Field Strength Assessment for Underground Wireless Communication at LF Bands

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***Abstract*—The low-frequency band is more suitable for underground wireless communication due to its better propagation in bedrock compared to MHz bands. In this study, we investigate the near-field strength distribution of a circular loop antenna at 255 kHz to establish a wireless link with electronic devices inside bedrock. The results showed that at a separation distance of up to 2 m from the loop antenna, the measurement and analytical results agree well, indicating the effectiveness of the antenna calibration and near-field evaluation at low frequency.**

***Index Terms*—underground communication, low frequency, loop antenna, near-field, calibration.**

I. Introduction

Recently, several research projects focused on developing technologies for integrated infrastructure management have been launched in Japan [1]. The remote control for various electronic devices using various wireless communication technologies at construction site is expected to improve efficiency and reduce the safety risks of operators. Specially for underground communication, a key technical challenge is ensuring reliable wireless propagation in an underground environment, such as inside bedrock or tunnel environment.

Previous studies have shown that slight changes in the tunnel environment, such as the tunnel's shape, dimensions, curvature, wall configuration, roughness, and the presence of moving equipment like truck excavators, may affect radio wave propagation [2]. The tunnel may also act as a waveguide [3], [4], which can have various unintended effects on the performance of the designed wireless communication system. Additionally, the composition of the rocks that make up the tunnel face varies from region to region, resulting in different electromagnetic characteristics, which is a highly significant factor in the wireless communication environment [5]. Consequently, UHF (Ultra High Frequency) band signals may not be suitable for wireless system design due to substantial penetration loss in bedrock or other underground environment, influenced by various geological factors such as rock fault structures and variations in dielectric properties due to groundwater content.

In this study, to clarify the penetration and coverage area of low frequency propagation, the free-space near-field strength distribution of a circular loop antenna, was investigated through both analytical and empirical methods.

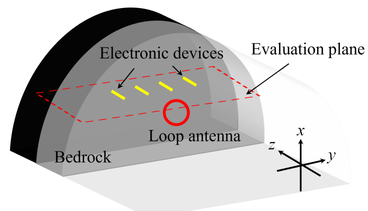

Fig. 1. Underground communication using wireless technology at low frequency.

II. Near-Field Distribution Analysis for Loop Antenna at Low Frequency Band

Figure 1 shows an example of the construction system using wireless communication technology. A circular loop antenna located at the center of the bedrock is used to communicate with distributed electronic devices positioned in drilled holes. In this study, we only examine the field distribution near the loop antenna in free space, represented by the red area in Fig. 1. For the measurements, the loop antenna was connected to a signal generator, while on the receiving side, a magnetic field probe was connected to a spectrum analyzer to detect the received power, which was then used to calculate the magnetic field strength using the following equations [7]–[9].

$$H = \sqrt{H_z^2 + H_r^2}, \tag{1}$$

$$H_r = \frac{I}{2\pi} \frac{(z - z_0)}{r\sqrt{(r+a)^2 + (z-z_0)^2}} \left\{ -K(k) + \frac{r^2 + a^2 + (z-z_0)^2}{(r-a)^2 + (z-z_0)^2} E(k) \right\}, \tag{2}$$

$$H_z = \frac{I}{2\pi} \frac{1}{r\sqrt{(r+a)^2 + (z-z_0)^2}} \left\{ K(k) - \frac{r^2 - a^2 + (z-z_0)^2}{(r-a)^2 + (z-z_0)^2} E(k) \right\}, \quad (3)$$

$$K(k) = \int_0^{\frac{\pi}{2}} \frac{1}{\sqrt{1 - k^2 \sin^2 \theta}} d\theta, \quad (4)$$

$$E(k) = \int_0^{\frac{\pi}{2}} \sqrt{1 - k^2 \sin^2 \theta}\, d\theta, \quad (5)$$

$$k = \sqrt{\frac{4ar}{(r+a)^2 + z^2}}. \quad (6)$$

Here, $K(k)$ and $E(k)$ are the complete elliptic integrals of the first kind and the complete elliptic integrals of the second kind, respectively, and are calculated using equations (4)–(6). The calculation conditions were set as follows: center frequency $f = 255$ kHz, antenna total input power $P_{\text{in}} = 13$ dBm, and loop antenna radius $a = 0.3$ m. The antenna factor of 31.29 dBS/m was obtained using a national standard calibration method [10].

III. Result

Figure 2 shows the measurement and simulation results of the magnetic field strength distribution near the loop antenna. At depths of $z = 1$ m and 2 m, the measurement and simulation results align well, indicating the accuracy of the antenna calibration and near-field analysis. However, as z increases to 3 m, a noticeable deviation between the measurement and analytical results is observed. This may be attributed to significant differences in the null direction of the near-field of the loop antenna. Table 1 shows the error between the measurement and calculated results, with a minimum error below 2.87 dB when $z \leq 2$ m. This indicates that our method provides a highly reliable analysis of the magnetic field strength distribution near the loop antenna.

IV. Conclusion

In this study, we measured the near-field distribution of a low frequency loop antenna and compared it with calculated results to verify the validity of the antenna calibration and theoretical near-field calculations. The results showed that the magnetic field strength distribution was almost consistent at a depth of $z \leq 2$ m, where the distributed electronic devices is planned to be placed. In the future, we plan to develop a numerical calculation algorithm for the low frequency band using the FDTD method and analyze propagation inside bedrock.

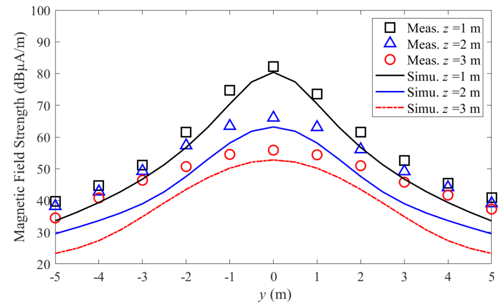

Fig. 2. Measurement and simulation results of magnetic field strength distribution near the loop antenna.

TABLE I
ERROR ANALYSIS OF MAGNETIC FIELD STRENGTH

Depth	*Maximum (dB)*	*Minimum (dB)*
z = 1m	7.36	1.83
z = 2m	10.48	2.87
z = 3m	13.96	3.09

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References

[1] https://sip-icas-project.org/en/
[2] L. M. Nemtoi, I. M. Moise, E. A. Stanciu, and M. C. Surugiu, "Considerations regarding the radio design of GSM-R systems, inside railway tunnels" , *2012 IEEE 18th International Symposium for Design and Technology in Electronic Packaging (SIITME)*, pp. 253-258, October 2012.
[3] Atawit Jantaupalee, "Low-Frequency Wave Propagation in The Cave", *2023 20th International Conference on Electrical Engineering/ Electronics, Computer, Telecommunications and Information Technology (ECTI-CON)*, pp. 1-4,May 2023.
[4] K. S. Kumar, Y. H. Lee, and Y. S. Meng, "Radio-wave Propagation in Tunnel Structures at ISM Band: A Preliminary Study," *2018 International Conference on Intelligent Rail Transportation (ICIRT)*, pp. 1-4, Dec. 2018.
[5] Serhan Yarkan, "Underground Mine Communications: A Survey", *IEEE Communications Surveys & Tutorial*, pp. 125-142, Aug. 2009.
[6] Robert A. Schill, "General relation for the vector magnetic field of a circular current loop: a closer look," *IEEE trans. on Magnetics*, vol. 39, no. 2, pp.961-967, Mar, 2003.
[7] W. R. Smythe, Static and Dynamic Electricity, 2nd ed. New York: Mc-Graw-Hill, 1950, pp. 270–271, 280–282.
[8] W. R. Smythe, Static and Dynamic Electricity, 3rd ed. New York: Hemisphere,1989, pp. 290–291, 300–302.
[9] J.Van Bladel, Electromagnetic Fields. NewYork: McGraw-Hill, 1964,pp. 155–156.
[10] K. Fujii, "Basic characteristics of magnetic field antenna factor of loop antennas for EMI measurements," *IEICE Commun. Exp.,* Vol.1, 1–6, Jul. 2022.