On Burial Depth of Underground Antenna in Soil Horizons for Decision Agriculture

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Abstract. Decision agriculture is the practice of accurately capturing the changing parameters of the soil including water infiltration and retention, nutrients supply, acidity, and other time changing phenomena by using the modern technologies. Using decision agriculture, fields can be irrigated more efficiently hence conserving water resources and increasing productivity. The Internet of Underground Things (IOUT) is being used to monitor the soil for smart irrigation. Moreover, the communication in wireless underground sensor networks is affected by soil characteristics such as soil texture, volumetric water content (VWC) and bulk density. These soil characteristics vary with soil type and soil horizons within a field. In this paper, we have investigated the effects of these characteristics by considering Holdrege soil series and homogeneous soil. It is shown that the consideration of soil characteristics of different soil horizons leads to 6% improved communication in wireless underground communications for smart agricultural practices.

Keywords: Cyber-physical systems, Underground electromagnetic propagation, Wireless underground sensor networks, Decision agriculture, Internet of Things.

1 Introduction

In decision agriculture, the soil horizons are the layers of soil which are formed by four soil processes and have unique chemical, physical, and visible characteristics. These soil process are additions, losses, transformations, and translocations. There are five horizons: *O*, *A*, *E*, *B*, and *C*. In soil, these horizons can form in any order. Some soils do not contain all horizons and in some soils multiple horizons can repeat. The horizon *A* and *B* are of most interest because of their high impact on plant growth. In wireless underground sensor networks, sensor nodes are buried in soil. Establishment of wireless communication links is important for data communication. As each soil horizon have unique soil texture, bulk density and water holding capability. Also depth and width of each horizon differs in different type of soils. These factors have a significant influence on the performance of a buried antenna and communication. These are :

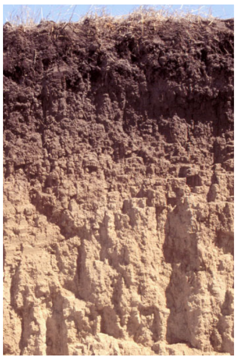

Fig. 1. The Holdredge Soil Profile

Soil Moisture
: Soil moisture changes with time due to climate and irrigation, which influence the soil permittivity.

Soil permittivity
: Electromagnetic waves propagation in soil exhibit different characteristics in soil due to higher permittivity of soil.

Soil-Air Interface
: Impedance of under ground antenna is changed because of current disturbance at antenna due to reflection from soil-air interface [20], [44], [71], [73].

In this paper, by using the model for underground to underground (UG2UG) communications model, we have analyzed the performance of wireless underground channel by using Holdrege soil profile [76] and homogeneous soil. Moreover, we provide analytical results for path loss for three different scenarios including same soil moisture level across all horizons, water infiltration, and water retention scenario. Based on the analysis it is shown that that antennas burried into soil horizons by taking soil characteristic into account experience less path loss as compared to antenna berried in homogeneous soil and path loss is decreased from 5-6 dB. It is also shown that path loss varies with soil moisture and increase in soil moisture also increase the path loss for all type of soils. It is also evident that in underground wireless sensor networks path loss increase with frequency therefore low operation frequencies are suitable for for wireless underground communication [15, 18, 19, 21–43, 45–69, 72, 78, 79].

The rest of the paper is organized as follows: In Section 2, related work on communication in medium and the impact of the medium on antenna impedance is introduced. Section 3 gives the brief overview of soil properties. The impedance and the return loss of dipole antenna buried in soil are analyzed both theoretically and using simulations in Section 4, where an antenna impedance model considering the impact of the soil-air interface is developed. The experiment results are shown and analyzed in Section 5. Conclusions are drawn in Section 6.

We have used 31 percent sand particles and 29 clay particles soil for comparison with Holdrege soil.

Table 1. Physical Properties of Holdrege Soil

Horizon	Depth in inches	Sand	Slit	Clay	Textual Class
`Ap`	0-7	16.6	61.4	22.0	Silt Loam
`A`	7-13	12.0	58.4	29.6	Silt Clay Loam
`Bt1`	13-16	13.3	55.3	31.4	Silt Clay Loam
`Bt2`	16-24	11.2	58.9	29.9	Silt Clay Loam

2 Related Work

Antennas used in WUSNs are buried in soil, which is uncommon in traditional communication scenarios. Antennas in matter have been analyzed in [14] where the electromagnetic fields of antennas in infinite dissipative medium and half space have been derived theoretically. In this analysis, the dipole antennas are assumed to be perfectly matched and hence the return loss is not considered. In [11], the impedance of a dipole antenna in solutions are measured. The impacts of the depth of the antenna with respect to the solution surface, the length of the dipole, and the complex permittivity of the solution are discussed. However, this work cannot be directly applied to WUSNs since the permittivity of soil has different characteristics than solutions and the change in the permittivity caused by the variation in soil moisture is not considered. The impact of these soil factors in underground communication has been analyzed in [24], [63], [21], [32], [25], [27], [30], [47], [31], [29], [26], [35], [46], [28].

In existing WUSN experiments and applications, the permittivity of the soil is generally calculated according to a soil dielectric model [1], [16], which leads to the actual wavelength of a given frequency. The antenna is then designed corresponding to the calculated wavelength [73]. Unfortunately, this approach often does not produce the desired antenna for the underground communication since the impedance of the antenna is not solely related to the wavelength of electromagnetic waves. In [73], an elliptical planar antenna is designed for a WUSN application. The size of the antenna is determined by comparing the wavelength in soil and the wavelength in air for the same frequency. However, this technique does not provide the desired impedance match. Moreover, when antennas are buried near the interface of a half-space, the impedance depends not only on the medium, but also on the reflections from the interface. This phenomenon is mentioned in [10], however, its impact is not modeled.

The disturbance caused by the interface is similar to the impedance change of a handheld device close to a human body [2], [74] or implanted devices in human body [3], [9]. In these applications, simulation and test bed results show that there are impacts from human body that cause performance degradation of the antennas. Though similar, these studies cannot be applied to the underground communication directly. First, the permittivity of the human body is higher than in soil. At 900 MHz, the relative permittivity of the human body is 50 [74] and for soil with a soil moisture of 5%, it is 5 [16]. In addition, the permittivity of soil varies with moisture, but for human body, it is relatively static. Most importantly, in these applications, the human body can be modeled as a block while in underground communications, soil is modeled as a half-space since the size of the field is significantly larger than the antenna.

3 Soil Characteristics

We have used Holdredge soil and homogenoius soil for our analysis. Table 1 shows physical properties Holdrege soil [75]. We have selected Holdrege series because it is one of the well-drained, highly productive and most fertile soil in the Nebraska, United States. It is also official state soil of Nebraska and almost all the soil is under cultivation. As per United States Department of Agriculture [76]:

The Holdrege series of the soil is composed of in-depth, good drainage, mildly penetrable particles developed in calcium carbonate sediments. These highland soil contains sloppy areas which range form 0-15% with annual average temperature of approximately 55^oF, and average annual rainfall is approximately at a particular location. It has fine particles of silt that are mixed with hyperactive, moist Typic Argiustolls.

Soils in the Holdrege series are recognized by features of their profile (created by horizontal layers) that are the result of the prairie environment. They are suggestive of soils formed under mixed grasses, in a climate where moisture stress is common, but where enough movement of water through the profile has resulted in downward movement of clays and lime. These processes have led to a soil with a thick, dark colored topsoil, a clay enriched subsoil and a substratum that contains free lime. Holdrege soils are among the most extensively cultivated soils in the state. Presently, nearly all Holdrege soils are cultivated. A very large part is irrigated. Corn and grain sorghum are the principal row crops. Winter wheat is the most commonly grown small grain. Their natural fertility, desirable tilth, and the landscape on which they exist join with irrigation water and the skillful management of Nebraska farms to provide a valuable agricultural resource [75].

4 Relative Permittivity of Soil

The EM wave propagation in soil is different from that of in air because of higher permittivity values of soil than that of air. Various soil factors effect the EM waves. These factors includes: soil texture, bulk density, soil moisture (also known as Volumetric Water Content), temperature and salinity. Relative permittivity has been investigated in detail by [5,16]. They define relative permittivity of various constituents (air, soil, bound and free water) of soil-water solution [5]. In [16], a semi-empirical permittivity model is presented which is used in this paper to find the effective permittivity of the soil-water mixture. Finally, the effective permittivity is calculated using the permittivity of all components, i.e., soil, water, and air, of the mixture

4.1 The Impact of soil on the Return Loss of an Antenna

Soil permittivity has direct effect on the return loss of an antenna. Variations in soil moisture causes the change in soil permittivity. This effect is visible in Fig. 3 which plots the effect of soil moisture on return loss of 70 mm monopole antenna. It can be observed that resonant frequency shifts to lower spectrum when the soil moisture is increased. An important thing to note is that return loss is minimum at resonant frequency f_{res}.

The primary reason of return loss is the impedance mismatch between the antennas, hence, it is important to calculate the impedance of the antenna. There is no closed form representation of antenna impedance, hence, impedance approximation given in [13] is used. This approximation is done for dipole antenna. Some other impedance approximation for dipole antennas are also presented in [14, 80]. As per [13], impedance of dipole can be calculated as follow by using the induce-emf method [21]:

$$Imp_D \approx f_1(\gamma l_D) - i\left(120\left(\ln\frac{2l_D}{D_D} - 1\right)\cot(\gamma l_D) - f_2(\gamma l_D)\right) , \tag{1}$$

where

$$f_1(\gamma l_D) = -0.4787 + 7.3246\gamma l_D + 0.3963(\gamma l_D)^2 + 15.6131(\gamma l_D)^3 , \tag{2}$$
$$f_2(\gamma l_D) = -0.4456 + 17.0082\gamma l_D - 8.6793(\gamma l_D)^2 + 9.6031(\gamma l_D)^3 , \tag{3}$$

where real portion of the wave number is given as γ, diameter of the dipole antenna is represented by D_D, and length (half) of the dipole is given by l. γl_D is calculated as follow:

$$\gamma l_D = \frac{2\pi l}{\lambda_{air}}\mathrm{Re}\left\{\sqrt{\epsilon_s}\right\} , \tag{4}$$

where subscript D represents the dipole antenna λ_{air} represents wavelength in air and ϵ_s represents the relative permittivity of the soil ([16]).

Soil permittivity ϵ_s rely on the frequency, therefore, γl_D and l_D/λ are not linearly related. Hence, when the antennas are deployed in soil instead of air, their impedance values (at resonant frequency) also becomes dependent on soil properties. This impedance mismatch due to different medium causes an antenna return loss which is given in dB as [21]:

$$RL_{dB} = 20\log_{10}\left|\frac{Imp_{soil} + Imp_{air}}{Imp_{soil} - Imp_{air}}\right| . \tag{5}$$

4.2 The Impact of Soil on Bandwidth

Bandwidth is also one of the major performance metric of the system. Shannon's equation [17] relates bandwidth of the system with channel capacity of medium. Shannon's equation shows that capacity is directly proportional to the bandwidth of the system. For wireless communications, antenna (return loss) also plays an important role in determining the final bandwidth of the system.

It has already been established in Section 4.1 that antenna return loss depends upon the frequency f and can be represented as $RL = R(f)$ and negative of return loss $-R(f)$ is given as S_{11}. For antenna operating at resonant frequency, bandwidth is given as the spectrum for which $\varDelta$ values is higher than the negative of return loss. For all other operational frequencies, i.e., apart from resonant frequency, bandwidth will be less than resonant frequency. Following equation calculates the systems bandwidth for any operation frequency [7]:

$$B_{sys} = \begin{cases} 0 & \text{if } S_{11} > \varDelta, \\ 2(f - f_{min}) & \text{if } S_{11} \leq \varDelta \text{ and } f < f_{res}, \\ 2(f_{max} - f) & \text{if } S_{11} \leq \varDelta \text{ and } f \geq f_{res}, \end{cases} \tag{6}$$

In above equation, resonant frequency is given by f_{res}, and f_{min} and f_{max} represents the minimum and maximum frequencies, respectively, for which $R(f) \leq \varDelta$.

As an example for estimation of antenna bandwidth, S_{11} is plotted with f. The operating frequency of the antenna is 24 MHz less than the values for resonant frequency and $\varDelta = -10\,\text{dB}$. The bandwidth is calculated as 14 MHz, S_{11} remains lower than $\varDelta$ for whole spectral band.

4.3 The Impact of Soil on Path Loss

A detailed investigation is performed in [6, 8] to understand the communication in WUSNs. The effect of soil on aboveground-to-underground (UG2AG) & underground-to-aboveground (AG2UG) channel has been studied in detail. It was found that EM waves attenuation in the soil is dependent on various factors such as: distance, soil moisture, and soil type. Irrespective of the direction, total path loss PL_T is calculated as:

$$PL_T = \left(PL_{ug}(d_{ug}) + PL_{ag}(d_{ag}) + PL_{(R,\rightarrow)}\right) \ , \tag{7}$$

In above equation, losses in both aboveground & underground area is given by $PL_{ag}(d_{ag})$ and $PL_{ug}(d_{ug})$, respectively. Moreover, depending upon the direction of the wave propagation $\rightarrow$, $PL_{(R,\rightarrow)}$ gives the refraction loss. The direction could be either $ag2ug$ or $ug2ag$.

The losses in equation (7) for both UG and AG environment are calculated as [77]:

$$PL_{ug}(d_{ug}) = 6.4 + 20 \log d_{ug} + 20 \log \gamma + 8.69 \alpha_{(const,soil)} d_{ug} \ , \tag{8}$$

$$PL_{ag}(d_{ag}) = -147.6 + 10 \alpha_{(coef,air)} \log d_{ag} + 20 \log f \ , \tag{9}$$

In above equation, the terms $\alpha_{(coef,air)}$ represents the attenuation coefficient in air, $\alpha_{(const,soil)}$ represents the attenuation constant, f represent the operation frequency and γ gives the phase shifting constant. The $\alpha_{(coef,air)} > 2$ because of ground reflection effect. The empirical experiments in [4] shows that $\alpha_{(coef,air)}$ values lies in the range of 2.8 - 3.3. In equation (8), $\alpha_{(const,soil)}$ and γ are used to incorporate the impact of soil on signal attenuation. The values for $\alpha_{(const,soil)}$ and γ is given as:

$$k_s = \alpha_{(const,soil)} + i\gamma = i\omega\sqrt{\mu_0 \epsilon_s} \ , \tag{10}$$

In above equation, k_s, μ_0, and ϵ represents the soil propagation constant, free space permeability, and soil effective permittivity, respectively.

Owing to the higher values of soil permittivity, EM waves can only penetrate the soil-air interface, if the incident angle θ_t is small, and are reflected or refracted otherwise. Therefore, waves with small θ_t in are able to perform UG2AG propagation, and refracted angle $\rightarrow 0$ for AG2UG propagation. Moreover, AG2UG propagation is vertical in soil. Therefore, for AG2UG and UG2AG communication links, the underground distance traveled by the wave is approximated as the burial depth h_u, i.e., $d_{ug} \simeq h_{ug}$. Similarly, aboveground communication path is approximated using height of AG node h_{ag} and horizontal distance between both nodes $d_{ag \leftrightarrow ug}$. The aboveground path is given as: $d_{ag} = \sqrt{h_{ag}^2 + d_{ag \leftrightarrow ug}^2}$.

A maximum power path, i.e., where $\theta_i \rightarrow 0$, is considered for the AG2UG link. Therefore, approximation of refraction loss in equation (7) is given as follow [12]:

$$PL_{(R,ag2ug)} \simeq 20 \log \frac{r_i + 1}{4} \ , \tag{11}$$

where refractive index of soil is represented by r_i. r_i is calculated in [8] as follow:

$$r_i = \sqrt{\frac{\sqrt{\epsilon'^2 + \epsilon''^2} + \epsilon'}{2}} \ . \tag{12}$$

Moreover, for UG2AG link. signal travels from the medium of high density to lower density, therefore, energy of the signal is refracted, i.e., $L_{(R,ug2ag)} = 0$.

4.4 Channel Capacity of Wireless Underground Communications

In addition to bandwidth, capacity of channel also effect the underground communication performance. To that end, the effect of soil properties on channel capacity is investigated. As per Shannon equation, capacity is dependent upon bandwidth B, noise N, and strength of the received signal R [7]:

$$C = B_{sys} \log_2 (1 + \frac{R}{N B_{sys}}) \ , \tag{13}$$

For this analysis, maximum achievable bandwidth is considered. As show in equation (6), this maximum bandwidth is estimated by antenna design. Antenna properties (return loss and path loss) will effect the power transmitted by the sender node P_t. Therefore, the received signal strength (dB) is calculated using

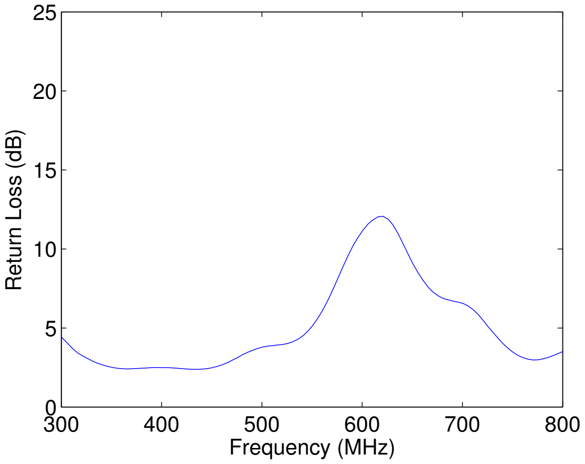

Fig. 2. Return Loss of the Antenna

antenna return loss in equation (5) and antenna path loss in equation (7). The received signal is given as [7]:

$$R_{dB} = P_t + 10\log_{10}(1 - 10^{-\frac{RL_{dB}}{10}}) - PL_T \ , \tag{14}$$

Moreover, the above signal strength is based on discussion in Section 4.1 and Section 4.3.

Underground noise is stable during the testbeds experiments, hence, N can be used as a constant value [70].

5 Numerical Analysis

We have considered three cases for analytical evaluation. First case we have compared the two soils under the same soil moisture case for all soil horizons and depths. In second case we analyses the the water infiltration scenario in which top soil horizons have more water content than the subsoil horizons. Third case compares the drainage scenario in which subsoil is more saturated as compared to the topsoil. We have used frequency range of 300 MHz to 800. Transmitted power is 15 dBm. Return Loss of the antenna used in the evaluation is shown in Figure . Antennas are buried at four depths. Four antenna burial depth corresponds to four different horizons (Ap, A, Bt1, Bt2)of Holdrege soil as shown in Table 1. For homogeneous soil these are 10 Cm, 20 Cm, 30 Cm and 40 Cm. Horizontal distance distance between transmitter receiver is 50 Cm. Bulk density is 1.5 grams/cm3 and particle density is 2.66 grams/cm3.

5.1 Same Soil Moisture Scenario

Fig. 3 shows the path loss for two soil types for Volumetric Water Content (VWC) of value of 10%. For all depths and across all frequency range Path loss

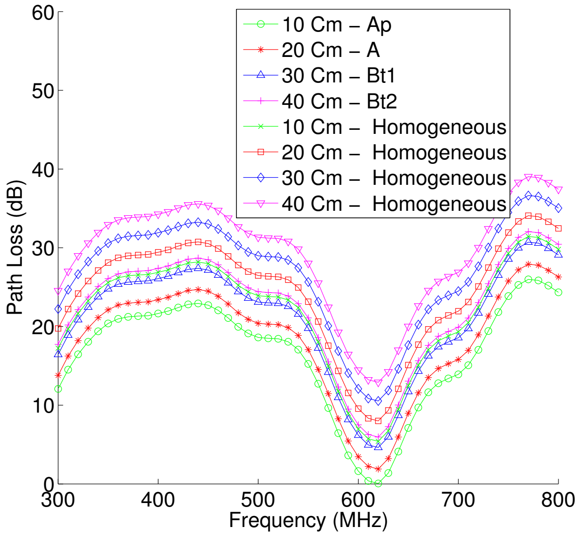

Fig. 3. Path Loss vs. Frequency - VWC 10%

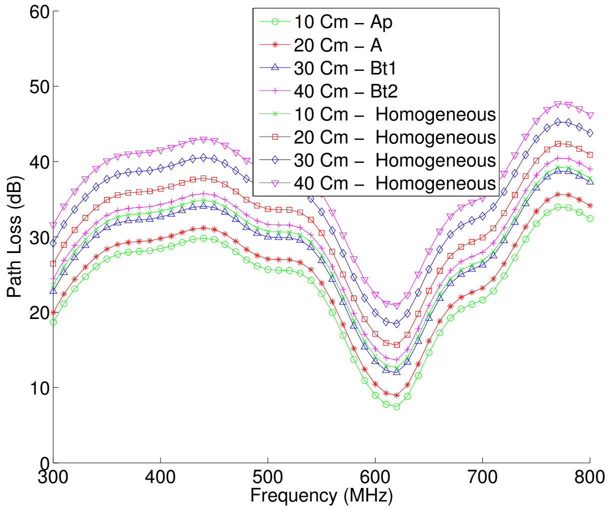

Fig. 4. Path Loss vs. Frequency - VWC 20%

for homogeneous soil is 5 dB to 6 dB higher than as compared to Holdrege soil. Moreover between 550 MHz to 650 MHz range path loss is low because of the low return loss of the antenna. It is also clear that path loss increases with frequency.

Fig. 4 shows the path loss for two soil types for Volumetric Water Content (VWC) of value of 20%. For all depths and across all frequency range Path loss for homogenous soil is 5 dB to 6 dB higher than as compared to Holdrege soil. Due to 10% increase in water content there is an increase of 8 dB for all horizons.

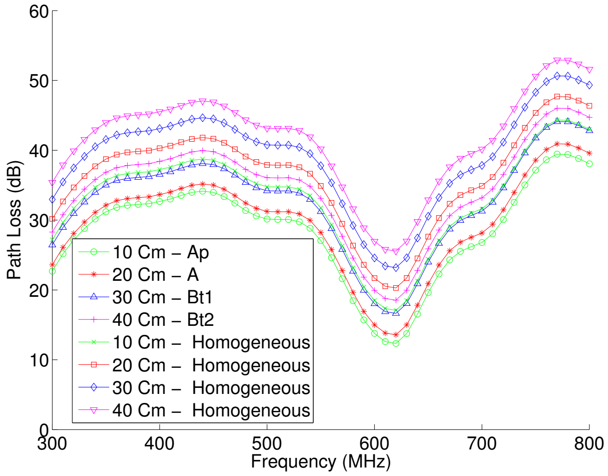

Fig. 5. Path Loss vs. Frequency - VWC 30%

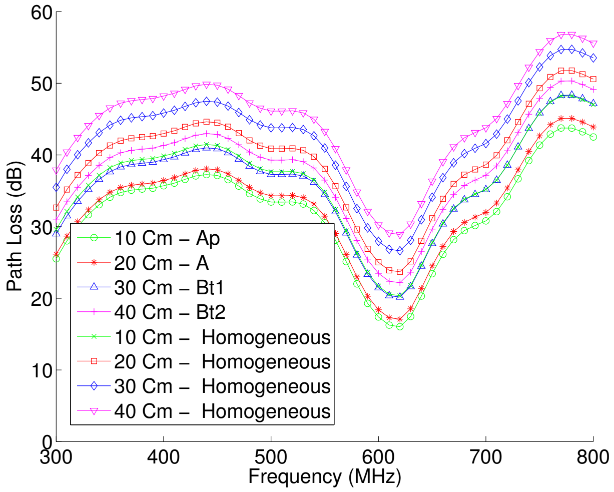

Fig. 6. Path Loss vs. Frequency - VWC 40%

Fig. 5 and Fig. 6 shows the path loss for two soil types for Volumetric Water Content (VWC) of value of 30% and 40%. For both soil moisture levels, for all depths and across all frequency range path loss for homogenous soil is 5 dB to 6 dB increased as compared to Holdrege soil. Path loss for 30% and 40% is considerably higher than dry than the 10%.

5.2 Water Infiltration Scenario

In this case we consider the scenario in which higher horizons have more water content as compared to lower soil horizons. Fig. 7 shows the path loss when Ap

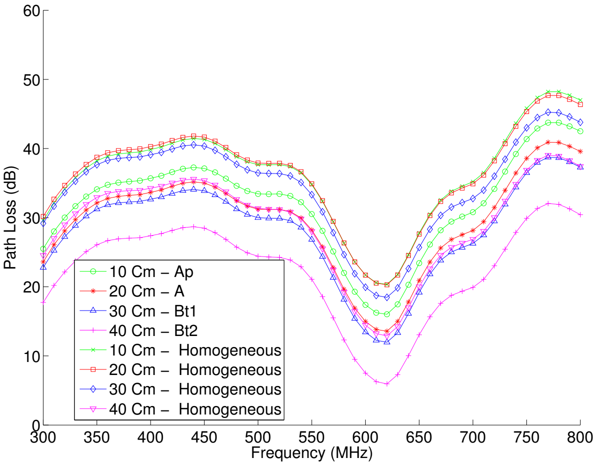

Fig. 7. Path Loss vs. Frequency - Water Infiltration Scenario

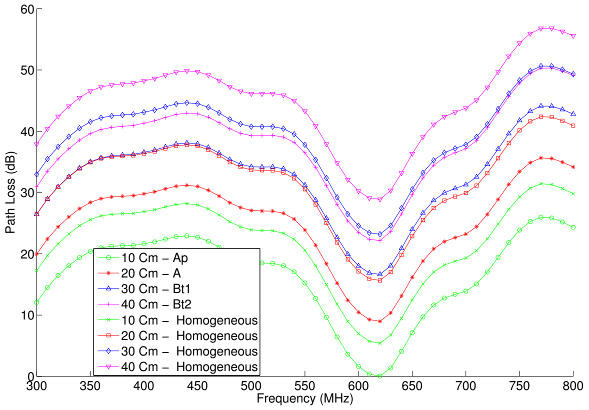

Fig. 8. Path Loss vs. Frequency - Drainage Scenario%

horizon have 40% VWC, A horizon have 30% VWC, Bt1 have 20% VWC and Bt2 have 10% VWC. It is evident that communication performance is best at Bt2 horizon because of low water content.

5.3 Water Retention Scenario

In this case we consider the scenario in which lower horizons have more water content as compared to higher soil horizons. Fig. 8 shows the path loss when Ap horizon have 10% VWC, A horizon have 20% VWC, Bt1 have 30% VWC and Bt2 have 40% VWC. Antenna buried at the A horizon experience lower path loss because of low attenuation due to lower VWC.

6 Conclusions

In this paper, the impacts of soil texture, soil moisture on burial depth of antenna in different soil horizons and on path loss are analyzed for underground wireless communications in Holdrege soil and homogeneous soil. It is shown that antennas buried into soil horizons by taking soil characteristic into account experience less path loss as compared to antenna berried in homogeneous soil. It is also shown that path loss varies with soil moisture and increase in soil moisture also increase the path loss for all type of soils. It is also evident that in underground wireless sensor networks path loss increase with frequency therefore low operation frequencies are suitable for for wireless underground communication.

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