

Review Article

Signal Propagation Models in Soil Medium for the Study of Wireless Underground Sensor Networks: A Review of Current Trends

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Radio signal propagation modeling plays an important role in the design of wireless communication systems. Various models have been developed, over the past few decades, to predict signal propagation and behavior for wireless communication systems in different operating environments. Recently, there has been an interest in the deployment of wireless sensors in soil. To fully exploit the capabilities of sensor networks deployed in soil requires an understanding of the propagation characteristics within this environment. This paper reviews the cutting-edge developments of signal propagation in the subterranean environment. The most important modeling techniques for modeling include electromagnetic waves, propagation loss, magnetic induction, and acoustic wave. These are discussed vis-a-vis modeling complexity and key parameters of the environment including electric and magnetic properties of soil. An equation to model propagation in the soil is derived from the free space model. Results are presented to show propagation losses and at different frequencies and volumetric water content. The channel capacity and the operating frequency are also analyzed against soil moisture at different soil types and antenna sizes.

1. Introduction

Wireless sensor networks are increasingly being used in new applications such as soil and underwater. Such networks are also being used in open underground tunnels and mines mainly to facilitate communication in transport systems and also for safety requirements in mines [1]. This calls for the use of innovative communication techniques in their realization. The wireless underground sensor network (WUSN) is thus one of such emergent areas that have gained the attention of many researchers [2–7]. WUSNs can be defined as a network of wireless devices operating in a subterranean environment. The devices may either be buried at a particular depth in soil or be positioned within an enclosed open underground space such as underground mines and tunnels [2]. The use of WUSNs opens up new possibilities for underground monitoring and communication. Capabili-

ties of WUSNs that make them attractive for use include timely data collection, concealment, easy deployment in hazardous areas, reliability, and coverage of large geographic areas. Research in the area of WUSNs in the past has focused on the deployment of networks in open subterranean environments such as coal mines, subways, or sewer systems [8]. Even though such networks are set up underground, the medium through which communication takes place is still air. The channel characteristics for underground sensor networks and terrestrial sensor networks do however reveal a lot of similarities. The terrestrial WSNs are assumed to operate in unbounded free space whilst WUSNs on the other hand operate in the air but are bounded or confined by soil.

An emerging area of WUSNs is one in which sensor nodes are completely buried in soil and communication takes place within the soil medium (WUSN-BS). These WUSN-BSs have several applications, including monitoring of soil

physical properties for precision agriculture and sports [3]. Additionally, WUSN-BS can be used to detect soil contamination in mining areas or refuse dumpsites. Furthermore, WUSN-BS has military and security applications including intrusion detection, detection of troupe movement, and border patrol.

In this paper, the latest development in signal propagation modeling related to the soil is reviewed. The most important modeling techniques used for propagation in the soil are described. Channel performance measures such as path loss and channel capacity as well as some research challenges are also discussed. They are discussed in terms of modeling complexity and required information on the environment including properties of soil.

2. Related Work

Earlier work has shown that EM techniques for modeling signal propagation may still apply to soil environments [2, 3, 6, 9, 10]. To the best of our knowledge, there is little research work on the channel characterization of EM waves in this environment. The magnetic induction (MI) method is another transmission technique that has been used for short-range communication in soil. As far as underground mines and tunnels are concerned, the use of EM waves has proven to be the most appropriate choice for the characterization of wireless signal propagation, since the medium is still air [2].

The literature on propagation in soil has been growing an indication of the increased interest in the area. It has been suggested that wireless communication through soil may be modeled as EM wave transfer through a transmission line [11]. In [12], the electromagnetic field principles of a dipole in a conducting half-space are analyzed over the frequency range from 1 to 10 MHz. In [13], the principles of the surface-penetrating radar are reviewed and an overview of the empirical attenuation and relative permittivity values of various materials, including soil, at 100 MHz is also presented. In another study, it was shown that the soil composition has significant effects on the ground-penetrating radar (GPR) detection of landmines [14]. A project on glacier monitoring using a network of buried sensors in Norway is presented in [8]. The sensor network in this project is intended to measure the parameters of ice caps and glaciers using sensors beneath the glaciers. The base stations are connected to two wired transceivers 30 m below the surface to avoid wet ice. Using very high transmit powers, communication takes place between the underice sensors and the base stations aboveground. It is observed that part of the signal travels through the glacier and part through the air. To guarantee the safety of mine workers, wireless sensor networks are increasingly being used to monitor underground mines. In this case, the signal propagation takes place in an open bounded area [1, 7, 15, 16]. In another project where a sensor network is used in a sewer system, a manhole cover is converted into a slot antenna. This established communication between sensors underground and the aboveground nodes through radiation from the manhole cover [17]. Once again, although the system is set up underground, the com-

munication is performed through the air. In similar works [10], the characteristics of the wireless channel in tunnels are investigated. In another related work [18], the largest residential water management project in Europe is described. The project deployed a sensor network used to gather information for inspection and cleaning systems in a sewer system.

WUSN was also used for increasing the efficiency of oil recovery processes. In this case, millimeter-scale sensors and antennas are deployed within confined oil reservoir fractures, which necessitates the sensor nodes operating in the terahertz range [19].

In [20], WUSNs have been used to characterize radio transmission between underground buried pipes and a base station using multilayer media. This is to identify the range of operating communication frequencies having lower energy loss, lower bit error rate, and power needed to transfer packets that carry data through the media.

In a more recent study, the complex refractive index model-Fresnel (CRIM-Fresnel) and the modified Fruis are considered the two electromagnetic signal attenuation models used to evaluate the signal strength in soil medium. These models were reviewed, and a methodology was developed to perform an experimental measurement of electromagnetic signal attenuation in the laboratory. Measured results from the laboratory are compared with the estimated values computed from the propagation loss models. A significant difference between the models and estimated values is established from the comparison [21].

In agriculture, IoUT is envisaged to provide total field autonomy and enable more efficient food production solutions through not only in situ monitoring and self-reporting capabilities (soil moisture, salinity, temperature, etc.) but also the interconnection of existing field machinery like irrigation systems, harvesters, and seeders [22, 23]. Enabling communication technologies for the Internet of underground things (IoUT), network issues, and localization techniques are presented in [24]. These enabling technologies include EM wave transmission, MI systems, acoustic wave transmission, wired networks, visible light communication (VLC), and mud pulse telemetry (MPT) communication systems for oil and gas monitoring.

To prolong the lives of energy-hungry sensor nodes in wireless sensor networks, energy management schemes have been proposed in the literature to keep the sensor nodes alive. This is to make the network operational and efficient. These energy management schemes include energy harvesting, energy transfer, and energy conservation [25, 26].

In [27], a new wave number model is proposed using the combination of the Peplinski principle and multiple scattering in soil medium. The new wave number is used in the computation of the path loss. The path loss is modeled based on the absorption due to permittivity and multiple scattering from obstacles in soil. The path loss is then analyzed against distance at two typical IoT frequencies of 433 MHz and 868 MHz. This work also showed the effect of VWC on the path loss for two proportions, 5% and 50%.

Table 1 presents a summary of the contributions of some selected current research work on WUSNs and IoUT.

TABLE 1: Summary of the contributions of some current related works.

Reference	Contribution	Year
[27]	A new wave number model is proposed using the Peplinski principle + multiple scattering in soil medium. The path loss is modeled based on the absorption due to permittivity and multiple scattering from obstacles in soil. The path loss is then analyzed at two typical IoT frequencies of 433 MHz and 868 MHz for two proportions of VWC, 5% and 50%.	2021
[22, 28]	An IoUT architecture has been proposed to provide a total field autonomy in agriculture and to enable more efficient food production solutions through in situ monitoring, self-reporting capabilities (soil moisture, salinity, temperature, etc.), and the interconnection of existing field machinery like irrigation systems, harvesters, and seeders.	2018, 2020
[29, 30]	An acoustic-based wireless data transmission system was proposed where sensing data was transmitted over 30 m distance through soil medium.	2017, 2018
[25, 26]	To prolong the lives of energy-hungry sensor nodes in wireless sensor networks, energy management schemes are proposed to keep the sensor nodes alive. This is to make the network operational and efficient. These energy management schemes include energy harvesting, energy transfer, and energy conservation.	2018, 2021
[20]	WUSNs are used to characterize radio transmission between underground buried pipes and a base station using multilayer media. This is to identify the range of operating frequencies having lower energy loss, lower bit error rate, and power needed to transfer packets that carry data through the media.	2017
[21]	The complex refractive index model-Fresnel (CRIM-Fresnel) and the modified Fruis considered the two EM signal attenuation models for evaluating the signal strength in soil medium were reviewed, and a technique was developed to perform an experimental measurement of EM signal attenuation in the laboratory. Measured results are compared with the estimated values computed from the propagation loss models. A significant difference between the models and estimated values is established from the comparison.	2019

3. Electromagnetic Propagation through Soil

The propagation characteristics of EM in soil differ significantly from other media. This may be attributed to the properties of the soil medium which is characterized by a high attenuation factor due to high absorption and multipath losses. EM wave transmission depends largely on the dielectric constant of the material. In most cases, smaller dielectric constant values yield better transmission conditions. Soil is a dielectric material made up of air, water, and bulk soil [2]. Higher air composition and porosity in the soil promote the better performance of EM wave propagation [3]. In contrast, a high percentage of volumetric water content greatly impedes communication.

3.1. The EM Wave Transmission and Attenuation in Soil. The received signal strength or the attenuation of EM waves depends mostly on the physical properties of the soil. These properties including density, volumetric water content, and mineral content play important roles in determining the attenuation properties for the transmitted EM waves. Valuable information on the physical properties of the medium as well as the properties of the transmitted EM wave can be obtained from the received signal strength. The main contributing factor to the EM wave attenuation in the soil is the volumetric water content (VWC) of the soil [31]. The variation of the dielectric constant of the soil is determined as a function of its components [9]. The EM wave attenuation in the soil is characterized by the attenuation constant, α , and the phase shift constant β . The propagation constant or the wave number k is expressed as [32]

$$k = \sqrt{\mu\epsilon\omega^2 + i\mu\sigma\omega} = \alpha + j\beta, \quad (1)$$

where

$$\begin{aligned} \alpha = \text{Re}(k) &= \omega \sqrt{\frac{\mu\epsilon'}{2} \left[\sqrt{1 + \left(\frac{\epsilon''}{\epsilon'}\right)^2} - 1 \right]}, \\ \beta = \text{Im}(k) &= \omega \sqrt{\frac{\mu\epsilon'}{2} \left[\sqrt{1 + \left(\frac{\epsilon''}{\epsilon'}\right)^2} + 1 \right]}. \end{aligned} \quad (2)$$

In the above, σ is the electric conductivity, ϵ is permittivity, μ is the magnetic permeability of the soil, and ω is the angular frequency of the EM wave.

The additional received power losses may be attributed to the porosity of the medium, water content, pore fluid conductivity, and soil fabric. These losses are directly linked to soil properties such as the electric conductivity (σ), permittivity (ϵ), and the magnetic permeability (μ) as well as the angular frequency (ω) of the EM wave.

The electrical conductivity of soil varies widely depending on the soil type and moisture content [33].

The relative permittivity of soil arises from the interaction of the electromagnetic field with charge in the form of electric dipoles and free monopoles within the soil. Polar molecules like water absorb energy from the electric field while becoming orientated with the field. Water has a strong relative permittivity of 80 as compared to 1 for air and 5 for quartz [34]. Thus, the water content in soil strongly influences the permittivity of the soil [35]. The permittivity of a material can be expressed as [4]

$$\begin{aligned} \epsilon &= (1 + \chi_e)\epsilon_0, \\ \epsilon &= \epsilon_r\epsilon_0, \end{aligned} \quad (3)$$

where χ_e is the electric susceptibility of the medium, ϵ_r is the relative permittivity, and ϵ_0 is the permittivity of free space. The magnetic permeability of most geologic materials is the same as that of a vacuum, and it is assumed that the relative magnetic permeability for these materials is 1. But the value is different for soils that have high iron content.

3.2. EM Wave Transmission Models in Soil. EM wave transmission through soil can be modeled based on Friis' free space propagation equation, where a tweaking factor is included to account for additional losses in the soil medium. The power of the received signal, P_r in free space, is modeled as [36]

$$P_r = P_t G_t G_r \left(\frac{\lambda}{4\pi d} \right)^2, \quad (4)$$

where P_t is the transmit power, G_r and G_t are the gains of the receiver and transmitter antennas, d is the distance separating sender and receiver antennas, and λ is the EM wavelength. In decibels, Equation (4) will be expressed as [37]

$$10 \log (P_r) = 10 \log \left[P_t G_t G_r \left(\frac{\lambda}{4\pi d} \right)^2 \right], \quad (5)$$

$$10 \log (P_r) = 10 \log (P_t) + 10 \log (G_t) + 10 \log (G_r) + 20 \log \left(\frac{\lambda}{4\pi d} \right), \quad (6)$$

$$P_r = P_t + G_r + G_t - L_p, \quad (7)$$

$$L_p = L_0 + L_s \quad (\text{in dB}), \quad (8)$$

where L_0 is the path loss in free space and L_s is the additional path loss accounting for the propagation in soil. The free space path loss can be directly derived from Equation (8), without the additional path loss with $L_s = 0$ as [36]

$$L_0 = 10 \log \left(\frac{P_t}{P_r} \right) = -10 \log \left[G_t G_r \left(\frac{\lambda}{4\pi d} \right)^2 \right]. \quad (9)$$

Ignoring antenna gains, i.e., $G_r = G_t = 1$, Equation (6) is reduced to

$$L_0 = 10 \log \left(\frac{P_t}{P_r} \right) = 20 \log \left(\frac{4\pi d}{\lambda} \right). \quad (10)$$

The computation of the additional path loss L_s is performed by considering the following differences of EM wave propagation in soil compared to that in the air:

- (i) The wavelength is different based on the difference in signal velocity
- (ii) Based on the signal frequency, the wave amplitude will be different

- (iii) Color scattering and delay distortion are caused by the correlation of the phase velocity with the frequency in the soil

Hence, the additional path loss L_s in the soil can be expressed as the addition of two components

$$L_s = L_\alpha + L_\beta, \quad (11)$$

where L_α (dB) is the transmission loss due to the attenuation constant α and L_β is the attenuation loss due to the phase shift constant β . Consequently, considering that the wavelength in the soil is $\lambda_s = 2\pi/\beta$ and that of free space is $\lambda_0 = c/f$,

$$L_\beta = 20 \log \left(\frac{\lambda_0}{\lambda_s} \right), \quad (12)$$

where β as previously defined is the phase shift constant, $c = 3 \times 10^8 \text{ ms}^{-1}$, and f is the operating frequency.

Substitute the expressions of λ_s and λ_0 into Equation (12) and simplify

$$L_\beta = 154 - 20 \log (f) + 20 \log (\beta). \quad (13)$$

Since L_α is the transmission loss caused by attenuation with attenuation constant α , it can be expressed as $L_\alpha = e^{2\alpha d}$ derived from the electric field equation. When expressed in decibel, it is given by

$$L_\alpha = 20 \log (4\pi\lambda_0). \quad (14)$$

Consequently, when we substitute Equations (13) and (14) into Equation (11), the path loss of an EM wave in the soil L_p is expressed as follows:

$$L_p = 6.4 + 20 \log (d) + 20 \log (\beta) + 8.69\alpha d. \quad (15)$$

It can be seen from Figure 1 that lower frequencies are required for adequate communication in soil medium. However, reducing the operating frequency below 300 MHz will increase the antenna size, which can also prevent practical implementation of WUSNs. It is a fact that most wireless underground sensor boards like MICA2 operate within 300–400 MHz range. A suitable operating frequency range between 300 and 900 MHz will be appropriate for preserving small antenna sizes [3, 34]. This is to ensure that the sensors remain discrete, a property that is particularly useful for security applications. Figure 1 shows the graph of the path loss, L_p in decibels as a function of distance d in sandy soil with $\epsilon'_r = 4.5$ and $\epsilon'' = 0.1$ for different values of operating frequency, f . It can be seen that the path loss increases with increasing distance, d , as anticipated. Furthermore, the increase in the operating frequency, f , leads to the increase of the path loss. This analysis motivates the need to operate at lower frequencies in soil medium. This confirms the fact that the path loss is far lower for communication in free space

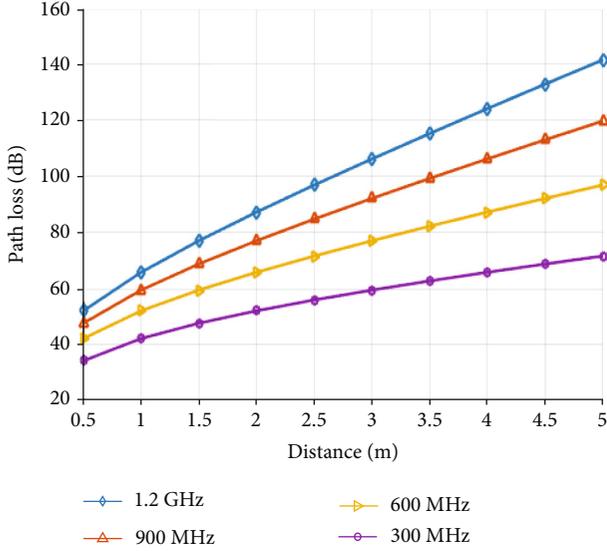


FIGURE 1: Path loss vs. distance in the soil at different frequencies.

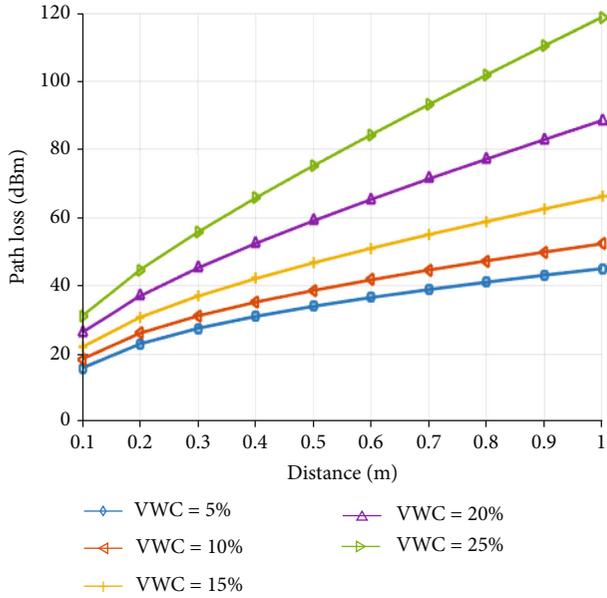


FIGURE 2: Path loss vs. distance in the soil at different VWC.

as compared to communication in soil medium. This is due to the additional path loss L_s , which is a function of the attenuation constant α and the phase shift constant β as mentioned earlier. In Figure 2, we show the effect of volumetric water content (VWC) on the path loss for values of the VWC between 5 and 25%. The path loss increases considerably with higher proportions of VWC and with the increase in distance. In Figure 3, the path loss increases even further with the increase of the frequency. A path loss increase of roughly 30 dB is possible with a VWC increase of about 20%. This effect is particularly important since water content not only depends on the location of the network but also varies during different seasons.

3.3. Underground to Above the Ground Model. The higher permittivity of soil compared to that of air results in reflection and refraction of signals that are incident to the soil-air interface. More specifically, signals can penetrate through the soil-air interface only if the incident angle is small. For underground to above the ground (UG2AG) propagation, only the waves with a small incident angle θ_i will transmit to air, as shown in Figure 4. In other words, for the UG2AG channel, the waves propagate vertically in the soil and resemble a new source at the air-soil interface.

Generally, WUSNs are deployed at depths that are less than 50 cm [38]. For the UG2AG link, due to proximity to the earth surface, a part of the EM waves propagates from soil to air, then travels along the soil-air interface, and enters the soil again to reach the receiver [39]. These EM waves called lateral waves are a major component of the underground channel. The three major contributors to the received signal strength include the direct, reflected, and lateral waves which are shown in Figure 4. The arrival time in nanoseconds of each of the three major waves contributing to EM wave attenuation in soil: the direct wave, the reflected wave, and the lateral wave, is expressed as [39]

$$\begin{aligned}\tau_d &= \left(\frac{\delta_s}{S_w}\right) + 2\left(\frac{L}{S_{\text{cox}}}\right), \\ \tau_r &= 2\left(\frac{\delta_s}{S_w}\right) + 2\left(\frac{L}{S_{\text{cox}}}\right), \\ \tau_l &= 2\left(\frac{\delta_s}{S_w}\right) + \left(\frac{\delta_a}{c}\right) + 2\left(\frac{L}{S_{\text{cox}}}\right),\end{aligned}\quad (16)$$

where δ_s is the distance traveled by the wave in the soil, L is the length of the coaxial cable attached to the antenna, S_{cox} is the speed of wave the coaxial cable calculated with the refractive index of 1.2, S_w is the speed of the wave in soil, δ_a is the distance traveled by the wave in the air, and c is the speed of light ($c = 3 \times 10^8$ m/s).

For above the ground to underground (AG2UG) channel, the refracted angle is near to zero and the propagation in the soil is also vertical. The attenuation loss due to the difference in the wavelength of the signal in soil L_β , which is also called the refraction loss for the AG2UG link, can be found as [40]

$$L_\beta = 20 \log \left(\frac{n_s \cos \theta_i + \cos \theta_t}{4 \cos \theta_i} \right), \quad (17)$$

where θ_i is the incident angle, θ_t is the refracted angle, and n_s is the refractive index of soil, which is given by

$$n_s = \left(\frac{(\epsilon' + j\epsilon'')^{1/2} + \epsilon'}{2} \right)^{1/2}, \quad (18)$$

with ϵ' and ϵ'' being the real and imaginary parts of the dielectric constant in soil.

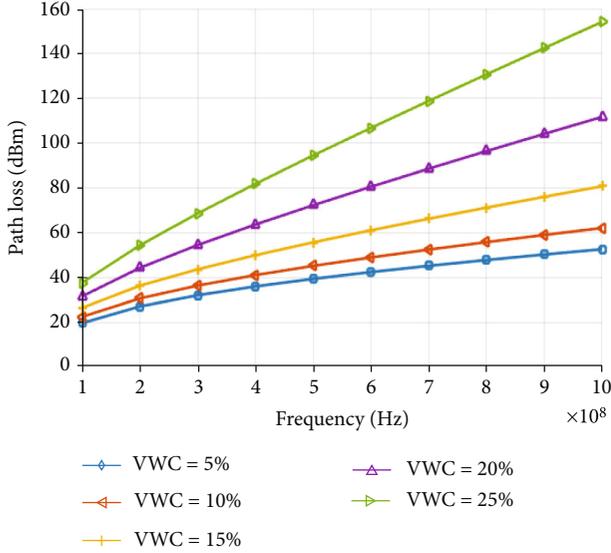


FIGURE 3: Path loss vs. frequency in the soil at different VWC.

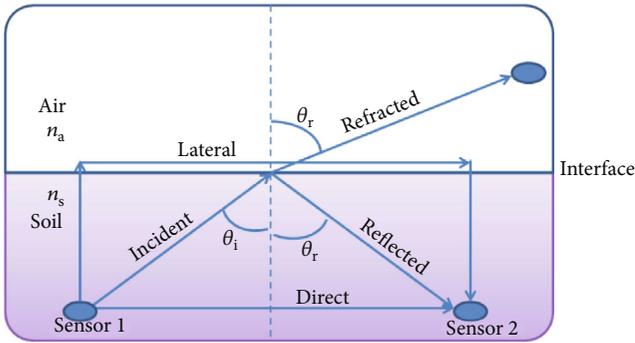


FIGURE 4: UG2AG channel model for the three EM waves' propagation.

For the AG2UG link, we consider the maximum path loss where the incident angle $\theta_i \rightarrow 0$ and $\theta_t \rightarrow 0$. Hence, L_β in Equation (17) can be approximated as

$$L_\beta = 20 \log \left(\frac{n_s + 1}{4} \right). \quad (19)$$

For the UG2AG link, the signal propagates perpendicularly from a higher density medium to a lower density one. Hence, we consider that all energy is refracted and $L_\beta = 0$.

4. Channel Capacity of EM Wave in Soil

During a wireless transmission in soil medium between the transmitter and receiver sensor nodes, the channel capacity is expressed as

$$C = B \log_2 \left(1 + \frac{S}{N_0 B} \right), \quad (20)$$

where B is the system bandwidth, S is the received signal strength (RSS) at the receiver, and N_0 is the noise power density. It is worth noting that the RSS is affected by the antenna return loss, which is given by

$$S_{dB} = P_t + 10 \log_{10} \left(1 - 10^{-(RL_{dB}/10)} \right) - L_p, \quad (21)$$

where P_t is the transmitter power, RL_{dB} is the antenna return loss, and L_p is the path loss in soil. It should be noted that all interferences are reduced to the thermal noise which is considered to be constant [41, 42].

The channel capacity and the operating frequency against soil moisture in sandy soil and clay soil are shown in Figures 5. The channel capacity in sandy soil estimated at 94.22 kbps for VWC = 10% is much higher than that of clay soil estimated at 52.86 kbps for the same proportion of VWC. In other words, sandy soil channel capacity is 78.2% higher than that of clay soil. Meanwhile, for VWC = 40%, the channel capacity of sandy soil is estimated at 307.8 kbps, which is 181.6% higher than that of clay soil estimated at 109.3 kbps. This performance is due to lower path loss in sandy soil [28, 41]. The soil type cannot be changed in practice; nevertheless, the antenna size could be modified and this can affect the behavior of the channel capacity. Figure 6 shows the frequency and the channel capacity against soil moisture for two different types of soil and at different antenna sizes of 60 mm, 100 m, and 140 mm.

5. Propagation through the Soil Using Magnetic Induction

A lot of work has been done in the area of underground magnetic induction (MI) communication. Two main deployment schemes can be identified: the direct MI transmission and the MI waveguides. The direct MI transmission has no relays deployed between sensor nodes. In comparison to the traditional wireless relaying concepts, the MI transmission solution has a lower path loss in the near and relatively far regions of transmission. As a result, the transmission range can greatly be improved compared to the EM wave-based approach for WUSNs [36]. Figure 7 shows the path losses of the MI system and EM wave system against the transmission distance at different VWC in soil [43]. It can be seen that the path loss of the MI system is a log function of the distance and the path loss of the EM wave system is a linear function of the distance. As expected, the EM wave system path loss increases vividly as VWC increases. At VWC = 1% when the soil is very dry, the path loss of the EM wave system is lower than that of the MI system. But after sufficiently long distances, MI systems achieve lower path loss. At VWC = 5% when the soil is moderately wet, the path losses of both systems are the same. It can also be observed in the near region (between 0.3 m and 3 m) that the EM wave system has a smaller path loss. In the relatively far region (a distance greater than 3 m), the MI system shows a smaller path loss than the EM wave system. When the soil is very wet, i.e., at VWC = 25%, the path loss of the EM wave system is considerably greater than that of the MI system.

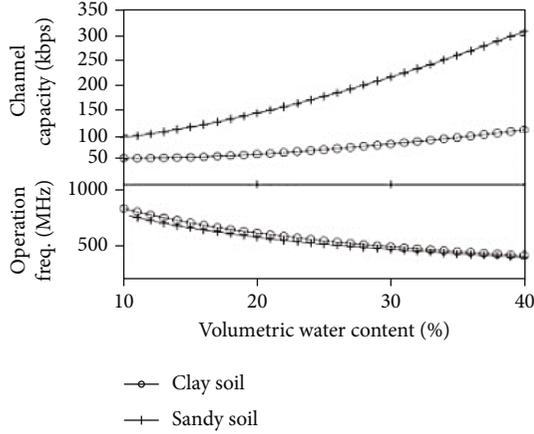


FIGURE 5: Channel capacity and frequency at different soil types [41].

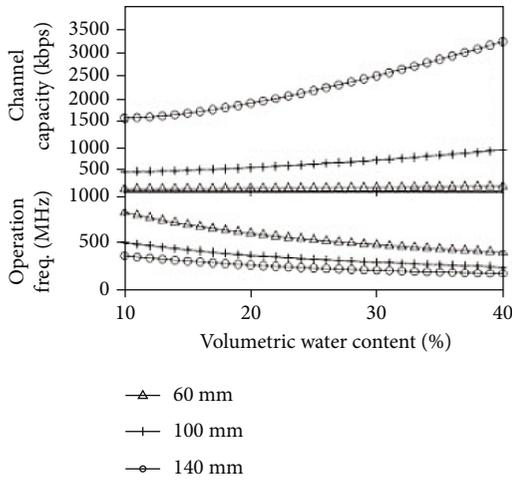


FIGURE 6: Channel capacity and frequency at different antenna sizes [41].

Table 2 presents the comparison of the three most common technologies of wireless sensor networks used for the implementation of IoUT.

5.1. Direct Magnetic Induction Propagation Models. Since all signal mappings involved in MI transmission are linear, a linear channel model should be adopted. The waveguide may be viewed as a chain of circuits made up of capacitors, resistors, and inductors. The capacitance of the capacitor is chosen to make each circuit resonate at frequency f_0 [2].

The effect of eddy currents leads to an exponential decrease of the field strength with the transmission distance. Hence, the loss factor G can be expressed as [4]

$$G = \exp\left(-\frac{r}{\delta}\right), \quad (22)$$

where δ is the skin depth, which depends on the signal frequency, conductivity, and permittivity of soil. In a two-

dimensional space, the polarization factor is expressed as [6]

$$J = 2 \sin(\theta_t) \sin(\theta_r) + \cos(\theta_t) \cos(\theta_r), \quad (23)$$

where θ_t and θ_r are the transmitting and receiving angles, respectively.

Direct magnetic induction propagation is the process where signals are transmitted and received through the use of a coil of wires. Figure 8 shows two coils in communication, where a_t is the radius of the transmitting coil, a_r the radius of the receiving coil, and r is the distance between the transmitter and the receiver [2].

The important signal propagation effects such as attenuation, signal reflections, and frequency splitting in the direct MI communication channels can be expressed as a path loss function [5].

5.2. Propagation Model Using Magnetic Induction Waveguide. A diagram of an MI waveguide with a transmitter, a receiver, and $(k-1)$ relays is shown in Figure 9.

The magnetic induction waveguide structure as shown in Figure 9 is made up of a transmitter circuit with a voltage source U_t , a receiver circuit with a load impedance Z_L , and $(k-1)$ passive relays. These circuits are placed at equal distances between the transceivers. Each circuit includes a magnetic antenna, a capacitor with capacitance C , an inductor with inductance L , and a resistor with resistance R .

5.3. Interference in Magnetic Induction Propagation. In direct MI transmission WUSNs, the sources of interference in the circuits of the nearby devices including the transmitter can be ignored due to a high path loss [5], such that only the interference produced in the receiver circuit needs to be taken into consideration. According to MI waveguide performance evaluation, the received interference power at the load impedance is necessary but thermal noise is assumed to be the dominant source of interference [35]. It is worth noting that this interference is caused by the resistors in the relay and the transceiver circuits. Meanwhile, the potential difference of the noise from resistor R in each relay is modeled as a supplementary voltage source. The received noise power at the load resistor is computed as the addition of the received noise power caused by the copper resistance of the coils including the transceiver coils and the received noise power produced by the load resistor. This is performed according to the superposition principle [4].

6. Acoustic-Based Wireless Transmission in Soil Medium

A lot of research work has been done in wireless underground communication systems based on acoustic wave transmission to support many applications. Depending on the signal generation, the acoustic-based techniques can be categorized into passive and active kinds of techniques. In the passive acoustic-driven technique, natural events such as volcano explosions, nuclear explosions, and earthquakes in the subterranean environment cause acoustic signals. Then, sensors placed in this vicinity detect infrasonic signals

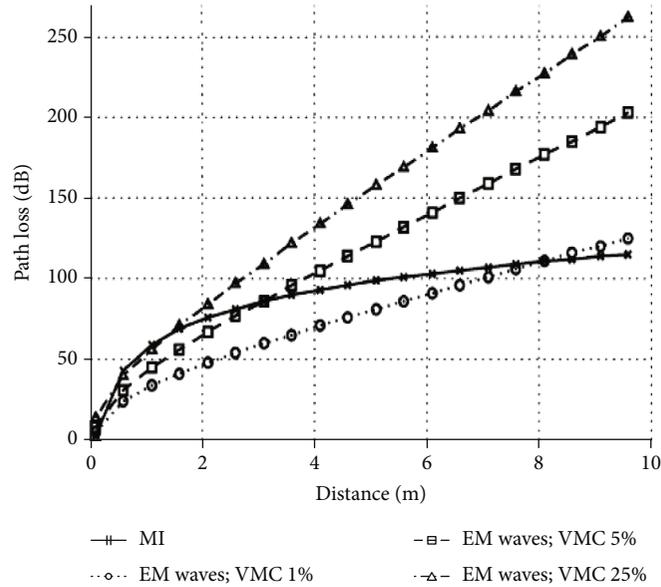


FIGURE 7: Path losses of the MI system and EM wave system with different VWC in soil [43].

TABLE 2: Comparison between IoUT communication technologies: EM, MI, and acoustic.

Parameters	EM	MI	Acoustic
Transmission range	Few meters	In 10s of meters	In 100s of meters
Attenuation	High	Low	High
Interference	High	Low	Medium
Installation cost	Moderate	Medium	Medium
Data rate	In bps	In kbps	In 10s of bps
Application	Agriculture, seismic exploration, intrusion detection, buried pipeline monitoring (oil and gas, water), downhole telemetry	Downhole telemetry	Seismic exploration, buried pipeline monitoring, downhole telemetry
Advantages	High data rate compared to acoustic systems, easy to install, support multihop communication	The high data rate, low attenuation, and support multihop communication	High data rate compared to MPT systems, long transmission range
Disadvantages	High attenuation and interference, limited transmission range, and requires a large antenna	The orientation between coils is required; limited transmission range needs dense deployment	High attenuation and lower data rate than EM and MI

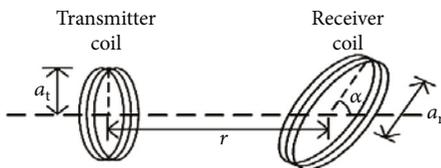


FIGURE 8: Direct MI transmission.

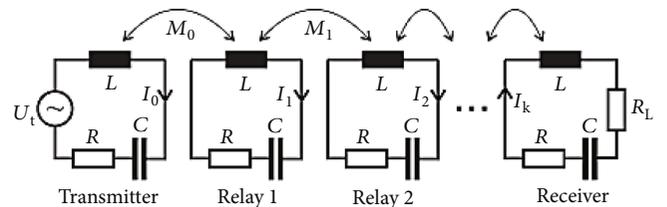


FIGURE 9: MI waveguide with transmitter diagram with transmitter, receiver, and $(k - 1)$ relays.

which are useful for the prediction of natural disasters. This technique can also be used to detect underground pipeline leakage. In the active acoustic-driven technique, an artificial explosion or vibration is used for the generation of signals which are sent underground to estimate the properties of reflection-based seismology. Acoustic waves are mostly used

for detection purposes in soil medium rather than for communication. This is because of the low propagation speed of these waves in the soil medium. In [29, 30], an acoustic-based wireless data transmission system was proposed where

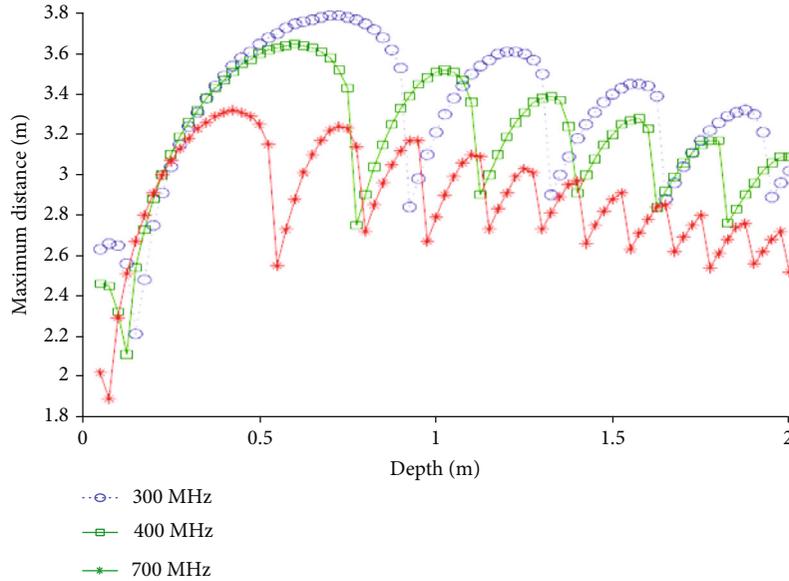


FIGURE 10: Maximum internode distance as a function depth for different operating frequencies [3].

sensing data was transmitted over 30 m distance through soil medium. In [44], a soil equation was derived for the propagation of acoustic waves in soil medium at the frequency of 16 kHz. Furthermore, acoustic waves at 900 Hz frequency was used for the estimation of the moisture content of the soil [45]. Acoustic waves are also commonly used for downhole telemetry purposes.

7. Research Challenges

WUSN promises a new future in agriculture, security, etc., but for us to derive those benefits, several challenges still need to be overcome. Whilst underground tunnels have been investigated in the past, very little is known about direct propagation in soil medium. To realize the promised benefits, a concerted effort is required on the part of researchers to address some of the outstanding issues.

7.1. Challenges of WUSNs in Soil Medium Using EM Waves

7.1.1. Limited Communication Range. Research has shown that the maximum attainable communication range and the reliability of wireless links in the underground environment are much more constrained as compared to over-the-air wireless sensor networks. As a result of these factors, multi-hop communication should be considered in the design of WUSN topology.

7.1.2. Soil Properties. Soil properties have a direct influence on the wireless sensor network performance. Transmission quality is greatly hampered by the increase of water content in the soil. So therefore, the design of network topology must be robust enough to adapt to changes in channel conditions.

7.1.3. Topology Design. It is important to carefully examine the composition of the soil at a specific location to adapt

the topology design according to the exact characteristics of the soil channel at that location [2].

7.1.4. Depths of Buried Sensor Nodes. EM wave transmission in soil medium is also affected by the changes in depths of buried sensor nodes. With the effect of reflection in a two-path channel model, there are fluctuations in the maximum internode distance as the bury depth increases as shown in Figure 10 [3]. Consequently, at various depths in the soil, diverse ranges of transmission distance can be achieved. Therefore, an optimal strategy for providing connectivity and coverage is required to design a well-structured topology that is adaptive to the effects of the channel.

7.1.5. Operating Frequency. Signal attenuation in soil has been very well illustrated by the WUSN channel model, and this is due to an increase in functional frequency. Studies have proven that it is important to deploy wireless sensor networks at low frequencies for efficient signal transmission. Nevertheless, signal propagation at smaller frequencies will lead to a trade-off between the antenna size and the frequency. Figure 10 [3] shows the internode distance as a function of bury depth of sensor nodes at a specific operating frequency. This graph describes the maximum sensor depths mapped to a maximum internode distance. Based on the analysis of the graph, the deployment of wireless sensor networks in the soil must be adapted to a specific operating frequency of the sensors. It should also be noted that the performance of transmission at low depths discloses the fact that using a static frequency is not promoting the best performance for WUSNs. Some other studies have suggested cognitive radio techniques where adaptive operations could be applied to wireless sensor networks in soil medium [14].

7.1.6. Environmental Conditions. Environmental circumstances are also a determining factor for wireless sensor network quality. Climatic and seasonal alterations resulting in

the variation of soil moisture content coupled with the effects of soil type significantly affect the performance of the signal transmission. So, therefore, environmental dynamics should be taken into account during the design of protocols for wireless sensor networks in the soil. Cognitive techniques could be applied for the design of environment aware protocols that can adapt to functional parameters of the area of deployment. Besides, the direct impact and the dynamic nature of the physical layer so far as transmission quality is concerned make it imperative for new crosslayer design processes adaptive to the changes in the environment for wireless sensor networks in soil [7].

7.2. Challenges of WUSNs in Soil Medium Using Magnetic Induction Waveguide. The communication range of the magnetic induction waveguide technique which is around 10 m is still limited. This could be improved through further research work. The magnetic induction method resolves the difficulties of deploying sensor nodes with large antenna size and dynamic channel situation encountered in the electromagnetic wave transmission method. The path loss is also reduced by half when using the magnetic induction technique in comparison to the EM wave transmission method. Nevertheless, communication by multiple hopping among sensor nodes remains relevant during the implementation of the magnetic induction method. More so, there is the need for the deployment of multiple relay coils between the transmitters and receivers. It is worth noting that the deployment of the coils in this setup is labor-intensive even though the relay coils consume less energy and are cost-effective. It is therefore important to take into account the factors mentioned above during the structural design of the network topology.

The magnetic induction waveguide also adopts a complex three-dimensional structural network topology. As a consequence, the relay coils in diverse communication networks would affect each other in a three-dimensional space. Hence, the necessity to develop a multiple-hop channel model in a three-dimension network for the wireless communication of sensor nodes in that kind of configuration [2].

8. Conclusion

A review of underground wireless channel models is presented. WUSNs can be modeled in soil medium taking into account the properties of soil. Channel models for EM, MI, and acoustic signal transmission through soil medium are described. A comparative table of these transmission techniques is also provided to establish the differences between them. EM signal propagation in soil was analyzed based on the path loss and channel capacity at a different volumetric water content of the soil. It is concluded that EM signals perform better at lower frequencies and in dry sandy soil. MI waveguide is described as a wireless communication technique in soil medium for certain applications. Path loss graphs for EM and MI have been provided to compare the performance of these techniques in soil medium. It has also been established that acoustic-based propagation is commonly used for detection purposes rather than communica-

tion purposes because of the low propagation speed of this technique in soil. Some critical research challenges for WUSNs are identified. An alternative approach that could be suggested to improve upon the performance of such systems is to consider the use of small hollow tunnels, which are buried in the soil. Such tunnels will have the advantage of providing communication characteristics of the air environment as such can help in overcoming some of the challenges of direct communication in soil.

Data Availability

Previously reported data were used to support this study and these prior studies and datasets are cited at relevant places within the article.

Conflicts of Interest

The authors declare that there is no conflict of interest regarding the publication of this paper.

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