Characteristics of Underground Channel for Wireless Underground Sensor Networks

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Abstract—**Wireless Underground Sensor Networks (WUSN) constitute one of the promising application areas of the recently developed wireless sensor networking techniques. The main difference between WUSN 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 proposed to completely characterize the underground wireless channel and lay out the foundations for efficient communication in this environment. In particular, the underground communication channel is modeled considering not only the propagation of EM waves in soil, but also other affects such as multipath, soil composition, water content, and burial depth. The propagation characteristics are shown 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. 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 WUSN.**

I. INTRODUCTION

Wireless Underground Sensor Networks (WUSN), which consist of wireless sensors buried under ground, enable a wide variety of novel applications that are not possible using current wired underground monitoring techniques. Compared to the current underground sensor networks, which use wired communication methods for network deployment, WUSN have several remarkable merits, such as concealment, ease of deployment, timeliness of data, reliability and coverage density [1].

WUSN phenomenon is applicable to many application scenarios[1]. Among these, monitoring the soil properties of sports fields, such as golf courses, football fields, has a potential to ease the maintenance of these fields. Moreover, WUSN can be exploited to monitor the presence and concentration of various toxic substances in particular areas to prevent pollution. In addition, WUSN can be exploited in underground coal mines to monitor air quality and prevent disasters. Moreover, WUSN techniques can be used to monitor aboveground objects, locating and even tracking them without being discovered, which is particularly important in border patrol.

Despite its potential advantages, the realization of WUSN is challenging. The main challenge in this area is the realization of efficient and reliable underground links to establish multiple hops underground and efficiently disseminate data for seamless operation. To this end, the propagation characteristics of electromagnetic (EM) waves in soil prevent a straightforward characterization of underground wireless channel. First, EM waves encounter much higher attenuation in soil compared to air, which severely hampers the communication quality. As an example, efficient communication between sensor nodes above and below ground is shown to be possible only at the distance of 0.5m when the 2.4 GHz frequency is used [8]. Moreover, the surface of the ground causes reflection as well as refraction, which prevents simple ray models characterize the underground channel accurately. In addition, multi-path 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 are primarily limited by the wireless channel capabilities, these challenges caused by underground channel should be carefully considered for the design of WUSN.

There has been some work focusing on the EM wave propagation through soil and rock for ground-penetrating radars [4], [5], [9], and [10]. In [4], 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 100MHz is presented. In [5], it has been shown that the soil composition has significant effects on the Ground Penetrating Radar (GPR) detection of landmines. Furthermore, in [9], the electromagnetic field principles of a vertical electric dipole in a conducting half-space over the frequency range from 1 to 10 MHz is analyzed. Similarly, in [10], communication through soil is regarded as an electromagnetic wave transfer through the transmission line and 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 multi-path effects due to obstacles in soil or the nonhomogeneous feature of soil have been analyzed before.

In this paper, we provide a complete characterization of the underground wireless channel to lay out the foundations for efficient communication in this environment. In particular, the $0.3-0.9$ GHz band, which is suitable for small size sensor development, is considered. Our model characterizes not only the propagation of EM wave through soil, but other affects such as multipath, soil composition, water content, and burial depth are also considered to provide a generic framework for underground wireless communication. First, combining the spreading principles of the EM waves and the Peplinski Principle [6], which governs the affects of soil composition on attenuation, the path loss formula at the 300-900MHz band is derived. The results obtained from this formalization reveal that the underground communication is severely affected by operating frequency and soil properties, especially, the volumetric water content (VWC) of soil. Furthermore, the underground multi-path fading characteristics are investigated such that the effects of reflection and refraction from the ground surface, the objects in soil, and the nonhomogeneous feature of soil are considered. Finally, the bit error rate (BER) corresponding to various underground deployments and soil types are illustrated. To the best of our knowledge, this is the first work that analyzes the multi-path channel characteristics in soil. The results of this work reveal the feasibility of WUSN. Moreover, important considerations for the deployment and operation of WUSN are highlighted to lay the fundamentals for the realization of these networks.

The rest of this paper is organized as follows: In Section II, the underground propagation characteristics of EM waves in the 300-900 MHz range are analyzed. In Section III, the characteristics of the underground wireless channel are described, which considers the reflection from ground surface as well as the multi-path fading. Finally, the future work and conclusions are provided in Section IV.

II. Underground Signal Propagation

The unique characteristics of signal propagation in soil necessitates derivation of path loss considering the properties of soil. From Friis equation [7], it is well known that the received signal strength in free space at a distance d from the transmitter is expressed in logarithmic form as

$$P_r(dBm) = P_t(dBm) + G_r(dB) + G_t(dB) - L_0(dB) \ , \quad (1)$$

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

$$L_0(dB) = 32.4 + 20\log(d(km)) + 20\log(f(MHz)) \ . \quad (2)$$

For the propagation in soil, a correction factor should be included in Friis equation (1) to account for the effect of the soil medium. As a result, the received signal is

$$P_r = P_t + G_r + G_t - L_0 - L_m \ , \quad (3)$$

where L_m stands for the additional path loss caused by the propagation in soil. L_m 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. (2) The amplitude of the wave will be attenuated as a function of the frequency. (3) The phase velocity is correlated to the frequency in the soil, which can cause color scattering and delay distortion. Consequently, the additional path loss, L_m, in soil is composed of two components

$$L_m(dB) = L_{m1}(dB) + L_\alpha(dB) \ , \quad (4)$$

where L_{m1} 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. Consequently,

$$L_{m1}(dB) = 20\log\left(\frac{\lambda_0}{\lambda}\right) . \quad (5)$$

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, $c = 3\times10^8$ m/s, and f is the operating frequency, then, L_{m1} becomes

$$L_{m1} = 154 - 20\log(f)(Hz) + 20\log(\beta) . \quad (6)$$

Considering the transmission loss caused by the attenuation constant, α, L_α can be represented as $L_\alpha = e^{2\alpha d}$, which is deduced from the electric field equation in [12]. It is, when represented in dB, given by $L_\alpha(dB) = 8.69\alpha d$. Given that the path loss in free space is $L_0 = 20\log(4\pi\lambda_0)$, the path loss of an EM wave in soil is found by combining L_0 with (4) as follows:

$$L_p = 6.4 + 20\log(d)(m) + 20\log(\beta) + 8.69\alpha d , \quad (7)$$

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 (7) 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 [6], the dielectric properties of soil in the 0.3-1.3 GHz band can be calculated as follows:

$$\epsilon = \epsilon' - j\epsilon'' , \quad (8)$$

$$\epsilon' = 1.15[1 + \frac{\rho_b}{\rho_s}(\epsilon_s)^{\alpha'} + (m_v)^{\beta'}(\epsilon'_{f_w})^{\alpha'} - m_v]^{1/\alpha'} - 0.68, \quad (9)$$

$$\epsilon'' = \left[(m_v)^{\beta''}(\epsilon''_{f_w})^{\alpha'}\right]^{1/\alpha'} , \quad (10)$$

where ϵ_m is the relative complex dielectric constant of the mixture of soil and water, m_v is the volumetric water content (VWC) of the soil, 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 soil-type and given by

$$\beta' = 1.2748 - 0.519S - 0.152C , \quad (11)$$

$$\beta'' = 1.33797 - 0.603S - 0.166C , \quad (12)$$

respectively, where S and C stand for the mass fractions of sand and clay, respectively. ϵ'_{f_w} and ϵ''_{f_w} are the real and imaginary parts of the relative dielectric constant of water. The Peplinski principle [6] governs the value of the complex propagation constant of the EM wave in soil, which is given as $\gamma = \alpha + j\beta$ with

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

$$\beta = \omega\sqrt{\frac{\mu\epsilon'}{2}\left[\sqrt{1 + (\frac{\epsilon''}{\epsilon'})^2} + 1\right]} , \quad (14)$$

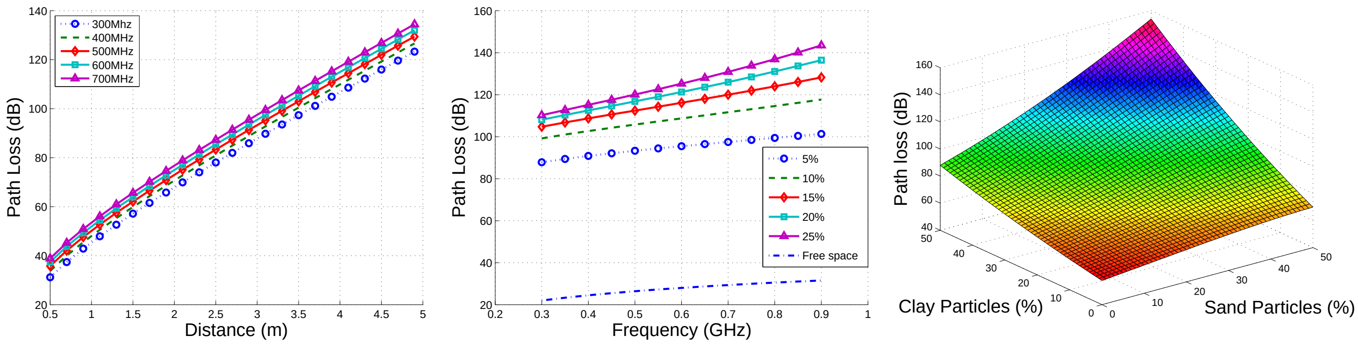
where $\omega = 2\pi f$ is the angular frequency, μ is the magnetic permeability, and ϵ' and ϵ'' are the real and imaginary parts of the dielectric constant as given in (9) and (10), respectively. Consequently, the path loss, L_p, in soil can be found by using equations (8 - 14) in (7).

From the above equations, it can be seen that the underground path loss, L_p, given in (7) depends on the *operating frequency, the composition of soil in terms of sand, silt, and clay fractions, the bulk density,* and *the volumetric water content (VWC).*

The path loss shown in (7) is evaluated using MATLAB to investigate the relationship between path loss and various parameters. The results are shown in Figs. 1. In the evaluations, we assumed the volumetric moisture content as $m_v = 5\%$, the sand particle percent as $S = 50\%$, the clay percent as $C = 15\%$, the bulk density as $\rho_b = 1.5$ grams/cm^3, and the solid soil particle density as $\rho_s = 2.66$ grams/cm^3 unless otherwise noted. The results are significantly different from those in [1] since lower frequencies in the 300-900 MHz band are used.

In Fig. 1(a), the path loss, L_p, in (7) is shown in dB versus distance, d, for different values of operating frequency, f, varying from 300MHz to 900MHz. It can be seen that the distance has an important impact on the path loss, L_p, which 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 the lower frequency band, i.e., several hundred MHz, it can be observed that the path loss is greatly decreased.

In addition to network parameters such as node distance and operating frequency, an important difference of 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 (VWC), m_v, 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 VWC, an increase of 30dB is possible with a 20% increase in the VWC of the soil. This effect is particularly important since the



(a) (b) (c)

Fig. 1. Path loss vs. (a) operating frequency and internode distance, (b) operating frequency and volumetric water content, and (c) clay particles and sand particles.

VWC not only depends on the location of the network but also varies during different seasons. Hence, network deployment, operation, and protocol design in WUSN should consider this dynamic nature of the underground channel. In addition to the VWC, the influence of the composition of soil in terms of clay and sand particles on path loss, L_p, is shown in Fig. 1(c). It can be observed that there is a homogeneous increase in path loss with increasing percentage of clay and sand particles in soil. Therefore, soil type needs to be carefully investigated before deployment of WUSN.

III. Underground Channel Characteristics

The characteristics of path loss in soil, as investigated in Section II, constitutes an important part of communication in soil. However, besides the attenuation in soil, various channel effects influence the performance of wireless communication. Multi-path spreading and fading are among these effects that should be considered. Moreover, the depth of the sensor nodes significantly affects the channel characteristics. In order to provide a complete characterization of the wireless channel in soil, next, we analyze the features of the underground channel. First, the effect of reflection from the ground surface on path loss is analyzed in Section III-A. Second, we characterize the multi-path effects using a Rayleigh channel model and derive the bit error rate for underground wireless channel in Section III-B.

A. Reflection from Ground Surface

In Section II, the path loss characteristics along a path of distance d is considered. However, as shown in Fig. 2, signal propagation in soil is also affected by the reflected rays from the ground surface due to the soil-air interaction. Although this effect is mainly dependent on the depth of the sensors in soil, it should be considered in low depth deployments as we explain next.

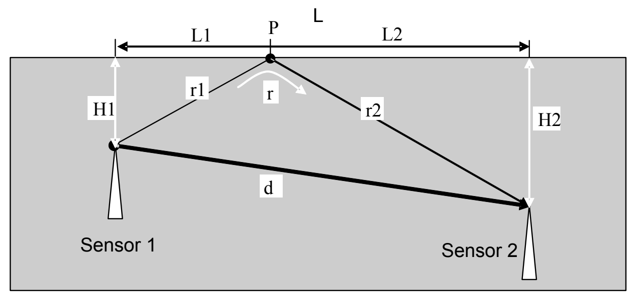


Fig. 2. Illustration of the two-path channel model.

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. While the direct path constitutes the main component of the received signal, the reflected path also affects communication especially when the sensors are buried close to the surface.

When the burial 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 (7) as investigated in Section II.

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

$$L_f(dB) = L_p(dB) - V_{dB} \ , \qquad (15)$$

where L_p is the path loss due to the single path given in (7) and V_{dB} is the attenuation factor due to the second path in dB, i.e., $V_{dB} = 10 \log V$.

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. Consequently, the attenuation factor, V, can be deduced as follows, using the electric field equation in [12] :

$$V^2 = 1 + (\Gamma \cdot \exp(-\alpha\Delta(r)))^2 - 2\Gamma \exp(-\alpha\Delta(r)) \times \cos\left(\pi - \left(\phi - \frac{2\pi}{\lambda}\Delta(r)\right)\right) , \quad (16)$$

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 and α is the attenuation constant given in (13).

Using (16) in (15), the path loss is shown as a function of the end-to-end distance, d, operating frequency, f, burial depth, H, and volumetric water content in Figs. 3. In these figures, we assume that the sensors are buried at the same depth, i.e., $H_1 = H_2 = H$ and $d = L$. As shown in Fig. 3(a), the path loss increases with increasing node distance, d. However, when compared to the single-path model results shown in Fig. 1(a), the two path model result is slightly changed with some ripples added. This is due to the reflection effect of ground surface. When the signal hits the ground surface and is reflected back, its phase is abruptly changed. When it is received, it is aggregated with the direct path signal and the total received signal is not homogeneously increased in phase and in signal strength. As a result, the ripples occur when the internode distance, d, is increased.

In Fig. 3(b), the path loss is shown as a function burial depth, H, for various operating frequency, f. It can be observed that for the two-path model, the effect of operating frequency, f, is significant and mainly depends on the burial depth, H. For a particular operating frequency, an optimum burial depth exists such that the path loss is minimized. This is particularly important in the topology design of WUSN, where deployment should be tailored to the operating frequency of the wireless sensors as well as the soil type. Moreover, if higher costs for sensor nodes are feasible, cognitive radio techniques [2] can be used to dynamically select the operating frequency depending on the burial depth of each sensor in the WUSN.

As explained before, the underground channel model can be characterized in two situations according to the burial depth of the sensors. At low depth, the reflection from ground surface affects the path loss, which is evident from Fig. 3(b). It can be observed that the effect of reflection diminishes as the burial depth, H, increases. More specifically, the underground channel exhibits a single-path characteristic when the burial depth is higher than a threshold value. The results shown in Fig. 3(b) reveal that if the burial depth is higher than 2 m, the influence of reflection is negligible and single-path model should be used. However, for low depth deployments, two-path channel model needs to be considered.

The effect of frequency and the volumetric water content is also shown in Fig. 3(c), where the path loss fluctuates according to both parameters. This fluctuation is due to the constructive or destructive interference of the second path based on the operating frequency and the volumetric water content. Fig. 3(c) suggests that dynamic frequency operation may be necessary in WUSN, where the operating frequency is determined based on the volumetric water content or in other words according to changes in weather.

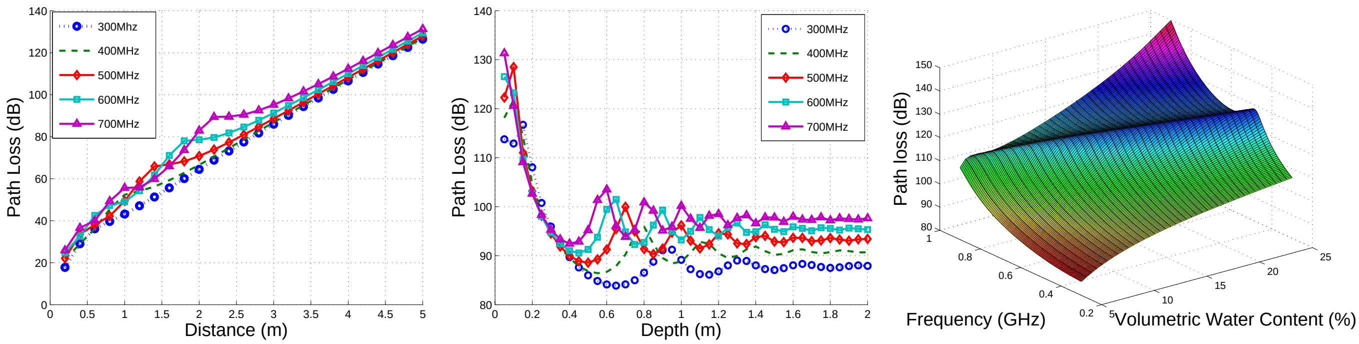
B. Multi-path Fading and Bit Error Rate

The two-path channel model described in Section III-A models the main propagation characteristics of EM waves underground. However, in fact, the underground channel exhibits additional complications 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 refraction. 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, multi-path fading should also be considered in addition to the basic two-path channel model.

The multi-path fading has been extensively investigated for the above ground situation [7]. In air, the random refraction due to air, the movement of objects, as well as other random effects result in fluctuation and refraction of EM waves. Therefore, the amplitude and the phase of the received signal exhibit a random behavior with time. Generally, this multi-path channel character obeys Rayleigh or log-normal probability distribution.

In underground communication, on the other hand, there is no random air refraction with time. This is because, the channel between two transceivers is relatively stable when the composition of soil is considered. Hence, the channel is almost stable in each path with respect to time. 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. Hence, except the time varying feature, the underground channel exhibits similar multi-path characteristics as that of air.

Considering a fixed internode distance, the received signal levels are different at different locations because



(a) (b) (c)

Fig. 3. Two-path channel model: Path loss vs. (a) internode distance, d, (b) depth, H, for different operating frequencies, and (c) operating frequency, f, and volumetric water content.

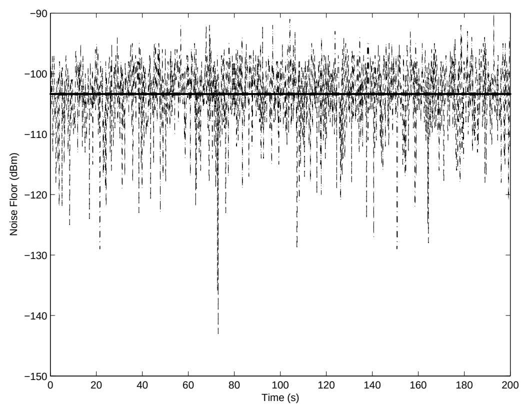


Fig. 4. Empirical noise floor measurements at 12 inch depth.

the signal travels through different multi paths. As a result, randomness 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 assume 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, $\chi_i,\ i \in \{1, 2\}$. Consequently, for the one-path model, the received energy per bit per noise power spectral density is given by $r = \chi^2 E_b/No$, which has a distribution as follows:

$$f(r) = \frac{1}{r_0} exp\left(\frac{r}{r_0}\right) , \quad (17)$$

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 the received signal is the sum of two independent Rayleigh fading signals. This assumption is motivated by the results reported in [3], where a two-path Rayleigh channel model is proposed for underwater communication. Moreover, here, we need to consider the additional attenuation through soil. So the model of two-path Rayleigh channel in soil is deduced. The χ in two-path Rayleigh channel is deduced using the electric field equation in [12].

$$\begin{aligned} \chi^2 \;\; = \;\; & \chi_1^2 + (\chi_2 \cdot \Gamma \cdot \exp\left(-\alpha\Delta\left(r\right)\right))^2 \\ & -2\chi_1\chi_2\Gamma \exp\left(-\alpha\Delta(r)\right) \\ & \times \cos\left(\pi - \left(\phi - \frac{2\pi}{\lambda}\Delta(r)\right)\right) \;, \quad (18) \end{aligned}$$

where χ_1 and χ_2 are two independent Rayleigh distributed random variables of two paths, respectively. 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 and α is the attenuation constant.

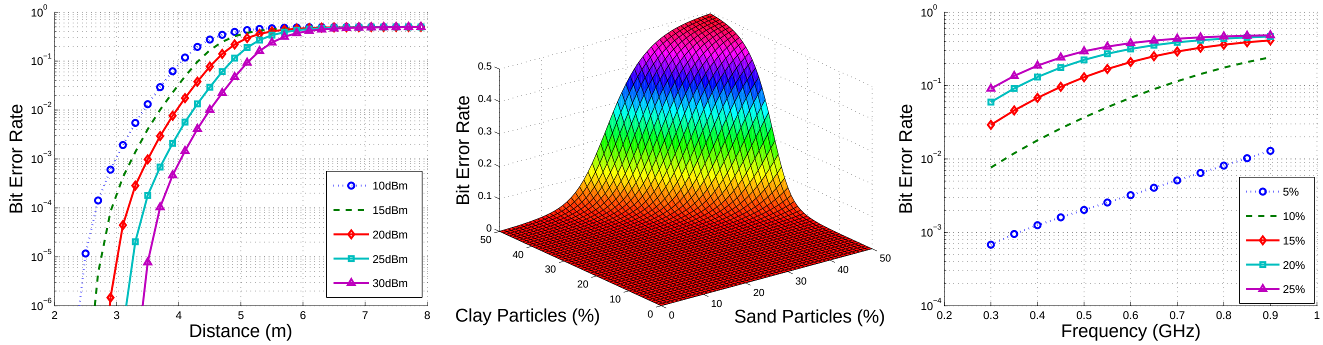
Based on the above model, we next show the bit error rate (BER) characteristics of the underground channel. The results will help the design of WUSN since BER is directly related to many networking parameters. The BER of a communication system depends mainly on three factors: 1) the channel model 2) the modulation method used by the system, and 3) the signal to noise ratio (SNR).

From above discussion, we have derived the underground channel model, which is *location dependent two-path Rayleigh channel*. We assume that 2PSK is used as the modulation. Therefore, the BER can be shown as

$$BER = \frac{1}{2} erfc(\sqrt{SNR}) \,, \quad (19)$$

where $erfc(\cdot)$ is the error function and SNR is given by

$$SNR = P_t - L_f - P_n \,, \quad (20)$$



(a) (b) (c)

Fig. 5. Bit error rate vs. (a) internode distance, d, for different transmit power, P_t, levels, (b) percentage of clay and sand particles, and (c) operating frequency, f, and volumetric water content

where P_t is the transmit power, L_f is the total path loss given in (15), and P_n is the energy of noise. We assume P_t between 10dBm to 30dBm for our evaluations. The next step is to determine the level of noise strength, P_n.

In order to determine the noise power, P_n, we performed field measurements using the BVS YellowJacket wireless spectrum analyzer [11]. The noise strength at 12 inch deep in soil is measured using the Yellowjacket. The results are shown in Fig. 4, where the received signal strength is plotted in dBm. From the field measurements, the average noise level is found to be -103 dBm. 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 show the properties of BER underground.

Using (15) and (20) in (19), we performed simulations to show the characteristics of BER using the same parameters used in Section III-B. The simulation results are shown in Figs. 5 for the single-path model and in Figs. 6 for the two-path model. Note that, two-path model is used for deployments of burial depth, $H < 2$m, while the single-path model is used for high depth deployments. The effect of transmit power, P_t, on BER is shown in Fig. 5(a). It is observed that as the transmit power increases, the BER decreases. However, this decrease is minimum since even when the transmit power increases to 30dBm, the horizontal distance can be extended to 4 meters with the limitation that BER is below 10^{-3}.

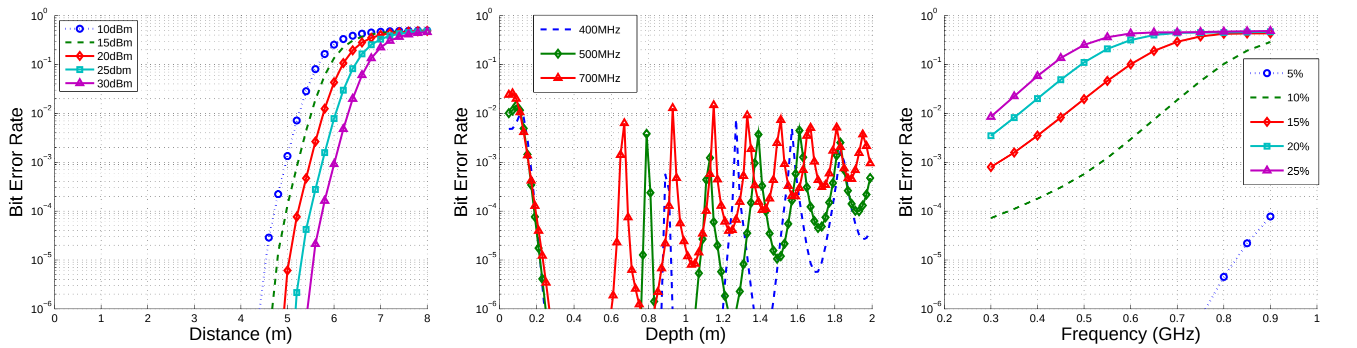
The effect of soil composition is shown in Fig. 5(b), where the BER is plotted for different percentage of clay and sand particles for a fixed distance of 3m at operating frequency of 400MHz. In accordance with our results for path loss in Section III-A, the BER has a smooth increase with increase in both clay and sand particle percentage. As a result, when the percent of sand particle is limited below 10%, and the percent of clay particles is limited below 20%, acceptable BERs are achieved.

A significant result from our simulations is that the volumetric water content (VWC) has an important impact on the BER compared to other parameters. As shown in Fig. 5(c), an increase in VWC from 5% to 10% results in almost an order of magnitude increase in BER. This result confirms that VWC is one of the most important parameters for underground communication.

Our simulations reveal that for burial depths less than 2m, two-path Rayleigh fading model is suitable for WUSN. In Figs. 6, the effect of the reflected path from the ground surface on BER can be clearly seen. An important result is that, as shown in Fig. 6(a), where the relation between BER and distance at different transmit power levels is shown, the BER plot shifts to right compared to Fig. 5(a). As a result, the communication distance can be extended for low depth applications due to the constructive effects of the reflected rays from the ground surface. Similarly, as shown in Fig. 6(a), the communication distance can be extended to $5.5-6$m with increased transmit power of 30 dBm and low operating frequency at 400 Mhz.

As discussed in Section III-A, the path loss is significantly affected by the burial depth of sensors. This fluctuation also results in varying BER values as shown in Fig. 6(b). As the burial depth increases, the fluctuation decreases and the BER becomes more stable, which is consistent with the result of path loss. These results reveal that for a particular operating frequency, there is an optimal depth for communication where BER is minimum.

Finally, the effect of VWC in two-path model is shown in Fig. 6(c). Compared to the single-path model results shown in Fig. 5(c), higher VWC is acceptable when the operation frequency is low. Moreover, for a particular VWC value, BER fluctuates with changing



(a) (b) (c)

Fig. 6. Two-path channel model: Bit error rate vs. (a) transmit power, (b) depth (H) and frequency, f, and (c) operating frequency, f, and volumetric water content.

frequency, contrary to the single-path case because the amplitude and phase angle of the reflection coefficient highly depend on the frequency of the signal.

IV. Conclusion and Future Work

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 is presented. Furthermore, a complete 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, we show that in the $300-400$ MHz frequency band, the path loss can be limited to a degree supporting feasible communication. Furthermore, we show that the channel characteristics depend 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 multi-path fading of spatial distribution. For high depth deployments, a single path channel is suitable to characterize communication. The results of this work lays the foundations of underground communication and helps the future research and applications of wireless underground sensor networks (WUSN), which is a promising application area of wireless sensor networks.

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 [13], field experiments will be performed to validate the results shown in this analysis.

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