Magnetic Induction Communications for Wireless Underground Sensor Networks

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***Abstract*—The main difference between the wireless underground sensor networks (WUSNs) and the terrestrial wireless sensor networks is the signal propagation medium. The underground is a challenging environment for wireless communications since the propagation medium is no longer air but soil, rock and water. The well established wireless signal propagation 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) create constant channel condition and can accomplish the communication with small size coils. In this paper, detailed analysis on the path loss and the bandwidth of the MI system in underground soil medium is provided. Based on the channel analysis, the MI waveguide technique for communication is developed in order to reduce the high path loss of the traditional EM wave system and the ordinary MI system. The performance of the EM wave system, the ordinary MI system and our improved MI waveguide system are quantitatively compared. The results reveal that the transmission range of the MI waveguide system is dramatically increased.**

***Index Terms*—Channel modeling, magnetic induction (MI), MI waveguide technique, underground communication, wireless sensor networks.**

I. Introduction

Wireless underground sensor networks (WUSNs) enable a wide variety of novel applications [1], [2], including soil condition monitoring, earthquake and landslide prediction, underground infrastructure monitoring, sports-field turf management, landscape management, border patrol and security, and etc. However, underground is a challenging environment for wireless communication [3]. The propagation medium is no longer air but soil, rock and water, where the well established wireless propagation techniques for terrestrial wireless sensor networks do not work well.

Traditional wireless communication techniques using electromagnetic (EM) waves encounter three major problems in underground environments: the high path loss, the dynamic channel condition and the large antenna size [3]. In particular, first, EM waves experience high levels of attenuation due to absorption by soil, rock, and water in the underground. Since the WUSN devices have very limited radio power due to the energy constraint, the transmission range between two sensor nodes using EM waves is very small (no more than 4 m). 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 location (soil properties change dramatically over short distances). Consequently, the bit error rate (BER) of the communication system also varies dramatically in different times or positions. The unreliable channel brings design challenges for the sensor devices and networks to achieve both satisfying connectivity and energy efficiency. Third, large size antenna is necessary for the efficient propagation of EM waves. Path loss can be reduced if lower operating frequencies are used. The lower the frequency is, the larger the antenna must be to efficiently transmit and receive EM waves [4], which obvious conflicts with the necessity that underground sensors remain small.

If the sensors of WUSNs are buried in the shallow depth, sensor can communicate with the aboveground data sinks directly using EM waves. This is because the underground path is short in this case. Hence the impacts of the additional path loss and the dynamic channel caused by the soil medium are much smaller. However, many WUSN applications, such as underground structure monitoring, require the sensors buried deep underground, where only underground-to-underground channel is available.

Magnetic induction (MI) is a promising alternative physical layer technique for WUSNs in deep burial depth. It can address the problems on the dynamic channel condition and the large antenna size of the EM waves techniques. Specifically, the underground 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 [2], [5], [6]. This fact guarantees that the MI channel conditions remain constant for a certain path in different times. Moreover, in the MI communication, the transmission and reception are accomplished with the use of a small size coil of wire. In addition, since the radiation resistance of coil is much smaller than electric dipole, very small portion of energy is radiated to the far field by the coil. Hence, the multi-path fading is not an issue for MI communication. However, MI is generally unfavorable for terrestrial wireless communication. As the transmission distance r increases, magnetic field strength falls off much faster $(1/r^3)$ than the EM waves $(1/r)$ in terrestrial environments. In underground environments, although it is known that the soil absorption causes high signal attenuation in the EM wave systems but does not affect the MI systems, it is not clear whether the total path loss of the MI system is lower than the EM wave

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system or not. Additionally, since the MI communication involves reactance coils as antenna, the system bandwidth needs to be analyzed.

In this paper, we first provide a detailed analysis on the path loss and the bandwidth of the MI communication channel in underground environments. Then based on the analysis, we develop the MI waveguide technique for WUSNs, which can significantly reduce the path loss, enlarge the transmission range and achieve practical bandwidth for MI communication in underground environments. In particular, the MI transmitter and receiver are modeled as the primary coil and secondary coil of a transformer. Multiple factors are considered in the analysis, including the soil properties, coil size, the number of turns in the coil loop, coil resistance, operating frequency. The analysis shows that the ordinary MI systems have larger transmission range but lower bandwidth than the EM wave systems. However, neither the ordinary MI system nor the EM wave system is able to provide enough communication range for practical WUSNs applications. Motivated by this fact, we develop the MI waveguide technique [7] to enlarge the communication range. In this case, some small coils are deployed between the transmitter and the receiver as relay points, which form a discontinuous waveguide.

The remainder of this paper is organized as follows. In Section II, the related work is introduced. Then in Section III, the path loss and the bandwidth of the underground MI communication system is analyzed. In Section IV, the MI waveguide technique for underground wireless communication is developed. Finally, the paper is concluded in Section V.

II. Related Work

The propagation characteristics of EM waves in underground environments (soil, water and rock) have been presented in [3]. The analysis shows that the path loss is much higher than the terrestrial case due to the material absorption. The communication success significantly depends on the composition of the soil and the operating frequency. Since lower operating frequency achieves lower path loss but requires larger antenna size, a middle course solution is proposed, where the 0.3 m long antenna is used to transmit and receive signals at 300 MHz. The transmission range is around 4 m, which is still too short for efficient deployment of WUSNs. The theoretical analysis of [3] has been validated by the testbed developed in [8].

Recently, the magnetic induction has been introduced as a new physical layer technique for wireless communication. However it suffers from the high path loss and low bandwidth problems. In [6], MI communication is employed in the mine warfare (MIW) operations to provide a more reliable wireless command, control and navigation channel. The EM channel is qualitatively analyzed and the low data rates of 100 to 300 bit/s are achieved in various MI communication experiments carried out in coastal areas. The authors notice that the high path loss limits the transmission range. They suggest to place more MI transceivers to mitigate the high path loss, which is not feasible for underground wireless networks due to cost/energy constraint and deployment difficulty.

In [9]–[11], the MI is utilized as an alternative personal communication technique to the Bluetooth. In the near-field communication applications (such as the link between a cell phone or an MP3 player and a headset), the rapid fall off of the MI signal strength is exploited to provide each user with his own private bubble, without having to worry about mutual interference among multiple users, and permitting bandwidth reuse. However, in the underground communication applications, the high path loss is obviously not an advantage.

In [5], the MI is first introduced to the field of wireless underground communication. It shows that the MI transmission is not affected by soil type, composition, compaction, or moisture content, and requires less power and lower operating frequencies than RF transmission. However, the theoretical/experimental results show that the communication range is no more than 30 inches (0.76 m). Moreover, the bandwidth of the MI system is not considered in the paper.

Besides underground, the MI communication can also be used in other RF-impenetrable environments, such as human body. In [12], a body network is built to collect data from, and transport information to, implanted miniature devices at multiple sites within the human body. The MI technique is employed to link information between a pair of implants, and to provide electric power to these implants. In [13], a new magnetic material is analyzed to guide magnetic information to the receiver coil, permitting a clear image deep within the body.

In [7], [14], [15], the MI waveguide is investigated. It is shown that an array of loops can act as a waveguide, propagating a new form of wave known as a MI wave. Up to now, the MI waveguide has been designed and used as artificial delay lines and filters, dielectric mirrors, distributed Bragg reflectors, slow-wave structures in microwave tubes, coupled cavities in accelerators, modulators, etc. However, there is no attempt to utilize the MI waveguide in the wireless communication field. The theoretical analysis of the MI waveguide in [14] is validated by experiments in [16]. Note that we adopt similar theoretical analysis method as [14] in this paper.

Currently, there is no solution to address the low communication range problem of both the EM wave technique and the MI technique in underground environments. Also no theoretical analysis on underground MI communications is provided. In this paper, we provide a detailed analysis on the path loss and bandwidth of the underground MI communications. Based on the analysis, we develop the MI waveguide communication technique to enlarge the transmission range of the MI systems in underground environments.

III. MI Channel Characteristics

A. System Modeling

In MI communications, the transmission and reception are accomplished with the use of a coil of wire, as shown in the first row in Fig. 1, 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.

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. $\omega = 2\pi f$ and f is the system operating frequency. This current can induce another sinusoidal current in the receiver then accomplish the communication. The interaction

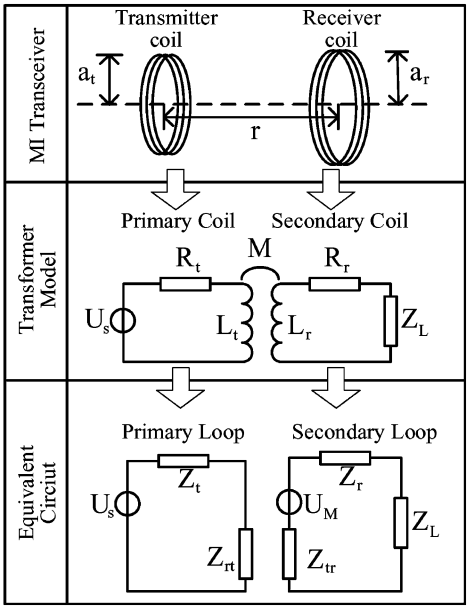

Fig. 1. MI communication channel model.

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 the second row in Fig. 1, 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 the third row in Fig. 1, where

$$\begin{aligned} Z_t &= R_t + j\omega L_t \\ Z_{rt} &= \frac{\omega^2 M^2}{R_r + j\omega L_r + Z_L} \\ Z_r &= R_r + j\omega L_r \\ Z_{tr} &= \frac{\omega^2 M^2}{R_t + j\omega L_t} \\ U_M &= -j\omega M \frac{U_s}{R_t + j\omega L_t} \end{aligned} \tag{1}$$

where Z_t and Z_r are the self impedances of the transmitter coil and the receiver coil, respectively; Z_{rt} is the influence of the receiver on the transmitter while Z_{tr} is the influence of the transmitter on the receiver; U_M is the induced voltage on the receiver coil.

In the equivalent circuit, the transmitting power is equal to the power consumed in the primary loop. The receiving power is equal to the power consumed in the load impedance Z_L. Both received power and transmitting power are functions of the transmission range r

$$\begin{aligned} P_r(r) &= Re\left\{ \frac{Z_L \cdot U_M^2}{(Z_r' + Z_r + Z_L)^2} \right\} \\ P_t(r) &= Re\left\{ \frac{U_s^2}{Z_t + Z_t'} \right\}. \end{aligned} \tag{2}$$

According to the transmission line theory, the reflections take place unless the line is terminated by its matched impedance. In the equivalent circuit described in Fig. 1, to maximize the received power, the load impedance is designed to be equal to the complex conjugate of the output impedance of the secondary loop, i.e.,

$$Z_L = \overline{Z_r + Z_r'}. \tag{3}$$

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

$$\begin{aligned} R_t &= N_t \cdot 2\pi a_t \cdot R_0 \\ R_r &= N_r \cdot 2\pi a_r \cdot R_0 \end{aligned} \tag{4}$$

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. According to American Wire Gauge (AWG) standard, R_0 can be a value from $2 \times 10^{-4}\ \Omega/\mathrm{m}$ to $3\ \Omega/\mathrm{m}$ with different wire diameter [17].

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 [18]

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

where μ is the permeability of the transmission medium; λ is the wavelength of the signal. By using Stokes' theorem [18], the mutual induction of the two coils can be calculated

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

The self induction can be derived in the same way

$$\begin{aligned} L_t &\simeq \frac{1}{2}\mu\pi N_t^2 a_t \\ L_r &\simeq \frac{1}{2}\mu\pi N_r^2 a_r. \end{aligned} \tag{7}$$

Consequently, by substituting (1), (3), (4), (6) and (7) into (2), the received power and the transmitting power can be calculated.

It should be noted that, the underground transmission medium contains different type of soil, water, rocks and etc. It is necessary to analyze the differences between the permeabilities of these materials. According to [19], the substances of the underground medium can be categorized into four main groups including organic materials, inorganic materials, air, and water, where organic materials come from plants and animals; inorganic materials include sand, silt and clay. The relative permeabilities of the plants, animals, air and water are very close to 1. If the sand, silt, and clay do not consist of magnetite, their permeabilities are also close to 1. An example is that the average value for sedimentary rocks is given in [19] as 1.0009. Since most soil in the nature does not contain magnetite, we can assume that the permeability of the underground transmission medium is a constant based on the above discussion.

B. Path Loss

For wireless communication using EM waves, the Friis transmission equation [20] gives the power received by one antenna, given another antenna some distance away transmitting a known amount of power. Since the radiation power is the major consumption of the EM wave transmitter, the transmitting power of the EM wave system is a constant and not influenced by the position of the receiver, i.e. for EM waves, P_r is a function of distance r while P_t is a constant. Hence the path loss is measured by the ratio of the received power to the radiation power. The path loss L_{EM} of the EM wave propagation in soil medium is given by [3]

$$\begin{aligned} L_{EM}(r) =& -10\lg\frac{P_r(r)}{P_t} \\ =& 6.4 + 20\lg r + 20\lg\beta + 8.69\alpha r \end{aligned} \tag{8}$$

where the transmission distance r is given in meters; the attenuation constant α is in 1/m and the phase shifting constant β is in radian/m. The values of α and β depend on the dielectric properties of soil, and is derived in [3, (8)–(14)] using the Peplinski principle [21]. Note that the reflection from the air-ground interface is neglected since the burial depth is large, which has been explained in [3].

Unlike the EM wave transmitter, the radiation power of the MI communication system can be neglected since the radiation resistance is very small. Meanwhile, the induced power consumed at the MI receiver is the major power consumption since the MI communication is achieved by coupling in the non-propagating near-field. The transmitting power of the MI system consists of the induced power consumed at the MI receiver and the power consumed in the coil resistance. If the coil resistance is small, the ratio of the received power to the transmitting power will be close to 1 since the receiving power and transmission power decrease simultaneously as the transmission distance increases. The advantage of this feature is that the limited transmission power won't be wasted on radiation to the surrounding space. Most power is transmitted to the receiver, which is favorable to the energy constrained WUSNs. However, as the transmission distance increases, less and less power is transmitted to the receiver. Hence there still exists a so called *Path loss*. It should be noted that the power is not really lost but in fact not transmitted. To fairly compare the performance of the EM wave system and MI system, the path loss of the MI system with transmission distance r is defined as $L_{MI}(r) = -10\lg(P_r(r)/P_t(r_0))$, where $P_r(r)$ is the received power at the receiver that is r meters away from the transmitter; $P_t(r_0)$ is the reference transmitting power when the transmission distance is a very small value r_0. We can consider that $P_t(r_0) \simeq U_s^2/R_t$ if r_0 is small enough. In case of low coil resistances and high operating frequency $(R_0 \ll \omega\mu)$, the path loss of the MI communication system can be simplified as

$$\begin{aligned} L_{MI}(r) =& -10\lg\frac{P_r(r)}{P_t(r_0)} \simeq -10\lg\frac{N_r a_t^3 a_r^3}{4N_t r^6} \\ =& 6.02 + 60\lg r + 10\lg\frac{N_t}{N_r a_t^3 a_r^3}. \end{aligned} \tag{9}$$

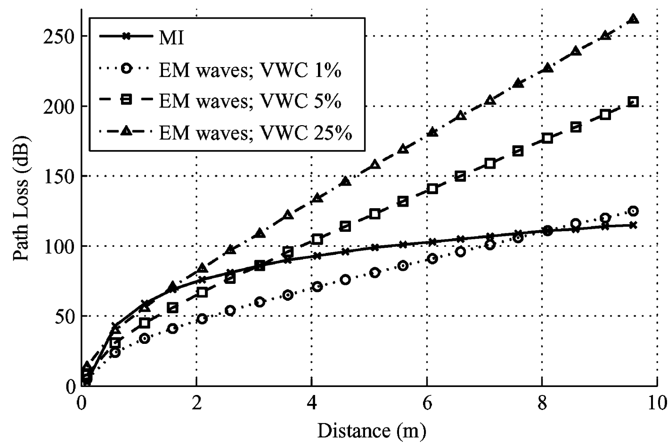

Fig. 2. Path loss of the EM wave system and the MI system with different soil water content.

We compare (8) with (9) to analyze the path loss of MI and EM wave systems in underground environments. In (8), there are two terms in the path loss that are determined by the distance r, where the term $(20\lg r)$ is due to the space spread and the term $(8.69\alpha r)$ is due to the material absorption. The transmission medium has significant influence in the path loss since it determines the propagation constants α and β. In (9), only one term $(60\lg r)$ is determined by the distance r, which is due to the spread of the magnetic field. The transmission medium has no obvious influence on the MI path loss since we assume that the permeability of the medium is a constant as discussed in the beginning. Although the path loss term $(60\lg r)$ in MI case is much higher than the term $(20\lg r)$ in EM waves case, it is not clear whether the total path loss of MI system is larger than that of the EM wave system or not, since the material absorption term $(8.69\alpha r)$ in EM wave path loss varies a lot in different transmission medium.

C. Numerical Analysis

1) Path Loss: The path losses of the MI system and the EM wave system shown in (8) and (9) are evaluated using MATLAB. The results are shown in Fig. 2. According to [3], the propagation of the EM waves in soil medium is severely affected by the soil properties, especially, the volumetric water content (VWC) of soil. Hence in the evaluations, we set the VWC of the soil medium as 1%, 5% and 25% The permittivity and conductivity of soil medium is calculated by the Peplinski principle [3, (8)–(12)], which are functions of VWC and soil composition. In our simulations, besides VWC, the soil composition is set as follows, the sand particle percent is 50%, the clay percent is 15%, the bulk density is 1.5 $\mathrm{grams/cm^3}$, and the solid soil particle density is 2.66 $\mathrm{grams/cm^3}$, which are typical values in nature. As discussed in the beginning, the permeability of the underground transmission medium is a constant and is the same as that in the air, which is $4\pi \times 10^{-7}$ H/m. Other simulation parameters are set as follows: for EM wave system, the operating frequency is set to 300 MHz. The reason for this choice is as follows: on the one hand, lower frequency bands are necessary for acceptable path loss. On the other hand, decreasing operating frequency below 300 MHz increases the antenna size, which

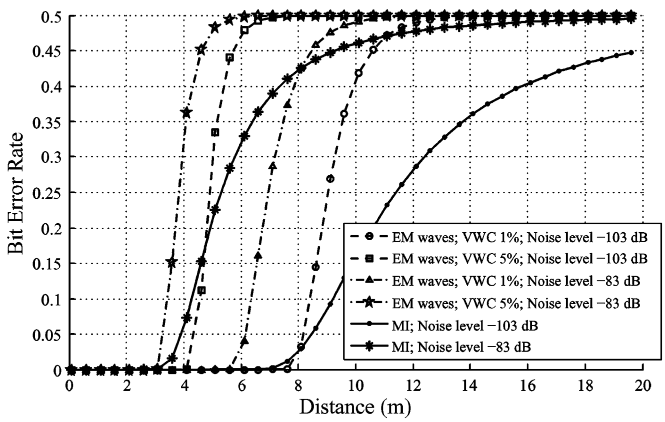

Fig. 3. Bit error rate of the EM wave system and the MI system with different soil water content and noise level.

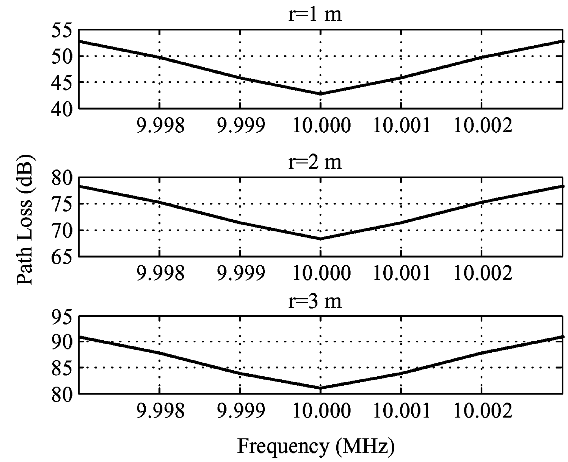

Fig. 4. Frequency response of the MI system with different transmission range.

can also prevent practical implementation of WUSNs. For MI system, the transmitter and the receiver coil have the same radius of 0.15 m and the number of turns is 5. The coil is made of copper wire with a 1.45 mm diameter. Hence the resistance of unit length R_0 can be looked up in AWG standard [17] as 0.01 Ω/m. The operating frequency is set to 10 MHz. This low operating frequency together with the small number of turns can effectively mitigate the influence of the parasitic capacitance [22].

In Fig. 2, the path losses of the MI system and EM wave system are shown in dB versus the transmission distance r with different soil VWC. As expected, the path loss of the MI system is not affected by the environment since the permeability μ remains the same. On the other hand, the path loss of the EM wave system dramatically increases as the VWC increases. When the soil is very dry $(\mathrm{VWC} = 1\%)$, the path loss of the EM waves is smaller than that of the MI system. When the soil is very wet $(\mathrm{VWC} = 25\%)$, the path loss of the EM waves is significant larger than that of the MI system. When $\mathrm{VWC} = 5\%$, the path losses of these two systems are similar. It can be seen that the path loss of the MI system is a lg function of the distance r while the path loss of the EM wave system is an approximately linear function of the distance r. This is because that the path loss caused by material absorption is the major part in the EM waves' propagation. When $\mathrm{VWC} = 5\%$, in the near region between 0.5 m and 3 m, the EM wave system has smaller path loss; in the relatively far region $(r > 3~\mathrm{m})$, the MI system has smaller path loss than the EM wave system. Even in the very dry soil medium $(\mathrm{VWC} = 1\%)$, the MI system can achieve smaller path loss than the EM wave system after a sufficient long transmission distance.

2) Bit Error Rate: Furthermore, we investigate the bit error rate (BER) characteristics of the two propagation techniques. The results are shown in Fig. 3. The BER characteristic depends mainly on three factors: 1). the path loss, 2). the noise level and 3). the modulation scheme used by the system. The path loss of the MI system and the EM wave system has been given in (8) and (9). The noise power in soil is measured using the BVS YellowJacket wireless spectrum analyzer [23] in [3]. The average noise level P_n is found to be -103 dBm. Besides the experiment measurement, we also assume a high noise scenario where the average noise level P_n is set to be -83 dBm. Then the signal to noise ratio (SNR) can be calculated by $SNR = P_t - L - P_n$, where P_t is the transmitting power and L is the path loss given in (8) and (9). We set P_t as 10 dBm in the simulation. Considering the modulation scheme as the simple but widely used $2PSK$, the BER can be derived as a function of SNR: $BER = 0.5erfc(\sqrt{SNR})$, where $erfc(\cdot)$ is the error function [24].

In Fig. 3, the BERs of the MI system and EM wave system are shown as a function of the transmission distance r with different soil VWC. In low noise scenario, the transmission range of the MI system is larger than the EM wave system no matter what VWC is, which can be explained by the following reasons: 1) path loss below 100 dB cannot influence the BER performance when the noise is low. 2) The MI system has higher path loss than the EM wave system at the near region where the path losses of both systems are below 100 dB; while in the far region where the path losses are higher than 100 dB, the MI system has lower path loss. 3) It is the path loss in the far region that determines the transmission range. In the high noise scenario, the transmission range of MI system is between the range of EM wave system in dry soil and the system in wet soil, since this time the path loss above 80 dB can influence the BER performance.

3) Bandwidth: It should be noted that, the path loss of the MI system derived above is based on the assumption that the load impedance is designed to be equal to the complex conjugate of the output impedance of the secondary loop. However, since the output impedance of the secondary loop consists of not only resistance but also reactance, only one central frequency can realize this load matching. Any deviation from the central frequency will cause the power reflections and increase the path loss. Hence it is necessary to analyze the bandwidth of the MI system. In Fig. 4, the frequency response of the MI system described above is shown with different transmission distance. It indicates that the 3-dB bandwidth of the MI system is around 2 KHz when the operating frequency is 10 MHz. The bandwidth is not affected by the transmission distance. Although the 2 KHz bandwidth is much smaller than the EM wave system, it should be enough for the WUSNs considering that the underground sensing and monitoring applications do not require very high data rate [2].

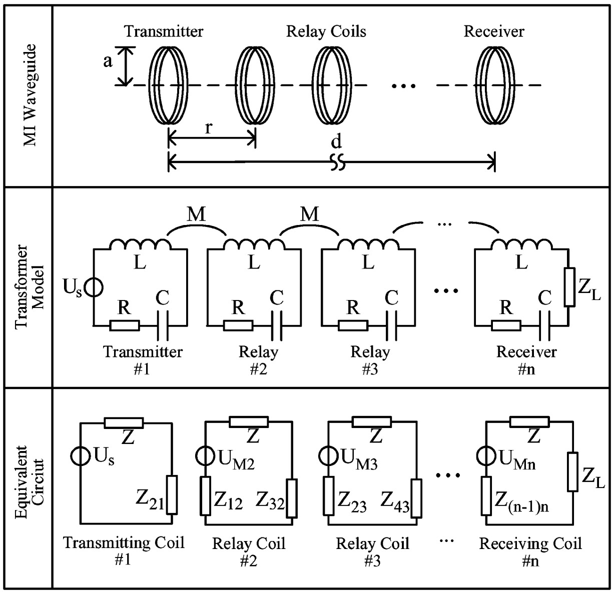

Fig. 5. MI waveguide communication channel model.

To sum up, the MI system provides larger transmission range (around 10 m) than that of the EM wave system (around 4 m). The MI system also has the advantage that its performance is not influenced by the soil medium properties, especially the water content. Although the bandwidth of the MI system is smaller than that of the EM wave system, it should to a large extent fulfill the requirements of the WUSNs applications. However, the transmission ranges of both systems are still too short for a practical applications in underground medium.

IV. MI Waveguide for Underground Communication

Although the ordinary MI system has constant channel condition and relatively longer transmission range than that of the EM wave system, its transmission range is still too short 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*.

A typical MI waveguide structure is shown in the first row in Fig. 5, where $n-2$ relay coils equally spaced along one axis between the transmitter and the receiver, hence the total number of coils is n; 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. Each relay coil (including the transmitter coil and the receiver coil) is loaded with a capacitor C. By appropriately designing the capacitor value, resonant coils can be formed to effectively transmit the magnetic signals. 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, we set the distance between two relay coils to 5 m, which is larger than the maximum communication range of the EM wave system. Hence the MI waveguide system do not cost more on deploying the underground device than the traditional EM wave system. A lot of money can be saved by replacing the expensive relay sensor devices using EM waves by the relay coils that have very low cost. In the later part of this section, we vary the relay distance of the MI waveguide to analyze the influence. We assume that the radius of the relay coil is around 0.15 m. Comparing to the coil radius, the relay distance is large enough to validate the fact 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 in this paper.

A. System Modeling

Similar to the strategy in Section III, the MI waveguide is modeled as a multi-stage transformer, where only adjacent coils are coupled, as shown in the second row in Fig. 5. 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). M is the mutual induction between the adjacent coils; U_s is the voltage of the transmitter's battery; L is the coil self induction; R is the resistances of the coil; C is the capacitor loaded in each coil; Z_L is the load impedance of the receiver. The equivalent circuits of the multi-stage transformer is shown in the third row in Fig. 5, where

$$
\begin{aligned}
Z &= R + j\omega L + \frac{1}{j\omega C} \\
Z_{i(i-1)} &= \frac{\omega^2 M^2}{Z + Z_{(i+1)i}} \\
&\quad \left(i = 2, 3, \ldots n-1 \text{ and } Z_{n(n-1)} = Z_L\right) \\
Z_{(i-1)i} &= \frac{\omega^2 M^2}{Z + Z_{(i-2)(i-1)}} \\
&\quad \left(i = 3, 4, \ldots n \text{ and } Z_{12} = \frac{\omega^2 M^2}{Z}\right) \\
U_{Mi} &= -j\omega M \frac{U_{M(i-1)}}{Z + Z_{(i-2)(i-1)}} \\
&\quad (i = 2, 3, \ldots n \text{ and } U_{M1} = U_s)
\end{aligned} \tag{10}
$$

where $Z_{i(i-1)}$ is the influence of the i^{th} coil on the $(i-1)^{th}$ coil and vice versa; U_{Mi} is the induced voltage on the i^{th} coil. Then the received power at the receiver can be calculated as

$$
P_r = Re\left\{ \frac{Z_L \cdot U_{Mn}^2}{\left(Z_{(n-1)n} + Z + Z_L\right)^2} \right\}. \tag{11}
$$

B. System Optimization

To maximize the received power is equal to maximize the induced voltage U_{Mn} at the receiver coil. According to (10), if the coils are resonant, then the impedance of each coil consists of only resistance and the absolute value becomes much smaller. Hence we design the capacitor to fulfill $j\omega L + (1/j\omega C) = 0$, then using the expression of the self induction in (7), the value of the capacitors should be

$$C = \frac{2}{\omega^2 N^2 \mu \pi a}. \tag{12}$$

In case that the coils are resonant, the expression of the received power U_{Mn} in (10) can be developed as

$$\begin{aligned} U_{Mn} &= U_s \cdot \frac{-j\omega M}{R} \cdot \frac{-j\omega M}{R + \frac{\omega^2 M^2}{R}} \\ &\cdot \frac{-j\omega M}{R + \frac{\omega^2 M^2}{R + \frac{\omega^2 M^2}{R}}} \cdots \frac{-j\omega M}{R + \frac{\omega^2 M^2}{R + \frac{\omega^2 M^2}{R + \cdots}}} \\ &= U_s \cdot (j)^{n-1} \cdot \frac{1}{x_1} \cdot \frac{1}{x_2} \cdots \frac{1}{x_{n-1}} \end{aligned} \tag{13}$$

where

$$x_i = \frac{R}{\omega M} + \frac{1}{x_{i-1}}, \quad \left(i = 2, 3, \ldots n-1 \quad \text{and} \quad x_1 = \frac{R}{\omega M}\right)$$

Basing on the above equations, it can be shown that the multiplication $x_1 \cdot x_2 \cdot x_3 \cdots x_{n-1}$ is in fact an $(n-1)$ order polynomial of $x_1 = R/\omega M$, which is denoted as $\zeta((R/\omega M), n-1)$ and

$$\begin{aligned} \zeta\left(\frac{R}{\omega M}, n-1\right) &= b_{n-1}\left(\frac{R}{\omega M}\right)^{n-1} + b_{n-2}\left(\frac{R}{\omega M}\right)^{n-2} \\ &+ \cdots + b_2\left(\frac{R}{\omega M}\right)^2 + b_1\left(\frac{R}{\omega M}\right) + b_0 \end{aligned} \tag{14}$$

where $\{b_i, i = 0, 1, 2, \ldots, n-1\}$ are the coefficients of the polynomial, which is fixed for a certain n and not affected by other parameters.

Since the coils are all resonant, the matched load impedance is pure resistance, which is $Z_L = \overline{Z_{(n-1)n} + R}$. Finally, in the MI waveguide system, if the receiver is d m away from the transmitter and there are $n-2$ relay coils between them, the received power can be expressed as

$$P_r(d) = \frac{1}{4\left(Z_{(n-1)n} + R\right)} \cdot \frac{U_s^2}{\zeta^2\left(\frac{R}{\omega M}, n-1\right)} \tag{15}$$

where d is the total transmission range and $d = (n-1)r$.

The same as the ordinary MI system, the transmission power and the receiving power of the MI waveguide system decrease simultaneously as the transmission distance increases. Hence, the path loss of the MI waveguide L_{MIG} is defined in the same way

$$\begin{aligned} L_{MIG}(d) &= -10\lg\frac{P_r(d)}{P_t(r_0)} \\ &\simeq 10\lg\frac{4\left(Z_{(n-1)n} + R\right)}{R} + 20\lg\zeta\left(\frac{R}{\omega M}, n-1\right) \\ &= 10\lg 4\left[1 + \frac{1}{\left(\frac{R}{\omega M}\right)^2 + \frac{1}{1 + \frac{1}{\left(\frac{R}{\omega M}\right)^2 + \frac{1}{1+\cdots}}}}\right] \\ &+ 20\lg\left[b_{n-1}\left(\frac{R}{\omega M}\right)^{n-1} + \cdots \right. \\ &\left. + b_1\left(\frac{R}{\omega M}\right) + b_0\right] \end{aligned} \tag{16}$$

where $P_t(r_0)$ is defined as the transmission power when the transmitter is very close to the receiver and no relay coil exists.

According to (16), the path loss of the MI waveguide system is actually a function of $R/\omega M$. It is the polynomial $\zeta((R/\omega M), n-1)$ that has the major influence on the path loss. Therefore the path loss is a monotone increasing function of the variable $R/\omega M$. Consequently, to minimize the path loss is equal to minimize the variable $R/\omega M$. By using the expressions of the wire resistance R and the mutual induction M in (4) and (6) respectively, the variable $R/\omega M$ can be expressed as

$$\frac{R}{\omega M} = \frac{4R_0}{\omega N \mu \pi} \cdot \left(\frac{r}{a}\right)^3. \tag{17}$$

Note that here the relay distance r is only $1/(n-1)$ of the total transmission range d. By this means the influence of the cubic function of the distance on the path loss can be significantly mitigated. Using this scheme, we can reduce the path loss by:

— reducing the ratio of the relay distance to the coil radius r/a;
— increasing the operating frequency ω and the number of turns of the coils N;
— reducing the wire resistance R_0.

However, there are other factors that constrain the path loss minimization.

- To ease the device deployment, the ratio of the relay distance to the coil radius is expected to be as large as possible, which conflicts with the requirements of the low total path loss. In this paper, to keep the incontrovertible advantage over the underground EM wave system, the relay distance is set to at least the maximum transmission range of EM wave system, which is 4 m. Considering the coil radius is 0.15 m, the ratio of the relay distance to the coil radius is over 27 in this paper.
- It is also impossible to unlimitedly increase the operating frequency and the number of turns of the coils, since these two parameters are constraint by (12). The loaded capacitors in each resonant coil should be larger than 10 pF, otherwise it is comparable to the coil parasitic capacitance. To achieve a practical value of the loaded capacitors in each resonant coil, the ω and N cannot be too large. Moreover, extreme high operating frequency and large number of turns may induce severe performance deterioration caused by the parasitic capacitance [22]. In this paper, we use 10 MHz operating frequency and the each coil contains 5 loops of wire. The loaded capacitor is around 35 pF in this case.
- Although reducing the wire resistance can reduce the total path loss, it may cause two problems: 1) lower wire resistance require larger wire diameter, which cost more and cause the coils heavier; 2) low wire resistance can also cause dramatical in-band signal fluctuation, which may create difficulties on equalization of the received signal. In this paper, the coil is made of copper wire with a 1.45 mm diameter. According to AWG standard [17], the resistance of unit length R_0 is 0.01 Ω/m. The influence of different wire resistances will be analyzed in the later part of this section.

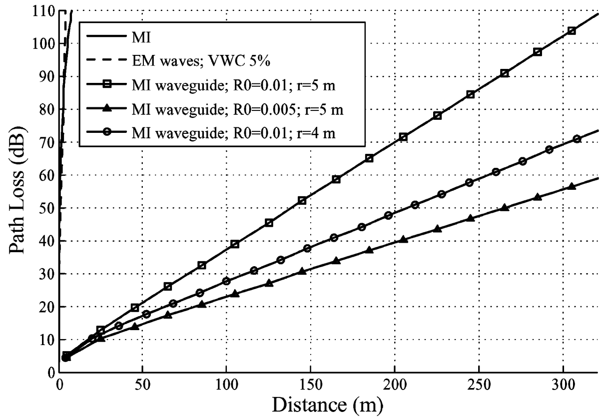

Fig. 6. Path loss of the MI waveguide system with different wire resistance and relay distance.

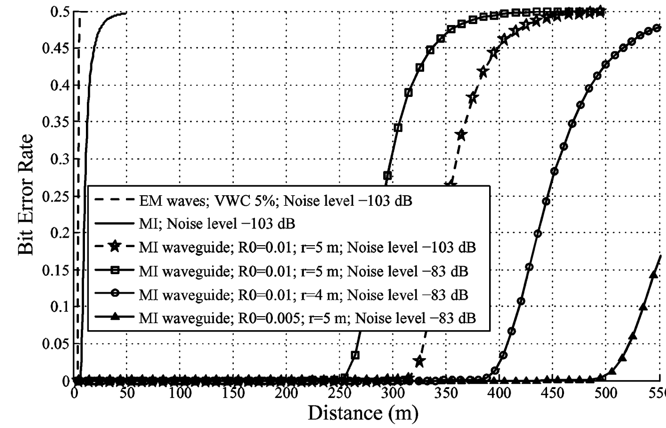

Fig. 7. Bit error rate of the MI waveguide system with different wire resistance, relay distance and noise level.

C. Numerical Analysis

1) Path Loss: The path losses of MI waveguide system shown in (16) are evaluated using MATLAB. The results are shown in Fig. 6. For better comparison, the path loss of the 300 MHz EM wave system in 5% VWC soil and the path loss of the 10 MHz ordinary MI system are also plotted. According to the discuss in Section III, the performance of the MI system is not affected by the soil properties and the soil medium has the same permeability as that in the air, which is $4\pi \times 10^{-7}$ H/m. Hence in the evaluation of the MI waveguide, we do not need to consider the environment parameters. Except studying the effects of certain parameters, the default values are set as follows: all the coils including the transmitter, receiver and relay points have the same radius of $a = 0.15$ m and the number of turns is $N = 5$. The resistance of unit length is $R_0 = 0.01\ \Omega/\mathrm{m}$ for normal coil and $R_0 = 0.005\ \Omega/\mathrm{m}$ for low resistance coil. The operating frequency is set to 10 MHz. The relay distance r is 5 m. The total number of coils n is determined by the transmission distance d, where $d = (n-1)r$. In Fig. 6, the path losses of the MI waveguide system are shown in dB versus the transmission distance d with different relay distances r and different wire resistances R_0. It can be found that the MI waveguide can greatly reduce the signal path loss comparing with the EM wave system and the ordinary MI system. The path loss of the MI waveguide is less than 100 dB even after 250 m transmission distance, while the path loss of the EM wave system and the ordinary MI system becomes larger than 100 dB when the transmission distance is larger than 5 m. In addition, the path loss can be further reduced by reducing the relay distance and the wire resistance.

2) Bit Error Rate: In Fig. 7, we investigate the bit error rate (BER) characteristics of the MI waveguide. The same as the analysis in Section III, $2PSK$ is selected as the modulation scheme. Two noise level are considered, where the average noise level P_n in low noise scenario is -103 dBm while P_n in high noise scenario is -83 dBm. The transmission power P_t is set to 10 dBm. In Fig. 7, the BER of the MI waveguide system are shown as a function of the transmission distance d with different relay distances r and different wire resistances R_0. The BER of the EM wave system and the ordinary MI system are also plotted for comparison. Comparing with the small transmission range of the other two techniques (less than 10 m), the transmission range of the waveguide system is above 250 meters even in the high noise scenario. It means that the transmission range of the MI waveguide system is increased for more than 25 times compared with the other two systems. In accord with the analysis on the path loss, the transmission range of the MI waveguide can be extended by reducing the relay distance and the wire resistance.

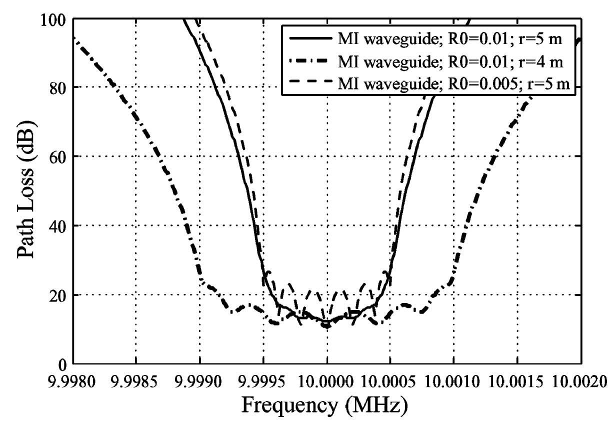

Fig. 8. Frequency response of the MI waveguide system with different wire resistance and relay distance.

3) Bandwidth: The above path loss and the transmission range of the MI waveguide system is calculated under the assumption that the transmitted signal has only one frequency. Under this central frequency, all the coils can achieve the resonant status. However, if there is any deviation from the central frequency, the resonant status of each coil will disappear and the load at the receiver also becomes unmatched with the system. Hence we need to analyze the bandwidth of the MI waveguide system. In Fig. 8, the frequency response of the MI waveguide system is shown with different relay distances r and different wire resistances R_0. The number of relay coils n are fixed to 7. The results indicate that, when the operating frequency is 10 MHz, the 3-dB bandwidth of the MI waveguide system is in the same range with the ordinary MI system, which is 1 KHz to 2 KHz. Although lower wire resistance can reduce the path loss in the central frequency, the fluctuation of the in-band frequency response becomes so serious that may cause difficulties in the equalization at the receiver. The bandwidth can be enlarged by

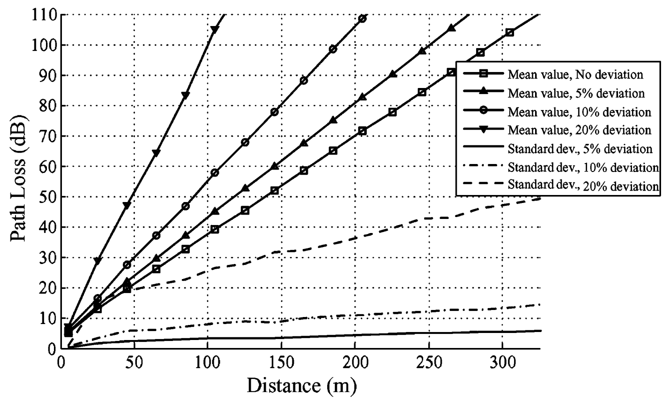

Fig. 9. Path loss of the MI waveguide system with different deviation from the designed relay distance.

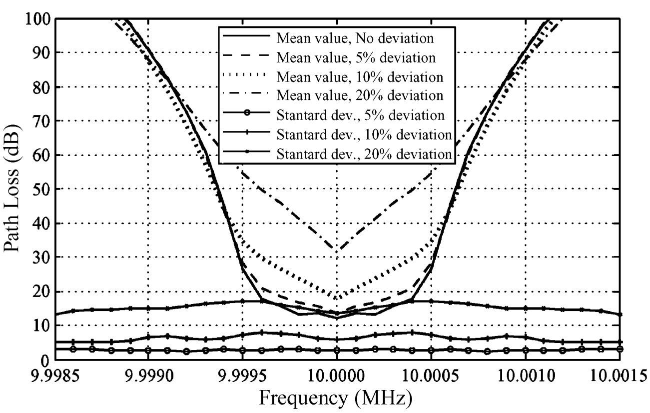

Fig. 10. Frequency response of the MI waveguide system with different deviation from the designed relay distance.

reducing the relay distance. However, for a certain transmission range, reducing the relay distance means that more relay coils needs to be deployed hence more effort is cost in the deployment. Two practical parameter sets maybe: 1) the relay distance $r = 5$ m and the unit length resistance $R_0 = 0.01\ \Omega/\mathrm{m}$. In this case, the 10 MHz operating MI waveguide system can accomplish the communications within 250 m range and achieve 1 KHz bandwidth. And 2) the relay distance $r = 4$ m and the unit length resistance $R_0 = 0.01\ \Omega/\mathrm{m}$. In this case, the 10 MHz operating MI waveguide system has 400 m transmission range and 2 KHz bandwidth.

4) Influence of Position Deviation: It should be noted that the above performance of MI waveguide system is derived in the ideal deployment case, where all the relay coils are accurately deployed so that the $n-2$ relay coils are uniformly distributed between the transceivers. The transmission range is divided into $n-1$ exactly equal intervals hence the mutual inductions between each relay coil are the same. However, in the practical applications, this requirements may not be precisely satisfied due to the following two reasons: on the one hand, in the initial deployment stage, the relay coils can not be set in the exact position as planned because of deployment constraints, such as rocks or pipes in the soil; on the other hand, the positions of the coils may change while the network is operating due to the above ground pressure or the movement of the soil. Hence, in Fig. 9 and Fig. 10, the influence of the non-ideal deployment is analyzed.

We assume that the relay coils are not deployed at the exact planed positions but may not deviate a lot. There are $n-2$ relay coils deployed between the transceivers and the transmission. Their designed positions are $\{i \cdot d/(n-1), i = 1, 2, \cdots n-2\}$. The position x_i of relay coil i is a Gaussian random variable with mean value $i \cdot d/(n-1)$ and standard deviation σ_r. Then the transmission distance d is divided into $n-1$ intervals with length: $r_1, r_2, \ldots r_{n-1}$, where $r_i = x_i - x_{i-1}$. x_0 and x_{n-1} are the positions of the transmitter and the receiver, respectively. We assume that the standard deviation are either 5%, 10% or 20% of the designed relay distance. Other simulation parameters are set to the default value. The results are the average of 100 iterations. Both mean value and the standard deviation of the results are plotted.

It is shown that there exists additional path loss in practical deployment. Moreover, the bandwidth decreases dramatically when the standard deviation is 20%. The level of the additional path loss and the bandwidth decrease are determined by the standard deviation. Higher standard deviation can cause larger performance deterioration. Moreover, the additional path loss also increases as the transmission distance increase, which is because that more relay coils are deployed with longer transmission distance hence more deployment deviation may occur. The standard deviation of the path loss and the bandwidth also increases dramatically as the deployment deviation increases, which indicates that the reliability of the MI waveguide system also decreases if deployment deviation occurs. It should be noted that the influence of the deployment deviation on the performance of the MI waveguide system can be neglected if the standard deviation is less than 10%.

V. Conclusion

In wireless underground communications, traditional techniques using EM waves encounter three major problems: high path loss due to material absorption, dynamic channel condition due to various soil properties, and too large antenna size. MI is an alternative technique that has constant channel condition and can accomplish the communication with small size coils. However currently there is no detailed analysis on the path loss and the bandwidth of the MI system in underground soil medium. In this paper, we provide an analytical model to characterize the underground MI communication channel. Based on the channel analysis, we develop the MI waveguide technique to significantly enlarge the transmission range in underground environments. Our analysis shows the following.

- The MI technique has constant channel condition because its path loss only depends on the permeability of the propagation medium, which remains the same if the medium is air, water and most kinds of soil and rock. However, the material absorption is the major part of the path loss of EM wave system, which may change a lot in different soil conditions.
- In underground environments, the path loss of the MI system is slightly smaller than the EM wave system in normal and wet soil medium; while in very dry soil, the EM wave system has smaller path loss. However, due to the high path loss, both the systems can not provide a transmission range that is more than 10 m, which prevent

them from practical applications. Although the bandwidth of the MI system and the MI waveguide system is only 1 to 2 KHz, which is much smaller than the EM wave system, it is enough for the low data rate monitoring applications of WUSNs. Another advantage of the MI and MI waveguide system is that, as the transmission range increases, the transmission power decreases simultaneously with the received power, which is favorable for the energy-constrained WUSNs.

- 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. The relay distance is also larger than the maximum transmission range of the EM wave system. The bandwidth of the MI waveguide system is in the same range as the ordinary MI system. The transmission range of the MI waveguide system is increased dramatically compared with that of the ordinary MI system and the EM wave system.

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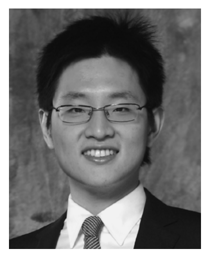

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