Impacts of Soil Moisture on Cognitive Radio Underground Networks

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***Abstract*—Wireless underground communications is mainly characterized by the effects of soil moisture on antenna return loss and bandwidth as well as path loss. In this paper, the impacts of soil moisture, especially on underground channel capacity, are analyzed for underground wireless communications. It is shown that for a given antenna and soil moisture level, there exits an optimal operation frequency that maximizes channel capacity. While existing research on wireless underground communication is focused on fixed-frequency systems, this paper motivates the use of cognitive radio systems, which can adjust operation frequency in a wide range, for efficiency for wireless underground communication. Moreover, it is shown that soil type significantly affects the channel capacity and the capacity can be improved by using longer antennas that allow lower operation frequencies. However, the size of the antenna is also limited by other factors, such as device size and deployment challenges.**

I. Introduction

Wireless underground sensor networks (WUSNs) are an emerging technology which has a wide range of potential applications, including border patrol [2], environment and infrastructure monitoring [14], [18] and precision agriculture [7]. A major challenge of WUSNs is the impact of soil on three main component of wireless communications.

First, the effective permittivity of soil is a complex number, which means besides diffusion attenuation, the electromagnetic waves also suffer from an additional attenuation caused by the absorption of soil. In addition, the path loss caused by the attenuation is frequency dependent.

Second, the permittivity of soil is much higher than that of air, and hence wavelength shortens when an electromagnetic wave travels in soil. Therefore, the antenna designed for a specific frequency in over-air communications does not work well underground.

Finally, the permittivity of soil varies with time due to the variation in soil moisture, and hence change the wavelength. In most WUSN applications, soil moisture changes over time due to natural precipitation or irrigation. Thus, given a frequency, the wavelength is not a constant over time. This characteristic of soil has profound impacts on the return loss and bandwidth of the antenna. In other words, the return loss and bandwidth of an underground antenna change with the variation in soil moisture over time.

The impacts of soil on wireless communications mentioned before have complicated effect on the overall performance of underground wireless communication. In communication systems, channel capacity is an important criterion of the performance. Due to the variations in return loss and bandwidth of the antenna as well as variations in path loss over frequency and soil moisture, given a specific antenna design for the underground device, the optimal operation frequency, at which the system achieves the highest capacity, changes in different soil moisture levels. In other words, underground device needs to have the ability to change its operation frequency to compensate for the adversity caused by the variation in soil moisture.

In this paper, we first model the impacts of soil on the return loss and the bandwidth of the antenna, as well as on the path loss of the propagation. Empowered by the models, we model the capacity of the underground communication system as a function of soil properties, especially soil moisture and operation frequency. It is shown that for each soil moisture level, there exists an optimal operation frequency at which the capacity of the system is maximized. While recent research focuses on fixed-frequency systems, these results motivate the effectiveness of cognitive radio systems in wireless underground communications.

The rest of the paper is organized as follows. The related work is introduced in Section II. The models describing the impact of soil on return loss and bandwidth of the antenna and on the path loss of the propagation are captured in Section III. Numerical analysis results, especially the overall impacts on capacity of the system, are discussed in Section IV and the paper is concluded in Section V.

II. Related Work

Antennas in matter have been analyzed in [11] where the electromagnetic fields of antennas in infinite dissipative medium and half space have been derived theoretically. In [11], the dipole antennas are assumed to be perfectly matched and hence the return loss is not considered. In [8], 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

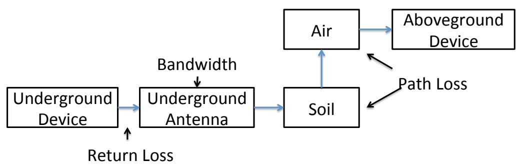


Fig. 1: The overview of the system.

in the permittivity caused by the variation in soil moisture is not considered.

The permittivity of the soil has been semi-empirically modeled in [5], [13]. Based on the permittivity model, channel models to analyze the path loss of wireless communications in WUSNs have been developed. The underground-to-underground communication channel is first modeled in [12], [19]. In [6], through electromagnetic field analysis and testbed verification, a three-path channel model is developed, which better describes the propagation of electromagnetic waves in soil. Models for underground-to-aboveground communication are developed in [4], [7], [16]. In [7], testbed experiments are conducted to verify the model.

Equipped with software-defined radio solutions, cognitive radio networks have recently gained significant interest [1]. The majority of the solutions in this area have mainly addressed the spectrum scarcity problem in wireless systems. While there exists recent interest in using cognitive radio systems for undewater communication to combat the challenges of acoustic channel [3], [17], [21], to the best of our knowledge, cognitive radio solutions have not been considered for wireless underground communications so far. Moreover, the overall impact of soil moisture on wireless underground communication, considering both the factors of antenna return loss and bandwidth, as well as path loss, has not been analyzed before. In this paper, we address this issue by analyzing the capacity of the system.

III. Impact of Soil on Wireless Underground Communication

In this section, we analyze the impact of soil on wireless communications. The overall system is shown in Fig. 1, where the three impacts, namely the return loss of the antenna, the bandwidth of the antenna and the path loss of the propagation are shown. Due to the fact that soil permittivity is a function of soil moisture and frequency, these impacts change with the variation in soil moisture and at different operation frequency. In this section, we first analyze the three impacts separately, following which the overall impact on channel capacity is captured.

A. Relative Permittivity of Soil

When an electromagnetic wave is incident into soil, the wavelength changes because of the higher permittivity of soil compared to that of air. Soil permittivity depends on soil properties, such as bulk density, soil texture, soil moisture (Volumetric Water Content), salinity, and temperature. Several models have been developed in the literature to capture the characteristics of the relative permittivity [5], [13]. These models describe the relative permittivity of different components of soil-water mixture, namely, soil, air, free water and bounded water [5]. Here, we utilize a semi-empirical permittivity model for soil in [13] but other models can readily be used. Accordingly, the effective permittivity of soil-water mixture, which is a complex number, is a combination of the permittivity of soil, air and water.

B. The Impact of soil on the Return Loss of an Antenna

When an antenna is buried underground, its return loss properties change due to the high permittivity of the soil. Moreover, with the variation in soil moisture and hence, soil permittivity, the return loss of the antenna varies as well. In Fig. 2(a), experiment results of the return loss of a buried 70 mm monopole antenna is shown at different soil moisture levels. Experiment results reveal that with the increase in soil moisture, the resonant frequency, which corresponds to the minimum return loss, shifts to the lower spectrum.

To analyze the turn loss, the impedance of the antenna need to be calculated first, since return loss is caused by impedance mismatch. Closed form representation of the impedance of an arbitrary antenna is not readily available. In [10], [11], [20], good approximations for the impedance of a dipole antenna are provided. In the following, we analyze the impedance of a dipole based on the model introduced in [10]. By employing the induce-emf method, the input impedance of a dipole less than a half of a wavelength long can be approximated as [10, Ch. 4]:

$$Z_a \approx f_1(\beta l) - i\left(120\left(\ln\frac{2l}{d}-1\right)\cot(\beta l) - f_2(\beta l)\right) \ , \quad (1)$$

where

$$f_1(\beta l) = -0.4787 + 7.3246\beta l + 0.3963(\beta l)^2 + 15.6131(\beta l)^3 \ ,$$
$$f_2(\beta l) = -0.4456 + 17.0082\beta l - 8.6793(\beta l)^2 + 9.6031(\beta l)^3 \ ,$$

β is the real part of the wave number, d is the diameter of the dipole, and l is half of the length of the dipole. βl is expressed as

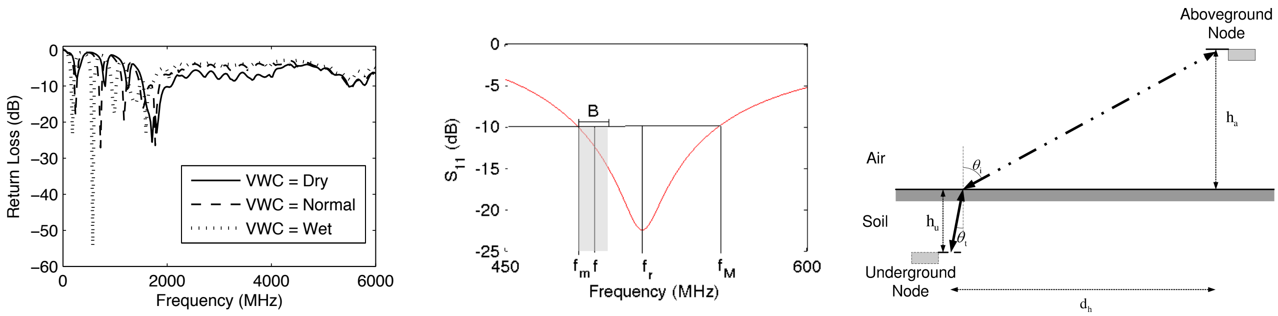
$$\beta l = \frac{2\pi l}{\lambda_0}\mathrm{Re}\left\{\sqrt{\epsilon_s}\right\} \ , \quad (2)$$

where ϵ_s is the relative permittivity of soil [13] and λ_0 is the wavelength in air. Since the permittivity of soil, ϵ_s, is frequency dependent, βl is not a linear function of l/λ_0. Thus, when the antenna is moved from air to soil, not only its resonant frequency changes, but its impedance value at the resonant frequency also varies with the soil properties.

The return loss of the antenna is caused by the impedance mismatch. Accordingly, the return loss of the antenna (in dB) is given by:

$$RL_{dB} = 20\log_{10}\left|\frac{Z_s+Z_a}{Z_s-Z_a}\right| \ . \quad (3)$$

which approximates well the experiment results.



(a) (b) (c)

Fig. 2: Models: (a) testbed results of antenna return loss at different soil moisture, (b) the bandwidth when the operation frequency is not resonant frequency, (c) the channel model for the system.

C. The Impact of Soil on Bandwidth

Another factor that impacts the performance of underground communications is the bandwidth as the channel capacity is proportional to it. However, in wireless devices, the bandwidth is affected by the antenna. Specifically, the return loss also determines the bandwidth of the antenna.

As shown in Section III-B, return loss, RL is a function of frequency, f, which can be denoted as $RL = R(f)$. When the antenna is excited at the resonant frequency, the bandwidth is defined as the spectrum where the negative of the return loss is less than a value Δ. However, if the resonant frequency is not used, the bandwidth of the antenna will be smaller than that of the resonant frequency. For a given operation frequency, f, the bandwidth is calculated as:

$$B = \begin{cases} 0 & \text{if } -R(f) > \Delta, \\ 2(f - f_m) & \text{if } -R(f) \leq \Delta \text{ and } f < f_r, \\ 2(f_M - f) & \text{if } -R(f) \leq \Delta \text{ and } f \geq f_r, \end{cases} \quad (4)$$

where f_r is the resonant frequency, f_m and f_M are the lowest and highest frequency at which $R(f) \leq \Delta$.

An example of the bandwidth calculation is illustrated in Fig. 2(b), where S_{11}, which is the negative of RL is shown as a function of f. In Fig. 2(b), the operation frequency is $24\,\text{MHz}$ lower than the resonant frequency and $\Delta = -10\,\text{dB}$. As shown in Fig. 2(b), the bandwidth is $14\,\text{MHz}$ and for the whole spectrum in the band, the negative of return loss is less than Δ.

D. The Impact of Soil on Path Loss

In [6], [7], we have investigated the communication channels in WUSNs, specifically, the underground-to-aboveground (AG2UG) channel and the aboveground-to-underground (UG2AG) channel. The communication path is shown in Fig. 2(c), where the attenuation of the electromagnetic waves in soil is a function of soil type, soil moisture and distance.

The path loss, regardless of the direction, is given as

$$L = \left(L_{ug}(d_{ug}) + L_{ag}(d_{ag}) + L_{(R,\to)}\right) \;, \quad (5)$$

where $L_{ug}(d_{ug})$ and $L_{ag}(d_{ag})$ are the loss at the underground and the aboveground portions, respectively. Finally, $L_{(R,\to)}$ is the refraction loss based on the propagation direction, $\to$, i.e., $ag2ug$ or $ug2ag$, which is the main source of asymmetry between the AG2UG and UG2AG channels.

The underground and aboveground losses in (5) are given as [19]:

$$L_{ug}(d_{ug}) = 6.4 + 20 \log d_{ug} + 20 \log \beta + 8.69 \alpha d_{ug} \;, \quad (6)$$

$$L_{ag}(d_{ag}) = -147.6 + 10 \eta \log d_{ag} + 20 \log f \;, \quad (7)$$

respectively, where η is the attenuation coefficient in air, f is the operation frequency, β is the phase shifting constant, and α is the attenuation constant. The attenuation coefficient in air, η, is higher than 2 due to the impacts of ground reflection. Our empirical experiments show that η is in the range of 2.8–3.3 [7]. The impact of soil properties on attenuation are captured by the last two terms in (6), where α and β are given as

$$k_s = \alpha + i\beta = i\omega\sqrt{\mu_0 \epsilon_s} \;, \quad (8)$$

where k_s is the propagation constant in soil, μ_0 is the permeability in free space and ϵ is the effective soil permittivity.

Due to the higher permittivity of soil, electromagnetic waves reflect and refract at the soil-air interface. Signals can penetrate through the interface only if the incident angle is small. For the UG2AG propagation, only the waves with small incident angle (θ_t in Fig. 2(c)) will transmit to air. On the other hand, for the AG2UG propagation, the refracted angle is near to zero and the propagation in soil is also vertical. Thus, for both links, the underground portion of communication distance can be approximated as $d_{ug} \simeq h_u$, where h_u is the burial depth and the aboveground portion is approximated as $d_{ag} = \sqrt{h_a^2 + d_h^2}$, where h_a is the height of the AG node and d_h is the horizontal distance between nodes.

For the AG2UG link, we consider the maximum power path where the incident angle, $\theta_i \to 0$. Thus, the refraction loss, $L_{(R,\to)}$, in (5) can be approximated as [9]:

$$L_{(R,ag2ug)} \simeq 20 \log \frac{n+1}{4} \;, \quad (9)$$

where n is the refractive index of soil, which is given by [7]

$$n = \sqrt{\frac{\sqrt{\epsilon'^2 + \epsilon''^2} + \epsilon'}{2}} \;. \quad (10)$$

For the UG2AG link, the signal propagates perpendicularly from a higher density medium to a lower density one. Hence we consider all energy is refracted (i.e., $L_{(R,ug2ag)} = 0$).

E. Wireless Underground Channel Capacity

To incorporate all the effects that soil has on wireless communication, channel capacity is employed as the criterion as follows:

$$C = B\log_2\left(1+\frac{S}{N_0 B}\right) \ , \tag{11}$$

where B is the bandwidth of the system, S is the received signal strength at the receiver and N_0 is the noise power density.

In our analysis, we consider the maximum bandwidth possible, which is determined by the antenna design as shown in (4). Given a transmit power P_t, the received signal strength at the receiver is affected by antenna return loss and path loss. Thus, based on the analysis in Section III-B and Section III-D, the received signal strength can be express in dB as

$$S_{dB} = P_t + 10\log_{10}(1-10^{-\frac{RL_{dB}}{10}}) - L \ , \tag{12}$$

where RL_{dB} is the antenna return loss denoted in (3) and L is the path loss denoted in (5).

In wireless underground communications, interference is low because of the small number of wireless devices. Thus, the noise is mainly thermal noise and N_0 can be considered as a constant [15].

IV. Numerical Analyses

In this section, numerical analyses are conducted to show the impact of soil on wireless underground communication. First, the impact of soil on antenna return loss, antenna bandwidth and propagation path loss are shown in Section IV-A. Then the capacity of the channel at different frequency and soil moisture levels is depicted and analyzed in Section IV-B. In the analyses, the default soil type employed in the analysis is clay soil with 31% clay and 29% sand. We also consider a sandy soil (50% sand and 15% clay) in Section IV-B. The underground device is buried at 0.4 m and the aboveground device is at the height of 2.5 m. The antenna employed in the analysis is a 60 mm long dipole, with the diameter of 2 mm.

A. Soil Impact on Return Loss, Bandwidth and Path Loss

In Fig. 3(a), S_{11} (the negative of the return loss) of the dipole is shown for a frequency range of 100 MHz to 1 GHz according to (3), where five different volumetric water content values (VWC=20%, 25%, 30%, 35% and 40%) are analyzed. Volumetric water content (VWC) is the volumetric ratio of water to the soil-water mixture and it is a major indicator of soil moisture. It can be observed that VWC values have a strong impact on the value of the resonant frequency. An increase in VWC from 20% to 40% results in a decrease in the resonant frequency from 649 MHz to 432 MHz.

In Fig. 3(b), the bandwidth of the antenna is shown as a function of the operation frequency for different soil moisture levels according to (4). The return loss threshold, Δ, is set to -10 dB. Since the bandwidth is defined as the frequency range where the return loss is less than Δ, it is expected that the bandwidth reaches the highest value when the system operates at the resonant frequency. Moreover, the bandwidth decreases fast when the system operates out of the resonant frequency. For example, when VWC=40%, the bandwidth is 62 MHz when the system operates at the resonant frequency (434 MHz). However, when the operation frequency decreases to 433 MHz, the bandwidth decreases to 52 MHz, which is 16.1% less than the bandwidth at the resonant frequency. It is also observed that the bandwidth decreases with the increase of soil moisture. When VWC is 20%, the bandwidth at the resonant frequency is 94 MHz, and it decreases to 74 MHz when VWC increases to 30% and further decreases to 62 MHz for a VWC value of 40%.

The path loss for the UG2AG channel is depicted in Fig. 3(c) as a function of the frequency for different soil moisture levels based on (5)-(10). As shown in Fig. 3(c), path loss increases with frequency. Moreover, soil moisture has a strong impact on the path loss, especially at high frequency range. When the frequency is at 200 MHz, path loss at 40% VWC is 107.6 dB. Compared to 102.9 dB at 20% VWC, when soil moisture is doubled, the path loss is 4.7 dB higher. However, when the frequency is at 900 MHz, path loss at 40% VWC is 138.6 dB. Compared to 131.4 dB at 20% VWC, doubling the soil moisture increases the path loss by 7.2 dB.

B. Capacity Analysis

In this section, channel capacity is employed as the criterion to analyze the overall impact of soil moisture on underground communication, considering all the three factors shown in Section IV-A. In the analyses, transmit power is 10 dBm, which is typical for battery-powered underground devices. The noise power density is 1.5625×10^{-16} W/Hz [15]. Note, the maximum bandwidth calculated in Section III-C is utilized to be the bandwidth of the communication system, even though specific modulation schemes, which are out of the scope of this paper, need to be designed to utilize the whole maximum bandwidth.

The channel capacity is depicted as a function of the operation frequency in Fig. 3(d) according to (11). It is shown that for each soil moisture level, there exists an optimal operation frequency that provides the highest channel capacity. Operating at the optimal frequency, the channel capacity achievable by the system is at $38-70$kbps for the VWC in the range of 20% to 40%. In addition, as the soil moisture increases, the optimal operation frequency shifts to the lower spectrum, just as the results on antenna return loss. However, the highest capacity is achieved not at the resonant frequency. Instead, the optimal frequency is much lower than the resonant frequency. For instance, when VWC is 20%, the resonant frequency is 649 MHz while the optimal frequency is 611 MHz. This is due to the fact that even though at resonant frequency, the system has the highest bandwidth, the noise power also increases since the noise power density N_0 is a constant. Moreover, at lower frequencies, path loss is lower as shown in Fig. 3(c).

The optimal operation frequency as well as the corresponding channel capacity are shown as a function of soil moisture level (measured as volumetric water content) in

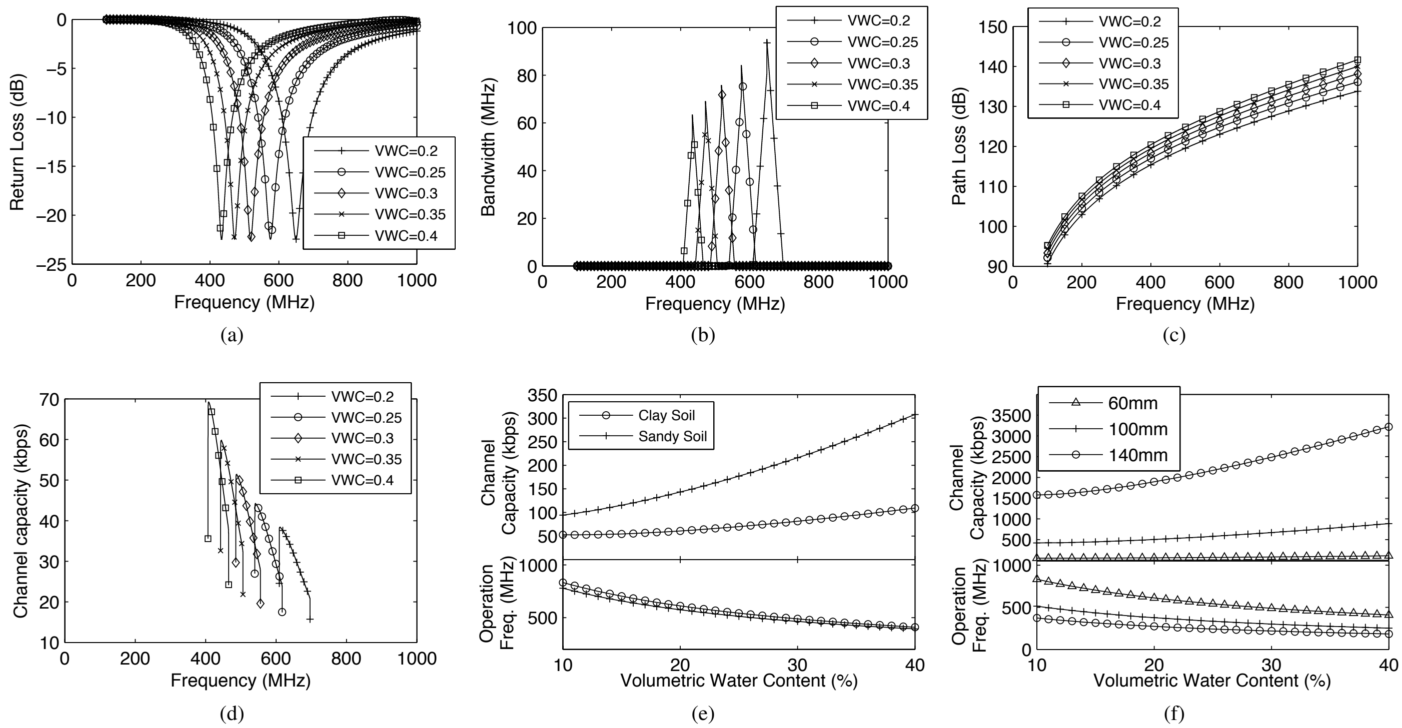


Fig. 3: Numerical analysis results: (a) return loss of the dipole antenna, (b) bandwidth of the dipole antenna, (c) path loss in underground-to-aboveground communication, (d) the capacity of the underground-to-aboveground channel, (e) the optimal operation frequency and the corresponding capacity over soil moisture, (f) the optimal operation frequency and corresponding capacity for different antenna sizes.

Fig. 3(e). Moreover, besides the clay soil, the situation in a sandy soil is also depicted. It is revealed that the optimal operation frequency is a monotonically decreasing function of soil moisture, and it moves in a wide range of spectrum. In clay soil, the optimal operation frequency increases from 409 MHz to 833 MHz when the soil moisture decreases from 40% to 10% and in the sandy soil situation, the optimal frequency is between 393.1 MHz and 778.6 MHz. Therefore, ideally, for a given antenna, the transceivers in WUSNs need to be capable of working at a wide range of spectrum to achieve the best performance in terms of channel capacity. When soil moisture increases, the transceiver should accordingly change its operation frequency to a lower spectrum.

In contrast to the operation frequency, the channel capacity is not a monotonic function of soil moisture. Especially in clay soil, channel capacity slightly decreases from 52.86 kbps to 52.58 kbps when VWC increases from 10% to 11%. The capacity then increases to 109.3 kbps when VWC further increases to 40% as the path loss is affected by both soil moisture and frequency. As shown in Fig. 3(c), for the same operation frequency, path loss increases with soil moisture. However, path loss also monotonically increases with frequency. At high soil moisture, even though the path loss curve moves up in Fig. 3(c), the optimal operation frequency also decreases due to the shortening of wavelength and low frequency corresponds to low path loss. Therefore, the path loss of the system may not decrease with the increase in soil moisture. This is also shown in the sandy soil case, where the channel capacity increases with the increase of soil moisture. This is because sandy soil has a lower attenuation compared with clay soil, especially for high soil moisture values.

Compared to clay soil, the system in sandy soil has a much higher capacity in all soil moisture cases. At 10% VWC, the capacity in sandy soil is 94.22 kpbs, 78.2% higher than the 52.86 kpbs in clay soil. At 40% VWC, the difference is even larger. The capacity in sandy soil is 307.8 kbps, 181.6% higher than 109.3 kpbs in clay soil. This is due to the much lower path loss in sandy soil.

For an application, the soil type is determined by the environment and cannot be changed. However, the antenna size can be adjusted. In Fig. 3(f), the optimal operation frequency and the corresponding capacity are shown for different size dipole antennas. The overall lengths of the antennas analyzed in this figure are 60 mm, 100 mm and 140 mm and the soil type is clay. It is revealed that with a longer antenna, the optimal operation frequency decreases and hence the capacity increases due to the low path loss at low frequency. When VWC is 15%, the optimal frequency for the 60 mm dipole is 703.4 MHz, and it decreases to 433.4 MHz for the 100 mm dipole and to 314.6 MHz for the 140 mm dipole. Correspondingly, the capacity increases from 54.42 kbps (60 mm) to 445.2 kpbs (100 mm) and 1680 kpbs (140 mm). The difference increases substantially with the increase of soil moisture. At 40% VWC, the capacity for 140 mm antenna is 3221 kbps, compared to 109.3 kbps for a 60 mm antenna. Thus, for underground communications, the analysis suggests that long antennas should be adopted to utilize the low path loss at low operation frequency. However, the size of the antenna is also limited by the size of

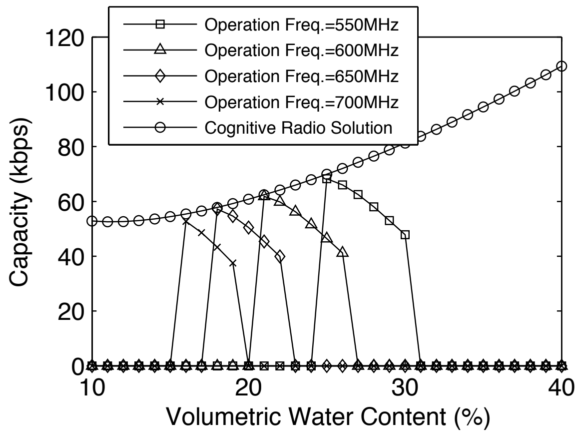


Fig. 4: The channel capacity comparison of fixed frequency system and cognitive radio system.

the device and spectrum availability. Besides, it is much more difficult to deploy an underground device with a long antenna.

In Fig. 4, the channel capacity of a fixed-frequency system, which operates at the same frequency at all soil moisture levels, is compared to the cognitive radio system. Four systems that operate at 550 MHz, 600 MHz, 650 MHz and 700 MHz are shown, together with the cognitive radio system which adjusts its operation frequency based on soil moisture levels. In the analysis, clay soil is employed. It is shown in Fig. 4 that at specific soil moisture level, the fixed-frequency system achieves the same capacity as the cognitive radio system. For example, when VWC is 21%, fixed-frequency system operating at 600 MHz has the same capacity as the cognitive radio system. However, the capacity of the fixed-frequency system is less than the cognitive radio system when soil moisture changes. Most importantly, the fixed-frequency system cannot work for a wide range of soil moisture levels. When the operation frequency is fixed at 550 MHz, the system works when VWC is in the range of 25% to 30%. The VWC range is 16% to 19% if the operation frequency is 700 MHz. However, by adjusting the operation frequency, the cognitive radio system can sustain channel capacity in the whole range of soil moisture levels and can maintain a capacity higher than 50 kbps.

V. Conclusion

In this paper, the impacts of soil moisture on antenna return loss and bandwidth as well as on propagation path loss is analyzed for underground wireless communications. It is shown that the optimal operation frequency, at which the maximum channel capacity is achieved, varies with soil moisture. Therefore, a cognitive radio, which can adjust its operation frequency at a wide range is suitable for wireless underground communication. Moreover, longer antennas correspond to lower operation frequencies and higher capacity. However, the size of the antenna is also limited by other factors, such as device size and deployment difficulty.

VI. Acknowledgments

This work is supported by an NSF CAREER award (CNS-0953900) and an NSF I-Corps grant (IIP-1248926).

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