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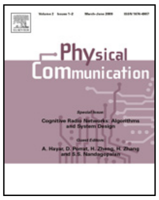

Full length article

Channel model and analysis for wireless underground sensor networks in soil medium

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ABSTRACT

Wireless underground sensor networks (WUSNs) constitute one of the promising application areas of the recently developed wireless sensor networking techniques. The main difference between WUSNs and the terrestrial wireless sensor networks is the communication medium. The propagation characteristics of electromagnetic (EM) waves in soil and the significant differences between propagation in air prevent a straightforward characterization of the underground wireless channel. To this end, in this paper, advanced channel models are derived to characterize the underground wireless channel and the foundational issues for efficient communication through soil are discussed. In particular, the underground communication channel is modeled considering not only the propagation of EM waves in soil, but also other effects such as multipath, soil composition, soil moisture, and burial depth. The propagation characteristics are investigated through simulation results of path loss between two underground sensors. Moreover, based on the proposed channel model, the resulting bit error rate is analyzed for different network and soil parameters. Furthermore, the effects of variations in soil moisture are investigated through field measurement results. The theoretical analysis and the simulation results prove the feasibility of wireless communication in underground environment and highlight several important aspects in this field. This work will lead to the provision of a generic framework for underground wireless communication and the realization of WUSNs.

1. Introduction

Recent developments in communication techniques for wireless sensor networks (WSNs) have enabled a vast amount of applications for these networks [1]. Among these applications, wireless underground sensor networks (WUSNs), which consist of wireless sensors buried underground, are a promising field that will enable a wide variety of novel applications that were not possible with current wired underground monitoring techniques. Compared to the current underground sensor networks, which use wired communication methods for network deployment, WUSNs have several remarkable merits, such as concealment, ease of deployment, timeliness of data, reliability and coverage density [2,3].

WUSNs so far had two implications in the literature. In recent work [4–6], the term *underground sensor networks* is used to refer to networks that have been deployed in subterranean spaces such as coal mines, subways, or sewer systems. Although the network is located *underground*, the communication takes place *through the air*, i.e., through the voids that exist underground. Consequently, even though the communication in these voids are more challenging

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than that in terrestrial WSNs, the channel characteristics exhibit similarities with the terrestrial WSNs.

In this paper, however, we consider WUSNs buried *underground* and communicate *through soil*. The main challenge for WUSNs in this medium is the realization of efficient and reliable underground links to establish multiple hops and efficiently disseminate data for seamless operation. The main difference between the well-established techniques in terrestrial wireless sensor networks is the communication medium, which prevents a straightforward characterization of underground wireless channel. First, EM waves encounter much higher attenuation in soil compared to air [7,8]. This severely hampers the communication quality. As an example, efficient communication between sensors nodes above and below ground is shown to be possible only at a distance of 0.5 m when the 2.4 GHz frequency is used [9]. Moreover, the ground surface causes reflection as well as scattering. In addition, multipath fading is another important factor in underground communication, where unpredictable obstacles in soil such as rocks and roots of trees make EM waves being refracted and scattered. Since underground communication and networking is primarily affected by the wireless channel capabilities, advanced models and techniques are necessary to characterize the underground wireless channel and lay out the foundations for efficient communication through soil.

In this paper, we provide a characterization of the underground wireless channel and lay out the foundations for efficient communication in this environment. In particular, the 300–900 MHz band, which is suitable for small size antenna and sensor development, is investigated. Our model characterizes not only the propagation of EM wave in soil, but also other effects such as multipath, soil composition, water content, and burial depth. The results obtained from this formalization reveal that underground communication is severely affected by frequency and soil properties, especially, the volumetric water content (VWC) of soil. Moreover, the effect of weather and season is investigated by considering two soil types as examples. Accordingly, important considerations for the deployment and operation of WUSNs are discussed.

The rest of this paper is organized as follows. In Section 2, the related work is introduced. In Section 3, the propagation characteristics of 300–900 MHz EM waves in soil are analyzed. In Section 4, the characteristics of the underground channel in soil are described, which takes the reflection of the surface as well as the multipath fading into consideration. Next, in Section 5, the effects of variations in volumetric water content in soil are analyzed. Then, in Section 6, the challenges in WUSN design are summarized according to the results provided by our model. Finally, the paper is concluded in Section 7.

2. Related work

Recently, there have been some experimental work that focus on underground applications. In [10], a shallow depth WSN is explained for predicting landslides. The network consists of Mica2 motes that are interfaced with stain gauges which can operate at low depths (25–30 cm). In this design, although the sensors are buried underground, the communication takes place over the air. In [11], the sensor network is constructed to detect the volcano activities, but the antenna of the sensors has to be above ground to create reliable links. Structural health monitoring (SHM) is another application that has gained interest in wireless sensor network community. In [12,13], Wisden, which is a data acquisition system for SHM, is presented. Similarly, in [14], Duranode is developed for SHM. Although underground systems such as sewers also require structural monitoring, these approaches only work with communication through air techniques.

In [4,5], wireless sensor networks are used to monitor underground mines to guarantee the safety of mine workers. Similarly, in [6,15], the characteristics of the wireless channel in tunnels are investigated. Although the mine is *underground*, the communication among the sensors is *through the air* in the mine tunnel, which is fundamentally different than our focus in this paper as discussed before. The largest residential water management project in Europe is introduced in [16], where sensors are used to gather information for inspection and cleaning systems in the Emscher sewer system. However, the communication methods are not described in detail. In [17], a sensor network used in a sewer system is presented, where the manhole cover is converted into the slot antenna and the sensors under ground can communicate with the above ground nodes through radiation from it. Again, although the system resides *underground*, the communication is performed *through air*. In [18], a glacier monitoring network, which is deployed in Norway, is presented. The sensor network aims to measure the parameters of ice caps and glaciers using sensors beneath the glaciers. To avoid wet ice, the base stations are connected to two wired transceivers 30 m below the surface. Using very high transmit powers (100 mW), the under*ice* sensors can communicate with the base stations. Although the work does not investigate channel characteristics or multi-hop routing, it is a good example of a practical underground application.

There are also some effort focusing on the EM wave propagation through soil and rock for ground-penetrating radars [19–22]. In [19], a review of the principles of the surface-penetrating radar is provided. More specifically, an overview of the empirical attenuation and relative permittivity values of various materials, including soil, at 100 MHz are presented. In [20], it has been shown that the soil composition has significant effects on the ground penetrating radar (GPR) detection of landmines. Furthermore, in [21], the electromagnetic field principles of a vertical electric dipole in a conducting half-space over the frequency range from 1 to 10 MHz are analyzed. Similarly, in [22], communication through soil is regarded as an electromagnetic wave transfer through the transmission line. Microwave analysis methods are exploited to provide a propagation model. The results of this work focus on the frequency range of 1–2 GHz. Although significant insight in EM wave propagation through soil can be gathered from these work, none of the existing work provides a complete characterization of underground communication. More specifically, neither the channel characteristics nor the multipath and scattering effects due to obstacles in soil or the nonhomogeneous feature of soil have been analyzed before. In this paper, we focus on this important issue to lay the foundations of networking in underground environment.

3. Underground signal propagation

The unique characteristics of signal propagation in soil require derivation of the path loss considering the properties of soil. From the Friis equation [23], it is well known that the received signal strength in free space at a distance r from the transmitter is expressed in the logarithmic form as

$$P_r = P_t + G_r + G_t - L_0, \tag{1}$$

where P_t is the transmit power, G_r and G_t are the gains of the receiver and transmitter antennas, and L_0 is the path loss in free space in dB, which is given by

$$L_0 = 32.4 + 20\log(d) + 20\log(f), \tag{2}$$

where d is the distance between the transmitter and the receiver in meters, and f is the operation frequency in MHz. For the propagation in soil, a correction factor should be included in the Friis equation (1) to account for the effect of the soil medium. As a result, the received signal can be rewritten as

$$P_r = P_t + G_r + G_t - L_p, \tag{3}$$

where $L_p = L_0 + L_s$ and L_s stands for the additional path loss caused by the propagation in soil, which 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 λ, is different and (2) the amplitude of the wave will be attenuated according to the frequency. The additional path loss, L_s, in soil is, hence, composed of two components

$$L_s = L_\beta + L_\alpha, \tag{4}$$

where L_β is the attenuation loss due to the difference of the wavelength of the signal in soil, λ, compared to the wavelength in free space, λ_0, and L_α is the transmission loss caused by attenuation with attenuation constant α. Consequently, $L_\beta = 20\log(\lambda_0/\lambda)$ and $L_\alpha = e^{2\alpha d}$. Considering that in soil, the wavelength is $\lambda = 2\pi/\beta$ and in free space $\lambda_0 = c/f$, where β is the phase shifting constant, $c = 3 \times 10^8$ m/s, and f is the operating frequency, the L_β and L_α can be represented in dB as follows:

$$L_\beta = 154 - 20\log(f) + 20\log(\beta), \qquad L_\alpha = 8.69\alpha d. \tag{5}$$

Given that the path loss in free space is $L_0 = 20\log(4\pi d/\lambda_0)$, the path loss, L_p, of an EM wave in soil is as follows:

$$L_p = 6.4 + 20\log(d) + 20\log(\beta) + 8.69\alpha d, \tag{6}$$

where the distance, d, is given in meters, the attenuation constant, α, is in $1/m$ and the phase shifting constant, β, is in radian/m. Note that the path loss, L_p, in (6) depends on the attenuation constant, α, and the phase shifting constant, β. The values of these parameters depend on the dielectric properties of soil.

Using Peplinski's principle [24], the dielectric properties of soil in the 0.3–1.3 GHz band can be calculated as follows:

$$\epsilon = \epsilon' - j\epsilon'', \tag{7}$$

$$\epsilon' = 1.15\left[1 + \frac{\rho_b}{\rho_s}(\epsilon_s^{\alpha'}) + m_v^{\beta'}\epsilon_{fw}'^{\alpha'} - m_v\right]^{1/\alpha'} - 0.68, \tag{8}$$

$$\epsilon'' = [m_v^{\beta''}\epsilon_{fw}''^{\alpha'}]^{1/\alpha'}, \tag{9}$$

respectively, where ϵ is the relative complex dielectric constant of the soil–water mixture, m_v is the water volume fraction (or volumetric moisture content) of the mixture, ρ_b is the bulk density in grams per cubic centimeter, $\rho_s = 2.66$ g/cm^3 is the specific density of the solid soil particles, $\alpha' = 0.65$ is an empirically determined constant, and β' and β'' are empirically determined constants, dependent on the soil type and given by

$$\beta' = 1.2748 - 0.519S - 0.152C, \tag{10}$$

$$\beta'' = 1.33797 - 0.603S - 0.166C, \tag{11}$$

where S and C represent the mass fractions of sand and clay, respectively. The quantities ϵ_{fw}' and ϵ_{fw}'' are the real and imaginary parts of the relative dielectric constant of free water.

The Peplinski principle [24] governs the value of the complex propagation constant of the EM wave in soil, which is given as $\gamma = \alpha + j\beta$ with

$$\alpha = \omega\sqrt{\frac{\mu\epsilon'}{2}\left[\sqrt{1 + \left(\frac{\epsilon''}{\epsilon'}\right)^2} - 1\right]}, \tag{12}$$

$$\beta = \omega\sqrt{\frac{\mu\epsilon'}{2}\left[\sqrt{1 + \left(\frac{\epsilon''}{\epsilon'}\right)^2} + 1\right]}, \tag{13}$$

where $\omega = 2\pi f$ is the angular frequency, μ is the magnetic permeability, and ϵ' and ϵ'' are the real and imaginary parts of the dielectric constant as given in (8), respectively. Consequently, the path loss, L_p, in soil can be found by using Eqs. (7), (8) and (10)–(13) in (6).

From (12) and (13), it can be seen that the complex propagation constant of the EM wave in soil is dependent on the operating frequency, f, the composition of soil in terms of sand and clay fractions, S and C, the bulk density, ρ_b, and the soil moisture or volumetric water content (VWC), m_v. Consequently, the path loss also depends on these parameters.

The path loss shown in (6) is evaluated using MATLAB to investigate the relationship between path loss and various parameters such as operating frequency, internode distance, and volumetric water content. The results are shown in Fig. 1. In the evaluations, we assume the VWC as 5%, the sand particle percent as 50%, the clay percent as 15%, the bulk density as 1.5 g/cm^3, and the solid soil particle density as 2.66 g/cm^3 unless otherwise noted. (The parameters reflect a typical soil condition as reported in [2,24].) The operating frequency is chosen between 300 and 900 MHz. The reason for this choice is as follows:

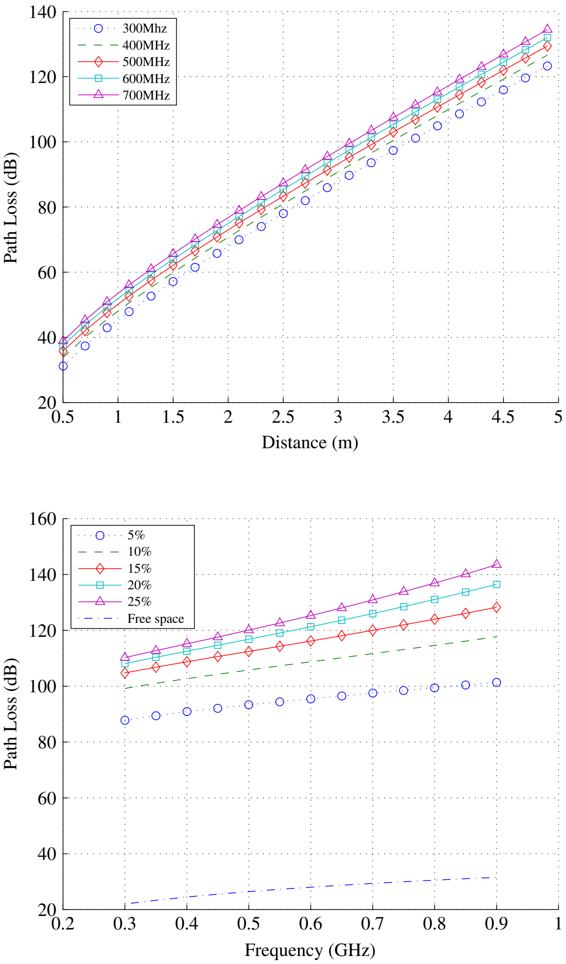

Fig. 1. Path loss versus (a) operating frequency and internode distance, (b) operating frequency and volumetric water content.

the recent experiments for underground communication using MICAz nodes, which operate in the 2.4 GHz band, reflect that communication range can be extended only up to 0.5 m at this band [9]. Consequently, lower frequency bands are necessary for acceptable communication. On the other hand, decreasing operating frequency below 300 MHz increases the antenna size, which can also prevent practical implementation of WUSNs. Considering that recent MICA2 motes operate in the 300–400 MHz range, while still preserving small antenna sizes, the operating frequencies between 300 and 900 MHz are suitable [7].

In Fig. 1(a), the path loss, L_p, which is given in (6), is shown in dB versus distance, d, for different values of operating frequency, f. It can be seen that the path loss increases with increasing distance, d, as expected. Moreover, increasing operating frequency, f, also increases path loss, which motivates the need for lower frequencies for underground communication.

In addition to network parameters, such as node distance and operating frequency, an important difference in underground communication is the direct influence of soil properties. Since the dielectric properties of soil changes significantly based on the composition of soil, communication is severely affected. In Fig. 1(b), the effect of volumetric water content on path loss, L_p, is shown for values of 5–25%. The difference between propagation in soil and that in free space can also be observed in Fig. 1(b). Since the attenuation significantly increases with higher water content, an increase of ∼30 dB is possible with a 20% increase in the volumetric water content of the soil. This effect is particularly important since water content not only depends on the location of the network but also varies during different seasons as will be investigated in Section 5. Hence, network deployment, operation, and protocol design in WUSNs should consider this dynamic nature of the underground channel as we will discuss in Section 6.

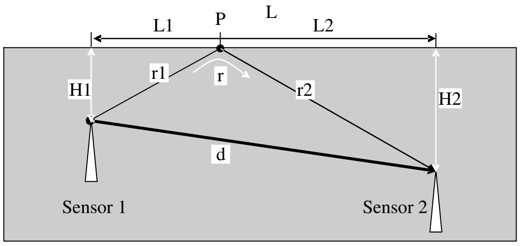

Fig. 2. Illustration of the two-path channel model.

4. Underground channel characteristics

Besides the attenuation in soil, various channel effects such as multipath spreading and fading influence the performance of wireless communication. Moreover, the burial depth of the sensor nodes significantly affect the channel characteristics. To provide an analytical characterization of the wireless channel in soil, next, we analyze the features of the underground channel in two main aspects. First, the effect of reflection from the ground surface on path loss is analyzed in Section 4.1. Second, we characterize the multipath effects using a Rayleigh channel model and derive the bit error rate for the underground wireless channel in Section 4.2. Throughout this section, we assume a homogeneous soil medium. In Section 5, the effects of variations in soil moisture will be investigated.

4.1. *Reflection from the ground surface*

Underground communication results in two main paths for signal propagation as shown in Fig. 2. 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 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. This is due to the increase in the path length of the reflected ray and the associated increase in attenuation. In this case, the path loss is given in (6) as investigated in Section 3. However, if the sensors are buried near the surface of ground, i.e., *low depth*, the influence of the wave reflection by ground surface should be considered. Considering ground surface reflection, the

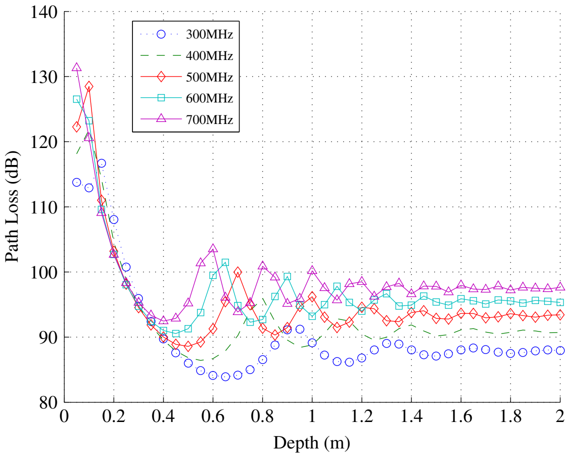

Fig. 3. Two-path channel model: path loss versus depth for different operating frequencies with the two-path channel model.

total path loss of the two-path channel model can be deduced as follows:

$$L_f(\mathrm{dB}) = L_p(\mathrm{dB}) - V_{\mathrm{dB}}, \qquad (14)$$

where L_p is the path loss due to the single path given in (6) and V_{dB} is the attenuation factor due to the second path in dB, i.e., $V_{\mathrm{dB}} = 10 \log V$.

Consider the case where two sensors are buried at a depth of H_1 and H_2, respectively, with a horizontal distance of L, and an end-to-end distance of d as illustrated in Fig. 2. From electromagnetic principles, the attenuation factor, V, is given as follows:.

$$V^2 = 1 + (\Gamma \cdot \exp(-\alpha \Delta(r)))^2 - 2\Gamma \exp(-\alpha \Delta(r)) \times \cos\left(\pi - \left(\phi - \frac{2\pi}{\lambda}\Delta(r)\right)\right), \qquad (15)$$

where Γ and ϕ 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, λ is the wavelength in soil, and α is the attenuation as given in (12).

Using (15) in (14), the path loss is shown as a function of depth, H, operating frequency, and volumetric water content in Fig. 3, where we assume that the sensors are buried at the same depth, i.e., $H_1 = H_2 = H$ and hence $d = L$. When compared to the single-path model results shown in Fig. 1(a), the two-path model results in a slightly less path loss with fluctuations based on depth and volumetric water content.

In Fig. 3, the path loss is shown as a function of burial depth, H, for various operating frequencies, f. It can be observed that for the two-path model, the effect of the bury depth, H, is significant and depends on 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 WUSNs, where deployment should be tailored to the operating frequency of the wireless transceivers. In Fig. 3, 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 a threshold value. According to the results shown in Fig. 3; if the bury depth is higher than 2 m, the influence of the reflection is negligible and the single-path model should be used. On the other hand, for shallow depth deployments, the two-path channel model should be considered.

4.2. *Multipath fading and bit error rate*

The two-path channel model described in Section 4.1 models the main propagation characteristics of underground EM waves. However, in fact, the underground channel exhibits additional characteristics other than that is modeled through the two-path channel model alone. First, the surface of the ground is not ideally smooth and, hence, not only causes reflection, but also scattering and diffraction. Second, 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, multipath fading should also be considered in addition to the basic two-path channel model.

The multipath fading has been extensively investigated for the above ground situation [23]. The random scattering due to air, the movement of objects, as well as other random effects result in fluctuation and scattering of EM waves in air. Therefore, the amplitude and the phase of the received signal exhibit a random behavior with time. Generally, this multipath channel characteristic obeys Rayleigh or log-normal probability distribution.

In underground communication, on the other hand, there is no scattering with time. This is because, the channel between two transceivers is relatively stable when the composition of soil is considered [7]. On the other hand, the roots of trees, rocks, clay particles and other objects in soil can still incur reflection and refraction for EM waves similar to the obstacles do in air. Considering a fixed inter-node distance, the received signal levels are different at different locations because the signal travels through different multipaths. As a result, randomness in underground environment is due to the locations of the nodes rather than time, which still obeys the Rayleigh probability distribution. The only difference is that the variable of Rayleigh probability distribution is location instead of time.

Accordingly, we consider that each path in the underground channel is Rayleigh distributed such that the envelope of the signal from each path is modeled as an independent Rayleigh distributed random variable, χ_i, $i \in \{1, 2\}$. Consequently, for the one-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, we assume that the received signal is the sum of two independent Rayleigh fading signals. Considering the above discussion, we develop the underground channel model denoted as *location-dependent Rayleigh multipath channel*. Consequently, the

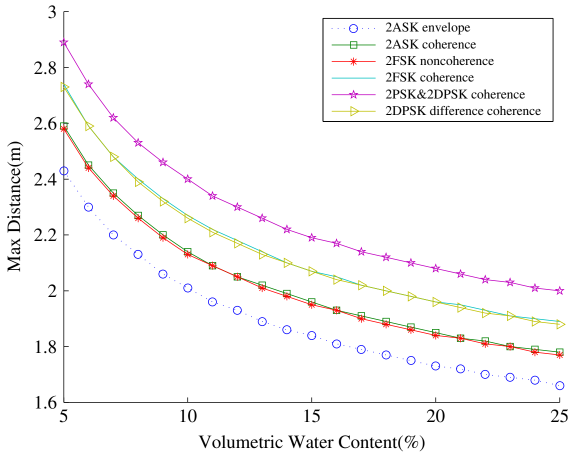

Fig. 4. The maximum inter-node communication distance of one path channel using different modulation schemes.

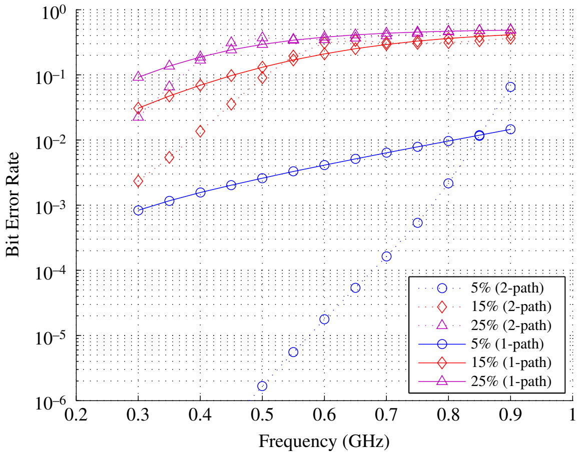

Fig. 5. BER versus operating frequency and VWC for one-path and two-path channel models.

composite attenuation constant, χ, in multipath Rayleigh channel is

$$\chi^2 = \chi_1^2 + (\chi_2 \cdot \Gamma \cdot \exp(-\alpha \Delta(r)))^2 - 2\chi_1\chi_2\Gamma \exp(-\alpha\Delta(r)) \times \cos\left(\pi - \left(\phi - \frac{2\pi}{\lambda}\Delta(r)\right)\right), \quad (16)$$

where χ_1 and χ_2 are two independent Rayleigh distributed random variables of two paths, respectively, Γ and ϕ are the amplitude and the phase angle of the reflection coefficient at the reflection point P, $\Delta(r) = r - d$ is the difference of the two paths, and α is the attenuation constant.

Based on the above model, next, we investigate the bit error rate (BER) characteristics of the underground channel. The results will help represent the underlying challenges in the design of WUSNs. The BER of a communication system depends mainly on three factors: (1) the channel model, (2) the SNR, and (3) the modulation technique used by the system.

Considering the channel model derived before, the SNR is given by $\text{SNR} = P_t - L_f - P_n$, where P_t is the transmit power, L_f is the total path loss given in (14), and P_n is the energy of noise. We assume that P_t is between 10 and 30 dBm for our evaluations and P_n is −103 dBm [25]. Although the noise, P_n, may change depending on the properties of the soil, this value is a representative value that can be used to represent the properties of underground BER.

The BER also depends on the modulation method. In order to provide an initial investigation at this area, various modulation methods are investigated to illustrate their effects on BER. For this investigation, we choose three kinds of modulation methods: ASK, FSK, and PSK. While this set is not an exhaustive set of the modulation schemes that can be used in WUSNs, it provides a general guideline to illustrate the effects of the underground channel on BER. The relation between the maximum inter-node distance of the single path channel model and the VWC is shown in Fig. 4. The maximum inter-node distance is found subject to a BER target of 10^{-3} for different modulation methods. In Fig. 4, it can be seen that the PSK modulation method provides the largest range. Consequently, in our analysis, we consider the PSK modulation. Considering the modulation scheme as 2PSK, the BER can be shown as a function of SNR as $\text{BER} = 0.5\text{erfc}\left(\sqrt{\text{SNR}}\right)$, where $\text{erfc}(\cdot)$ is the error function and SNR is the signal to noise ratio.

We analyze the characteristics of BER using the same parameters used in Section 4.2 in Fig. 5, where the simulation results are shown for single-path and two-path models. Note that the two-path model is used for deployments of bury depth, $H < 2$ m, while the single-path model is used for high depth deployments. A significant result from our simulations is that the VWC has an important impact on the BER compared to other parameters. As shown in Fig. 5, an increase from 5% to 10% results in almost an order of magnitude increase in BER. This result shows that *VWC is one of the most important parameters for underground communication*.

As explained before, for burial depths less than 2 m, the two-path Rayleigh fading model is suitable for WUSNs. In Fig. 5, the effect of the reflected path from the ground surface on BER can also be clearly seen. For the single path model, the BER plots are significantly higher compared to the two-path model. As a result, the communication distance can be extended for low depth applications, where the two-path model is applicable. Finally, the effect of VWC in two-path model is also shown in Fig. 5. Compared to the single-path model results shown also in this figure, higher VWC is acceptable for low depth deployments when the operation frequency is low.

In addition to BER, the effective communication range of a node is important in the design of effective networking protocols for WUSNs. In Fig. 6, the maximum inter-node distance is shown for the two-path model according to a certain BER target as a function of the burial depth. More specifically, the BER target is assumed as 10^{-3}. Accordingly, the maximum inter-node distance that provides the BER target is shown for different operating frequencies. It is shown that as the frequency increases, the maximum distance decreases. Moreover,

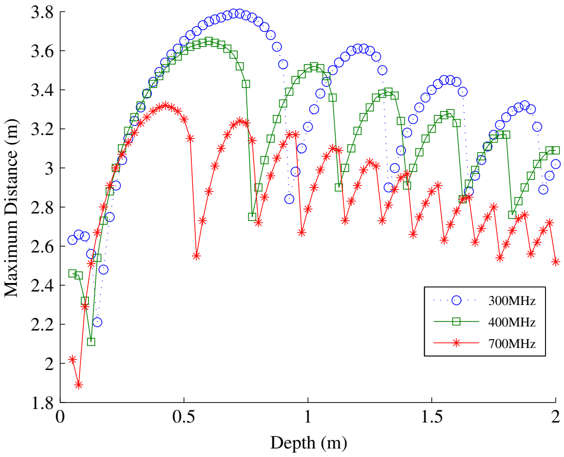

Fig. 6. Maximum inter-node distance versus depth.

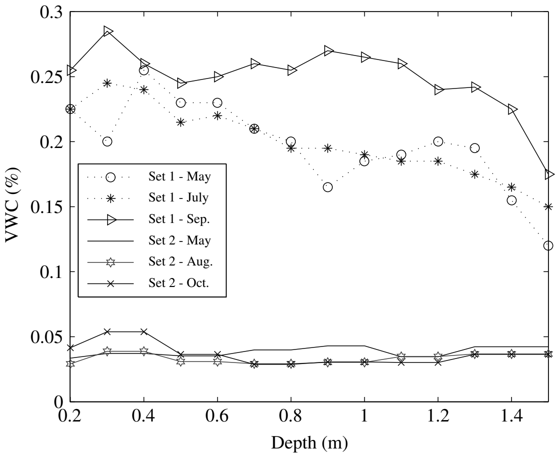

Fig. 7. The VWC values from the two data sets. The values taken at different times of the year are also shown.

it can be observed that as the burial depth increases, the communication range of a node can be improved up to a certain value. However, if the burial depth is further increased, reduction in the communication range is observed and the maximum distance fluctuates as a function of the burial depth. This suggests that an optimal burial depth exists for a particular operation frequency, which is important for deployment of WUSNs.

5. Effects of VWC variations in soil

The results obtained from our channel model clearly represent the direct influence of soil properties on communication performance. Especially, VWC influences the maximum communication range attainable in WUSNs. The above simulations, however, are performed assuming that VWC is constant throughout the soil at different depths. However, field measurements reveal that VWC also changes with depth [26–28]. Here, we also investigate the effects of VWC variations at different depths. Consequently, a comprehensive profile of the underground communication is presented. Soil moisture varies as the depth increases in soil. In addition, significant variations are possibly related to weather, season, time of the day, as well as the external environmental effects. This variation is also reflected on the dielectric constant of soil at different depths and times, which in effect change the path loss and BER. Consequently, these variations should also be accounted for in the channel model for underground communication.

The VWC is the most important factor contributing to the total soil dielectric constant [29]. The water in the soil is usually classified into two based on its amount. The *bound water* is tightly bounded to the surface of the soil particles. However, above a limit, as more water is added to the soil, the soil dielectric constant rapidly increases. The effect of VWC on communication, therefore, depends on the capacity of the particular soil type to hold the bound water. As an example, compared to sand, clay particles have a larger surface area, which enables soil with higher clay content to hold more bound water. Therefore, the VWC has less effect on clay dominant soil than on sand dominant soil.

In addition to the type of soil, the depth also influences VWC, which results in the variation of dielectric properties of soil at different depths. Moreover, site measurements reveal that the soil moisture does not linearly change with the depth [26–28]. Generally, VWC increases with the depth first and then decreases with it. However, the variation characteristics as well as the specific depths where VWC start to decrease also depend on the type of the soil.

To investigate the relation of underground communication quality with the burial depth, the BER at different depth are found based on the discussion in Section 4.2 and using the experimental data in [28,27] for the VWC. We denote these data sets as *Set* 1 and *Set* 2, respectively, 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 [28]. The VWC values for different times of the year as well as different depths are shown in Fig. 7.
- *Set* 2. The second data set is from a sandy soil with 50% sand and 15% clay [27]. Since sandy soil keeps 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 VWC on the communication range. The measured VWC values at different times of the year are also shown in Fig. 7 as a function of depth.

It can be observed from Fig. 7 that the VWC values for Set 1 are significantly higher. Intuitively, this would correspond to worse communication performance compared to Set 2. Furthermore, VWC varies significantly with depth for Set 1 as well as season. These fluctuations would significantly affect the communication performance of WUSNs. On the other hand, the VWC measured in Set 2 is relatively constant with respect to both depth and season.

Using the VWC values shown in Fig. 7, the maximum inter-node communication distance is calculated based on our channel model presented in Section 4 and shown in Fig. 8, where the effects of variations of VWC on the communication performance can be seen. We also compare these results with the case where the VWC is assumed to

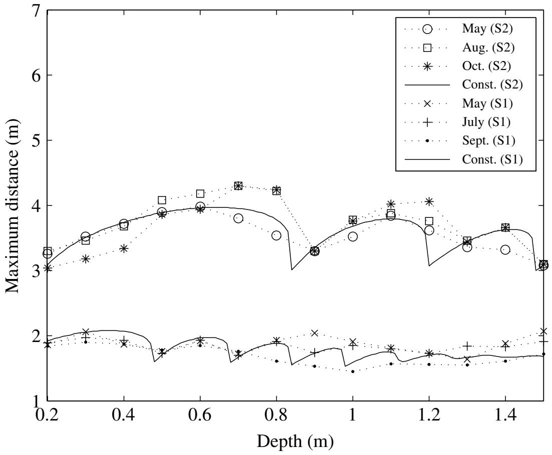

Fig. 8. The maximum inter-node distance versus depth for the data Set 1 (S1) and Set 2 (S2) at different times of the year. The maximum distance calculated by considering constant VWC at all depths is also shown.

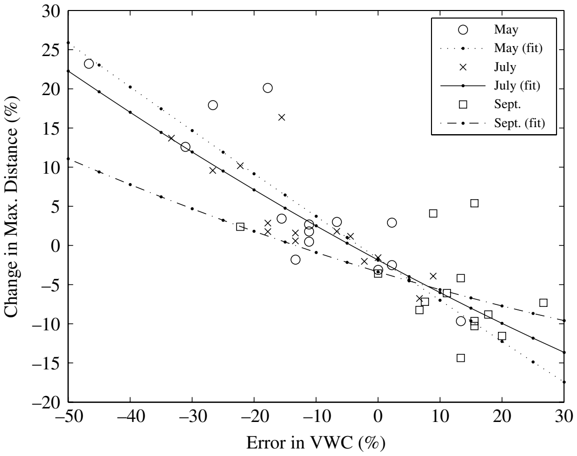

Fig. 9. Relationship between change in VWC and change in the maximum inter-node distance.

be uniform throughout the soil at different depths (shown in Fig. 8 by solid lines for both sets). This provides a guideline for the deployment of WUSNs. We are particularly interested in whether it is necessary to gather VWC information for all the points in a network or a representative value taken at a specific depth would be sufficient.

In Fig. 8, the maximum inter-node distance for 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 uniform 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 [28] 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. However, at higher depths, longer hop distances are possible compared to the uniform VWC assumption. This is due to the decrease in VWC with increasing depth as shown in Fig. 7.

The seasonal influence on communication is also shown in Fig. 8. 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. Compared to the uniform VWC case, although there are differences in the maximum distance, using a single measurement of VWC can predict the communication characteristics accurately for burial depths less than 0.8 m. However, higher variations are observed when the depth is higher than 0.8 m.

The results in Fig. 8 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 WUSNs.

Besides the influence of depth and seasons, the soil type also affects the relationship between communication and VWC. The black soil in data Set 1 can hold more water compared to sandy soil in Set 2. This lower moisture level has the potential to improve the communication significantly. As shown in Fig. 7, the VWC does not vary significantly by depth or season in Set 2. Consequently, as obtained in Fig. 8, the uniform VWC model closely matches the maximum distance achieved through actual VWC measurements. Moreover, since the VWC of Set 2 is significantly lower than Set 1, the communication range obtained for Set 2 is almost twice that for Set 1.

Since VWC significantly affects the communication characteristics, the relation between variations in VWC and the corresponding changes in communication range is of importance. In Fig. 9, the effect of a change in VWC on the maximum inter-node distance is shown. The x-axis shows the change in percentage in VWC based on the measured data in Set 1 and the y-axis shows the corresponding change in the maximum inter-node distance. The actual values as well as the fitted lines for three different months are given in Fig. 9. It is shown that an increase in VWC results in decrease in the communication range. Interestingly, although quadratic fitting is used, the relationship is linear. It is also important to note that the rate of change in the distance with VWC, i.e., the slope of the line, also depends on season. As an example, a 20% decrease in VWC corresponds to a 10% increase in the communication range in July, whereas, in September, this corresponds to a 4% increase in the communication range.

6. Challenges in the design of WUSNs

The channel model for underground communication highlights the peculiarities of this medium. Consequently, the following challenges emerge for the design of WUSNs:

Topology design. The results for maximum attainable communication range illustrates that underground environment is much more limited compared to terrestrial WSNs. In particular, at the operating frequency of 300–400 MHz, the communication range can only be extended up to 5 m. This suggests that multi-hop communication is essential in WUSNs. Consequently, in the design of WUSNs topology, multi-hop communication should be emphasized.

Another important factor is the direct influence of soil properties on the communication performance. It is clear that any increase in water content significantly hampers the communication quality. The network topology should be designed to be robust to such changes under channel conditions. Furthermore, soil composition at a particular location should be carefully investigated to tailor the topology design according to specific characteristics of the underground channel at that location.

As described in Section 5, underground communication is also affected by the changes according to depth. As a result, different ranges of the communication distance can be attained at different depths. This requires a topology structure that is adaptive to the 3D effects of the channel. Optimum strategies to provide connectivity and coverage should be developed considering these peculiarities [30].

Operating frequency. Our channel model clearly illustrates the fact that the attenuation increases with operating frequency, which motivates smaller frequency values considering the high attenuation. However, this results in a trade off between the frequency and the antenna size for the WUSN device. Our results show that the 300–400 MHz band is suitable for WUSNs. On the one hand, our simulation results show that acceptable communication ranges are possible. Moreover, there is already sensor motes working in this band in the market.

As explained in Section 4, the communication performance at low depth reveals that using a fixed operating frequency may not be the best option for WUSNs. Cognitive radio techniques [31] can be exploited to adapt to the changing environmental conditions. Furthermore, our analysis reveal that the optimal frequency to reach the maximum communication range varies by depth. Consequently, cognitive radio techniques can provide an adaptive operation for the WUSNs in this dynamic environment.

*Cross-layer protocol design.*Our findings in Section 5 reveal that the communication quality is also related to the environmental conditions. Besides the effect of soil type, the seasonal changes result in variation of volumetric water content, which significantly affects the communication performance. Therefore, in the protocol design for WUSNs, the environment dynamics need to be considered. Furthermore, the dynamic nature of the physical layer and its direct influence on communication quality call for novel *cross-layer* design techniques that are adaptive to environmental changes for WUSNs. We provide an initial step based on this concept through a packet size optimization framework for WUSNs in [32].

7. Conclusion

Compared to that in air, the underground communication exhibits significant challenges for the development of wireless underground sensor networks. Among these challenges, the attenuation caused by the soil is the most important aspect of underground communication and has to be completely characterized. In this paper, the propagation characteristics of electromagnetic waves in soil are presented. Furthermore, an underground channel model, referred to as the *location-dependent two-path Rayleigh channel model* is derived to characterize underground communication. Our analysis shows that the communication success significantly depends on the operating frequency and the composition of the soil. Through simulations, it is shown that in the 300–400 MHz frequency band, the path loss can be limited to a degree supporting feasible communication. Furthermore, it is shown that the channel characteristics vary depending on the burial depth of the sensors. For low depth deployments, the channel is shown to exhibit a two-path channel model with the effect of multipath fading of spatial distribution. For high depth deployments, a single path channel is suitable to characterize communication. The results of this work lay the foundations of underground communication and help the future research and applications of wireless underground sensor networks (WUSNs), which is a promising application area for WSNs.

The focus of this paper is the communication of sensors buried underground. However, in a generic WUSN architecture, there may still be some devices, such as sink nodes, deployed aboveground. Hence, the communication between the underground sensors and the aboveground sinks should also be considered. Finally, using existing wireless sensor nodes that operate at 433 MHz [33], field experiments will be performed to further improve the results shown in this analysis.

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