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Full length article

## Signal propagation techniques for wireless underground communication networks

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## ARTICLE INFO

## Keywords:

Wireless networks  
Channel model  
Soil medium  
Underground mine  
Tunnel  
Magnetic induction  
Waveguide

## ABSTRACT

Wireless Underground Communication Networks (WUCNs) consist of wireless devices that operate below the ground surface. These devices are either (i) buried completely under dense soil, or (ii) placed within a bounded open underground space, such as underground mines and road/subway tunnels. The main difference between WUCNs and the terrestrial wireless communication networks is the communication medium. In this paper, signal propagation characteristics are described in these constrained areas. First, a channel model is described for electromagnetic (EM) waves in soil medium. This model characterizes not only the propagation of EM waves, but also other effects such as multipath, soil composition, water content, and burial depth. Second, the magnetic induction (MI) techniques are analyzed for communication through soil. Based on the channel model, the MI waveguide technique for communication is developed to address the high attenuation challenges of MI waves through soil. Furthermore, a channel model, i.e., the *multimode model*, is provided to characterize the wireless channel for WUCNs in underground mines and road/subway tunnels. The multimode model can characterize two cases for underground communication, i.e., the *tunnel channel* and the *room-and-pillar channel*. Finally, research challenges for the design communication protocols for WUCNs in both underground environments are discussed based on the analysis of the signal propagation.

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## 1. Introduction

Wireless Underground Communication Networks (WUCNs) constitute one of the promising application areas of the recently developed wireless networking techniques. The WUCNs consist of wireless devices that operate below the ground surface. These devices are either (i) buried completely under dense soil or (ii) placed within a bounded open underground space such as underground mines and road/subway tunnels. In the former case, networks of wireless nodes are buried *underground* and communicate *through soil*. In this case, the WUCNs promise a

wide variety of novel applications, including intelligent irrigation, environmental monitoring, infrastructure monitoring, localization, and border patrol [1]. In the latter case, although the network is located *underground*, the communication takes place *through the air*, i.e., through the voids that exist underground. In this case, the WUCNs are necessary to improve the safety and productivity in underground mines, to realize convenient communication for drivers and passengers in road/subway tunnels, and to avoid attacks by continuously monitoring these vulnerable areas.

The main challenge for WUCNs is the realization of efficient and reliable underground wireless links to establish multiple hops and disseminate data for seamless operation. The main difference between the WUCNs and the terrestrial wireless communication networks is the

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communication medium. For the WUCNs deployed in soil, the propagation medium is no longer air but soil, rock, and water. Although the well established terrestrial signal propagation techniques based on electromagnetic (EM) waves may still work in a soil medium, the channel model of EM waves in this environment needs to be developed. Besides EM waves, alternate signal propagation techniques, such as magnetic induction (MI) can also be used for short-range communication in soil. For the WUCNs deployed in underground mines and road/subway tunnels, the EM waves are the best choice for wireless signal propagation, since the radio signal propagates through the air in this case. However, the propagation characteristics of EM waves are significantly different from those of terrestrial wireless channels because of the restrictions caused by the lossy dielectric walls and ceilings in the underground mines or road/subway tunnels.

This paper analyzes the underground wireless signal propagation techniques and presents current research challenges of the WUCNs. More specifically, the following are provided:

**Channel models for communication through soil:** For WUCNs in soil, we provide a channel model for EM and MI waves. The former model characterizes not only the propagation of EM waves in soil, but also other effects such as multipath, soil composition, water content, and burial depth [2,3]. Our analysis shows that the communication success significantly depends on the operating frequency and the composition of the soil. For low depth deployments, the channel is shown to exhibit a two-path channel model with the effect of multi-path fading of spatial distribution. For high depth deployments, a single path channel is suitable to characterize communication. We also analyze the MI communication channel in the soil medium. Based on the channel model, the MI waveguide technique for communication is developed to address the high attenuation rate of MI signals through multi-hop communication [4,5].

**Channel models for communication in underground mines and tunnels:** For WUCNs in underground mines and road/subway tunnels, the channel model for the EM waves is developed in two categories: *tunnel* channel model and *room-and-pillar* channel model. We provide an analytical channel model, i.e., the *multimode model* [6, 7]. For a tunnel environment, the multimode model can completely characterize natural wave propagation in both near and far regions of the source. For the room-and-pillar environment, the multimode model is combined with the shadow fading model. Based on the new channel model, we present an in-depth analysis of the wireless channel characteristics in underground mines and road/subway tunnels.

**Research challenges for WUCNs:** The analysis of the signal propagation techniques in both the soil medium and the underground mines/tunnels lays out the foundations for efficient communication in these environments. Based on the analysis, research challenges to design communication protocols in both underground environments are discussed.

The remainder of this paper is organized as follows: In Section 2, the channel model and the evaluations for

communication based on EM waves in a soil medium are presented. In Section 3, the magnetic induction (MI) communication channel in a soil medium is provided, and the MI waveguide technique for communication is developed. Then in Section 4, our solution for channel modeling in underground mines and road/subway tunnels is presented. Next in Section 5, research challenges to design communication protocols for WUCNs are discussed. Finally, the paper is concluded in Section 6.

## 2. Wireless communication through soil using electromagnetic waves

EM waves encounter much higher attenuation in soil compared to air. This severely hampers the communication quality. Moreover, the ground surface causes reflection as well as refraction, which requires a comprehensive investigation of the channel model. In addition, multi-path fading is another important factor in underground communication, since unpredictable obstacles in soil such as rocks and roots of trees make EM waves refracted and scattered. Therefore, advanced models are necessary to accurately and completely characterize the underground channel and to lay out the foundations for efficient underground communication.

### 2.1. 2-path rayleigh fading channel model

For the derivation of the underground channel model, we first model the propagation characteristics in soil. Then, the effects of reflections from the ground surface and the multi-path fading are captured. Finally, the bit error rate (BER) is derived as a function of communication parameters such as operating frequency, modulation type, distance as well as soil parameters such as volumetric water content, sand and clay percentage, and temperature.

#### 2.1.1. Signal propagation through soil

The propagation through soil is modeled based on the Friis free space propagation equation [8], where a correction factor is included to account for the effects of the soil medium. As a result, the received signal,  $P_r$ , at a receiver sensor node is modeled as

$$P_r = P_t + G_r + G_t - L_p, \quad (1)$$

where  $P_t$  is the transmit power,  $G_r$  and  $G_t$  are the gains of the receiver and transmitter antennae,  $L_p = L_0 + L_s$ ,  $L_0$  is the path loss in free space, and  $L_s$  stands for the additional path loss caused by the propagation in soil. The additional path loss,  $L_s$ , is calculated by considering the following differences of EM wave propagation in soil compared to that in air: (1) The signal velocity, and hence, the wavelength  $\lambda$ , is different, (2) the amplitude of the wave will be attenuated according to the frequency, and (3) the phase velocity is correlated with the frequency in the soil, which can cause color scattering and delay distortion. The additional path loss,  $L_s$ , in soil is, hence, composed of two components

$$L_s(\text{dB}) = L_\beta(\text{dB}) + L_\alpha(\text{dB}), \quad (2)$$

where  $L_\beta$  is the attenuation loss due to the difference of the wavelength of the signal in soil,  $\lambda$ , compared to the wavelength in free space,  $\lambda_0$ , and  $L_\alpha$  is the transmission loss caused by attenuation with attenuation constant  $\alpha$ .

Then,  $L_p$  can be represented in dB as follows [3]:

$$L_p = 6.4 + 20 \log(d)(m) + 20 \log(\beta) + 8.69\alpha d, \quad (3)$$

where distance,  $d$ , is given in meters, the attenuation constant,  $\alpha$ , is in 1/m and the phase shifting constant,  $\beta$ , is in rad/m. Note that the path loss,  $L_p$ , in (3) depends on the attenuation constant,  $\alpha$ , and the phase shifting constant,  $\beta$ , which depends on the dielectric properties of soil. Using the Peplinski principle [9], the dielectric properties of soil in the 0.3–1.3 GHz band can be calculated as follows:

$$\begin{aligned} \epsilon &= \epsilon' - j\epsilon'', \\ \epsilon' &= 1.15 \left[ 1 + \frac{\rho_b}{\rho_s} (\epsilon_s^{\alpha'}) + m_v^{\beta'} \epsilon_{fw}^{\alpha'} - m_v \right]^{1/\alpha'}, \\ \epsilon'' &= [m_v^{\beta''} \epsilon_{fw}^{\alpha'']}]^{1/\alpha'}, \end{aligned} \quad (4)$$

respectively, where  $\epsilon$  is the relative complex dielectric constant of the soil-water mixture,  $m_v$  is the volumetric water content (VWC) of the mixture,  $\rho_b$  is the bulk density in grams per cubic centimeter,  $\rho_s = 2.66 \text{ g/cm}^3$  is the specific density of the solid soil particles,  $\alpha' = 0.65$  is an empirically determined constant, and  $\beta'$  and  $\beta''$  are empirically determined constants, dependent on soil type and given by

$$\begin{aligned} \beta' &= 1.2748 - 0.519S - 0.152C, \\ \beta'' &= 1.33797 - 0.603S - 0.166C, \end{aligned} \quad (5)$$

where  $S$  and  $C$  represent the mass fractions of sand and clay, respectively. The quantities  $\epsilon'_{fw}$  and  $\epsilon''_{fw}$  in (4) are the real and imaginary parts of the relative dielectric constant of water. Consequently, the attenuation constant,  $\alpha$ , and the phase shifting constant,  $\beta$ , are found as

$$\begin{aligned} \alpha &= \omega \sqrt{\frac{\mu\epsilon'}{2} \left[ \sqrt{1 + \left(\frac{\epsilon''}{\epsilon'}\right)^2} - 1 \right]}, \\ \beta &= \omega \sqrt{\frac{\mu\epsilon'}{2} \left[ \sqrt{1 + \left(\frac{\epsilon''}{\epsilon'}\right)^2} + 1 \right]}, \end{aligned} \quad (6)$$

where  $\omega = 2\pi f$  is the angular frequency,  $\mu$  is the magnetic permeability, and  $\epsilon'$  and  $\epsilon''$  are the real and imaginary parts of the dielectric constant as given in (4), respectively. Consequently, the path loss,  $L_p$ , in soil can be found by using Eqs. (4)–(6) in (3).

It can be seen from above equations that the complex propagation constant of the EM wave in soil is dependent on the operating frequency, the composition of the soil in terms of sand and clay fractions,  $S$  and  $C$ , the bulk density,  $\rho_b$ , and the volumetric water content (VWC),  $m_v$ . Consequently, the path loss,  $L_p$ , also depends on these parameters.

### 2.1.2. Reflection from ground surface

Underground communication results in two main paths for signal propagation as shown in Fig. 1. The first path is the direct path between two sensors and the second path is the reflection path due to the ground surface. When the

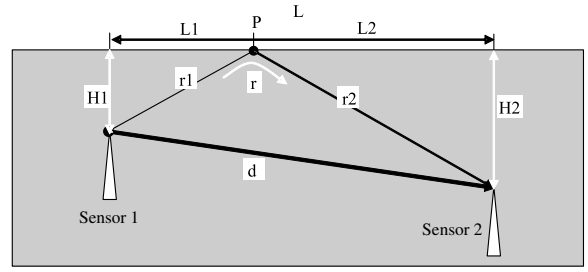


Fig. 1. Illustration of the two-path channel model.

bury depth increases to a certain degree, i.e., *high depth*, the effect of reflection can be neglected and the channel can be considered as a single path. In this case, the path loss is given in (3). However, if the sensors are buried near the surface of ground, i.e., *low depth*, the total path loss of a two-path channel model can be deduced as follows:

$$L_f(dB) = L_p(dB) - V_{dB}, \quad (7)$$

where  $L_p$  is the path loss due to the single path given in (3) and  $V_{dB}$  is the attenuation factor due to the second path in dB, i.e.,  $V_{dB} = 10 \log V$  and is given as follows:

$$\begin{aligned} V^2 &= 1 + (\Gamma \cdot \exp(-\alpha \Delta(r)))^2 \\ &\quad - 2\Gamma \exp(-\alpha \Delta(r)) \cos \left( \pi - \left( \phi - \frac{2\pi}{\lambda} \Delta(r) \right) \right), \end{aligned} \quad (8)$$

where,  $\Gamma$  and  $\phi$  are the amplitude and phase angle of the reflection coefficient at the reflection point  $P$ ,  $\Delta(r) = r - d$ , is the difference of the two paths and  $\alpha$  is the attenuation constant mentioned before. The effects of a two-path channel model have also been observed through our recent field experiments [10].

### 2.1.3. Multi-path fading

The two-path channel model captures the main propagation characteristics of EM waves underground. However, the surface of the ground is not ideally smooth and, hence, not only causes reflection, but also refraction. Moreover, usually, there are rocks or roots of plants in soil and the clay of soil is generally not homogeneous. As a result of the impurities in the soil, multi-path fading should also be considered in addition to the basic two-path channel model.

In underground communication, randomness in an underground environment is due to the locations of the nodes rather than time, which obeys the Rayleigh probability distribution. The only difference compared to communication through air is that the variable of Rayleigh probability distribution is location instead of time. Accordingly, we model each path in the underground channel such that the envelope of the signal is modeled as an independent Rayleigh distributed random variable,  $\chi_i$ ,  $i \in \{1, 2\}$ . Consequently, for the *single-path model*, the received energy per bit per noise power spectral density is given by  $r = \chi^2 E_b / N_o$ , which has a distribution as  $f(r) = 1/r_0 \exp(r/r_0)$ , where  $r_0 = E[\chi^2] E_b / N_o$  and  $E_b / N_o$  can be directly found from the signal-to-noise ratio (SNR) of the channel.

Similarly, for the *two-path model*, the received signal is the sum of two independent Rayleigh fading signals, which is denoted as *location dependent two path Rayleigh channel*. Consequently, the composite attenuation constant,  $\chi$ , in

multi path Rayleigh channel is:

$$\begin{aligned} \chi^2 = & \chi_1^2 + (\chi_2 \cdot \Gamma \cdot \exp(-\alpha \Delta(r)))^2 \\ & - 2\chi_1\chi_2\Gamma \exp(-\alpha \Delta(r)) \cos \\ & \times \left( \pi - \left( \phi - \frac{2\pi}{\lambda} \Delta(r) \right) \right), \end{aligned} \quad (9)$$

where  $\chi_1$  and  $\chi_2$  are two independent Rayleigh distributed random variables of two paths, respectively.  $\Gamma$  and  $\phi$  are the amplitude and phase angle of the reflection coefficient at the reflection point  $P$ ,  $\Delta(r) = r - d$ , is the difference of the two paths and  $\alpha$  is the attenuation constant. The relatively stable nature of the underground channel with respect to time has also been observed through our recent field experiments [10].

## 2.2. Characteristics of EM waves in soil

Based on the developed channel model, the bit error rate (BER) profile in underground settings can be evaluated. The BER of a communication system depends mainly on three factors: (1) the channel model (2) the signal-to-noise ratio (SNR), and (3) the modulation method used by the system. Considering the channel model derived before, the signal to noise ratio (SNR) is given by  $SNR = P_t - L_f - P_n$ , where  $P_t$  is the transmit power,  $L_f$  is the total path loss, and  $P_n$  is the noise energy. In the following part, we will discuss the effects of various factors on the BER in wireless channel of soil medium, including modulation method, operation frequency, deployment depth, transmit power, and volumetric water content.

### 2.2.1. Modulation scheme

In order to provide an initial investigation in this area, various modulation schemes including ASK, FSK and PSK are investigated to illustrate their effects on the BER [2]. The relation between the maximum inter-node distance of the single path channel model and the VWC is shown in Fig. 2(a). The maximum inter-node distance is found subject to a BER target of  $10^{-3}$  for different modulation methods. In Fig. 2(a), it can be seen that the PSK modulation method provides the largest range. Consequently, in our analysis, we consider the PSK modulation.

### 2.2.2. Operation frequency and deployment depth

In Fig. 2(b), the path loss is shown as a function of the burial depth,  $H$ , for various values of the operating frequency,  $f$ . For a particular operating frequency, an optimum bury depth exists such that the path loss is minimized. This is particularly important in the topology design of WUCNs, where deployment should be tailored to the operating frequency of the wireless sensors. In Fig. 2(b), it can also be observed that the effect of reflection, and hence, the fluctuations in path loss diminishes as the bury depth,  $H$ , increases. More specifically, the underground channel exhibits a single-path characteristic when the bury depth is higher than 2 m since the influence of reflection is negligible. On the other hand, for low depth deployment, a two-path channel model should be considered.

### 2.2.3. Transmit power and volumetric water content

The effects of transmit power and the volumetric water content (VWC) on the BER are shown in Fig. 3, where the

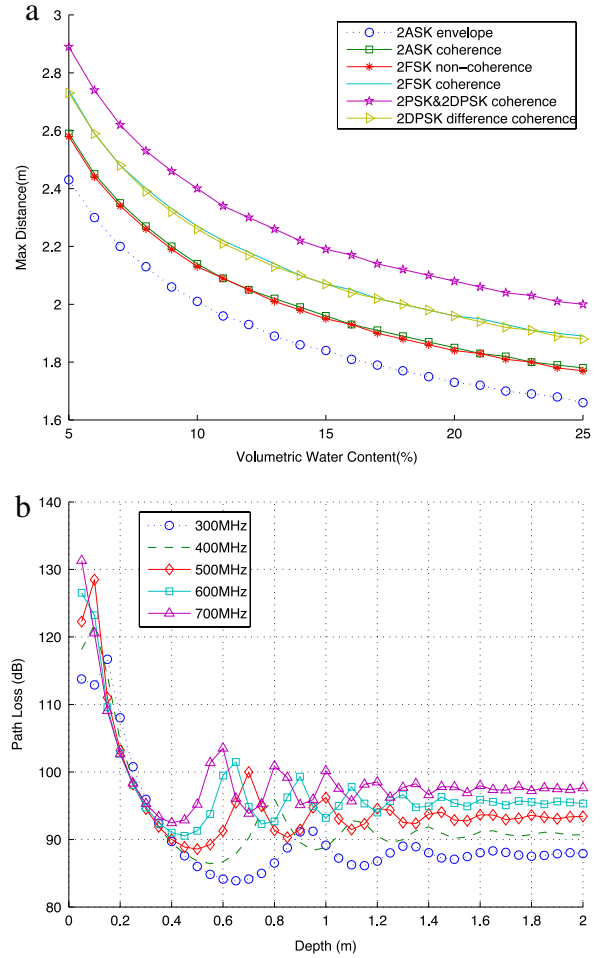
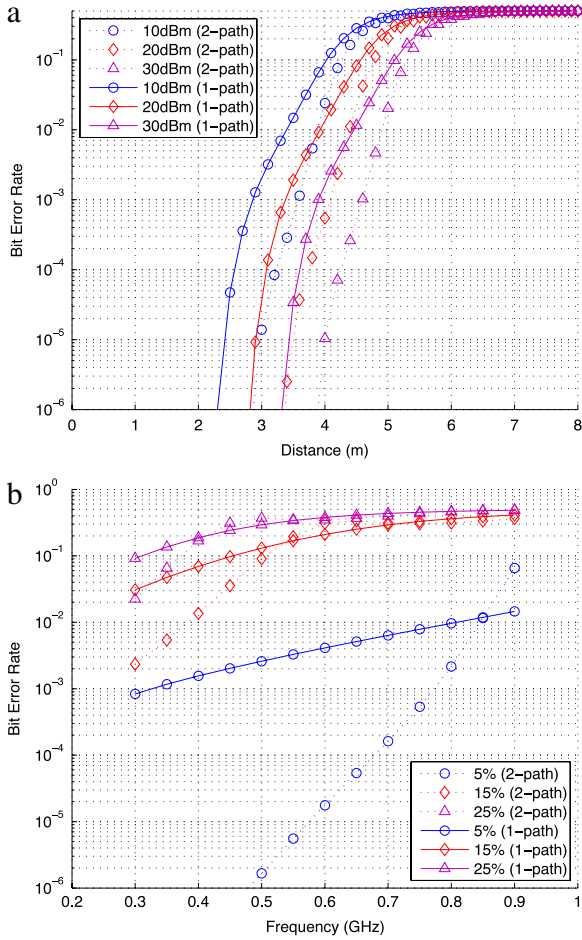


Fig. 2. (a) The maximum inter-node communication distance of one path channel using different modulation schemes. (b) Path loss vs. depth for different operating frequencies with two-path channel model.

results are shown for single-path and two-path models. In Fig. 3(a), the relation between BER and horizontal distance for different transmit power values is shown. It is observed that as the transmit power increases, the BER decreases. However, this decrease is a minimum since even when the transmit power increases to 30 dBm, the horizontal distance can only be extended to 4 m with the limitation that the BER is below  $10^{-3}$ . As shown in Fig. 3(b), an increase in the VWC from 5% to 10% results in almost an order of magnitude increase in the BER. In addition to the theoretical analysis, our recent field experiments also illustrate the effect of the VWC [10]. These results confirm that VWC is one of the most important parameters for underground communication.

In Fig. 3, the effect of the reflected path from the ground surface on the BER can also be clearly seen through the 2-path model. As shown in Fig. 3(a), the BER results for the two-path model shifts to right compared to the one-path model. More specifically, the communication distance can be extended for low depth applications to 4.5–5 m with transmit power of 30 dBm with depth 0.5 m at 400 MHz. Finally, the effect of the VWC in two-path model is shown



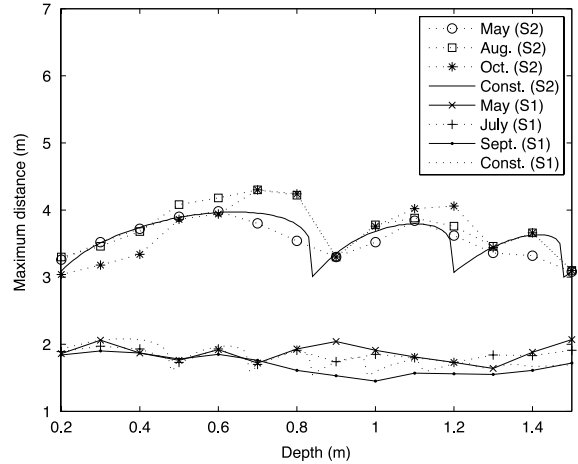
**Fig. 3.** (a) BER vs. internode distance with different transmitting power and (b) BER vs. operating frequency and volumetric water content for one-path and two-path channel models.

in Fig. 3(b). Compared to the single-path model results shown also in this figure, a higher VWC is acceptable for low depth deployments when the operation frequency is low.

**2.2.4. Volumetric water content variation**

The above analysis is performed assuming that the VWC is constant throughout the soil. However, field measurements reveal that the VWC also changes with depth [11–13]. Moreover, even at the same depth, communication range can change by as much as 25% depending on the time of the year. To investigate the relation between communication quality and the burial depth, the BER is evaluated based on the experimental data in [13,12]. We denote these data sets as *Set 1* and *Set 2*, where the properties of each experiment are described as follows:

- *Set 1*: The first data set consists of volumetric water content values measured at different depths in a black soil with 22.75% sand, 28.1% clay [13].
- *Set 2*: The second data set is from a sandy soil with 50% sand and 15% clay [12]. Since sandy land soil keeps



**Fig. 4.** The maximum inter-node distance vs. depth for the data Set 1 (S1) and Set 2 (S2) at different times of the year. Maximum distance calculated by considering a constant VWC at all depths is also shown.

less water compared to the black soil, this data set was included to illustrate the effect of soil content on the influence of variation of the VWC on communication range.

The maximum inter-node communication distance is calculated for these two data sets. In Fig. 4, the maximum inter-node distance for the BER target of  $10^{-3}$  is shown as a function of depth for both data sets. The solid lines represent the cases where the VWC is considered constant throughout all depths for each data set. For Set 1,  $VWC = 20\%$ , which is the value measured at 0.3 m depth in May according to [13] and for Set 2,  $VWC = 3.7\%$ . When Set 1 is considered, it can be observed that the fluctuations estimated by the uniform VWC model are closely followed when the depth is  $d \leq 0.8$  m.

The seasonal influence on communication is also shown in Fig. 4. Especially, for burial depths higher than 0.8 m, the communication range is higher during May and lower during September compared to the uniform VWC case. This is related to higher precipitation, which starts in July. The results in Fig. 4 reveal that even at the same depth, the communication range can change by as much as 25% depending on the time of the year. Consequently, environmental adaptive protocols, which can adjust the operating parameters according to the seasons, are necessary for robust operation in WUCNs.

**3. Wireless communication through soil using magnetic induction**

As discussed in Section 2, traditional signal propagation techniques using EM waves encounter three major problems in soil medium: 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 rainfall) and space (soil properties change dramatically over short distances). Consequently,

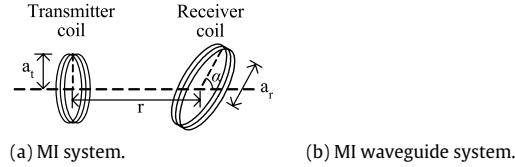


Fig. 5. The structure of the MI transceiver and the MI waveguide.

the bit error rate (BER) of the communication system also varies dramatically in different times or positions. An unreliable channel brings design challenges for the underground devices and networks to achieve both satisfying connectivity and energy efficiency. Third, operating frequencies in MHz or lower ranges are necessary to achieve a 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 an alternative signal propagation technique for underground wireless communication, which addresses the dynamic channel condition and large antenna size challenges of the EM wave techniques. In particular, a dense medium such as soil and water causes little variation in the attenuation rate of magnetic fields from that of air, since the magnetic permeabilities of each of these materials are similar [1,14,15]. Therefore the MI channel conditions remain constant in a soil medium. Moreover, in the MI communication, the transmission and reception are accomplished with the use of a small coil of wire. Therefore, no lower limit of the coil size is required. However, the magnetic field strength falls off much faster than the EM waves [16,17]. Consequently, MI is generally unfavorable for terrestrial wireless communication. In a soil medium, 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 section, we first derive the analytical expression of the path loss of the underground MI communication channel. 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 [4,5] for underground wireless communication. 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 constituting the MI waveguide do not consume any energy and the cost is very small. Third, the MI waveguide is not a continuous structure like a real waveguide hence it is relatively flexible and easy to deploy and maintain. We compare the performance of the traditional EM wave systems, the current MI systems and our improved MI waveguide system. It is shown in the results that our MI waveguide system has a much lower path loss than the other two systems for any channel conditions.

### 3.1. MI channel model

In MI communication, the transmission and reception are accomplished with the use of a coil of wire, as shown

in Fig. 5(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  $(90^\circ - \alpha)$  is the angle between the axes of two coupled coils.

The ratio of the received power to the transmitting power, i.e. the path loss, is [4,5]:

$$\frac{P_r}{P_t} \simeq \frac{\omega^2 \mu^2 N_t N_r a_t^3 a_r^3 \sin^2 \alpha}{8r^6} \cdot \frac{1}{4R_0(2R_0 + \frac{1}{2}j\omega\mu N_t)} \quad (10)$$

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;  $\mu$  is the permeability of the medium (i.e., soil); and  $\omega$  is the angle frequency of the transmitting signal. If a low-resistance loop, high signal frequency and a large number of turns are employed ( $\omega\mu N_t \gg R_0$ ), then the ratio can be further simplified:

$$\frac{P_r}{P_t} \simeq \frac{\omega\mu N_r a_t^3 a_r^3 \sin^2 \alpha}{16R_0 r^6}. \quad (11)$$

According to (11), the received power loss is a 6th-order function of the transmission range  $r$ . A higher signal frequency  $\omega$ , a larger number of turns  $N$ , lower loop resistance  $R_0$  and a larger coil size  $a$  can enlarge the received power. The angle between the axes of the two coupled coils also affects the received power: the smaller the angle is, the higher the power that is received. It should be noted that the received power is not affected by the environmental conditions. It is because only one environment parameter  $\mu$  exists in (11) and the permeability  $\mu$  of soil and water is similar to that of air.

We compare (11) with the Friis transmission equation for the EM wave communication [18], where

$$\frac{P_r}{P_t} \simeq G_t G_r \left( \frac{\lambda}{4\pi r} \right)^2 = G_t G_r \frac{\pi}{4\mu\epsilon\omega^2 r^2}. \quad (12)$$

It shows that a higher operating frequency induces a higher path loss in the EM wave case but achieves a lower attenuation rate in the MI case. The received power of MI communication attenuates much faster than the EM wave case ( $1/r^6$  vs.  $1/r^2$ ). However, the permittivity  $\epsilon$  in (12) is much larger in soil than that in air. Furthermore,  $\epsilon$  varies a lot at different times and locations. Hence, the path loss of EM waves is dramatically influenced by those environmental conditions. Accordingly, the MI technique has a constant channel condition while the EM wave technique results in lower attenuation.

### 3.2. MI waveguide

Although the MI techniques address the dynamic channel condition and large antenna size challenges of

























