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Wireless Underground Channel Modeling

Abdul Salam
Purdue University, salama@purdue.edu

Usman Raza
Purdue University

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Chapter 3

Wireless Underground Channel Modeling

3.1 Introduction

Wireless underground sensor networks (WUSNs) can be considered as one of the emerging technologies having broad set of applications. The potential applications of WUSNs include environment and infrastructure monitoring [32, 53, 69], precision agriculture [14, 61, 62], and border patrol [1]. An efficient and a reliable UG channel plays a very important role in implementing these applications. There is a need to theoretical explain and empirically validate the models of underground channel for further advancement of WUSNs. This chapter focuses on characterization of these channels and measures the effect of different parameters on UG communication. The discussion in this chapter is divided into two major parts: (1) The first part presents the effect of soil on communication components, i.e., UG channel, UG signal attenuation, return loss in soil and channel capacity, etc., and (2) The second part discusses different channel models under various soil factors and their effect on UG communication. Figure 3.1 shows the general structure of the chapter.

3.2 Effect of Soil Properties on UG Communication

Wireless communication is highly medium-dependent and wireless UG communication is accomplished using soil as a medium. Therefore, soil components play an important role in determining the efficiency of UG communication. These components are described below:

- (i) **Soil Effective Permittivity:** It is a complex number that adds extra attenuation to electromagnetic (EM) waves in addition to diffusion attenuation. The extra

Fig. 3.1 Chapter organization

attenuation is due to absorption of EM waves by soil and is also frequency-dependent [57].

- (ii) **Permittivity of Soil:** Permittivity of soil has much greater value than the permittivity of air which reduces the wavelength of EM waves propagating through soil. Therefore, aboveground antennas do not perform well in underground environment [56].
- (iii) **Temporal Variation of Soil Moisture:** Permittivity of soil keeps on changing with the change in soil moisture which in turn changes the wavelength. Soil moisture mostly changes due to irrigation and precipitation, therefore, for a given frequency, wavelength is always varying with the time. This soil behavior has great effect on the return loss and bandwidth of antenna [49].

From the above discussion, it can be concluded that soil properties significantly impact the performance of the underground wireless communication. Therefore, it is necessary to measure the effect of soil on wireless communication. To that end, extensive experimentation is done over the period of 2–3 years to study UG communication and its response to different soil-related deployment (e.g., burial depth) and operational parameters (e.g., antenna, soil moisture). In the following sections, the methodology and results from these experiments are discussed in detail.

Fig. 3.2 Phases in development of an indoor testbed: (a) wooden box of the testbed, (b) gravel in the testbed (placed at the bottom), (c) soil in the testbed, (d) placement of antenna in testbed, (e) final testbed look [61]

3.2.1 Experimental Setup

3.2.1.1 The Indoor Testbed

Outdoor experimentation in WUSN is not an easy task. Outdoor settings face challenges of extreme weather and temperature conditions. It is very important to get timely results of experiments and getting the different soil moisture level in a short span of time is difficult in outdoor settings. Furthermore, it lacks dynamic soil moisture control, difficult to get changing soil types and deployment of equipment is also cumbersome. An indoor testbed can overcome these challenges. Figure 3.2

shows an indoor testbed. This indoor testbed is developed in a greenhouse setting. It is a wooden box with a dimension of 100 in $\times$ 36 in $\times$ 48 in (see Fig. 3.3b) having 90 ft³ of soil in it (see Fig. 3.2a). It is equipped with a drainage system at the bottom and has waterproof sides. The sides are waterproofed using waterproof tarp to prevent leaks from the side. The box has a 3 in layer of gravel underneath to allow free water drainage (see Fig. 3.2b). Figure 3.2c shows the box with soil in it.

It uses Watermark sensors to monitor the soil moisture level. A total of 8 sensors are installed on the sides of the box. These sensors are placed at the depth of 10 cm, 20 cm, 30 cm, and 40 cm. Two Watermark dataloggers are connected to these sensors. For each installed antenna, a tamper tool is used to pack soil every 30 cm. It is done to

Fig. 3.3 (a) Change in soil moisture vs. time, (b) box dimensions, (c) layout of antennas in the experiment [61]

Table 3.1 Particle size distribution and classification of testbed soils [61]

Textural class	% Sand	% Silt	% Clay
Sandy soil	86	11	3
Silt loam	33	51	16
Silty clay loam	13	55	32

achieve the bulk density¹ to simulate the real-world scenario. A total of 12 antennas, divided into sets of three, are installed (see Fig. 3.2d) at increasing depths of 10cm, 20cm, 30cm, and 40cm (Fig. 3.2d). These sets are separated at 50cm from each other. Figure 3.2e shows the final testbed.

Two different soil types were used for the experimentation: silt loam and sandy soil. Table 3.1 lists the soil type used and distribution of the particle size within the soil type. Experiments were performed to investigate the effect of soil texture on underground communications. To that end, soil having sand content from 13% to 86% and clay content from 3% to 32% was chosen. For experimentation, a nearly saturated soil is used as an input to achieve maximum volumetric water content (VWC) level. Afterwards, results are gathered as the soil water potential decreases from saturated state to field capacity² and then finally to wilting point.³ Figure 3.3a shows the moisture level change in silt loam soil.

3.2.1.2 The Field Testbed

A field testbed consists of dipole antennas, buried at 20cm depth, with silty clay loam soil (see Fig. 3.5a). Figure 3.4 shows the different stages in which field testbed is developed. The purpose of this testbed is to perform underground-to-aboveground (UG2AG) experiments. Field testbed is also used to compare the results from the indoor testbed. For UG2AG experiments, an adjustable height pole is used. The experiments are conducted with the radii of 2m, 4m, 5.5m, and 7m. The distance of max 73 is used due to cable limitations of antenna used for vector network analyzer (VNA). Receiver angles of 0°, 30°, 45°, 60° and 90° are used. The testbed is shown in Fig. 3.5.

3.2.1.3 UG Software-Defined Radio (SDR)

Another testbed is used for conducting experiments with underground software-defined radios. This testbed consists of a total of 16 dipole antennas, divided into 4 sets, in silt loam soil. For each set, the antenna's burial distance is 50cm, 2m, and 4m from the first antenna. In each set, antennas are buried at the depth 10cm,

¹Ratio of dry soil weight to the volume of soil (also including volume of pores in particles).

²Water content in the soil after the drainage of excess water.

³Minimum level of water in the soil.

Fig. 3.4 Field testbed development in the silty loam soil: (a) testbed layout, (b) antenna placement, (c) outlook after antenna installation, (d) antenna cables out of soil at different depths, (e) USRPs and datalogger for soil moisture measurements [33]

Fig. 3.5 The field testbed [61]

20cm, 30cm, and 40cm. This dipole antenna uses the resonant frequency of 433MHz for over-the-air communication. Figure 3.4 shows step by step development of the testbed (starting from Fig. 3.4a till Fig. 3.4e). Figure 3.4a shows the layout,

Fig. 3.4b,c shows the testbed after placement and installation of the antenna, Fig. 3.4d shows the cable coming out of the antennas buried at different depths. Finally, Fig. 3.4e shows the testbed with USRPSs and datalogger used for measuring soil moisture.

3.2.1.4 Soil Moisture Logging

As discussed previously, soil moisture has an impact on the communication. Therefore, it is important to log the soil moisture data after each experiment for correct characterization of channel. Oven drying method can be used for determining soil moisture, however, it requires removal of soil from the testbed. Watermark sensors are used because of their ability of logging soil moisture data with timestamp. Watermark sensors are fast, efficient, and less error prone. It also overcomes the challenge of oven drying method. If there is metallic object in the soil within the vicinity of buried antennas, it can cause interference during the communication. Therefore, to avoid interference, sensors are deployed at the edges of the testbed.

3.2.2 Measurement Techniques and Experiments Description

This testbed uses Keysight Technologies N9923A, FieldFox, and VNA for taking measurements. The layout of the measurements is shown in Fig. 3.3c. In the following section, measurements taken for the indoor testbed are explained in detail.

3.2.2.1 Path Loss Measurements

VNA uses a UG transmitter and receiver (T-R) pair for measuring the signal loss. It transmits a known signal and comparison of received and incident signal is performed to calculate the loss. Path loss is defined as the ratio of power of a signal at sender end P_t to power of the signal reached at receiver end P_r . Path loss is calculated by the following equation:

Table 3.2 Underground channel measurement parameters [61]

Parameter	Value
Start frequency	10 MHz
Stop frequency	4 GHz
Number of frequency points	401
Transmit power	5 dBm
Vector network analyzer	Agilent FieldFox

$$PL = P_t - P_r = 10 \cdot \log_{10}(P_t/P_r) \quad (3.1)$$

where PL denotes the path loss of the system. It also includes the effect of transmitting antenna gain G_t and receiving antenna gain G_r . The frequency range used for the measurement of path loss is 10 Mhz to 4 GHz. A total of 401 discrete frequency points were taken at varying distance and depths. These measurements were used to study how physical properties of the soil impact the attenuation of UG channel.

3.2.2.2 Power Delay Profile (PDP) Measurements

Power delay profile (PDP) is a way to measure signal intensity through a multipath channel. The intensity is measured as a time delay. Time delay is the difference of time taken by signal to travel through multiple paths. The multipath characteristic of a wireless underground channel is studied by channel sounding experiment. VNA accurately characterizes the UG channel by transmitting multiple sine waves at transmitter and measuring them at receiver end. These sine waves are from low to high frequency. Impulse response of UG channel is measured by VNA using one frequency at a time. It measures the impulse response in frequency domain instead of time-domain.

3.2.3 Measurement Campaigns

This section presents the measurements parameters for experiments on each type of the soil.

3.2.3.1 Sandy Soil Experiments

For a distance of 50cm between transmitter and receiver, antenna was buried at the depth of 10cm, 20cm, 30cm, and 40cm in a sandy soil. For a soil moisture range of 0–250 CB, they are buried at the depth of 1m.

3.2.3.2 Silty Clay Loam Experiments

For a distance of 50cm between transmitter and receiver, antenna was buried at the depth of 20cm in a silty clay loam soil. In field testbed, it is buried 1m for a soil moisture range of 0–50 CB.

3.2.3.3 Silt Loam Experiments

For a distance of 50cm between transmitter and receiver, antenna was buried at the depth of 10cm, 20cm, 30cm, and 40cm in a silt loam soil. In indoor testbed, for a soil moisture range of 0–50 CB, they are buried at the depth of 1m.

3.2.3.4 Planar Antenna Experiments

Indoor testbed and two planar antennas are used for the planar antenna experiments. These experiments are conducted in silty clay loam and sandy soils. The return loss and path loss are measured without obstructions and with obstruction between these two antennas. For former experiment, the antenna is kept 1m apart and buried at the depth of 20cm. For latter, another antenna is placed in the middle (50cm) of the two antennas acting as an obstruction and depth for all the antennas is kept same (20cm). These experiments were also conducted with silty clay loam soil using the same empirical parameters and return loss and path loss are compared for both types of the soil.

3.2.4 Empirical Results

This section explores the channel transfer function (S_{12}) for different type of soil using varying values for distances, soil moisture, and depth.

3.2.4.1 Channel Transfer Function Measurement

3.2.4.2 Impact of Burial Depth and Antennas Distance on Attenuation

Figure 3.6 plots the attenuation at different depth and distance in silt loam soil. Figure 3.6a and b shows the attenuation, when the antennas are 50cm apart with varying frequency and depths (10cm, 20cm, 30cm, and 40cm). It can be observed in these figures that at 200MHz path loss differs by 5dB at 10cm (where path loss = 40.37dB) from 40cm (where path loss = 45.26dB). The difference further increases to 8dB at 250 MHz. Figure 3.6c and d shows the attenuation, when the antennas are 1m apart with frequency and depth (10cm, 20cm, 30cm, and 40cm).

At 200 MHz, path loss for the depth of 10cm is 44.37 dB and that for 40cm is 60.12 dB. The difference in path loss is 16dB which is higher as compared to difference at 50cm. The difference increases to 20 dB at the frequency of 250 MHz.

Results for similar experiments with same depths and frequencies, but with different soil type (silt loam soil), are shown in Figs. 3.7 and 3.8. Figure 3.7 shows the results with transmitter and receiver 50cm apart and Fig. 3.8 shows for the

Fig. 3.6 Attenuation in silt loam soil at 50 cm distance: (a) with frequency, (b) at different depths. Attenuation in silt loam soil at 1 m distance: (c) with frequency, (d) at different depths [33]

Fig. 3.7 Attenuation in sandy soil at 50 cm distance: (a) with frequency, (b) at different depths

distance of 1m. For both distances attenuation is highest at the frequency of 400 MHz for all depths.

Another important impact to consider is that of distance between the antennas on attenuation. From Figs. 3.6a (50cm) and 3.6c (1m), it can be observed that path loss increases as the distance between antennas is increased from 50cm to 1m. For example, when antennas distance increases from 50cm to 1m at 200 MHz, path loss is increased by 5 dB, 7 dB, 3 dB, and 15 dB at depths of 10cm, 20cm, 30cm, and 40cm, respectively. Similar trend can be observed for the increased distance in sandy soil (see Figs. 3.7 and 3.8), however, the difference is very low as compared to silt loam soil.

Hence, it can be concluded that path loss is affected by frequency, depth, and distance, i.e., increases with increasing frequency, distance, and depth of antennas. This variation because of frequency is due to soil permittivity. There are three major paths in underground–underground communication: (1) direct, (2) reflected, and (3) lateral. Direct wave is the line of sight path; reflected path is the one taken by wave when it is reflected from soil–air interface; and lateral path is taken because of the propagating along the soil–air interface. The reason for the path loss variation due to depth is because of multipath effect. The direct path has no effect due to the depth increase, however, it affects the lateral and reflected path. So when the depth is increased, path loss due to lateral and reflected wave increases which in turn increases the overall path loss.

3.2.4.3 Impact of Soil Type on Attenuation

Figure 3.9 shows the comparison of attenuation in different soil type for varying depths and frequency. Figure 3.9a shows the result at transmitter–receiver distance of 50cm and Fig. 3.9b shows for the distance of 1m. For 50cm, sandy soil has 10–30 dB, 13 dB, 18 dB, and 20 dB lower path loss value at the depth of 10cm, 20cm,

Fig. 3.8 Attenuation in sandy soil at 1 m distance: (a) with frequency, (b) at different depths [33]

Fig. 3.9 (a) Comparison of attenuation in silt loam and sandy soils at 50 cm distance at different frequencies, (b) comparison of attenuation in silt loam and sandy soils at 1 m distance at different frequencies [33]

30cm, 40cm, respectively. Similarly, for 1m, sandy soil has 12 dB, 20 dB, 18 dB, and 38 dB lower path loss value at the depth of 10cm, 20cm, 30cm, 40cm, respectively.

It can be observed that, for both distances, path loss in sandy soil is less as compared to silt loam soil for all depths. The reason for this is that electromagnetic waves are absorbed by the bound water present in the soil and sandy soil absorbs less bound water as compared to silt loam soil. The water holding power of medium textured soil, e.g., silt loam and silty clay loam, is much higher than that of coarse soils such as sand and sandy loam. This is because coarse soils have lower size of pores hence low resistance against gravity and no aggregation.

3.2.4.4 Impact of Soil Moisture on Attenuation

This section evaluates the experiments done to study the effect of soil moisture on the signal attenuation. Different soil moisture levels, ranging from 0 to 50 CB, are used for these experiments. Figure 3.10 shows the experiment results at transmitter–receiver distance of 50cm in silt loam soil. It can be seen that in Fig. 3.10a there is a decrease of 5 dB as moisture level goes from 0 to 50 and frequency increases. Figure 3.10b uses the frequency of 200 MHz to show the soil moisture effect at varying depth levels. There is a consistent path loss decrease at each depth value as the soil moisture level increases from 0 to 50 CB. For example, path loss decreases 5 dB, 3 dB, 5dB, and 3dB at depths of 10cm, 20cm, 30cm, and 40 cm, respectively, with increasing soil moisture. Figure 3.10c plots the path loss by keeping the fixed depth value, i.e., 10cm, and varying frequency. For fixed depth of 10cm, path loss decreases by 2dB (at 250 MHz) and 3dB (at 250 MHz).

Figure 3.11 shows the experiment results at transmitter–receiver distance of 1m in silt loam soil. In Fig. 3.11a, a 3 dB decrease in path loss can be observed at 250 MHz as soil moisture goes from 0 to 50 CB. In Fig. 3.11c, experiments with varying

Fig. 3.10 Attenuation with soil moisture in silt loam soil at 50 cm distance: (a) S_{21} , (b) effect of change in soil moisture at different depths at 200 MHz frequency, (c) effect of change in soil moisture at different frequencies at 10 cm depth [33]

Fig. 3.11 Attenuation with soil moisture in silt loam soil at 1 m distance: (a) S_{21} , (b) effect of change in soil moisture at different frequencies at 10 cm depth, (c) effect of change in soil moisture at different depths at 200 MHz frequency

frequency and fixed depth of 10cm show that path loss decreases by 2–3 dB as soil moisture goes from 0 to 50 CB. This difference increases further as frequency increases. Figure 3.11b uses the frequency of 200 MHz to show the soil moisture effect at varying depth levels. The trend is similar to the one observed in Fig. 3.10b, i.e., path loss decreases with increasing depth. For example, path loss decreases 1 dB, 5 dB, 5dB, and 4dB at depths of 10cm, 20cm, 30cm, and 40 cm, respectively, with increasing soil moisture.

Figures 3.12 and 3.13 show the effect of soil moisture on path loss for sandy soil at transmitter–receiver distance of 50cm and 1m, respectively. Values of soil moisture considered for this experiment are in the range of 0 to 255 CB. In Fig. 3.12a, it can be seen that the path loss is minimum at 300 MHz and after 300 MHz it starts increasing. Figure 3.12b shows that, for a fixed depth of 10cm, path loss is showing negative trend (increasing) at 200 MHz and positive trend (decreasing) at 250 MHz and 300 MHz. Figure 3.12c plots the effect of soil moisture with fixed frequency but varying depths. It can be observed that for all depth levels path loss is increasing with decreasing soil moisture. The reason for this is the change of resonant frequency to high spectrum with decreasing soil moisture.

Figure 3.13a shows similar trends as of Fig. 3.12a, however, for 1m distance path is minimum at 250 MHz at 0 CB soil moisture level and it is minimum 300

Fig. 3.12 Attenuation with soil moisture in sandy soil at 50 cm distance: (a) S_{21} , (b) effect of change in soil moisture at different frequencies at 10 cm depth, (c) effect of change in soil moisture at different depths at 200 MHz frequency [33]

Fig. 3.13 Attenuation with soil moisture in sandy soil at 1 m distance: (a) S_{21} , (b) effect of change in soil moisture at different frequencies at 10 cm depth (c) effect of change in soil moisture at different depths at 330 MHz frequency [33]

MHz at 255 CB soil moisture level. In Fig. 3.13b, path loss is decreasing at 200 and 250 MHz and decreasing at 300 MHz as soil moisture goes from 0 to 250 CB. Figure 3.13c shows decrease in path loss for all depths at 200 MHz.

These experiments conclude that soil moisture is inversely proportional to path loss, i.e., path loss increases with decrease in soil moisture for both soil types. This is because of high permittivity at high soil moisture.

3.2.4.5 Power Delay Profile Measurements

Figure 3.14 shows the result of power delay profiling (PDP) for the experiments at 50cm and 1m.

Speed of the wave in soil is given as: $S = c/n$, where n is the refractive index and c is the speed of light 3×10^8 m/s. Since the permittivity of soil is a complex number, the refractive index of soil is calculated as:

$$n = \sqrt{\frac{\sqrt{\epsilon'^2 + \epsilon''^2} + \epsilon'}{2}}, \quad (3.2)$$

Fig. 3.14 Power delay profiles (PDP) measured at 50 cm and 1 m distance, at different depths in silt loam soil at near-saturation: (a) 10 cm, (b) 20 cm, (c) 30 cm, (d) 40 cm [33]

where ϵ' and ϵ'' are the real and imaginary parts of the relative permittivity of the soil.

The wave speed is calculated in silt loam soil using refractive index. Refractive index is calculated as 5.6×10^7 on the basis of properties given in Table 3.2. It is 5 times slower and 19% of speed of light.

Figure 3.14 shows the results from the experiments done at the distance of 50cm and 1m for all depths. First multipath component is the direct wave. It is present at delay of 18–28 ns at 50cm and is not appearing for 1m distance. The reason for this is that direct wave is more attenuated at 1m than 50cm. Lateral waves can be seen at time delay of 30–40 ns as the strongest component among all PDPs. The delay for lateral wave is similar for both, 1m and 50cm, because it propagates faster in air. In general, power of lateral wave is 10–15 dB faster than direct wave.

Figure 3.15 compares PDP for all four depths at the distances of 50cm (see Fig. 3.15a) and 1m (see Fig. 3.15b) between transmitter and receiver. It can be observed from the results that if distance is kept same, increase in depth causes decrease in power and time delay of received signal. For example, at 1m, peak power

Fig. 3.15 Power delay profile in silt loam soil at different depths at: (a) 50 cm T-R distance, (b) 1 m T-R distance [33]

of lateral wave is -75 dB and -83 dB at the depth of 10cm and 40cm, respectively. Similarly, same trend is seen for the time delay, i.e., in Fig. 3.15a lateral wave arrives at 29 ns and 32 ns at the depth of 10cm and 40cm, respectively.

Figure 3.16 shows the PDP measurement results at distance of 50cm and 1m and depth of 20cm. The effect of soil moisture is measured by varying the soil moisture values. For both distances, the received signal strength is increasing with decreasing soil moisture. An important observation to note is that direct component vanishes with increasing distance due to higher soil attenuation.

Figure 3.17 shows the measurement of PDP with different type of soil. It is observed that, due to its low water holding capacity, the power of received signal is highest in sandy soil as compared to silt loam and clay loam soil.

3.2.4.6 UG Antenna Return Loss Measurements

The return loss of the antenna (in dB) is calculated as:

$$RL_{dB} = 20 \log_{10} \left| \frac{Z_a - Z_0}{Z_a + Z_0} \right|, \quad (3.3)$$

where Z_a = the antenna impedance and Z_0 = the characteristics impedance of the transmission line.

The reflection coefficient Γ is calculated using return loss as: $|\Gamma| = 10^{\frac{RL}{20}}$. Reflection coefficient is converted to impedance using: $Z_a = Z_0 \frac{1+\Gamma}{1-\Gamma}$. Standing wave ratio (SWR) is calculated as: $SWR = \frac{1+|\Gamma|}{1-|\Gamma|}$.

The frequency where the antenna's input impedance is pure resistance is known as resonant frequency (f_r). At resonant frequency f_r :

Fig. 3.16 Power delay profiles (PDP) measured at 50 cm and 1 m distance, at 20 cm depths for different soil moisture levels: (a) 0 CB-50cm, (b) 50 CB-50cm, (c) 0 CB-1m, (d) 50 CB-1m [33]

Fig. 3.17 Power delay profiles (PDP) measured in different soils: (a) silt loam, (b) silty clay loam, (c) sandy soil

$$Z_a|_{f=f_r} = Z_r = R_a. \quad (3.4)$$

It is the frequency where return loss is maximum such that:

$$f_r = \max(RL_{dB}). \quad (3.5)$$

The return loss experiments are done to measure the effect of soil type, soil moisture, and burial depth on the resonant frequency of the UG antenna.

3.2.4.7 Effects of Soil Type

Figure 3.18 shows the effect of soil type on antenna return loss. There is a difference of 63 MHz, 59 MHz, 55 MHz and 43 MHz at the depths of 10cm, 20cm, 30cm, and 40cm, respectively.

3.2.4.8 Impact of Change in Soil Moisture

Figure 3.19 shows different parameters effecting the return loss of antenna. It uses the soil matric potential values from 0 to 50 CB for all experiments. The soil used for this experiment is silt loam soil. Figure 3.19a shows the return loss for 10cm depth at varying frequencies. It can be seen in Fig. 3.19b, for a soil moisture values of 0 CB and 50 CB, resonant frequency changes from: 211 MHz to 219 MHz at the depth of 10cm, 221 MHz to 227 MHz at the depth of 20cm, 221 MHz to 231 MHz at the depth of 30cm, and 201 MHz to 231 MHz at the depth of 40cm.

In Fig. 3.19c, at shifted frequency, reflection coefficient changes from: -15 dB to -17 dB at the depth of 10cm, -18 dB to -15 dB at the depth of 20cm, -20 dB to -17 dB at the depth of 30cm, and -20 dB to -18 dB at the depth of 40cm. Figure 3.19c plots change in antenna bandwidth at soil moisture values of 0 CB and 255 CB. It can be observed that with decreasing soil moisture bandwidth changes from: 40 MHz to 29 MHz at the depth of 10cm, 30 MHz to 34 MHz at the depth of 20cm, 39 MHz to 34 MHz at the depth of 30cm, and 37 MHz to 30 MHz at the depth of 40cm.

Figure 3.20 plots the return loss for sandy soil with change in soil moisture. It uses the soil matric potential values from 0 to 255 CB for all experiments. Figure 3.20a shows the antenna return loss for 10cm depth. The resonant frequency

Fig. 3.18 Change in return loss in different soil: (a) silt loam, (b) sandy soil [33]

Fig. 3.19 Return loss in silt loam soil: (a) S_{11} at different frequencies, (b) change in resonant frequency with burial depth, (c) reflection coefficient (dB) at different burial depths, (d) antenna bandwidth at different burial depths [33]

changes from 278 MHz to 305 MHz with decrease in soil moisture. It can be seen in Fig. 3.20b, for soil moisture values of 0 CB and 255 CB, resonant frequency changes from: 276 MHz to 301 MHz at the depth of 20cm and 30cm, and 251 MHz to 279 MHz at the depth of 40cm.

In Fig. 3.20c, reflection coefficient changes from: -20 dB to -16 dB at the depth of 10cm, -14 dB to -12 dB at the depth of 20cm, -31 dB to -15 dB at the depth of 30cm, and -16 dB to -15 dB at the depth of 40cm. Figure 3.20d plots change in antenna bandwidth at soil moisture values of 0 CB and 255 CB. It can be observed that as the soil moisture decreases bandwidth changes from: 22 MHz to 8 MHz at the depth of 10cm, 23 MHz to 15 MHz at the depth of 20cm, 25 MHz to 16 MHz at the depth of 30cm, and 18 MHz to 16 MHz at the depth of 40cm.

The analysis has shown that antenna return loss is affected by soil moisture for sandy and silt loam soils. As the soil moisture increases, the resonant frequency goes to lower range. Contrary to over-the-air communications, resonant frequency and optimal frequency (where maximum capacity is achieved) of antenna are different. Finding an optimal frequency for UG antenna in soil is a potential area to work on.

Fig. 3.20 Return loss in sandy soil: (a) S_{11} at different frequencies, (b) change in resonant frequency with burial depth, (c) reflection coefficient (dB) at different burial depths, (d) antenna bandwidth at different burial depths [33]

3.2.4.9 Impact of Burial Depth

Figure 3.18 shows the effect of burial depth on return loss in sandy soil (Fig. 3.18b) and silt loam (Fig. 3.18a). The chosen depths are: 10cm, 20cm, 30cm, and 40cm. Resonant frequency increases from 215 MHz (at 10cm depth) to 227 MHz (at 20cm depth) and decreases to 220 MHz (at 30cm) and 208 MHz (at 40cm). Reflection coefficient is -19.92 dB, -15.76 dB, -16.04 dB, and -19.57 dB at the depths of 10cm, 20cm, 30cm, and 40cm, respectively. To analyze the bandwidth of antenna, -10 dB is chosen as threshold power value. Bandwidth is measured as 40MHz, 32 MHz, 37MHz, and 42 MHz at the depths of 10cm, 20cm, 30cm, and 40cm, respectively.

Figure 3.18b shows the effect of sandy soil on return loss. As in the case of silt loam soil, resonant frequency increases from 278 MHz (at 10cm depth) to 286 MHz (at 20cm depth) and then decreases to 275 MHz (at 30cm) and 251 MHz (at 40cm). Reflection coefficient is -19.92 dB, -15.76 dB, -16.04 dB, and -19.57 dB at the depths of 10cm, 20cm, 30cm, and 40cm, respectively. Reflection coefficient is -20.66 dB (for 10cm depth), -14.57 dB (for 20cm depth), -32 dB (for 30cm depth), and -16.07 dB (for 40cm depth). Bandwidth was measured as 22MHz,

21 MHz, 26 MHz, and 17 MHz at the depths of 10cm, 20cm, 30cm, and 40cm, respectively.

It is very important to characterize underground channel models to design IoUT applications [27, 33, 41, 55–59, 61, 62, 64, 65, 71, 72]. In this chapter, design of different types of testbeds for underground channel modeling is presented. It also presented a detailed measurement campaign which was completed over several years. Empirical results for the underground antenna performance and underground channel transfer functions were presented using different types of soil (sandy and silt loam). Experiments show that indoor testbed gives speedy, efficient, and improved characterization of underground communications. From experiments, it is shown how soil moisture, soil texture, and burial depth of the antenna effect the performance of underground channel and communication. These empirical measurements can act as the preliminary step in designing next generation IoUT communication protocols for the development of improved wireless underground communications [34–40, 42–54, 63, 68].

3.3 UG Channel Models

Ideally, a generalized UG channel model is needed for an optimized and integrated UG applications. However, it is a very challenging task because of many factors involved in an underground ecosystem. These factors include: unpredictable environment, continuously changing topology, capacity of the channel, operational frequency, and antenna parameters. The capacity of a channel is an important metric for analysis of the performance of communication channel. Optimal operational frequency can be defined as the frequency at which system achieves maximum bandwidth. For a given antenna design, change in bandwidth, return loss, path loss because of soil moisture and frequency also result as a change in optimal operational frequency. Underground devices must adapt, in real-time, to changes that may occur because of soil moisture.

In [25, 59], the electromagnetic fields of antennas in half space and infinite dissipative medium have been theoretically derived. However, it assumes that the dipole antennas are matched and do not consider the return loss. [22, 71, 72] measures the impedance of dipole antenna in a solution. It discusses the effect of antenna depth on the length of the dipole, solution surface, and the complex permittivity of the solution. However, that does not apply to WUSN because the soil permittivity is not same as of solution and it does not consider the effect on permittivity due to change in soil moisture.

The permittivity model in [11, 30, 39] provides the basis for developing path loss model in WUSNs channel. References [28, 70] were first to model the underground-to-underground (UG2UG) communication channel. In [13, 65], the authors develop a three-path channel model for the explanation of electromagnetic waves propagation in soil. They use electromagnetic analysis and testbed verifica-

tion for the model. References [6, 14, 67] develops underground-to-aboveground communication models and [14] verifies them through testbed experiments.

Cognitive radio networks are made up of software-defined radios and have recently gained popularity [3, 27]. Most of the literature uses them to deal with scarcity of the spectrum. While there are studies on using cognitive radio to develop underwater solutions [4, 13, 76], there are no solutions, to the best of our knowledge, that consider cognitive radio for wireless underground communication. Moreover, impact of soil moisture on the WUSN communication in terms of path loss, antenna return, loss and bandwidth, has not been yet analyzed.

In the following sections, different UG channel models are discussed with experimental setup and results.

3.4 Underground Soil Propagation Models

There are three major components of a wireless signal: direct wave (DW), reflected wave (RW), and lateral wave (LW) (Fig. 3.23). A signal, propagating through the soil, can exhibit any of the three paths involved in an underground channel propagation. Among these three paths, DW and RW are through soil only. However, LW propagates through, both, soil and air [34, 58]. This section presents the discussion on the characterization of the propagation of these three waves through various channel models.

3.4.1 Path Loss Model

In this section, a path loss model is developed to predict the impact of soil type, soil moisture, operation frequency, distance, and burial depth of sensors for through-the-soil wireless communications channel. The soil specific model is developed based on empirical measurements [61] in a testbed and field settings. The model can be used in different soils for a frequency range of 100 MHz to 1 GHz. The standard deviation between measured and predicted path loss is from 4 dB to 6 dB in the silt loam, sandy, and silty clay loam soil types. The model leads to development of sensor-guided irrigation system in the field of digital agriculture [71].

Digital agriculture [48, 64, 65, 71] is an emerging field in which technology is used to effectively manage agriculture by understanding the temporal and spatial changes in soil, crop, production, and management through innovative techniques. In literature, the Hata-Okumura models are widely used for prediction and simulation of signal strength in cellular environments. Such empirical models do not exist in digital agriculture to predict path loss in through-the-soil wireless communications channel. The wireless communications in wireless underground channel is effected by different factors [40, 61] (e.g., soil type, soil moisture, operation frequency, T-R distances, and burial depths). The prediction of path

loss in through-the-soil communications is vital for digital agriculture sensing and communication system design. In this section, a path loss model is developed to predict the impact of soil type, soil moisture, operation frequency, distance, and burial depth of sensors.

3.4.2 Model Parameters

The standard formula for the model is given as [61]:

$$P_r(f, \delta, \phi, \rho, \nu) = -58.8 - 20 \times \log_{10}(r1) - 20 \times \log_{10}(r2) - 20 \times \log_{10}(\delta) + ((\nu \times -10) + \gamma) \times 3 - \xi \times r1 - \xi \times r2 - \xi \times (\phi + \rho) + F + K \quad (3.6)$$

where f is the operational frequency, δ is the distance between transmitter and receiver, ϕ and ρ are the transmitter and receiver depths, respectively, ν is the volumetric water content in percentage unit, $r1 = \sqrt{(\phi - \rho)^2 + \delta^2}$, $r2 = \sqrt{(\phi + \rho)^2 + \delta^2}$, K is the soil dependent constant, and F is the frequency dependent constant. The γ and ξ , soil moisture and soil attenuation factor, respectively, are given in (3.7) and (3.8):

$$\begin{aligned} \gamma &= p1 * f^3 + p2 * f^2 + p3 * f + p4 \\ \text{where } p1 &= -1.6748e^{-26}, \\ p2 &= 3.8512e^{-17}, \\ p3 &= -3.6971e^{-08}, \\ p4 &= -4.9007, \end{aligned} \quad (3.7)$$

$$\begin{aligned} \xi &= ((\nu * 10) * (p1 * f) + p2 + \nu) * 8.7 + (\nu * 20) \\ \text{where } p1 &= 4.1355e^{-10} \\ p2 &= 2.1161 \end{aligned} \quad (3.8)$$

and the path loss PL is given as:

$$PL(f, \delta, \phi, \rho, \nu) = P_t + G_t + G_r - P_r(f, \delta, \phi, \rho, \nu) \quad (3.9)$$

where P_t is the transmitted power, G_t is the transmitter antenna gain, and G_r is the receiver antenna gain. The values of soil dependent constants are given in Table 3.3.

The frequency dependent constants for silty clay loam, sandy, and silt loam soil types are given in Tables 3.4, 3.5, and 3.6, respectively.

Table 3.3 Soil dependent constant

Param	Silty clay loam	Sandy	Silt loam
K	1	21	6

Table 3.4 Numerical values of frequency dependent constant for silty clay loam soil

Frequency	$\delta < 1$ m	$\delta \geq 1$ m
$f < 300$ MHz	5	15
$300 \text{ MHz} < f < 600$ MHz	-10	5
$f > 600$ MHz	-25	1

Table 3.5 Numerical values of frequency dependent constant for sandy soil

Frequency	$\delta < 1$ m	$\delta \geq 1$ m
$f < 400$ MHz	1	15
$400 \text{ MHz} < f < 600$ MHz	-15	15
$f > 600$ MHz	-15	1

Table 3.6 Numerical values of frequency dependent constant for silt loam soil

Frequency	$\delta < 1$ m	$\delta \geq 1$ m
$f < 400$ MHz	1	15
$400 \text{ MHz} < f < 600$ MHz	-15	1
$f > 600$ MHz	-25	1

3.4.3 Model Validation with Empirical Data

The model is validated through data collected during an empirical campaign in an indoor testbed and outdoor field settings [48, 61]. The measured and model results are compared in Figs. 3.21 and 3.22. The experiments are performed in silt loam, sandy, and silty clay loam soil at 50 cm and 1 m distances. It can be observed that the path loss changes with change in the soil type. The sandy soil has 19 dB less path loss as compared to the silt loam soil. The soil types rich in clay content suffers from higher propagation path loss because of the higher water holding capacity [16, 43]. Overall, the developed model matches with an empirical measured data with maximum prediction difference of 5 dB.

It can also be observed that the path loss in through-the-soil wireless communications is high. A 50 cm increase in the communication distance, i.e., T-R separation, leads to 21 dB increase in the propagation path loss due to complex permittivity of the soil [30, 36]. The short communication range is a major challenge in development of in-soil communications system for digital agriculture field operation. Therefore, an advanced signal processing technique (e.g., moisture adaptive beamforming, multi-carrier) is needed for long-range communications in soil for sensor-guided variable-rate irrigation applications [34, 58, 71].

1. Path differences because of soil type.
2. Soil moisture impact on Path Loss.
3. Effect of operation frequency.
4. Distance and depth

Fig. 3.21 The model comparison with measurement data: (a) in silty clay loam at 1 m, (b) in silty clay loam at 50 cm (c) in silt loam at 1 m

Based on an extensive set of measurements, a model has been developed to investigate the impact of different parameters on communications in silt loam, sandy, and silty clay loam soils. The model is useful to predict the propagation path loss in digital agriculture through-the-soil wireless communications channel. For in-soil system design, the model allows path loss prediction in various soil types under different soil moisture levels without conducting extensive measurements.

3.4.4 Two-Ray Underground Reflection Model

The two-ray UG reflection model considers two signal paths for channel modeling, i.e., DW and RW (Fig. 3.23) [36, 39, 70]. DW is direct between sender and receiver whereas RW is the path of the wave reflected from the ground. Reflected wave is completely negligible at high depths because of longer propagation path. Therefore,

Fig. 3.22 The model comparison with measurement data: (a) in silt loam at 50 cm, (b) in sandy soil at 1 m (c) in sandy soil at 50 cm

Fig. 3.23 EM wave propagation in soil [61]

only direct path is dominant in the communication. Hence, an adjusted Friis free space path loss equation for the soil is given as:

$$P_r = G_t + G_r + P_t - L_p, \quad (3.10)$$

where P_r is the received power, G_t is the transmitter gain, G_r is the receiver antenna gain, $L_p = L_0 + L_s$ where L_0 is the free space path loss, and L_s is the path loss exhibited in soil. $L_s = L_\beta + L_\alpha$, where L_α is the transmission loss and L_β is the attenuation loss due to difference of wavelength in soil and free space. L_p is given as (in dB):

$$L_p = 20\log_{10}(d) + 20\log_{10}(B) + 8.69 \cdot A \cdot d + 6.4, \quad (3.11)$$

where d is the distance in meters, A is the attenuation constant, B is the phase shift constant. Path loss results are shown in Fig. 3.24.

Figure 3.24b compares the path loss in soil with the path loss in the free space for soil moisture. It is observed that path loss increases with the increase in soil water content. For example, at 5 % volumetric water content (VWC), path loss in soil exceeds free space path loss by 64 dB. It becomes worse as the VWC reaches to 25 %.

3.4.5 Three-Ray Underground Reflection Model

Three-wave channel model also considers lateral waves [12, 27]. Lateral waves propagate through soil and air medium (Fig. 3.23). These waves are modeled as follows:

Direct Wave The direct wave has a line-of-sight path between the sender and receiver, i.e., no obstruction is present between both ends and wave completely travels through the soil. It is expressed as:

$$\mathcal{P}_{av}^d = \left(\frac{D_d}{4\pi r_1^2} \right) e^{i2k_s r_1} G_t, \quad (3.12)$$

where $\mathcal{P}_{av}^d$ is the averaged Poynting vector, distance between the transmitter and receiver is given by r_1 ; D_d is a constant factor and its value relies on the permittivity of the soil, wave number in soil is $k_s = \beta_s + i\alpha_s = \omega\sqrt{\mu_0\hat{\epsilon}_s}$, and β_s is the phase shifting constant, α_s attenuation constant; $\omega = 2\pi f$, where f is the wave frequency; μ_0 is the permeability and $\hat{\epsilon}_s$ is the soil permittivity.

Reflected Wave Soil and air have different permittivity values. This difference in permittivity causes a wave to reflect and is known as reflected wave. Similar to direct waves, complete travel path of reflected waves is also through soil. The reflected wave is expressed as:

$$\mathcal{P}_{av}^r = D_r \left(\frac{1}{4\pi r_2^2} \right) e^{i2k_s r_2} G_t \Gamma^2, \quad (3.13)$$

Fig. 3.24 Two-wave path loss model [70]: (a) path loss with variation in distance at different frequencies, (b) path loss with variation in frequencies at different VWC

where D_r represents the permittivity dependent constant. The length of reflection path r_2 is given as:

$$r_2 = \sqrt{(h_t + h_r)^2 + d^2} \quad (3.14)$$

and Γ is the reflection coefficient given by [24]:

$$\Gamma = \frac{\frac{1}{n} \cos \theta_{ri} - \cos \theta_{rt}}{\frac{1}{n} \cos \theta_{ri} + \cos \theta_{rt}}, \quad (3.15)$$

where θ_{ri} and θ_{rt} are the incident and refracted angle, respectively. n represents the refractive index of soil. As per Snell's law,

$$\sin \theta_{ri} = \frac{d}{r_2}, \quad \cos \theta_{ri} = \frac{h_t + h_r}{r_2}, \quad \sin \theta_{rt} = n \sin \theta_{ri}, \quad \cos \theta_{rt} = \sqrt{1 - \sin^2 \theta_{rt}}.$$

To determine the refractive index of soil, real imaginary parts of soil relative permittivity are used as follows:

$$n = \sqrt{\frac{\sqrt{\epsilon'^2 + \epsilon''^2} + \epsilon'}{2}}, \quad (3.16)$$

Lateral Wave Unlike DW and RW, travel path of LW is through soil and air. It propagates horizontally, along soil-air interface and reaches the receiver through soil. Therefore, propagation model for the lateral wave is the mix of both soil and air. The lateral wave is given as:

$$\mathcal{P}_{av}^L = \left(\frac{D_l}{4\pi d^4} \right) e^{i2k_s(h_t+h_r)} e^{i2k_0 d} T^2 G_t, \quad (3.17)$$

where D_l is based on permittivity of the soil and is a constant value, T is the refraction coefficient calculated as :

$$T = \frac{2 \cos \theta_{li}}{n \cos \theta_{li} + \cos \theta_{lt}}, \quad (3.18)$$

The power received by DW component is given as $P_r^D = P_t + 20 \log_{10} \lambda_s - 20 \log_{10} r_1 - 8.69 \alpha_s r_1 - 45$. The power received by reflected component is given by: $P_r^R = P_t + 20 \log_{10} \lambda_s - 20 \log_{10} r_2 - 8.69 \alpha_s r_2 + 20 \log_{10} \Gamma - 45$. Similarly, for lateral wave it is: $P_r^L = P_t + 20 \log_{10} \lambda_s - 40 \log_{10} d - 8.69 \alpha_s (h_t + h_r) + 20 \log_{10} T - 30$,

Fig. 3.25 Comparative results for the models at: (a) volumetric water content of 10 %; (b) volumetric water content of 35 % [58]

$$\begin{aligned}
 P_r^D &= P_t + 20 \log_{10} \lambda_s - 20 \log_{10} r_1 - 8.69 \alpha_s r_1 - 45, \\
 P_r^R &= P_t + 20 \log_{10} \lambda_s - 20 \log_{10} r_2 - 8.69 \alpha_s r_2 + 20 \log_{10} \Gamma - 45, \\
 P_r^L &= P_t + 20 \log_{10} \lambda_s - 40 \log_{10} d - 8.69 \alpha_s (h_t + h_r) + 20 \log_{10} T - 30,
 \end{aligned}
 \tag{3.19}$$

and the total received power is expressed as:

$$P_r = 10 \log_{10} \left(10^{\frac{P_r^D}{10}} + 10^{\frac{P_r^R}{10}} + 10^{\frac{P_r^L}{10}} \right). \tag{3.20}$$

Figure 3.25 gives a comparison graph between attenuation of the model and EM wave. The graph is for multiple distances and two different soil moisture levels of 10 % and 30 %. The parameters include depths of 10 cm, 40 cm, and 80 cm, and distance of $D_1 = 0.15$, and $D_d = D_r = 0.005$. Maxwell equation is used for EM analysis. EM analysis also uses electromagnetic field analysis presented in [26, 33, 65]. With increase in depth of 0.1 m to 0.81 m, up to 21 dB of attenuation is observed at 10 % VWC. Similarly, for same values of distance and depth, the attenuation increases by 130 dB, at 35 % VWC.

The 3-wave model shows better match with empirical measurements than two-wave model (Fig. 3.26). Empirical measurements are obtained using Mica2 motes with 10 dBm transmit power and burial depth of 40 cm. The minor difference between empirical measurements and 3-wave model is because of inaccuracies in received signal strength of Mica2 motes.

Fig. 3.26 Comparing with measured data at burial depth=0.4 m

3.5 UG Channel Impulse Response Model

An efficient communication scheme requires an in-depth investigation of an underground channel model. To that end, a UG channel impulse response model characterizes the underground channel, helps in designing the physical and link layer protocols, and ensures that the required bandwidth is provided for the effective communication. This section presents the UG channel impulse response model [35, 44, 61]. Moreover, outdoor experiments for validation of UG channel models is a challenging task due to changing weather conditions and highly dynamic properties of the soil medium. To that end, an indoor testbed can be developed to simulate the outdoor environment for underground channel characterization.

The results show that indoor testbed is an efficient way to validate UG channel models. It also gives the flexibility of using different types of soil which is very difficult to do in outdoor setup. The effect of soil properties and implementation parameters, e.g., soil moisture, texture, and burial depth, has been analyzed on UG communication and performance of UG antenna. Moreover, power delay profile of UG channel was also analyzed. Results from the experiments facilitate the development of a mature WUSN platform for the practical implementation.

UG channel impulse response of a wireless underground channel is given as [61]:

$$h(t) = \sum_{l=0}^{N-1} \alpha_l \delta(t - \tau_l), \quad (3.21)$$

where the total number of multipaths is given as N , gain and arrival delay for the n -th multipath are represented by α_n and τ_n , respectively.

Impulse response of the UG model with all three wave components, i.e. RW, DW, and LW, is given as:

$$h_{ug}(t) = \sum_{l=0}^{L-1} \alpha_l \delta(t - \tau_l) + \sum_{d=0}^{D-1} \alpha_d \delta(t - \tau_d) + \sum_{r=0}^{R-1} \alpha_r \delta(t - \tau_r), \quad (3.22)$$

where L, D, and R represent the lateral, direct, and refracted wave multipaths, respectively.

The magnitude square method gives the total received power of these components [37, 63]. This method sums up the power of all three components over the total delays of the components.

$$P_r = \sum_{l=0}^{L-1} |\alpha_l|^2 + \sum_{d=0}^{D-1} |\alpha_d|^2 + \sum_{r=0}^{R-1} |\alpha_r|^2. \quad (3.23)$$

After calculating the total received power, path loss is given as:

$$PL(\text{dBm}) = G_r(\text{dBi}) + G_t(\text{dBi}) + P_t(\text{dBm}) - P_r(\text{dBm}), \quad (3.24)$$

G_r is the receiver gain, G_t is the transmitter gain, P_t is the transmitted power, and P_r is the received power.

Metrics for Impulse Response Characterization

The metrics for the analysis of the impulse response model are: mean excess delay and RMS delay spread [55, 64]. Time between the first and last component arriving at receiver is known as excess delay. Mean excess delay (τ) is defined as the first power delay profile (PDP) definition [31]:

$$\tau = \frac{\sum_k P_k \tau_k}{\sum_k P_k}, \quad (3.25)$$

where τ_k is the k -th bin delay, and absolute instantaneous power, of k -th bin, is given by P_k . It is important to mention that multipath component is only considered when it is within 30 dB of the strongest component.

In wireless channel, the inter-symbol interference (ISI) is given by Root Mean Square (RMS) delay spread as follows [31]:

$$\tau_{rms} = \sqrt{(\tau^2) - (\tau)^2}, \quad (3.26)$$

where $(\tau^2) = \sum_k P_k \tau_k^2 / \sum_k P_k$,

$$(\tau^2) = \sum_k P_k \tau_k^2 / \sum_k P_k v, \quad (3.27)$$

where τ_k is the delay of the k -th bin, and P_k is the absolute instantaneous power at k -th bin.

3.5.1 Testbed Setup

Testbed shown in Fig. 3.2 is used to conduct experiments for wireless channel modeling. It is an indoor facility housed in a greenhouse setting [46, 61]. UG communication devices have been used with burial depth of 50 cm which is close to the earth surface [5, 43]. Four dipole antennas are buried at the four different depths of: 10 cm, 20 cm, 30 cm and 40 cm, at horizontal distances of 50 cm and 1 m [49, 61]. The maximum distance is kept at 1 m due to the fact that signal attenuates more in the soil. It is helpful in analyzing the channel symmetry by reversing node roles, i.e., switching transmitter and receiver. Furthermore, it also helps to verify accuracy and repeatability of the experiments. Using the multiple burial depth will allow to measure the effect of the burial depth on channel performance. Water is drained through the pipes at the bottom of the testbed. Soil is packed to simulate the same bulk density as of the field.

Soil moisture has a large effect on the performance of UG communication channel. Hence, the effect of this important property of soil should also be measured with channel characterization. To that end, Watermark sensors are used to measure the time-varying soil moisture values as it is less prone to error. An outdoor testbed has also been prepared. It consists of dipole antennas buried at 20 cm depth at distances of up to 12 m. Table 3.1 shows properties of the soils used in the testbed.

3.5.2 Time-Domain Parameters

The impulse response metrics used for the characterization of UG channel are: Excess delay, mean access delay given by Eq. (3.25), RMS delay spread [7, 31, 50, 51, 66] given by Eq. (3.26), and coherence bandwidth [21, 53].

The difference between flat fading and frequency selective channels lies in the extent of frequency distortion of different components. In frequency selective channel, each component has different distortions whereas distortion is same for all components in flat fading channel. In flat fading channel, delay spread is always less than the symbol period [40, 54]. In over-the-air channel (OTA), channels become frequency selective due to mobility whereas in UG channel soil properties (texture, moisture, soil-air interface, etc.) and other organic matter present in the soil cause major disturbance in the channel.

Fig. 3.27 (a) Mean excess delay in silt loam soil for the indoor experiments, (b) excess delay in silty clay loam soil for the field experiments at the depth of 20 cm [61]

Table 3.7 Silt loam experiment for indoor experiment: standard deviation (σ) and mean (μ) (ns) [61]

Depth	Mean excess delay τ				RMS delay spread τ_{rms}			
	50 cm		1 m		50 cm		1 m	
	μ	σ	μ	σ	μ	σ	μ	σ
10 cm	33.53	1.24	36.09	0.80	20.05	2.24	21.94	2.32
20 cm	34.66	1.07	37.12	1.00	24.93	1.64	25.10	1.77
30 cm	35.87	0.72	37.55	0.65	24.84	2.17	25.34	3.41
40 cm	36.43	0.74	40.18	0.94	23.91	2.84	25.62	1.87

Excess delay of the UG channel is related to the transmitter–receiver separation (distance). It is also shown in Fig. 3.27a, where mean excess delay is plotted at the distance of 50 cm and 1 m at varying depths. Mean excess delay increases by 2 ns to 3 ns for increase of 50 cm in a distance, i.e., 50 cm to 1 m. Table 3.7 shows the values for mean μ and standard deviation, σ , at varying depths. It is observed that mean excess delay increases not only with increase in distance but also with increase in depth. Figure 3.27b plots excess delays along with the distance in silty clay loam soil at the depth of 20 cm. The graph shows that the excess delay is 116 ns for distance of up to 12 m.

Figure 3.28b plots RMS delay spread at transmitter–receiver (T-R) distance of 50 cm and 1 m. Similar to mean excess delay, RMS delay is also dependent upon the distance and burial depths. The increased delay spread is due to reflected and lateral waves. Table 3.7 presents the detailed RMS delay spread statistics for varying burial depths and distances.

Another important metric for analyzing the impulse response of the channel is the coherence bandwidth [41, 68]. It is defined as the inverse of RMS delay spread of UG channel. Figure 3.28d plots coherence bandwidth with T-R distances of 50 cm and 1 m. It is shown that coherence bandwidth decreases from 1 MHz to 600 kHz and then 400 kHz. As the RMS delay value increases, coherence bandwidth of the UG channel decreases. The coherence bandwidth is an important factor to consider

Fig. 3.28 (a) RMS delay spread distribution, τ_{rms} in silt loam soil (indoor testbed), (b) RMS delay spread, τ_{rms} silty clay loam (field experiment), (c) coherence bandwidth distribution in silt loam soil (indoor testbed), (d) coherence bandwidth in silty clay loam (field experiment) [61]

while designing practical UG communication systems. Section 3.5.2.1 discusses the effect of soil moisture, and Sect. 3.5.2.3 discusses the effect of change in operation frequency on underground communication system.

3.5.2.1 Capturing the Water Content Changes

Soil water can be classified as bound and free water. Bound water is present in the initial soil layer and is strongly held by soil particles, thus the named *bound* [16, 48]. The strong bonding is because of osmotic and matric forces in the initial layers of soil and forces start decreasing after these layers. EM waves scatter because of the bound water in the soil [42, 45, 52]. Soil dielectric constant is dependent upon the soil moisture, therefore, it changes with the time as the soil moisture changes. The change in dielectric constant causes the wavelength of the signal to change which effects EM attenuation in the soil. Figure 3.29a shows the soil moisture effect on

Fig. 3.29 Experiment from indoor testbed using silt loam soil: (a) variation in power with delay (Power Delay Profile (PDP)) [61], (b) variation in Path loss at different soil moisture values, (c) variation in RMS delay spread at different soil moisture values at distance of 50 cm, (d) mean amplitudes at all depths at distances of 50 cm and 1 m [61, 61]

delay profiles. The results are for silt loam soil at the distance of 50 cm. It can be observed that gain consistently decreases for all delay range from 5 dB to 8 dB for complete power delay profile.

Figure 3.29b plots the path loss with changing soil moisture. The experiments were performed at the distances of 50 cm and 1 m and burial depth of 10 cm in silt loam soil. It can be seen that path loss decreases by 7 % as the soil moisture changes from 0 cbar to 50 cbar (Centibar).

The variation in amplitude and RMS delay spread are key factors in designing wireless communication system. It is due to the fact that parameters of the system which are suitable for low soil moisture value might not be effective for high soil moisture values. Therefore, a wireless communication system should have the ability to use the optimal values of the system parameters [3, 38].

3.5.2.2 Soil Type Considerations

Texture of a soil is determined by their particle size [20, 57]. Soil texture also plays an important role in the performance of communication system. Therefore, it is important to understand the impact of soil texture on communication systems. To that end, this section studies the impact of soil types on the metrics, i.e., RMS delay spread, mean excess delay, and path loss. The three different soils used for this experiment are: silt loam, silty clay loam, and sandy (see Table 3.8). The change in soil texture leads to significant changes in pore size, and space between the particles. Due to these differences, water retaining capacity of a soil also changes from one type to another [16, 47]. A soil with high water retention capabilities will suffer from high attenuation and vice versa. Furthermore, there is a trade-off between RMS delay and attenuation. Hence, soil retaining high water will have high attenuation but lower RMS delay and vice versa.

3.5.2.3 Radio Frequency Selection

Figure 3.30 studies the effect of frequency on attenuation of the signal. The experiment is done at the T-R separation distances of up to 12m and burial depth of 20 cm is used for both transmitter and receiver. For a distance of 2 m, a 24 dB of attenuation is experienced for a frequency increase of 200 MHz, i.e., from

Table 3.8 Standard deviation (σ) and mean (μ) for all three soil types (ns)

Soil type	Mean excess delay				RMS delay spread				Path loss	
	Distance				Distance				Distance	
	50 cm		1 m		50 cm		1 m		50 cm	1 m
	μ	σ	μ	σ	μ	σ	μ	σ		
Silty clay loam	34.77	2.44	38.05	0.74	25.67	3.49	26.89	2.98	49 dB	52 dB
Silt loam	34.66	1.07	37.12	1.00	24.93	1.64	25.10	1.77	48 dB	51 dB
Sandy soil	34.13	1.90	37.87	0.80	27.89	2.76	29.54	1.66	40 dB	44 dB

Fig. 3.30 Attenuation with frequency [61]

200 MHz to 400 MHz. Similarly, an 80 % increase in attenuation is observed when distance is increased from 1 m to 12 m at a fixed frequency of 200 MHz.

EM waves with higher frequency attenuate quickly in the soil because of its shorten wavelength due to high soil permittivity. Hence, to get large communication range, lower frequency is more desirable for communication in underground channel [47]. An optimal operation frequency is required for the optimal operation of a particular distance and depth combination. This shows that deployment of such system needs to be customized for a number of factors such as distances, depths, frequency range, and soil texture.

3.5.3 Empirical Validation

This section calculates the wave speed in soil to compare the results of models. The following equation calculates the speed of EM waves in the soil [10]:

$$S = c/\eta, \quad (3.28)$$

where c is the speed of light measured in m s^{-1} . The value of $c = 3 \times 10^8 \text{ m s}^{-1}$. η is the refractive index of the soil. It is calculated as: $\eta = \sqrt{\epsilon'^2 + \epsilon''^2} + \frac{\epsilon'}{2}$. ϵ' and ϵ'' are the real and imaginary parts of soil's permittivity, respectively.

The three components of EM wave (DW τ_d , LW τ_l , and RW τ_r) may arrive at different time. Therefore, time of arrival for all three components is given as:

$$\tau_d = (\delta_s/S) + 2 \times (L/S_c), \quad (3.29)$$

$$\tau_r = 2 \times (\delta_s/S) + 2 \times (L/S_c), \quad (3.30)$$

$$\tau_l = 2 \times (\delta_s/S) + (\delta_a/c) + 2 \times (L/S_c). \quad (3.31)$$

Some of the components may travel through the soil, therefore, δ_s and S in Eqs. (3.29), (3.30), and (3.31) represent the distance and speed of wave in the soil, respectively. S_c is the speed of the EM waves, and L is the length of EM waves in coaxial cable.

For testbeds (Table 3.1), soil's refractive indices (Table 3.9) are calculated using Eqs. (3.29), (3.30), and (3.31). Moreover, exact arrival time of all components is also measured for comparison with experimental results of these components.

Figure 3.31 compares the results for sandy, silt loam, and silty clay loam soils. The results from the three-wave model for UG channel are shown in dotted lines. The burial depth used for these results is 40 cm. These results are similar to the measurement results from the model. Owing to the high speed of lateral waves, it always arrives before all other components except at depth of 10 cm and T-R separation of 50 cm.

Table 3.9 Wave speed using refractive index (n) of soil [61]

Soil type	Speed in soil m/s	% of c	Refractive index n
Silt loam	5.66×10^7	18.89	5.28
Sandy soil	5.01×10^7	16.71	5.98
Silty clay loam	5.67×10^7	18.91	5.29

Fig. 3.31 Comparison of impulse response (represented by dotted lines) and impulse response model (represented by solid lines) for soil types of: (a) silt loam, (b) silty clay loam soil, and (c) sandy soil [61]

It can be observed from Fig. 3.31 that the lateral wave is the dominant component of EM wave and suffers from least attenuation. The reason for this is that lateral waves travel from air and soil whereas direct and reflected components completely travel from the soil.

3.6 Underground Channel Sounding and Multipath Characteristics

This section discusses the characterization of a wireless underground channel in terms of path loss, channel sounding, multipaths, and BER analysis. The experiments were conducted in underground testbed in SCAL (South Central Agricultural Laboratory). Theoretical foundation of these experiments along with results is explained in the following sections.

3.6.1 Path Loss Experiments

The testbed consists of 4 sets of buried dipole antennas. Each set contains four antennas buried at a distances of 50 cm, 200 cm, 400 cm, respectively, from each other. Burial depths are 10 cm, 20 cm, 30 cm and 40 cm, respectively. Figure 3.32 shows the testbed.

A wideband Gaussian signal (2 MHz) RF waveform is transmitted from underground dipole antenna buried to 40 cm depth by using one USRP. Signal is received on other buried dipole antenna by using USRPs connected to antennas buried at four different depths (10 cm, 20 cm, 30 cm and 40 cm) with a fixed T-R distance of 50 cm. Experiment is repeated for all these depths by varying the distance to 200 cm and 400 cm. For each frequency, sender transmits data for one second. Receivers collect

Fig. 3.32 The cable layout in the testbed [58]

Fig. 3.33 The power spectral density of the transmitted signal

IQ data of 4 Mega Samples. Receivers acknowledge sender after finishing and then transmitter moves to the next frequency. Three measurements are taken for each depth and distance. Analysis is done in Matlab [29]. GNU Radio [17] and USRPs [15] are used to conduct experiments. Figure 3.33 shows PSD of a sent signal.

For spectral estimation and path loss analysis Welch's method [73] has been used. This method is an enhanced form of periodogram analysis. By using a computationally efficient discrete Fourier transforms, data is divided into fixed blocks to calculate periodograms and modified periodograms. These modified periodograms are averaged to calculate the power spectrum. The analysis follows details from [73].

Collected data $X[n]$, for $n = 0, \dots, N - 1$, is divided into K blocks. Length of these overlapping block is L with a difference of D units from each other. Then

$$\mathbf{X}_1(j) = X(j), \quad j = 0 \dots L - 1 \quad (3.32)$$

Similarly,

$$\mathbf{X}_2(j) = X(j + D), \quad j = 0 \dots L - 1 \quad (3.33)$$

and

$$\mathbf{X}_K(j) = X(j + (K - 1)D), \quad j = 0 \dots L - 1. \quad (3.34)$$

For each block of length L , modified periodogram is calculated by selecting a data window $W(j)$ for $j = 0 \dots L - 1$, in order to form the

sequence $X_i(j)W(j), \dots, X_K W(j)$. Fourier transforms of these sequences $A_i(n), \dots, A_k(n)$ are taken as follows:

$$\mathbf{A}_k(n) = \frac{1}{L} \sum_{j=0}^{L-1} X_k(j) W(j) e^{-2kijn/L} \quad (3.35)$$

where $i = (-1)^{\frac{1}{2}}$. K modified periodograms are obtained as follows:

$$\mathbf{I}_k(f_n) = \frac{L}{U} |A_k(n)|^2 \quad (3.36)$$

where

$$f_n = \frac{n}{L} n = 0, \dots, L/2 \quad (3.37)$$

and

$$U = \frac{1}{L} \sum_{j=0}^{L-1} W^2(j) \quad (3.38)$$

Power spectral density (PSD) is the average of these periodograms and is given by:

$$\mathbf{P}(f_n) = \frac{1}{K} \sum_{k=0}^K I_k(f_n) \quad (3.39)$$

Figure 3.34 shows PSD of a received signal at 50 cm distance and depths of 10 cm, 20 cm, 30 cm, and 40 cm. Sender's burial depth is 40 cm. It is clearly evident that with an increase in burial depth PSD decreases significantly.

Figure 3.35 shows received signal strength for depths of 10 cm, 20 cm, 30 cm, and 40 cm. Received signal strength decreases significantly as burial depth is increased. Figure 3.36 shows path loss with varying frequencies at depths of 10 cm, 20 cm, 30 cm, and 40 cm. Our results show that path loss increases significantly with frequency. This shows that lower frequencies (less than 500 MHz) are more suitable for underground communications. Results of path loss model are compared with theoretical model [12]. Received power for isotropic antennas with $G_t = G_r = 1$ and for all three components is given by Eq. (3.19) and total power is given by Eq. (3.20) [12].

Figure 3.37 compares experimental results with theoretical model of Eq. (3.20). Experimental results for 30 cm and 40 cm depth are in complete match with the theoretical model. In order to use wireless underground channel for effective and efficient communication, a characterization of its impulse response and multipath is needed. These characteristics like delay spread, power delay profile, and rms delay spread are crucial to characterize a wireless channel [33, 41, 58]. We

Fig. 3.34 PSD of received signal. $d = 50 \text{ cm}$, $f = 225 \text{ MHz}$ [58]

Fig. 3.35 Received signal strength $d = 50 \text{ cm}$, $f = 225 \text{ MHz}$

have done underground channel measurement experiments to estimate multipath characteristics of underground channel. Experiment methodology is explained first followed by results of UG channel impulse responses as function of transmitter–receiver distance, burial depth, frequency, and soil moisture.

Fig. 3.36 The path loss with frequency

Fig. 3.37 Comparative analysis between experiment and theoretical results [58]

3.6.2 Experiment Methodology

A channel sounding system, designed in [23, 38], is used in experiments which follows channel measurement techniques of [9]. In this design, pseudo-random sequences are used for measurement of channel impulse response. These sequences

consist of series of 1 and -1 and are generated by shift register. Auto-correlation function of these sequences $s(t)$ is given by [9, 54]:

$$\mathbf{R}_s(\tau) = \frac{1}{T} \int_0^\tau s(t)s(t-\tau) dt \quad (3.40)$$

Correlation output of the N -length x and y sequences is given as follows[18]:

$$\mathbf{R}_{xy}[\mathbf{n}] = \begin{cases} 1, & \text{if } n = 0, N, -N, 2N, -2N, \dots \\ \frac{-1}{N}, & \text{otherwise} \end{cases} \quad (3.41)$$

Let $s(t)$ and $r(t)$ be the sent and received signals, respectively. $h(\tau)$ is an impulse response of the channel where τ represents a multipath delay. $r(t)$ can be written as a convolution of the $s(t)$ with $h(\tau)$.

$$\mathbf{r}(t) = s(t) \otimes h(\tau) = \int_{\inf}^{-\inf} s(t)h(\tau)d\tau \quad (3.42)$$

Important system parameters are summarized below [8]:

1. Power delay profile (PDP): is described as power associated with each component delayed in time. It is given as [8]:

$$\mathbf{p}(\tau) = E \left[|c(\tau)|^2 \right] \quad (3.43)$$

2. *Multipath Resolution*: It is the capability to estimate the maximum detectable component. It is smaller than rate at which sequence starts repeating itself.
3. *Minimum Multipath Resolution*: Difference between two contiguous multipath components is called minimum multipath resolution and it depends on chip rate.
4. *Dynamic Range*: Dynamic range is the ratio of the magnitude of the correlation peak and the magnitude of the maximum correlation value [8, 63]:

$$\mathbf{DR} = 10\log_{10}(L^2) \quad (3.44)$$

where L is the m-sequence length. It represents the ability to detect weak signals.

3.6.2.1 Transmitter

Our experiment uses Ettus Research's Universal Software Radio Peripheral (USRP) [15] along with a GNURadio platform [17]. GNURadio and USRPs provide a very flexible, configurable functionality for implementation of this algorithm. The transmitter and receiver are synchronized by using MIMO cable of [15]. A shift register is used with angle of 10° , and 17 MHz bandwidth to give a resolution

of 60 ns. The sequence repeats after every 61 μ s. This sequence is then amplitude modulated using root raised cosine filter (RRC) and forwarded to USRP block for transmission. Sent signal is given by [23, 45]

$$\mathbf{s}(\mathbf{t}) = \sum_n x[n]p(t - nT_s) \quad (3.45)$$

The effects channel dispersion can be modeled as follows [23]:

$$\mathbf{h}(\mathbf{t}) = \sum_{l=0}^{L-1} \alpha_l \delta(t - \tau_l) \quad (3.46)$$

Here L , α_l , τ_l are the number of multipaths, complex gain of multipaths, and delays associated with multipaths, respectively.

3.6.2.2 Receiver

Received signal in time-domain is given by [23]:

$$\mathbf{r}(\mathbf{t}) = (x * h)(t) = \sum_{l=0}^{L-1} \alpha_l x(t - \tau_l) \quad (3.47)$$

Properly synchronized discrete symbol is given by:

$$\mathbf{r}[\mathbf{j}] = \sum_{l=0}^{L-1} \alpha_l \sum_n x[n]p(j - nT_s - \tau_l) \quad (3.48)$$

With the assumption that τ_l is the integer multiple of T_s , then $\tau_l = c_l T_s$ where c_l is a nonnegative integer. Hence,

$$\begin{aligned} r[j] &= \sum_{l=0}^{L-1} \alpha_l \sum_n x[n]p[(j - n - c_l)T_s] \\ &= \sum_{l=0}^{L-1} \alpha_l x[j - c_l] \end{aligned} \quad (3.49)$$

Correlator's output is given as:

$$R_{cy}[n] = \text{corr}(c, y) = \sum_{l=0}^{L-1} \alpha_l R_{cx}[n - c_l] \quad (3.50)$$

in this equation R_{cx} is $\text{corr}(c, y)$. Complex multipath gains α_l are found using Eqs. (3.41) and (3.50). Taking magnitude squared of these complex multipath gains α_l gives us multipath delay profile. Path loss is obtained by subtracting combined power of all multipath components from the transmitted power.

The system uses sliding correlator based channel sounding technique in literature and has been widely used by researchers for doing channel sounding in different environments. Equipment consists of USRPs connected with MIMO synchronization cables. The transmitter rate is 25 MHz, which gives 40 ns time resolution. With 40 nanoseconds chip rate all the components arriving 40 ns apart at receiver can be easily identified by the measurement system. Symbol level synchronization is achieved by use of 10 training sequences. Each sequence consists of 1000 bits. Gold Sequences of 10° are used for correlation.

Experiments are conducted in 800 MHz and Power Delay Profiles (PDP) are taken. Each PDP shows normalized correlation value over time. The LOS case is simple, however, OLOS scenarios are complicated where the line-of-sight has been blocked by inserting two metal plates of 8 mm thickness and then further blocking by two 15 mm thick cabinet covers.

3.6.3 Experimental Results and Analysis

A measurement system has been developed for wireless underground channel modeling and to characterize underground wireless channel. This system expands path loss modeling and bit error rate analysis experiments to measure underground channel multipath delays and channel attenuation. This section presents results of channel sounding experiments conducted in Cyber Physical Networking (CPN) laboratory for both Line-of-Sight (LOS) and Non-Line-of-Sight scenarios (OLOS). These experiments are conducted to verify the functionality of sliding correlator based channel sounding system developed in lab and to validate system's ability to detect multipath in different environments. These experiments were done in underground testbed in SCAL (South Central Agricultural Laboratory). Theoretical foundation of these experiments along with results is explained in the following sections.

All the power delay profile figures depict the normalized correlation power of first arriving signal at the receiver relative to the peak power of the first arriving signal. X-axis shows propagation delay. Delay components within 15 dB are categorized as multipaths and over 15 dB can be categorized as noise.

Figures 3.38, 3.39, 3.40 show the power delay profile for LOS scenario. There is a one peak that is the strongest one and indicates the line of sight. Its propagation delay is approximately 300 ns. Low peaks, followed by the strongest one, are the weak multiple components and its difference from the strongest one is more than 15 dB.

These figures also show the one component at 300 ns and then multiple components within 15 dB range and last till 500 ns with delay spread of total 200 ns.

Fig. 3.38 Power delay profile—line of sight

Fig. 3.39 Power delay profile—obstructed LOS—Case 1

Since line-of-sight is obstructed, delayed components experience delay due to more distance covered. These delayed multipaths can contribute to intersymbol interference.

The system's ability to detect multipath with delay resolution of 40 ns has been validated. For indoor LOS scenario delay spread is less than 80 ns and for OLOS scenario delay spread range is 100 ns to 150 ns. This system can be used for taking underground channel measurements and these results along with path loss experiments and BER results are presented in subsequent chapters.

Fig. 3.40 Power delay profile—obstructed LOS—Case 5

3.7 UG Prediction Model for Subsurface Attenuation

Electromagnetic signals suffer attenuation with increase in distance [2] because of which the wireless communication has a limited range. It is very rare to achieve long ranges in WUC and if it is achieved in some cases, it is due to randomness of wireless channel. Wireless signals change their direction because of reflection and scattering phenomenon. The arrival time of these electromagnetic signals is different because of multipath effect. Therefore, a channel model considering the multipath effect in UG communication is required. To that end, Eq. (3.51) takes multipath effect and attenuation into consideration in wireless communication. In this section, the effect of distance and angle on path loss and multipath effect of the channel is investigated using empirical evaluations [59, 71, 72].

$$P_{rx}(d_{x,\theta}) = P_{tx}(d_{x,\theta}) - PL(d_{0,\theta}) - 10n \log_{10} \left(\frac{d}{d_0} \right) + X_\sigma \quad (3.51)$$

where

- $d_{x,\theta}$: is the T-R separation with angle θ
- $d_{0,\theta}$: is the reference distance with angle θ
- P_{rx} : is the receiving power
- P_{tx} : is the transmission power
- $PL(d_{0,\theta})$: is the path loss at the reference distance
- n : is the path loss exponent
- X_σ : is a normal random variable with zero mean and standard deviation σ

For a normal random variable, the path loss exponent and standard deviation are measured using the empirical data by the following method:

1. Packets are classified into multiple bins on the basis of communication links. For example, there can be a separate bin for East UG to counterclockwise AG node and similarly separate bins for other links.
2. All items within the bins are classified on the basis of communication angles. Due to symmetric radiation pattern of aboveground (AG) antenna, packets with same angle but opposite direction, e.g., 30° and -30° , can be considered same and placed together.
3. A reference distance with at least hundred entries is selected.
4. Next step is to calculate the mean of the receiving power. This mean is calculated at reference distance $d_{0,\theta}$. It is because averaging over hundred readings will cause the random variable to approach zero. Equation (3.51) can be re-written as Eq. (3.53).

$$\bar{P}_{rx}(d_{0,\theta}) = P_{tx}(d_{x,\theta}) - PL(d_{0,\theta}) - 10n \log_{10} \left(\frac{d_{0,\theta}}{d_{0,\theta}} \right) + X_\sigma \quad (3.52)$$

$$P_{rx}(d_{x,\theta}) = \bar{P}_{rx}(d_{0,\theta}) + 10n \log \left(\frac{d_{x,\theta}}{d_{0,\theta}} \right) + X_\sigma \quad (3.53)$$

5. Only those entries are selected from the leftovers where distance $> d_{0,\theta}$.
6. Calculate $P_{rx}(d_{x,\theta}) - \bar{P}_{d_{0,\theta}}$ and $\frac{dx,\theta}{d_{0,\theta}}$.
7. After plotting the values, path loss coefficient n is given by the slope of best fit line. Standard deviation is the root mean squared error of the normal random variable. The communication process between UG node at east and the UG node at opposite direction is shown using AG2UG communication link in Fig. 3.41.

The path loss coefficients and the corresponding log normal variable standard deviation values are used to perform this procedure.

3.8 UG Statistical Channel Model

A standard OTA modeling approach given in [19, 31, 66, 74] is adopted, with a slight modification, to statistically model the UG wireless channel. Some assumptions for the analysis are given below:

- multipath components (LW, RW, and DW) are not correlated practically, however, individual component is affected by the strongest one. Therefore, within each component, a uniformly spaced tap-delay-lines are assumed.
- The random phases of the components are assumed at the receiver. The phases follow the uniform distribution over $[0, 2\pi]$.

Fig. 3.41 Empirical evaluation of channel path loss [75]

To reduce the model complexity, each component has constant arrival rate of delay and statistically independent amplitude. It is helpful in analyzing the UG channel along with the delay statistics. Different factors are involved in deciding which component will arrive first. These factors include T-R separation (distance) and burial depth. It is due to the fact that propagation speed is different in soil and air. Hence, order of arrival will vary based on the characteristics of these mediums. Direct component arrives earlier for T-R distances of up to 50 cm. For all other distances, lateral component is dominant because of its high speed in the air. Component overlapping does not occur because of the big difference between component's speed, and gain of each components decays before the other one arrives. In the given measurements, no components were detected after the delay of 100 ns.

Next, the amplitudes of individual component are derived. The delays of each component's amplitude, i.e., Lateral (α_{li}), Direct (α_{dj}), and Reflected (α_{rk}) are τ_{li} , τ_{di} , τ_{ri} , respectively. Figure 3.42 plots the mean amplitude of a profile with time decay at a distance of 50 cm. It is observed that the gain of each component exhibits an exponential decay, hence, amplitude of a component is modeled as exponentially decaying. For lateral waves, arrival time τ_L , decay rate γ_L , and amplitude α_L are used for the calculation of amplitude and it is given as [66]:

$$\alpha_{li} = \alpha_{l0} e^{-(i-\tau_L)/\gamma_L} \quad \forall i > \tau_l \text{ and } i < \tau_l + L. \quad (3.54)$$

Similarly, same parameters, i.e., decay rate γ_D , arrival time τ_D , and amplitude α_D , are used for calculating the amplitude of direct component α_{dj} . It is expressed as:

Fig. 3.42 Decay of L,D, and R wave-components [62]

$$\alpha_{dj} = \alpha_{d0} e^{-(j-\tau_D)/\gamma_D} \quad \forall j > \tau_d \text{ and } j < \tau_d + D. \quad (3.55)$$

Following the same method for the reflected component, α_{rk} is calculated as:

$$\alpha_{rk} = \alpha_{r0} e^{-(k-\tau_R)/\gamma_R} \quad \forall k > \tau_r \text{ and } k < \tau_d + R. \quad (3.56)$$

To calculate the gain of first multipaths (α_{d0} , α_{l0} , and α_{r0}) both model and measured values can be used. First multipath gain is given as: α_{d0} , α_{l0} , and α_{r0} . Each multipath is calculated as follows [12]:

$$\begin{aligned} \alpha_{d0} &= P_t + 20 \log_{10} \lambda_s - 20 \log_{10} r_1 - 8.69 \alpha_s r_1 - 22 + 10 \log_{10} D_{rl}, \\ \alpha_{r0} &= P_t + 20 \log_{10} \lambda_s - 20 \log_{10} r_2 - 8.69 \alpha_s r_2 + 20 \log_{10} \Gamma - 22 + \\ &\quad 10 \log_{10} D_{rl}, \\ \alpha_{l0} &= P_t + 20 \log_{10} \lambda_s - 40 \log_{10} d - 8.69 \alpha_s (h_t + h_r) + 20 \log_{10} T - 22 + \\ &\quad 10 \log_{10} D_{rl}, \end{aligned} \quad (3.57)$$

where P_t is the transmitted power, Γ is the reflection coefficient, T is the transmission coefficients [12], r_2 is the length of the reflection path, $r_1 = \sqrt{(h_t - h_r)^2 + d^2}$, $r_2 = \sqrt{(h_t + h_r)^2 + d^2}$, where h_t is the transmitter depth and h_r is the receiver burial depth, and λ_s represents the wavelength in soil [60].

The exponential decay seems reasonable because of the different time delays due to different travel paths. Moreover, path gains are affected by the soil, hence, multipath gains are also dependent upon the delays. Other important factors effecting the multipath gains (α_{li} , α_{dj} , α_{rk}) are soil moisture and soil type, e.g.,

Fig. 3.43 Impulse response of wireless underground channel [62]

sandy soil has higher path gain as compared to the silty clay loam and silt loam soils. This is because of sand holds less water as compared to later soil types. However, this effect of soil type on multipath gains does not need to be remodeled in Eqs. (3.54)–(3.56) and is captured in main components α_{l0} , α_{d0} , α_{r0} . As multipath gains are dependent upon these components, the effect will be reflected in gains (Eqs. 3.54–3.56) as well.

A threshold value for the gain is selected for estimating the number of multipaths L , D , and R in each component and after that, multipath generation is stopped for that particular component. The threshold value is usually within 30 dB from peak. As discussed earlier, the effect of soil texture will result in relatively large number of components for sandy soil than the silt loam and silty clay loam soils. This shows a very good matching with empirical results. Furthermore, the number of components also represent the channel spread which is also inversely proportional to the soil moisture values, i.e., low soil moisture will result in large spread and vice versa. It is because of the decreased attenuation for low soil moisture values. Figure 3.43 shows the underground impulse response model and model parameters are given in Table 3.10.

To summarize, delays within multipath components are used to calculate α_l , α_d , α_r . These delays rely on the exponential decay of multipaths. However, for normalized path gains, the amplitudes become independent of their corresponding delays [66]. The normalized delays are calculated using average such that $\alpha_{li}/\bar{\alpha}_{li}$, $\alpha_{dj}/\bar{\alpha}_{dj}$, and $\alpha_{rk}/\bar{\alpha}_{rk}$. Figure 3.44 shows normalized path gains, calculated from similar process, following a Weibull probability distribution.

3.8.1 Model Parameters and Evaluation

Table 3.10 lists all parameters required to evaluate the statistical model. First, the component's gains (α_{li} , α_{dj} , α_{rk}) and their corresponding delays (τ_{li} , τ_{di} , τ_{ri})

Table 3.10 The impulse response model parameters [62]

Parameter	Description	Model	Values
S	Speed of wave in soil [61]	C/η	$C = 3 \times 10^8$
η	Refraction index [61]	$\eta = \sqrt{\epsilon'^2 + \epsilon''^2} + \epsilon'/2$	ϵ', ϵ''
ϵ'	Real part of relative permittivity of the soil [30]	$\epsilon'_s = \begin{cases} 1.15 \left[1 + \rho_b/\rho_s (\epsilon_s^\delta - 1) + (m_v)^{v'} (\epsilon'_{fw})^\delta - m_v \right]^{1/\delta} - 0.68 & 0.3 \text{ GHz} \leq f \leq 1.4 \text{ GHz} , \\ \left[1 + \rho_b/\rho_s (\epsilon_s^\delta - 1) + (m_v)^{v'} (\epsilon'_{fw})^\delta - m_v \right]^{1/\delta} & 1.4 \text{ GHz} \leq f \leq 18 \text{ GHz} , \end{cases}$	$S = \text{Sand in } \%, C = \text{Clay in } \%,$ $\delta = 0.65, \quad v' = 1.2748 - 0.519S - 0.152C, \quad v'' = 1.33797 - 0.603S - 0.166C$ $\epsilon'_{fw}, \epsilon''_{fw}$
ϵ''	Imaginary part of relative permittivity of the soil [30]	$\epsilon''_s = \left[(m_v)^{v''} (\epsilon''_{fw})^\delta \right]^{1/\delta}$	
ϵ'_{fw}	Real part of relative permittivity of the free water [30]	$\epsilon'_{fw} = e_{w\infty} + \frac{\epsilon_{w0} - \epsilon_{w\infty}}{1 + (2\pi f \tau_w)^2}$	$\epsilon_{w\infty} = 4.9$ is the limit of ϵ'_{fw} when $f \rightarrow \infty$, ϵ_{w0} is the static dielectric constant for water, τ_w is the relaxation time for water, and ϵ_0 is the permittivity of free space. At room temperature, $2\pi \tau_w = 0.58 \times 10^{-10} s$ and $\epsilon_{w0} = 80.1$, effective conductivity, δ_{eff}
ϵ''_{fw}	Imaginary part of relative permittivity of the free water [30]	$\epsilon''_{fw} = \frac{2\pi f \tau_w (\epsilon_{w0} - \epsilon_{w\infty})}{1 + (2\pi f \tau_w)^2} + \frac{\delta_{eff}}{2\pi \epsilon_0 f} \frac{(\rho_s - \rho_b)}{\rho_s m_v}$	
δ_{eff}	Effective conductivity of soil [30]	$\delta_{eff} = \begin{cases} 0.0467 + 0.2204\rho_b - 0.4111S + 0.6614C & 0.3 \text{ GHz} \leq f \leq 1.4 \text{ GHz} . \\ -1.645 + 1.939\rho_b - 2.25622S + 1.594C & 1.4 \text{ GHz} \leq f \leq 18 \text{ GHz} \end{cases}$	ρ_b is the bulk density

τ_d	Arrival time of direct component	$\tau_d = (\delta_s/S)$	S is the speed of wave in soil
τ_r	Arrival time of reflected component	$\tau_r = 2 \times (\delta_s/S)$	S is the speed of wave in soil
τ_l	Arrival time of reflected component	$\tau_l = 2 \times (\delta_s/S) + (\delta_a/c)$	S is the speed of wave in soil C is the speed of wave in air
$\alpha_{d0}, \alpha_{r0}, \alpha_{l0},$	Gains of the three main components	$\alpha_{d0} = P_t + 20 \log_{10} \lambda_s - 20 \log_{10} r_1 - 8.69 \alpha_s r_1 - 22 + 10 \log_{10} D_{rl}$ $\alpha_{r0} = P_t + 20 \log_{10} \lambda_s - 20 \log_{10} r_2 - 8.69 \alpha_s r_2 + 20 \log_{10} \Gamma - 22 + 10 \log_{10} D_{rl}$ $\alpha_{l0} = P_t + 20 \log_{10} \lambda_s - 40 \log_{10} d - 8.69 \alpha_s (h_t + h_r) + 20 \log_{10} T - 22 + 10 \log_{10} D_{rl}$, See also analysis from Table VI.	μ and σ
$\alpha_{di}, \alpha_{rj}, \alpha_{lk}$	Path amplitudes of the three components	$\alpha_{li} = \alpha_{l0} e^{-(i-\tau_l)/\gamma_L} \forall, i > \tau_l \text{ and } i < \tau_l + L$ $\alpha_{dj} = \alpha_{d0} e^{-(j-\tau_d)/\gamma_D} \forall, j > \tau_d \text{ and } j < \tau_d + D$ $\alpha_{rk} = \alpha_{r0} e^{-(k-\tau_r)/\gamma_R} \forall, k > \tau_r \text{ and } k < \tau_r + R$

Fig. 3.44 Amplitude gains resulted from the Weibull distribution [62]

Algorithm 1 UG channel impulse response simulation

- 1: *Initialization* :
 - 2: Input soil parameters
 - 3: Obtain the soil moisture level
 - 4: **BEGIN**
 - 5: Generate decay exponents for the lateral, direct, and reflected components
 - 6: Determine the arrival time
 - 7: Calculate the first multipath gain of each of the three components
 - 8: Generate multipaths and impulse response
 - 9: **END**
-

are calculated numerically. After that, measured data is compared with the other impulse response parameters. Algorithm 1 is used to generate the UG channel impulse response.

The different soil parameters, e.g., soil texture and moisture, act as an input to the algorithm. Equations (3.29) to (3.31) are used to calculate the arrival time of direct component (τ_d), lateral component (τ_l), and reflected component (τ_r). Peak power gains for the components τ_{d0} , τ_{r0} , τ_{l0} are calculated considering soil type. These gains are estimated from [61]

Table 3.9 shows the comparison between statistical parameters from measured and numerically computed channel model. The error rate of RMS delay spread is 14.67 % and for coherence bandwidth is 14.08 %. This difference in theoretical and experimental values is because of erroneous observation or model uncertainty, nonetheless, the overall error rate stays below 15 %. Therefore, it can be said that statistical model results agree with the empirical results.

Table 3.9 Comparison of parameters for impulse response model [62]

Impulse response parameter	Measured	Modeled
RMS delay spread (τ_{rms})	45.52 ns	38.84 ns
Coherence bandwidth	439 kHz	514 kHz

Fig. 3.45 Comparative analysis of results for impulse response from model and empirical evaluation experiments in silt loam [62]

3.8.2 Empirical Validation

A desirable property of a good statistical model is that it should simulate the empirical measurements with high accuracy, and that too with a very little difference between the characteristics of the measured results. This section validates the multipath component arrival. To that end, results from the indoor testbed experiments are used for validation [61].

Equations (3.29), (3.30), and (3.31) are used to estimate the refractive indices of each component. The refractive index differs for each soil type as given in [61] along with the results. Reference [61] gives the value of $5.6 \times 10^7 \text{ m s}^{-1}$ which is approximately one-fifth of speed of light.

The comparative graph measures empirical PDP values in silt loam soil as shown in Fig. 3.45. The depth is 40 cm and T-R separation is kept at 50 cm. It was observed that, for a fixed T-R separation of 50 cm and varying depths, lateral component is arriving (at receiver) before direct component at 10 cm depth only. For all other depths, measured and model values are similar.

It is also observed from Fig. 3.45 that lateral component is the strongest of all other components. The reason is that the direct and reflected components propagate radially outward because of their spherical nature. On the contrary, lateral waves exhibit two different paths: vertical path in upward direction (source to boundary) and horizontal path as cylindrical wave. Smart lighting is the feasible application for

the proposed model. However, it is important to improve this model for customized smart lighting in IOUT environments with specific sensing and communication systems deployed in the IOUT.

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