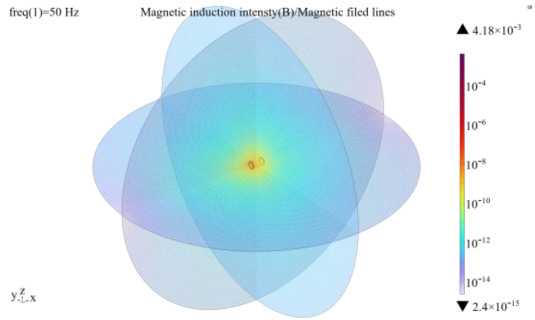

Figure 7 Magnetic Induction Intensity Cloud Map Between Coils

The simulation data of magnetic induction signal variation with coil spacing is shown in Figure 8 Path loss variation with coil distance.

The experimental values generally align well with the simulation results; however, some discrepancies are present due to the following reasons:

(1)**Background noise interference**: At longer distances, unshielded noise added to the reception power calculation.

(2)**Coil attitude**: During adjustments for distance, changes in coil angle affected the results.

As a result, the power path loss in the above-ground experiment follows a distance-based decay of approximately the fifth power, while the theoretical equation suggests a sixth power, resulting in some discrepancy. It is believed that with improvements to the filtering equipment, a better match can be achieved.

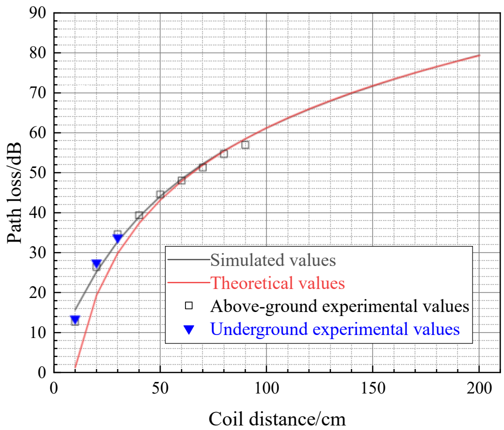

Figure 8 Path loss variation with coil distance

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By comparing the path loss in the above-ground and underground experiments in Table 2 Path Loss Above and Below Ground with 10V Transmission Signal, and excluding experimental errors, it can be observed that the soil has no effect on the path loss of the magnetic signal, which is consistent with the theory.

Table 2 Path Loss Above and Below Ground with 10V Transmission Signal

Depth/d	Above Ground Experimental Value	Below Ground Experimental Value
10cm	12.70	13.50
20cm	26.40	27.51
30cm	34.65	33.79

4 CONCLUSION

This study validates magnetic signal propagation theory in uniform underground media through numerical simulations and experimental measurements. The results demonstrate low path loss in soil environments due to their air-like permeability characteristics. Experimental data show excellent agreement with theoretical models, confirming permeability as the dominant factor in signal attenuation, while soil moisture and composition exhibit negligible effects. The consistent correlation between simulation and experimental results establishes a reliable framework for predicting magnetic signal behavior in homogeneous underground environments. These findings provide fundamental insights for developing magnetic induction-based communication systems in applications such as agricultural monitoring and underground utility networks.

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