

Performance Analysis of Near-Field Magnetic Induction Communication in Extreme Environments

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Abstract—Ultra-reliable and low-power wireless communications are desirable for wireless networking in extreme environments such as underground tunnels, underwater, and soil. Existing wireless technologies using electromagnetic (EM) waves suffer from unpredictable multipath fading and blockage. The recent development of magnetic induction (MI) communication provides a low-power and reliable solution, which demonstrates negligible multipath fading, high penetration efficiency, and low attenuation loss in lossy media. However, existing works neglect the fact that MI communication only demonstrates such advantages in the near-field, beyond which the MI communication converges to electromagnetic wave-based communication and all the aforementioned advantages disappear. This letter develops a magnetic field propagation model to show MI communication's different performances in the near-field and the far-field. We develop rigorous models to capture the multipath fading, the penetration efficiency through inhomogeneous media, and the attenuation loss in lossy media. The results show that although MI communication can provide reasonable signals in the far-field, it only demonstrates negligible multipath fading, high penetration efficiency, and low attenuation loss in the near-field.

1. INTRODUCTION

Magnetic Induction (MI) communication is a reliable low-power solution for extreme environment wireless networking [4, 7, 11]. Thanks to its reliable wireless channel, it requires simple signal processing algorithms [6, 8], which consume negligible power. Also, its low propagation loss in extreme environments demands small transmission power to successfully send data packets to a receiver. MI communication has been extensively adopted in underground and underwater environments [8, 9, 11]. The advantages that distinguish it from electromagnetic (EM) wave-based communication are its negligible multipath fading, high penetration efficiency through inhomogeneous media, and low attenuation loss in lossy media. Therefore, MI communication is much more reliable and power-efficient than that of EM wave-based communication in extreme environments.

It is well known that in the vicinity of an antenna the electric fields and magnetic fields are decoupled, i.e., quasi-stationary [1, p. 241]. The information in MI communication is carried by magnetic fields instead of EM waves. By using small magnetic coils and relatively low carrier frequency, the transceivers are coupled by magnetic induction, through which wireless information can be delivered. Since most of the materials in nature have the same permeability, using magnetic fields for communication has more significant advantages than using EM waves. However, as the distance from the antenna increases, the magnetic fields and the electric fields are coupled together and become EM waves, which demonstrate RF signal behaviors. Originally, the magnetic induction communication only considers the near-field [11], which has a very limited communication range since the field strength fall-offs in the speed of d^3 , where d is the distance between the transmitter and receiver. Later on, researchers noticed that this model is not comprehensive since it neglects the far-field of a coil, which

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can propagate a long distance [5, 10]. However, this raises an important question: does the far-field MI communication also demonstrate those advantages in the near-field?

This is an important problem since if we aggressively increase the MI communication range by increasing the radiation resistance of coil antennas, it may become EM communication and suffers from multipath fading. Although the communication range is increased, we sacrifice the primary advantages of MI communication. Thus, it is desirable to compare MI communication's performance in the near-field and far-field.

In this letter, we first review the fundamental reason for using MI communication using a wave impedance model. Then, we analyze the performance of MI communication from the perspectives of multipath fading, penetration efficiency through inhomogeneous media, and attenuation loss in lossy media. After that, we provide discussions on how to properly use MI communication in extreme environments.

2. MOTIVATION FOR USING MAGNETIC INDUCTION COMMUNICATION

The EM wave-based communication suffers from multipath fading and low penetration efficiency through inhomogeneous media because most of the materials in nature have different permittivities. Thus, EM waves are reflected, scattered, or diffracted at media boundaries. We can consider an ideal scenario, where the communication only relies on magnetic fields. Since most of the materials in nature have the same permeability, there is almost no reflection and the multipath fading can be alleviated. However, according to Maxwell's equations, this can only happen when the carrier frequency is zero, which is impossible for wireless communication since it requires bandwidth to modulate signals.

To show how MI communication reduces reflections from media boundaries, we consider a magnetic dipole and an electric dipole, both of which are infinitesimally small [1]. The wave impedance is defined as $\eta = E/H$, where E is the electric field and H is the magnetic field. To remove the effect of frequency, we scale the distance from the antenna using the wavelength (λ). We consider two media, i.e., a lossless medium and a lossy medium with a conductivity of 0.01 S/m. Let the relative permittivity and relative permeability of both media be 1, respectively. As shown in Fig. 1, when the distance is larger than a half wavelength, the generated wave impedances of both the magnetic dipole and the electric dipole converge to around $377\ \Omega$ in the lossless case, which is a well-known result. For the lossy medium, the impedance converges to a smaller value. However, in the near-field, especially when the distance is smaller than 0.1λ , the wave impedance of the magnetic dipole is much smaller than $377\ \Omega$, which means that there are more magnetic fields in the near-field of the magnetic dipole. Since the magnetic dipole has more magnetic fields in its near-field, we can leverage this property for inhomogeneous extreme environment wireless communication.

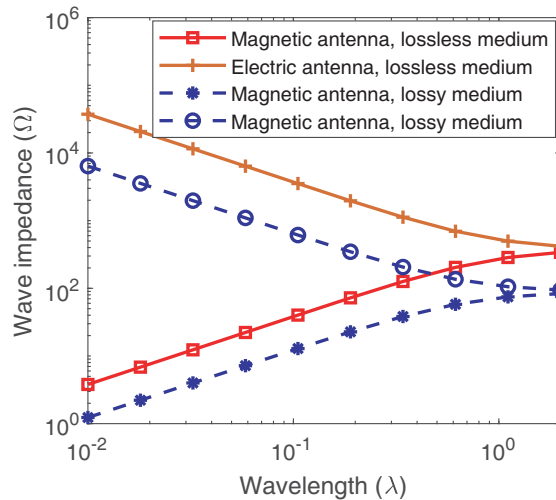


Figure 1. Wave impedance E/H of electric and magnetic dipoles in lossless and lossy media.

3. ADVANTAGES OF MI COMMUNICATION IN THE NEAR-FIELD

The main advantages of MI communication compared with EM communication are the negligible multipath fading, high penetration efficiency, and low attenuation loss in lossy media. In this section, we develop a channel model to study the differences of these advantages in the near-field and the far-field.

3.1. Negligible Multipath Fading

To study the effect of multipath fading, we use the classical two-ray model [3], which is shown in Fig. 2(a). If we use EM communication, signals can be transmitted through two paths, i.e., the direct path and the reflected path, and create constructive or destructive additions at the receiver. As discussed in the preceding section, when the communication range is small, the magnetic field is dominant and thus the reflection from the air-ground boundary is weak. Therefore, the multipath fading is negligible. However, as the distance increases, magnetic fields and electric fields are coupled and the reflection cannot be neglect. Next, we develop a model to capture the multipath effects in MI communication, which has not been studied in the literature.

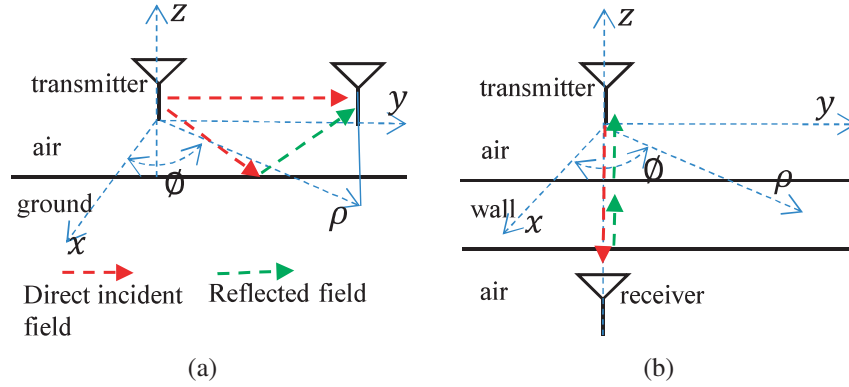


Figure 2. Geometric models for reflection and penetration analysis. (a) Two-ray model. (b) Penetration model.

The transmitter and receiver with coil antennas can be regarded as infinitesimal dipoles. According to [2, p. 74], the magnetic fields above ground in a Cylindrical coordinates system, as shown in Fig. 2, can be expressed as

$$H_r = \frac{-jIA}{4\pi} \int_0^{\infty} \frac{k_{\rho}^3}{k_{1z}} J_0(k_{\rho}\rho) \left[e^{jk_{1z}|z|} + R_{12}e^{jk_{1z}(z+2d_1)} \right] dk_{\rho} \quad (1)$$

where d_1 is the height of the transmit antenna, I the coil current, $A = n_c\pi a^2$ the overall area of the transmit coil antenna, n_c the number of turns, a the coil radius, k the propagation constant, $k_i = \sqrt{k_{\rho}^2 + k_{iz}^2} = \omega\sqrt{\mu_i\epsilon_i}$, ω the angular frequency, μ_i the permeability, ϵ_i the complex permittivity, $J_0(x)$ the zero order Bessel function of the first kind, ρ the horizontal distance, and R_{12} the reflection coefficient of the air-ground boundary. In the above equation, k_{iz} can be written as a function of k_i and k_{rho} . Here, we use subscript $i = 1$ to represent the parameters for the air, and use $i = 2$ to represent the parameters for ground/wall. When a coil is vertically orientated, it generates TE waves and the corresponding reflection coefficient is

$$R_{ab} = \frac{\mu_b k_{az} - \mu_a k_{bz}}{\mu_b k_{az} + \mu_a k_{bz}}, \quad (2)$$

where $a = 1$ and $b = 2$. By substituting Eq. (2) into Eq. (1), we can obtain the magnetic fields intensity at the receiver.

In Fig. 3, we increase the distance between the transmitter and receiver gradually to change the range from the near-field to the far-field. Both of them have the same height, i.e., 0.1 m. The carrier

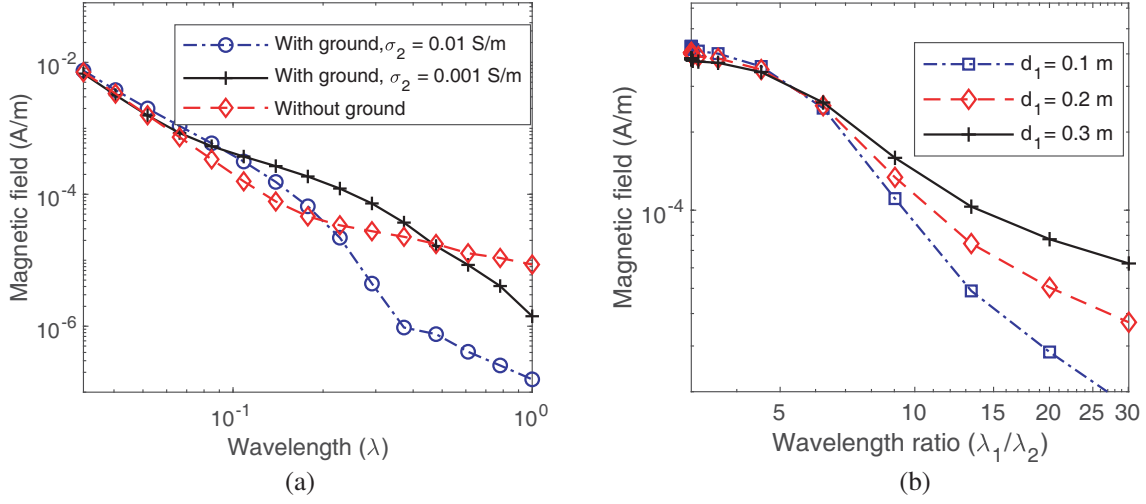


Figure 3. Effect of ground reflections on the received magnetic field intensity. (a) Magnetic field intensity vs distance from the transmitting coil (the distance is scaled by the wavelength in the air). (b) Effects of the distance to the ground (d_1) and ground conductivity on magnetic field intensity at 3m from the transmitting coil.

frequency is 10 MHz, and the relative permittivity of the ground is 10 and the conductivity is 0.01 S/m and 0.001 S/m. The coil size is 0.05 m in radius, the number of turns is 10, and the excitation current is 1 A. To numerically compute Eq. (1), we use the Gaussian Quadrature. Also, we consider the z for the observation point is 0.05 m rather than 0 to ensure the computation can converge fastly. In Fig. 3(a), we compare the magnetic field intensity at the receiver with and without ground reflections. It is worth noting that within one wavelength, the magnetic field generated by a coil without ground reflections can be separated into two regions: in the first region magnetic fields fall-off in $1/d^3$ and reflections from the ground are not significant, whereas in the second one magnetic fields fall-off in $1/d$ and reflections change the overall received magnetic field dramatically.

When we consider the ground reflection, in the first region the Bessel function $J_0(k_\rho \rho)$ can be approximated by $J_0(0)$, which is a constant. k_ρ tends to be large since it can increase the ratio k_ρ^3/k_{1z} and reduce the reflection term by creating an imaginary k_{1z} . In the second region, the Bessel function becomes smaller due to a large ρ . As a result, k_ρ tends to be small to increase $J_0(k_\rho \rho)$, which in turn increases the effect of the reflection term. That is why when ρ is small we can neglect the reflection, but when ρ is large we cannot.

As suggested in Fig. 3(a), the reflection is affected by the ground dielectric parameters. Also, the distance from the ground affects the reflection strength. In Fig. 3(b), we increase the ground conductivity from 10^{-5} S/m to 1 S/m and observe the magnetic field at 3m ($0.1\lambda_1$) from the coil. We define the wavelength ratio as λ_1/λ_2 , i.e., the wavelength in the air over the wavelength in soil. As shown in the figure, when the wavelength ratio is smaller than 5, the reflection does not take strong effects and, thus, the distance to the ground d_1 does not affect the magnetic field intensity. However, as the wavelength ratio increases, the reflection from the ground becomes strong and a smaller d_1 results in smaller magnetic field intensity.

Generally, when the distance from the transmit coil is smaller than $0.1\lambda_1$ and the wavelength ratio smaller than 5, it is safe to neglect the reflection from the ground or other reflectors. In other words, in the near-field, we can neglect the ground reflections, but in the far-field, the MI communication behaves like EM wave-based communication, which suffers from multipath fading.

3.2. High Penetration Efficiency

Next, we study the penetration performance of MI communication. The considered scenario is shown in Fig. 2(b), where a transmitter and a receiver are located on two different sides of a concrete wall. When

they are close, the transceivers are coupled by magnetic induction. The penetrated magnetic field can be written as [2, chap. 2],

$$H_t = \frac{-jIA}{4\pi} \int_0^\infty \frac{k_\rho^3}{k_{1z}} J_0(k_\rho \rho) \tilde{T} e^{jk_{1z}|z|} dk_\rho, \tag{3}$$

where \tilde{T} is the transmission coefficient considering the two air-wall boundaries (i.e., the upper one and the lower one). For each of the boundary, the transmission coefficient can be expressed as

$$T_{ab} = \frac{2\mu_b k_{az}}{\mu_b k_{az} + \mu_a k_{bz}} \tag{4}$$

where subscripts a and b denote the penetration direction, i.e., from medium a to medium b . We consider the upper air layer as layer 1, the wall as layer 2, and the lower air layer as layer 3. By considering the two boundaries, the overall transmission coefficient can be written as

$$\tilde{T}_{13} = \frac{T_{12}T_{23}e^{jk_{2z}(d_2-d_1)}}{1 - R_{23}R_{21}e^{j2k_{2z}(d_2-d_1)}}, \tag{5}$$

where the reflection coefficient is given in Eq. (2).

In Fig. 4, we show the effect of the transmitter’s distance to the wall and the wavelength ratio by increasing the conductivity of the wall, which reduces the wavelength λ_2 . The wall has a thickness of 0.2m and relative permittivity of 10. The observation point is 0.2m below the wall. From the figure, first, we can observe that as the wavelength ratio increase, the magnetic field intensity decreases since the material parameters become very different and it is hard to penetrate through the wall. Second, as the distance from the wall increases, this effect becomes more obvious. The reason is that since the distance is large, the penetrated signals are mainly carried by EM waves which suffer from strong attenuation and reflections. This is different from the reflection that was discussed in the preceding subsection. Generally, if a transmitter is close to the ground/wall, the reflection is weak, and the penetration efficiency is high. We can also observe that when the distance to the wall is $0.1\lambda_1$ and the wavelength ratio is smaller than 5, the penetration efficiency is almost 100%. This observation indicates that in the near-field MI communication has strong penetration efficiency, but it decreases fast as the communication range increases to the far-field.

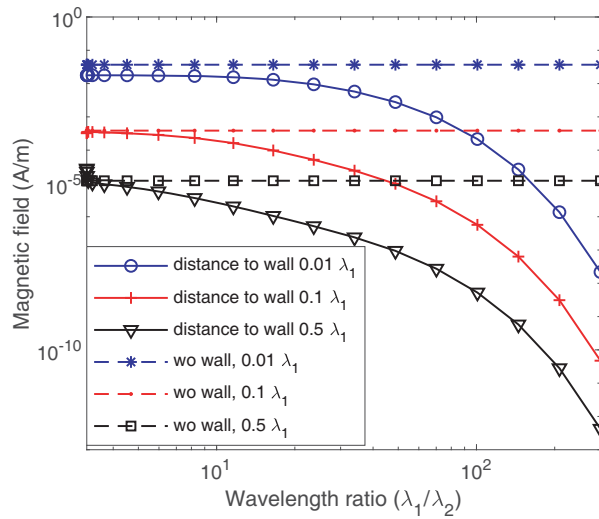


Figure 4. Effect of wavelength ratio and the distance to wall. For the cases without the wall (wo wall), the distances between transmitter and the receiver is the same as the cases with the wall, which are noted with the same distance, i.e., $0.01\lambda_1$, $0.05\lambda_1$, and $0.5\lambda_1$.

3.3. Low Attenuation Loss in Lossy Media

Next, we consider that the medium is homogeneous but lossy. In this case, we consider that the coil is placed in an infinite environment without boundaries. It is well known that EM waves cannot propagate efficiently in such media due to the absorption loss. The attenuation loss is evaluated using the ratio of the received power P_r over the transmitted power P_t . For a matched receiving magnetic antenna, the received power is $P_r = |V|^2/8R_a$, where $|V|^2 = \omega^2 \mu^2 \pi^2 a^4 \mathbf{H}_s \cdot \mathbf{H}_s^*$, R_a is the antenna conductive resistance, and $\mathbf{H}_s = [H_t, H_\theta, H_\phi]$ is the generated magnetic field by a magnetic dipole [1, chap. 5]. The dominant component in \mathbf{H}_s can be written as

$$\begin{aligned} \mathbf{H}_s &= \left[\frac{a^2 I \cos \theta}{2d^3}, 0, 0 \right], \quad \text{when } |kd| \ll 1 \\ \mathbf{H}_s &= \left[0, -\frac{(ka)^2 I \sin \theta}{4d} e^{-jkd}, 0 \right], \quad \text{when } |kd| \gg 1 \end{aligned} \quad (6)$$

Note that in a lossy medium, the propagation constant $k = k_r + jk_c$ is a complex number, where k_r is the real part, and k_c is the imaginary part. The transmission power P^t for magnetic antenna is $R_a I_0^2/2$. Hence, the path loss can be written as

$$\frac{P_r}{P^t} = \begin{cases} \frac{a^8 \pi^2 \omega^2 \mu^2}{16R_a^2 d^6}, & \text{when } |kd| \ll 1 \\ \frac{|k|^4 a^8 \pi^2 \omega^2 \mu^2}{64R_a^2 d^2} e^{-2k_c d}, & \text{when } |kd| \gg 1 \end{cases} \quad (7)$$

where $\Im(k)$ is the imaginary part of the propagation constant. As suggested by Eq. (7), if the communication range d is much smaller than λ , the signals do not experience attenuation loss in a lossy medium. Therefore, the attenuation loss can be as low as zero for MI communication in the near-field, whereas it is $-10 \log(e^{-2k_c d})$ dB in the far-field. Since k_c is the imaginary part of the propagation constant, it is a function of the conductivity, which can be considered as an indicator of the absorption loss. In view of Eq. (7), MI communication experiences low attenuation loss in the near-field. However, in the far-field, MI communication suffers from a similar attenuation loss to EM wave-based wireless communication.

3.4. Discussions

The results in preceding subsections show that MI communication in the near-field is reliable since it experiences negligible multipath fading, demonstrates high penetration efficiency, and suffers from small attenuation loss. Therefore, in extreme environments such as underground and underwater, MI communication is a promising solution to provide reliable wireless connections. However, as the communication range increases to the far-field, MI communication becomes complicated. It behaves like EM wave-based communication, which suffers from multipath fading, low penetration efficiency, and high attenuation loss.

Although we can still receive MI communication signals in the far-field due to the slow fall-off speed, the signals may be weak and suffer from inter-symbol interference. In such a case, we have to increase the complexity of MI receivers to tackle these changes and, thus, the cost and power consumption of MI radios increase. In general, MI communication is a reliable and low-power technology, which has great potentials in wireless applications in extreme environments. However, we should be aware that its advantages mainly lie in the near-field.

4. CONCLUSION

Magnetic induction (MI) communication is an important solution for wireless applications in extreme environments such as soil, tunnel, cave, underwater, and in-body. MI communication enjoys negligible reflection, high-penetration efficiency, and small absorption loss in a lossy medium. However, these advantages lie in the near-field since as distance increases the electric fields and magnetic fields are coupled and the communication relies on electromagnetic waves, which suffers from multipath fading

and absorption loss. In this letter, we derived analytical models to evaluate the strength of MI communication and compare its performance in the near-field and the far-field. The results show that MI communication in the far-field behaves like electromagnetic wave-based communication, which does not demonstrate the aforementioned advantages. In MI communication system design, if the required communication range is within the near field, we can design very simple and reliable wireless systems, whereas if the required communication range is in the far field, we may need to carefully choose between MI communication and the electromagnetic wave-based communication.

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