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Underground Wireless Communication using Magnetic Induction

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***Abstract*—Underground is a challenging environment for wireless communication since the propagation medium is no longer air but soil, rock and water. The well established wireless communication techniques using electromagnetic (EM) waves do not work well in this environment due to three problems: high path loss, dynamic channel condition and large antenna size. New techniques using magnetic induction (MI) can solve two of the three problems (dynamic channel condition and large antenna size), but may still cause even higher path loss. In this paper, a complete characterization of the underground MI communication channel is provided. Based on the channel model, the MI waveguide technique for communication is developed in order to reduce the MI path loss. The performance of the traditional EM wave systems, the current MI systems and our improved MI waveguide system are quantitatively compared. The results reveal that our MI waveguide system has much lower path loss than the other two cases for any channel conditions.**

I. Introduction

Underground wireless communication enables a wide variety of novel applications, including soil condition monitoring, earthquake and landslide prediction, underground infrastructure monitoring, sports-field turf management, landscape management, border patrol and security, and etc [1]. However, underground is a challenging environment for wireless communication [2]. The propagation medium is no longer air but soil, rock and water, where the well established terrestrial wireless communication techniques do not work well.

Traditional techniques using electromagnetic (EM) waves encounter three major problems in underground environments: high path loss, dynamic channel condition and large antenna size [2]. First, EM waves experience high levels of attenuation due to absorption by soil, rock, and water in the underground. Second, the path loss is highly dependent on numerous soil properties such as water content, soil makeup (sand, silt, or clay) and density, and can change dramatically with time (e.g., increased soil water content after a rainfall) and space (soil properties change dramatically over short distances). Consequently, the bit error rate (BER) of the communication system also varies dramatically in different time or position. The unreliable channel brings design challenges for the underground devices and networks to achieve both satisfying connectivity and energy efficiency. Third, there exist conflicts in antenna design for underground communication using EM waves. On the one hand, antenna size is expected to be as small as possible to ease the deployment of the networks. On the other hand, operating frequencies in MHz or lower ranges are necessary to achieve practical transmission range [1]. To efficiently transmit and receive signals at that frequency, the antenna size is too large to be deployed in the soil.

Magnetic induction (MI) is a promising alternative physical layer technique for underground wireless communication. It solves the dynamic channel condition problem and large antenna size problem of the EM wave techniques. Specifically, the dense medium such as soil and water cause little variation in the attenuation rate of magnetic fields from that of air, since the magnetic permeabilities of each of these materials are similar [1], [3], [4]. This fact guarantees that the MI channel conditions remain constant. Moreover, the MI communication solves the issue of antenna size since the transmission and reception are accomplished with the use of a small coil of wire. No lower limit of the coil size is required. However, MI is generally unfavorable for terrestrial wireless communication since magnetic field strength falls off much faster than the EM waves [5], [6]. In underground environment, although the path loss of MI caused by the soil absorption is much less than the EM waves, the total path loss may still be higher.

In this paper, we first provide a complete characterization of the underground MI communication channel. Based on the analysis, we then present a new technique to effectively reduce the path loss of the MI communication. In particular, the MI transmitter and receiver are modeled as the primary coil and secondary coil of a transformer. We derive the analytical expression of the relationship between the transmitting power and receiving power (i.e., path loss). Multiple factors are considered in the analysis, including the soil properties, coil size, the number of turns in the coil loop, coil resistance and operating frequency. To reduce the high path loss and extend the transmission range, we develop the MI waveguide technique [7], [8], [9] for underground wireless communication. In this case, some small coils are deployed between the transmitter and the receiver as relay points, which form a discontinuous waveguide. The MI waveguide has three advantages in underground wireless communication: first, by carefully designing the waveguide parameters, the path loss can be greatly reduced. Second, the relay coils do not consume

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any energy and the cost is very small. Third, MI waveguide is not a continuous structure hence is very flexible and easy to deploy and maintain. We quantitatively compare the performance of the traditional EM wave systems, the current MI systems and our improved MI waveguide system. The results reveal that our MI waveguide system has much lower path loss than the other two systems for any channel conditions.

The remainder of this paper is organized as follows. In Section II, the underground MI communication channel is completely modeled. In Section III, the MI waveguide technique for underground wireless communication is developed. In Section IV, the performance of the EM wave systems, MI systems and MI waveguide system is evaluated. Finally, the paper is concluded in Section V.

II. MI Channel Model

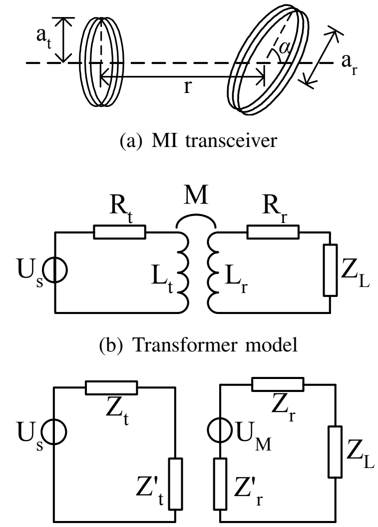
In MI communication, the transmission and reception are accomplished with the use of a coil of wire, as shown in Fig. 1(a), where a_t and a_r are the radii of the transmission coil and receiving coil, respectively; r is the distance between the transmitter and the receiver; and $(90° - \alpha)$ is the angle between the axes of two coupled coils.

Suppose the signal in the transmitter coil is a sinusoidal current, i.e., $I = I_0 \cdot e^{-j\omega t}$, where ω is the angle frequency of the transmitting signal. This current can induce another sinusoidal current in the receiver then accomplish the communication. The relationship between the two coupled coils is represented by the mutual induction. Therefore, the MI transmitter and receiver can be modeled as the primary coil and the secondary coil of a transformer, respectively, as shown in Fig. 1(b), where M is the mutual induction of the transmitter coil and receiver coil; U_s is the voltage of the transmitter's battery; L_t and L_r are the self inductions; R_t and R_r are the resistances of the coil; Z_L is the load impedance of the receiver. We use its equivalent circuit to analyze the transformer, as shown in Fig. 1(c), where,

$$
\begin{aligned}
Z_t &= R_t + j\omega L_t; \quad Z_t' = \frac{\omega^2 M^2}{R_r + j\omega L_r + Z_L};\\
Z_r &= R_r + j\omega L_r; \quad Z_r' = \frac{\omega^2 M^2}{R_t + j\omega L_t};\\
U_M &= -j\omega M \frac{U_s}{R_t + j\omega L_t}. \qquad (1)
\end{aligned}
$$

For wireless communication techniques using EM waves, the Friis transmission equation [10] gives the power received by one antenna, given another antenna some distance away transmitting a known amount of power. In the MI communication case, similarly, our goal is to work out the equation to describe the relationship between the transmitting power P_t and the receiving power (P_r). In the equivalent circuit, it is equal to find the relationship between the power consumed in the primary loop and the power consumed in the load impedance Z_L:

$$
\frac{P_r}{P_t} = \frac{Z_L \cdot U_M^2}{(Z_r' + Z_r + Z_L)^2} \cdot \frac{Z_t + Z_t'}{U_s^2} \qquad (2)
$$



(a) MI transceiver

(b) Transformer model

(c) Equivalent circuit

Fig. 1. MI communication channel model

To maximize the circuit efficiency, the load impedance is designed to be equal to the complex conjugate of the output impedance of the secondary loop, i.e., $Z_L = \overline{Z_r + Z_r'}$. Substitute (1) into (2), then the ratio of the receiving power to the transmitting power is:

$$
\begin{aligned}
\frac{P_r}{P_t} =& \frac{[j\omega M/(R_t + j\omega L_t)]^2}{4R_r + 4R_t\omega^2 M^2/(R_t^2 + \omega^2 L_t^2)}\\
&\cdot \left(R_t + j\omega L_t + \frac{\omega^2 M^2}{2R_r + \omega^2 M^2/(R_t - j\omega L_t)} \right) \qquad (3)
\end{aligned}
$$

The following task is to find the analytical expression for the resistance, self and mutual induction of the transmitter and receiver coils. The resistance is determined by the material, the size and the number of turns of the coil:

$$
R_t = N_t \cdot 2\pi a_t \cdot R_0; \qquad R_r = N_r \cdot 2\pi a_r \cdot R_0 \qquad (4)
$$

where, N_t and N_r are the number of turns of the transmitter coil and receiving coil, respectively; R_0 is the resistance of a unit length of the loop.

Since the coil is modeled as a magnetic dipole, the self induction and mutual induction can be deduced by the magnetic potential A of the magnetic dipole, which is provided in polar coordinate system by [11],

$$
\mathbf{A}(r,\theta,\phi) = \frac{\mu}{4\pi r}\pi a_t^2 I_0 e^{-j\omega t} \sin\theta \left(\frac{1}{r} - j\frac{2\pi}{\lambda} \right) \cdot \hat{\mathbf{a}}_\phi \qquad (5)
$$

where μ is the permeability of the medium (i.e., soil); λ is the wavelength of the signal. By using Stokes' theorem [11], the mutual induction of the two coils can be calculated:

$$
M = \frac{N_r \oint_{\mathbf{l}_r} \mathbf{A} \cdot d\vec{\mathbf{l}}_r}{dI} \simeq \mu\pi N_t N_r \frac{a_t^2 a_r^2}{2r^3} \sin\alpha \qquad (6)
$$

The self induction can be derived in the same way:

$$
L_t \simeq \frac{1}{2}\mu\pi N_t^2 a_t; \qquad L_r \simeq \frac{1}{2}\mu\pi N_r^2 a_r \qquad (7)
$$

By substituting (4), (6) and (7) into (3), we derive the ratio of the receiving power to the transmitting power in MI communication:

$$\frac{P_r}{P_t} \simeq \frac{\omega^2\mu^2 N_t N_r a_t^3 a_r^3 \sin^2\alpha}{8r^6} \cdot \frac{1}{4R_0(2R_0 + \frac{1}{2}j\omega\mu N_t)} \quad (8)$$

If the low-resistance loop, the high signal frequency and the large number of turns are employed ($\omega\mu N_t >> R_0$), then the ratio can be further simplified:

$$\frac{P_r}{P_t} \simeq \frac{\omega\mu N_r a_t^3 a_r^3 \sin^2\alpha}{16 R_0 r^6} \quad (9)$$

It can be observed from (9) that the receiving power loss is a 6^{th}-order function of the transmission range r. Higher signal frequency ω, larger number of turns N, lower loop resistance R_0 and larger coil size a can enlarge the receiving power. The angle between the axes of two coupled coils also affects the receiving power: the smaller the angle is, the higher the power is received. It should be noted that the receiving power is not affected by the environmental conditions. It is because that only one environment parameter μ exists in (9) and the permeability μ of soil and water is similar to that of the air.

We compare (9) with the Friis transmission equation for the EM wave communication [11], where

$$\frac{P_r}{P_t} \simeq G_t G_r \left(\frac{\lambda}{4\pi r}\right)^2 = G_t G_r \frac{\pi}{4\mu\varepsilon\omega^2 r^2}. \quad (10)$$

It shows that the higher operating frequency induces higher path loss in the EM wave case but achieves lower attenuation rate in the MI case. The receiving power of MI communication attenuates much faster than the EM wave case ($1/r^6$ vs. $1/r^2$). However, the permittivity ε in (10) is much larger in soil than that in the air. Furthermore, ε varies a lot in different times and locations. Hence, the path loss of EM waves is dramatically influenced by those environmental conditions. To sum up, the most obvious characteristics of the two physical layer techniques can be explained as follows: the MI technique has constant channel condition while the EM wave technique provides lower attenuation rate. The performance of EM wave systems and MI systems are quantitively compared in Section IV.

III. MI Waveguide for Underground Communication

Although the MI technique solves the dynamic channel condition problem and large antenna size problem of the EM wave techniques, its receiving power loss is much higher than in the EM wave case as discussed in the previous section. For practical applications, one solution is to employ some relay points between the transmitter and the receiver.

Different from the relay points using the EM wave technique, the MI relay point is just a simple coil without any energy source or processing device. The sinusoidal current in the transmitter coil induces a sinusoidal current in the first relay point. This sinusoidal current in the relay coil then induces another sinusoidal current in the second relay point, and so on and so forth. Those relay coils form an MI waveguide in underground environments, which act as a waveguide that guides the so-called *MI waves*.

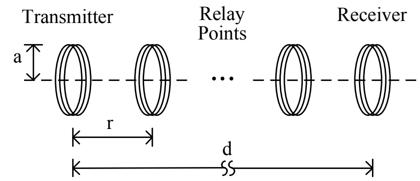


Fig. 2. MI waveguide structure

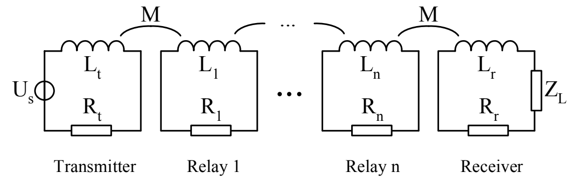


Fig. 3. Transformer model of the MI waveguide

A typical MI waveguide structure is shown in Fig. 2, where, n relay coils equally spaced along one axis between the transmitter and the receiver; r is the distance between the neighbor coils; d is the distance between the transmitter and the receiver and $d = (n+1)r$; a is the radius of the coils. In fact, there exists mutual induction between any pair of the coils. The value of the mutual induction depends on how close the coils are to each other. In underground communication, the practical distance between two relay coils is around 1 m and the coil radius is no more than 0.1 m. Therefore we assume that the coils are sufficiently far from each other and only interact with the nearest neighbors. Hence, only the mutual induction between the adjacent coils needs to be taken into account.

Similar to the strategy in section II, the MI waveguide is modeled as a multi-stage transformer, where only adjacent coils are coupled, as shown in Fig. 3. Since in practical applications, the transceivers and the relay points usually use the same type of coils, we assume that all the coils have the same parameters (resistance, self and mutual inductions). By utilizing the equivalent circuit of the transformer, the ratio of the receiving power to the transmitting power can be derived:

$$\frac{P_r}{P_t} \simeq \frac{(\frac{j\omega M}{R+j\omega L})^2}{4R + \frac{4R\omega^2M^2}{R^2+\omega^2L^2}} \left(R + j\omega L + \frac{\omega^2M^2}{2R + \frac{\omega^2M^2}{R-j\omega L}}\right) \cdot \left(\frac{j\omega M}{R + j\omega L + \frac{\omega^2M^2}{R-j\omega L}}\right)^{2n} \quad (11)$$

By substituting (4), (6) and (7) into (11), we derive the path loss of the MI waveguide:

$$\frac{P_r}{P_t} \simeq \frac{\omega^2\mu^2N^2a^6}{8r^6} \frac{1}{4R_0(2R_0 + \frac{1}{2}j\omega\mu N)} \cdot \left[\frac{j}{\frac{4R_0}{\omega\mu N}(\frac{r}{a})^3 + j(\frac{r}{a})^3 + \frac{\omega\mu N}{4R_0+j\omega\mu N}(\frac{a}{r})^3}\right]^{2n} \quad (12)$$

Under the condition that high signal frequency and large number of turns are employed ($\omega\mu N >> R_0$), equation (12) can be further simplified:

$$\frac{P_r}{P_t} \simeq \frac{\omega\mu N}{16R_0}\left(\frac{a}{r}\right)^{6n} = \frac{\omega\mu N}{16R_0}\left[\frac{a}{d}(n+1)\right]^{6n} \tag{13}$$

It is shown in (13) that the transmission range d is divided into $n+1$ intervals with length r. However, the path loss becomes a $6n^{th}$-order function of the relay interval r. Hence, to reduce the path loss of the MI waveguide, the relay interval r needs to be on par with the coil size to make the term a/r approximately 1. It means that if the coils with a radius of 0.1 m are utilized, we need to deploy this kind of coils every 0.1 m, which is infeasible in underground communication considering the deployment difficulty. Consequently, the simple relay coils cannot reduce the path loss.

By analyzing (12), we find that if the last term with exponent $2n$ is converged to a value around 1, the MI waveguide path loss can be greatly reduced. Fortunately, we can achieve this goal by adding a capacitor in each coil and carefully designing the capacitor value, the operating frequency and the number of turns in the coil. We assume that each coil is loaded with a capacitor C, then the ratio of the receiving power to the transmitting power of the MI waveguide is:

$$\frac{P_r}{P_t} = \frac{\omega^2\mu^2N^2a^6/4r^6}{(2R_0 + j\frac{\omega\mu N}{2} + \frac{1}{j\omega CN\pi a})(4R_0 + \frac{\omega^2\mu^2N^2a^6/4r^6}{2R_0 - j\frac{\omega\mu N}{2} - \frac{1}{j\omega CN\pi a}})}$$
$$\cdot\left[\frac{j}{\frac{4R_0r^3}{\omega\mu Na^3} + j(\frac{r}{a})^3 - j\frac{2(\frac{r}{a})^3}{\omega^2\mu CN^2\pi a} + \frac{\omega\mu N(\frac{a}{r})^3}{4R_0 + j\omega\mu N + \frac{2}{j\omega CN\pi a}}}\right]^{2n} \tag{14}$$

By assigning the capacitor C an appropriate value, the self-induction term can be neutralized. Then the term with exponent $2n$ can be greatly diminished. Specifically, we set the value of the capacitor C to be:

$$C = \frac{2}{\omega^2N^2\mu\pi a} \tag{15}$$

Then the MI waveguide path loss becomes:

$$\frac{P_r}{P_t} = \frac{\omega^2\mu^2N^2a^6/4r^6}{2R_0(4R_0 + \frac{\omega^2\mu^2N^2a^6}{2R_0\cdot 4r^6})}\cdot\left[\frac{j}{\frac{4R_0}{\omega\mu N}(\frac{r}{a})^3 + \frac{\omega\mu N}{4R_0}(\frac{a}{r})^3}\right]^{2n} \tag{16}$$

After that, the operating frequency and the number of turns are designed to further reduce the path loss. In particular, if

$$\frac{\omega\mu N}{4R_0}(\frac{a}{r})^3 = 1, \tag{17}$$

then

$$\frac{P_r}{P_t} = \frac{1}{3}\left(\frac{1}{2}\right)^{2n}. \tag{18}$$

From (18), we find that the MI waveguide path loss is greatly reduced compared with current MI techniques and the traditional EM wave techniques. The path loss is a function of the number of the relay point n. Larger n may cause higher path loss. n is determined by the transmission distance d and the relay interval r. The longer r is, the lower the path loss would be. r is expected to be as large as possible but restricted by (15) and (17). Specifically, in (17), the relay interval r and the coil size a determine the operating frequency ω and the number of turns N. In (15), the capacitor value C is determined by a, N and ω. Hence, when designing the relay interval, we need to guarantee that the operating frequency, the number of turns and the capacitor value can be assigned feasible and appropriate values. We assume that the operating frequency is several hundred MHz and the coil radius is 0.1 m. Under these conditions, the relay interval around 1 m can satisfy the above requirements.

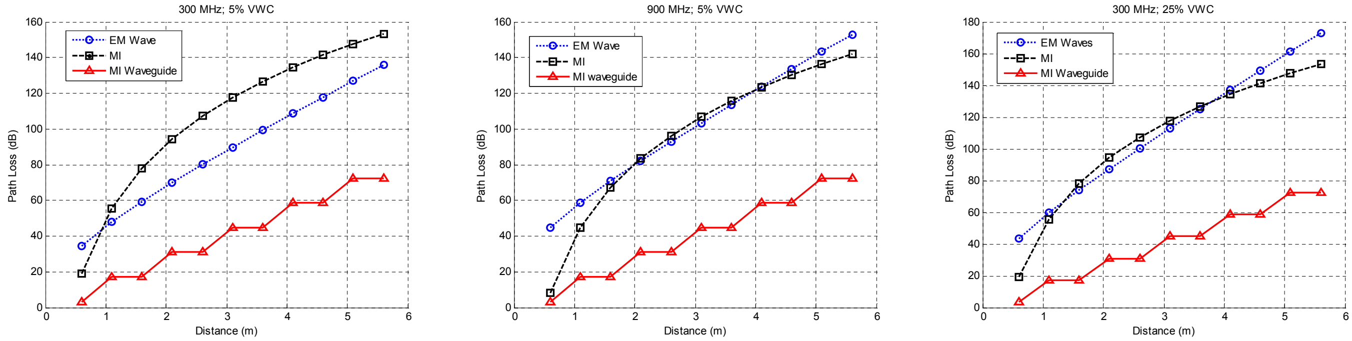
IV. Evaluation

In this section, we use MATLAB to compare the performance of the traditional EM wave technique, the current MI technique and the improved MI waveguide technique for wireless underground communication. For EM wave propagation in soil, we utilize the channel model developed in [2]. For MI and MI waveguide systems, the models described in Section II and Section III (equation (9) and (18)) are used.

Except studying the effects of certain parameters, the default values are set as follows: the volumetric water content (VWC) is 5% and the operating frequency is 300 MHz. The transmitter, receiver and relay coil all have the same radius of 0.1 m. The coil is made of copper wire with a 0.1 mm diameter (AWG 38). Hence the resistance of unit length R_0 can be calculated as 2.16 Ω/m. The permeability of soil medium is the same as that in the air, which is $4\pi \times 10^{-7}$ H/m. The relay interval r of the MI waveguide is 1 m. The number of relay coils n is determined by the transmission distance d, where $n = \lceil d/r \rceil$.

First, in Fig. 4(a), the path loss of the three techniques using 300 MHz signal in soil with 5% VWC is shown in dB versus the transmission distance d. It can be seen that in the very near region ($d < 1$ m), the MI technique has smaller path loss than the EM wave technique. However, as the transmission distance increases, the MI signal attenuates much faster than the EM wave signal. It may have up to 20 dB higher path loss than that of the EM wave signal. As expected, the MI waveguide technique greatly reduces the signal path loss compared to the other two techniques. It shows that the MI waveguide transceivers only need less than 50% of the energy consumed by the MI or EM wave transceivers to communicate in a certain range.

Then, we keep the VWC of soil the same and increase the operating frequency to 900 MHz. Fig. 4(b) shows the path loss of the three techniques using 900 MHz signal in soil with 5% VWC. On the one hand, the path loss of EM wave system slightly increases. The increase can be explained by (10) where the operating frequency ω is in the denominator. Because the material absorption is the major part of the EM wave path loss in soil, the attenuation caused by the higher operating frequency is not so dramatical. On the other hand, the path loss of MI system decreases as the operating frequency increases,



(a) 300 MHz signal in soil with 5% VWC (b) 900 MHz signal in soil with 5% VWC (c) 300 MHz signal in soil with 25% VWC

Fig. 4. Path loss of the three techniques using different operating frequency in soil with different VWC.

which can be explained by equation (9) where the operating frequency ω is in the numerator. Hence it can be concluded that with high operating frequency, the path loss of EM wave system becomes higher than that of the MI system. The path loss of the MI waveguide system remains the lowest when high operating frequency is used. From the discussion in Section III, we find that the operating frequency does not affect the path loss but will influence the design of the capacitor value and the number of turns of the coil. Higher operating frequency requires lower number of turns or lower capacitor value.

Finally, we analyze the influence of the underground environment on the three propagation techniques. For MI and MI waveguide systems, we have demonstrated in the previous sections that the performance is not affected by the environment since the permeability μ remains the same, no matter the medium is air, water or soil. From the channel models of EM waves in soil [2], we note that the water content is the major environmental parameter that influences the EM wave propagation in soil. Therefore, we investigate the path loss of the three techniques in soil with higher water content (25% VWC) in Fig. 4(c). As expected, the path loss of the MI and MI waveguide system remain the same as that in soil with lower water content. However, the path loss of EM wave system increases dramatically (up to 40 dB) in soil with higher water content.

V. Conclusion

In wireless underground communication, traditional techniques using EM waves encounter three major problems: high path loss, dynamic channel condition and large antenna size. MI is an alternative technique that can solve two of the three problems: the dynamic channel condition problem and large antenna size problem, however, the high path loss problem is even worse in the MI case. In this paper, we provide an analytical model to characterize the underground MI communication channel. Based on the channel model, we develop the MI waveguide technique to solve the high path loss problem. Our analysis shows that:

- The MI technique has constant channel condition because its path loss only depends on the permeability of the propagation medium, which remains the same, no matter the medium is air, water or soil. However, the path loss of EM wave depends on the permittivity of the transmission medium, which may change a lot in different soil conditions.
- The path loss of the MI system is a 6^{th}-order function of the transmission range, while that of the EM wave system is a 2^{nd}-order function of the range. As operating frequency increases, the path loss of the MI system decreases but that of EM wave system increases. Usually the EM wave system has lower path loss than the MI system. However, it is not constantly true if high frequency signal is used in the soil with high water content.
- The MI waveguide technique can greatly reduce the path loss, which is attributed to the relay coils deployed between the transceivers. It should be noted that the relay coils do not consume any energy and the cost is very low.

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