Analysis of Wireless Underground Sensor Networks (WUSNS)

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***Abstract*— This research paper focuses on Wireless Underground Sensor Networks (WUSNs). Wireless Underground Sensor Networks (WUSNs) is a specialized kind of WSN that mostly focuses on the exploit of sensors at the subsurface area of the soil. It can be used to monitor a variety of conditions, such as soil properties for agricultural applications and toxic substances for environmental monitoring, border patrol, and infrastructure monitoring. They are deployed completely below ground and do not require any wired connections. Each device contains all necessary sensors, memory, a processor, a radio, an antenna, and a power source. The benefits of WUSNs are seen in Timeliness of data, Reliability, Coverage density, Concealment, Ease of deployment. The Soil Subsurface Wireless Communication (SSWC) channel model is essential for the development of cross-layer communication solutions for WUSNs and for the development of underground to aboveground and aboveground to underground channel models for WUSNs. The results from this research confirm that the wireless underground channel exhibits a smaller attenuation at low burial depths, presents a high degree of temporal stability compared to its air counterpart, and is negatively affected by the volumetric water content (VWC) of the soil.**

***Index Terms*— Wireless Underground Sensor Networks, Soil, Agriculture, Channel**

I. INTRODUCTION

Wireless underground sensor networks (WUSN) consist of wireless devices that operate below the ground surface. These devices are buried completely under dense soil, thus electromagnetic wave transmits only through soil medium. Wireless Underground Sensor Networks (WUSNs) is a dedicated type of WSN that chiefly focuses on the use of sensors at the subsurface region of the soil. It is an up-and-coming area of research that promises to offer communication capabilities to the Network sensors [1]. WUSNs have numerous extraordinary intrinsic worth, such as concealment, ease of deployment, timeliness of data, reliability and coverage density [2][3]. The apprehension of wireless underground communication and networking techniques spirited to the prospective applications in the fields of intelligent irrigation, border patrol, assisted navigation, sports field maintenance, intruder detection, and infrastructure monitoring. This is achievable by exploiting real-time soil condition information from a network of underground sensors and enabling localized interaction with the soil. The underground channel is notably dissimilar from the air channel. Underground communication is one of the few fields where the environment has a considerable and direct impact on the communication performance. Environmental aspects, such as soil moisture and texture, potentially change the dielectric properties of the soil and affect the wireless communication [4]. Moreover, deployment parameters, such as the burial depth and the frequency, also have strong impact on the communication [4][5]. Therefore, an underground communication channel must capture these aspects related to the environment and nodes deployment. The chief challenges associated to the exploit of soil as a communication medium are Attenuation; EM waves encounter greatly higher attenuation in soil compared to air and this fact relentlessly hampers the communication superiority. Reflection; the ground surface may cause the reflection effect, which can have positive or negative effects over the communication. Multi path fading; unpredictable obstacles in soil such as rocks and roots of trees make EM waves being refracted and scattered also cause problems in the communication. In [6], Silva and Vuran studied the impact factors of the nodes, including antenna bandwidth of WSN nodes at 433MHz frequency, burial depth of nodes in the soil (15 cm and 35 cm), and water content of the soil (volumetric water content was 9.5% and 37.3%, respectively). The field experiment showed that the ultra-wideband antenna could increase the communication range by more than 350% compared to the original antennas. Volumetric water content increased from 9.5% to 37.3% leading to 70% drop of transmission distance. When nodes buried depth were changed from 35 cm to 15 cm, the transmission distance of the signal for the terrestrial nodes to underground nodes (downlink transmission) increased three times, but the transmission distance of the signal for the underground nodes to terrestrial nodes (uplink transmission) only increased by 0.4.

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II. TYPES OF COMMUNICATIONS IN WUSNS.

A WUSN which uses aboveground nodes in conjunction with the underground nodes is called Hybrid WUSN. Three different communication links exist in WUSNs based on the locations of the transmitter and the receiver. Hybrid WUSNs can potentially use all links.

A. Underground-to-underground (UG2UG) Link:

In UG2UG, both the sender and the receiver are buried underground and communicate through soil. This type of communication is employed for multi-hop information delivery.

B. Underground-to-aboveground (UG2AG) Link:

In UG2AG, the sender is buried and the receiver is above the ground. Monitoring data is transferred to aboveground relays or sinks through these links.

C. Aboveground-to-underground (AG2UG) Link:

In AG2UG, aboveground sender node sends messages to underground nodes. This link is used for management information delivery to the underground sensors.

Figure 1 shows a typical WUSN architecture employing underground-to-underground (UG2UG), underground-to-aboveground (UG2AG), and aboveground-to-underground (AG2UG).

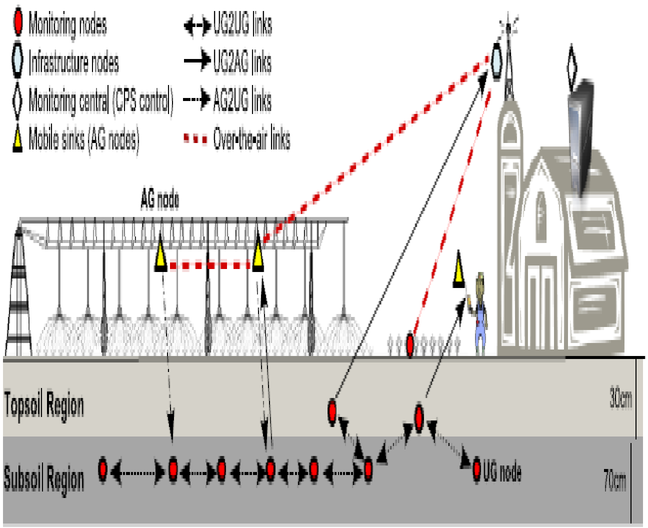

Figure 1: WUSN architecture

III. COMPOSITION OF THE SOIL

The soil is a dielectric material, characterized by a dielectric constant. The propagation of EM waves is directly related to the dielectric constant of the material. The soil medium behaves as a dielectric material composed of air, bound water, free water, and bulk soil. If the soil presents small density and high porosity, the performance of the propagation of EM waves is better due to the high quantity of air. However, the presence of water in soil has a contrary effect on the communication. The dielectric constant of the soil varies as a function of its components [7].

Soil composition is generally classified in terms of the percent of sand, clay, and silt, as shown in Figure 2. Depending on the amount of clay, silt, and sand, the soil texture receives a particular name or classification [8]. The soil also contains water. The volumetric water content (VWC) of the soil represents the fraction of water in the soil. However, the water can be classified into two: the bound water, which corresponds to water molecules tightly held to the surface of the soil particles, and the free water, which corresponds to water molecules free of action of soil particles [9][10].

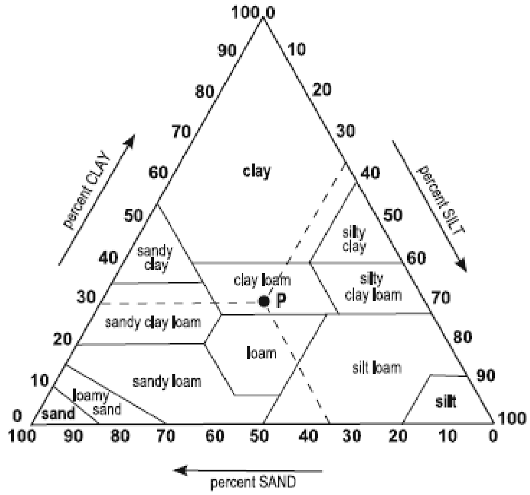

Figure 2: Soil texture triangle

Table 1 below shows an example of a soil analysis report.

Table1: Example of a soil analysis report.

Depth	Organic Matter	Texture	% Sand	% Silt	% Clay
0-15cm	6.4	Loam	27	45	28
15-30cm	2.6	Clay, Loam	31	40	29
30-45cm	1.5	Clay, Loam	35	35	30

IV. MODELING OF SOIL SUBSURFACE WIRELESS COMMUNICATION (SSWC) CHANNEL

In this model, the SSWC attenuation model for the UG2UG communication in the soil subsurface region is provided. The study of the propagation of EM waves through the soil begins with the basic model of the propagation of EM waves over-the air, followed by the addition of the path loss factor specifically considering the properties of soil. From Friis equation [11], the received signal strength (RSS) in free space at a distance r from the transmitter is expressed in logarithmic form as

$Pr = Pt + Gr + Gt - L_0$,…………………. (i)

where Pt is the transmit power, Gr and Gt are the gains of the receiver and transmitter antennas, and L_0 is the path loss in free space in dB, which is given by

$L_0 = 32.4 + 20\log(d) + 20\log(f)$ …………… (ii)

where d is the distance between the transmitter and the receiver in kilometers, and f is the operation frequency in Mhz. For the propagation in soil, an additional factor is included in Friis equation (i) due to the attenuation of the EM wave caused by the soil medium. As a result, the received signal is expressed as [12];

$Pr = Pt + Gr + Gt - L_0 - Ls$,……….. (iii)

where Ls stands for the additional path loss caused by the propagation in soil.

The Ls in soil is composed of two components;

$Ls = L\beta + L\alpha$,…………… (iv)

where $L\beta$ is the attenuation loss due to the difference of the wavelength of the signal in soil, λ, compared to the wavelength in free space, λ_0, and $L\alpha$ is the transmission loss caused by attenuation with attenuation constant α. Thus,

$L\beta = 20\log(\lambda_0/\lambda)$ and $L\alpha = e^{2\alpha d}$.

Considering that in soil, the wavelength is $\lambda = 2\pi/\beta$ and in free space $\lambda_0 = c/f$, where β is the phase shifting constant, c = 3 × 108 m/s, and f is the operating frequency in Hz, then, Lβ and Lα can be represented in dB as follows:

$L\beta = 154 - 20 \log(f) + 20 \log(\beta)$,

$L\alpha = 8.69\alpha d$……….. (v)

Knowing that the path loss in free space is $L_0 = 20 \log(4\pi d/\lambda_0)$.

The main formula for the path loss, L p, of an EM wave in soil is as;

$L\,p = 6.4 + 20 \log(d) + 20 \log(\beta) + 8.69\alpha d$……. (vi)

where distance, d, is given in meters, the attenuation constant, α, is in 1/m and the phase shifting constant, β, is in radian/m.

Using the Peplinski's principle [VII], the dielectric properties of soil can be calculated as follows;

$\varepsilon = \varepsilon' - j\varepsilon''$ ……………………….(vii)

$\varepsilon' = 1.15[1 + \frac{\rho b}{\rho s} (\varepsilon_s^{\alpha'} - 1) + m_v^{\beta'} \varepsilon'^{\alpha'}_{fw} - m_v]^{1/\alpha'} - 0.68$,

$\varepsilon'' = [m_v^{\beta''} \varepsilon''^{\alpha'}_{fw}]^{1/\alpha'}$ …………………………… (viii)

where ε is the relative complex dielectric constant of the soil-water mixture, mv is the volumetric water content of the mixture, ρb is the bulk density in grams per cubic centimeter, ρs = 2.66 g/cm3 is the specific density of the solid soil particles, $\alpha' = 0.65$ is an empirically determined constant, and β' and β'' are empirically determined constants, dependent on soil-type and given by

$\beta' = 1.2748 - 0.519S - 0.152C$,

$\beta'' = 1.33797 - 0.603S - 0.166C$………. (ix)

where S and C represent the mass fractions of sand and clay, respectively. The quantities ε' fw and ε''fw are the real and imaginary parts of the relative dielectric constant of free water. Note that, at this point of the model, the influences of free water and bounded water are both considered in the above formula. The mass fractions of sand and clay considered in (ix) and also the volumetric water content mv are used to determine the amount of free water and bounded water in the soil. This distinction is important because the amount of free water causes a stronger attenuation effect for EM wave's propagation when compared with the effects of the bounded water.

The Peplinski principle governs the value of the complex propagation constant of the EM wave in soil, which is given as $\gamma = \alpha + j\beta$ with

$\alpha = \omega \sqrt{\frac{\mu\varepsilon'}{2}} [\sqrt{1 + (\frac{\varepsilon''}{\varepsilon'})^2} - 1]$,

$\beta = \omega \sqrt{\frac{\mu\varepsilon'}{2}} [\sqrt{1 + (\frac{\varepsilon''}{\varepsilon'})^2} - 1]$…………………(x)

where $\omega = 2\pi f$ is the angular frequency, μ is the magnetic permeability, and ε' and ε'' are the real and imaginary parts of the dielectric constant.

V. RESULT

The investigation of the above equations shows that the intricate transmission constant and hence, the path loss of the EM wave in soil, are dependent on the following factors:

a. Operating frequency, f , which is, the selected frequency for the sensor nodes.

b. Composition of soil in terms of sand and clay fractions, S and C, which depend on the deployment region of the sensor nodes.

c. Bulk density, ρb, indirectly expressing the amount of air in the soil, which also depends on the deployment region of the sensor nodes;

d. Soil moisture or volumetric water content (VWC), mv, which depends on the deployment section as well as time.

VI. CONCLUSION

WUSN has been viewed as a group of nodes whose means of data transmission and reception is completely subterranean. Positive features of the underground environment, such as the sequential steadiness, that can be exploited to achieve reliable and energy-efficient communication. The benefits of WUSNs are seen in Timeliness of data, Reliability, Coverage density, Concealment, and ease of deployment. It exhibit a smaller attenuation at low burial depths, presents a high degree of temporal stability compared to its air counterpart, and is negatively affected by the volumetric water content (VWC) of the soil

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