Wireless Underground Sensor Networks Path Loss Model for Precision Agriculture (WUSN-PLM)

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Abstract— **Despite a large number of applications in the field of health care, military, ecology or agriculture, the Wireless Underground Sensor Network (WUSN) faces the problem of wireless Underground Communication (WUC) which largely attenuate the signal on the ground. For the case of precision agriculture, the motes are buried and they have to check the good growth of plants by verifying data like the water content. However, due to soil composition, the wave signal is attenuated as it travels across the ground. Thus, before a real deployment of WUSN, the prediction of the path loss due to signal attenuation underground is an important asset for the good network functioning. In this paper, we proposed a WUSN path loss for precision agriculture called WUSN-PLM. To achieve it, the proposed model is based on an accurate prediction of the Complex Dielectric Constant (CDC). WUSN-PLM allows evaluating the path loss according to the different types of communication (Underground-to-Underground, Underground to Aboveground and Aboveground to Underground). On each communication type, WUSN-PLM takes into account reflective and refractive wave attenuation according to the sensor node burial depth. To evaluate WUSN-PLM, intensive measurements on real sensor nodes with two different pairs of transceivers have been conducted on the botanic garden of the University Cheikh Anta Diop in Senegal. The results show that the proposed model outperforms the existing path loss models in different communication types. The results show that our proposed approach can be used on real cheap sensor with 87.13% precision and 85% balanced accuracy.**

Index Terms— **Wireless Underground Sensor Network, path loss, Complex Dielectric Constant, precision agriculture.**

I. INTRODUCTION

NOWADAYS, the Wireless Underground Sensor Network (WUSN) has become one famous domain of interest for the Internet Of Things (IOT). Furthermore, WUSN has several applications such as military tracking, health care, ecological monitoring, human rescues after natural disasters or intelligent agriculture [1-5]. For the kind of applications linked to agriculture, the sensor nodes are mostly buried under the ground and the communication between nodes is done through electromagnetic (EM) waves. The collected data by nodes are routed through Wireless Underground Communications up to a Base Station (BS) generally located above the ground surface. However, as the soil is denser than the air, the theoretical communication range of a terrestrial sensor node decreases drastically when the node is buried [6]. Thus, contrary to traditional wireless technologies that work on high frequency (mostly 2.4 GHz) like WiFi, Bluetooth or ZigBee, in WUSN, such signals are easily attenuated when they cross the ground. In order to have an acceptance communication range under the ground, WUSN considers low frequency transceiver (433MHz). Moreover, according to the soil properties, the wave behaviours could change and therefore affect the sensor communication range. Among these properties, the soil dielectric that depends on the soil moisture (percent portion) is the most important parameter for underground signal attenuation [7-8]. Since the soil properties could be different at several points of the field, the wave signal attenuation should vary according to these properties. Then, the wireless underground signals have to be predicted with accuracy according to *in situ* soil parameters.

The prediction of the signal attenuation goes with designing a path loss model which becomes a necessity before any real deployment [9]. Most of the existing path loss models for WUSN are based on empirical measurements of the bulk density, particle size, soil moisture, sand and clay portions. The measured parameters are used to find a constant called Complex Dielectric Constant (CDC) that outlines the soil properties [10]. However, these semi-empirical path loss models require laboratory tests of a soil sample [11-15]. Therefore, if the deployment field becomes larger, the soil sample analysis could be a major problem. For example, on large scale WSN, there are several efficient techniques for data routing along with the network [16]. However, these techniques are based on path loss models initially designed for terrestrial WSN and cannot be successfully applied in WUSN. In order to have an accurate path loss prediction based on *in situ* parameters for WUSN, the prediction of the CDC as the more accurate as possible like it was shown in our previous study in [17]. Therefore, signal strength received by a receiver node from a sender node is predicted with a lower error.

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The main goal of this paper is to propose a path loss model for wireless underground sensor networks called WUSN-PLM, it considers the different types of underground communications. To achieve it, we conducted a review of existing path loss approaches used in WUSN fields. Considering their limits and advantages, we designed a new path model for agriculture precision of onions through buried cheap sensor node devices. In order to compare and validate our proposition, several tests are conducted in several scenarios. In short, our contributions can be summarized as follows:

- Design a new wireless underground communication scheme for precision agriculture;
- Propose a path loss model for three types of wireless underground communications;
- Integrate a more accurate CDC prediction model;
- Propose a more accurate and more reliable path loss model for WUSN;
- Evaluate the proposed model on two different pairs of transceivers on real sensor nodes and real agriculture field;
- Validate the proposed path loss model through intensive measurements and tests.

The rest of this paper is organized as follows: In Section 2 the WUC types are presented; Section 3 describes the existing path loss for WUSN; the proposition of a path loss for WUSN is done with details in Section 4; In Section 5, the experimentations, materials and the adopted methodology are presented; in order to validate our proposed WUSN-PLM, results and discussion are presented in Section 6; the conclusion and future work are in Section 7.

II. WUSNs Communications

In this Section, we briefly present the type of communications in the WUSN field.

Figure 1 gives an overview of the different communications in WUSN.

There are three main types of WUC [18]:
- Underground-to-Underground communication (UG2UG): here the two nodes are buried, the wave travels through the ground from a transmitter to a receiver. The soil is divided into two regions known as subsoil and topsoil. The topsoil considers the first 30cm depth; beyond 30cm, it is the subsoil region.
- Underground-to-Aboveground communication (UG2AG): in this case, a buried sensor node sends its collected data to another node or a BS located above the ground. The transmitter can either be located at the topsoil or the subsoil region according to the application. The wave crosses successively an underground and a free surface region.
- Aboveground-to-Underground communications (AG2UG): It is similar for UG2AG, but in this case, an above node (transmitter) or a BS sends data to another node buried in the soil. The buried node can be located in the topsoil region or at the subsoil region.

III. Path Loss Models for WUSN

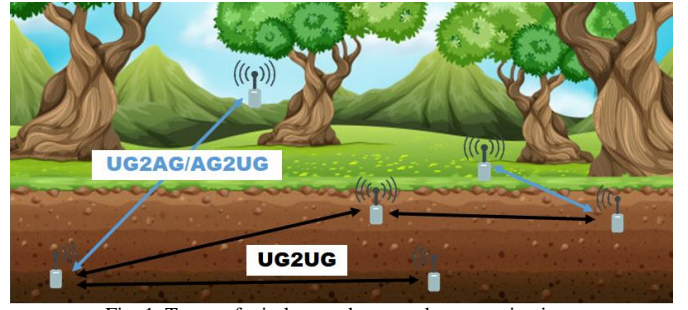In this Section, we present the existing path loss models used

Fig. 1. Types of wireless underground communications

for WUC. We classified them into underground path loss (UG2UG) and mixing path loss models (UG2AG/AG2UG).

A. Underground path loss models

This kind of path models are designed for fully UG2UG communication. The famous models are presented hereafter.

1) Complex Refractive Index Model Fresnel

The semi-empirical model proposed in [11] is a combination of the Complex Refractive Index Model (CRIM) [19] and Fresnel equations [20]. The proposed model assumes that the transmitter radiates equally in all directions. Furthermore, the authors highlight the path loss due to spherical divergence and the additional path losses caused by signal attenuation, reflection, refraction and diffraction. However, the signal attenuation in soils depends on the soil attenuation constant (1).

$$\alpha = 8.68 \frac{60\pi\left(2\pi f \varepsilon_0 \varepsilon_r'' + \sigma_b\right)}{\sqrt{\frac{\varepsilon_r'}{2}\left\{1+\sqrt{1+\left[\left(\varepsilon_r'' + \frac{\sigma_b}{2\pi f \varepsilon_0}\right)\Big/\varepsilon_r'\right]^2}\right\}}} \qquad (1)$$

f is the frequency in Hertz, $\varepsilon_0 = 8.85 \times 10^{-12} F.m^{-1}$ is the dielectric permittivity in free space, σ_b is the bulk electrical conductivity, ε' and ε'' are respectively the real (dielectric constant) and the imaginary (loss factor) parts of the mixing model. To find the soil CDC value, the CRIM considers the permittivity of solid, the complex permittivity of water and the permittivity of the air. However, authors assume that the water is the unique element responsible for the dielectric losses, thus the air and solid permittivity do not depend on the operating frequency.

In addition to the signal attenuation in the soil, the CRIM-Fresnel model takes into account the loss due to the wave reflection. It uses the Fresnel equation to calculate the reflection coefficient R. Furthermore, the proposed model neglects the effect due to magnetic permeability, therefore, R is simplified by (2). The total signal attenuation A_{tot} computed by CRIM-Fresnel depends on the signal attenuation due to reflection R_c, the soil attenuation and the distance d between the transmitter and the receiver (3).

$$R = \left(\frac{1-\sqrt{\varepsilon}}{1+\sqrt{\varepsilon}}\right)^2 \qquad (2)$$

$$A_{tot} = \alpha d + R_c \;\; ; \;\; R_c = 10log\left(\frac{2R}{1+R}\right) \qquad (3)$$

2) Conventional Modified Friis

This path loss model is based on Friis transmission equation initially designed for Free Space communications [20]. Meanwhile, the modified Friis model [21] takes into account the loss due to wave attenuation in soil (4). It assumes that underground path loss is the addition of free space path loss and the wave attenuation in soil, it can then be simplified in (5). The total path loss L_{tot} depends on α and β constants.

$$L_s(dB) = 154 - 20\,log(f) + 20\,log(\beta) + 8.69\alpha d \qquad (4)$$
$$L_{tot}(dB) = 6.4 + 20\,log(d) + 20log(\beta) + 8.68\,\alpha d \qquad (5)$$

The values of $\alpha\ (1/m)$ and $\beta\ (radian/m)$ are related to soil conditions, they are the attenuation due to material absorption and the phase shifting respectively. These constants are the key elements of the modified Friis model and constitute respectively the real (6) and the imaginary part (7) of the complex propagation constant γ [23-24]. This latter constant depends on the relative complex permittivity ε the relative permeability μ_r of the soil and the wave frequency. Furthermore, most of the soils used for agriculture do not contain metallic elements (they are not rich in iron), for such soils, the magnetic permeability is neglected ($\mu_r = 1$). Where μ_0 is the permeability in vacuum and ε_0 is the permittivity in free space.

$$\alpha = 2\pi f \sqrt{\frac{\mu_0\mu_r\varepsilon_0\varepsilon'}{2}\left(\sqrt{1 + \left(\frac{\varepsilon''}{\varepsilon'}\right)^2} - 1\right)} \qquad (6)$$

$$\beta = 2\pi f \sqrt{\frac{\mu_0\mu_r\varepsilon_0\varepsilon'}{2}\left(\sqrt{1 + \left(\frac{\varepsilon''}{\varepsilon'}\right)^2} + 1\right)} \qquad (7)$$

The modified Friis path loss model is widely used in WUSN researches [4], [15], [25-26]. However, this model needs to analyze a soil sample in a laboratory to find the empirical input values needed by the model. However, on a large experimental field, soil conditions can be different at different points; then, a sample of soil is not sufficient for a reliable path loss prediction in a heterogeneous deployment field.

3) NC Modified Friis

Chaamwe et al. [12] proposed a semi-empirical model that merged the modified Friis and the CRIM-Fresnel [11] approaches. It adds wave attenuation due to reflection R_c from CRIM-Fresnel (8) to the modified FRIIS model. Where R is the reflection factor and depends on the dielectric constant (ε'). Moreover, the authors consider the signal attenuation due to wave refraction by adding the attenuating factor K of the angular defocussing (9). Where θ_1 and θ_2 are the incoming and outgoing angle respectively, ε_1 and ε_2 denote the dielectric constant of the source and the destination environment of the wave. The NC Modified Friis path loss model proposed by Chaamwe et al. [12] is resumed by L_{tot} (10).

$$R_c = 10log\left(\frac{2R}{1+R}\right); \ R = \left(\frac{1-\sqrt{\varepsilon'}}{1+\sqrt{\varepsilon'}}\right)^2 \qquad (8)$$

$$K(dB) = 20log\left(\sqrt{\frac{\varepsilon_1 Cos\theta_1}{\varepsilon_2 Cos\theta_2}}\right) \qquad (9)$$

$$L_{tot} = 6.4 + 20\,log\left(d\beta K\sqrt{\frac{2R}{1+R}}\right) + 8.68\alpha d \qquad (10)$$

The authors claim that their model integrates realistic phenomena responsible for the signal attenuation than the modified FRIIS and the CRIM-Fresnel models. Meanwhile, the path loss model presented in [12] also needs a laboratory analysis of a soil sample like the modified Friis model. This analysis aims at finding the values of the dielectric constant (ε') and the loss factor (ε'') of the soil based on Peplinski equations [23-24].

4) TDR Modified Friis

Sadeghioon et al. [15] proposed an in situ path loss prediction model by using measurements of the Time Domain Reflectometry (TDR). The TDR method is used to find the CDC values. This in situ method estimates the effective wave frequency of the TDR in soil that holds the most amount of the energy and thereafter gives accurate values of the dielectric permittivity. Moreover, in order to evaluate the path loss, this approach uses the output of the TDR measurements (real and imaginary parts of the CDC) as inputs in the modified FRIIS model in (5). Experiments reveal that the proposed in situ path loss model of [15] is more accurate than the conventional Modified Friis in 02 soil types (Clayey silt and gravelly sand) and 03 different configurations. In order to evaluate the TDR Modified Friis, the authors compared their approach to conventional modified Friis and to real measurements on the 03 configurations. The results have shown that the value of the root means squared error in the TDR Modified Friis is smaller than in the CRIM-Fresnel and the conventional modified Friis. The proposed model is more accurate than the existing path loss models. However, despite the slight increase of the proposed model accuracy, the use of TDR equipment is very expensive and its deployment within a network is a costly problem. However, like the CRIM-Fresnel, this model needs to analyze a sample of soil in a laboratory so that to find the empirical values needed by the model. Thus, for a larger experimental field, soil conditions can be different, then, a sample of soil is not sufficient for an accurate path loss prediction.

5) MBSDM Modified Friis

A limit of the Peplinski model is that it considers only the presence of free water inside the soil. Moreover, as it is said by Topp et al. [27], bound water seems to dominate over free water in moist soil. Thus, to increase the accuracy of path loss, we considered a powerful approach for predicting the CDC named Mineralogy-Based Soil Dielectric Model (MBSDM) [28]. This approach takes into account the presence of free and bound water in the soil for a better prediction. Contrary to the Peplinski, the MBSDM can operate on a wider frequency range between 45MHz and 26.5GHz. Due to the large set of soil types used to design MBSDM, only three inputs parameters (wave frequency, the clay portion and the volumetric water content *VWC*) are needed for the CDC prediction.

The MBSDM Modified Friis proposed in [17] is an improved version of the conventional modified Friis. However instead

TABLE I
COMPARISON OF THE DIFFERENT PATH LOSS MODELS.

Approaches	Communication Types	CDC prediction	Inputs parameters	Additional losses
Conventional Modified Friis	UG2UG	Peplinski	VWC, bulk density, particle size, Clay and Sand proportions, Wave frequency.	-
CRIM Fresnel	UG2UG	CRIM	VWC, bulk density, particle size, Clay and Sand proportions, Wave frequency.	Reflection
NC Modified Friis	UG2UG	Peplinski	VWC, bulk density, particle size, Clay and Sand proportions, Wave frequency.	Reflection + Refraction
ZS model	UG2AG / AG2UG	Peplinski	VWC, bulk density, particle size, Clay and Sand proportions, Wave frequency.	Reflection
XD model	UG2AG / AG2UG	Peplinski	VWC, bulk density, particle size, Clay and Sand proportions, Wave frequency.	Reflection
TDR Modified Friis	UG2UG	TDR device	VWC, bulk density, particle size, Clay and Sand proportions, Wave frequency.	-
WUSN-PLM	UG2UG / UG2AG / AG2UG	MBSDM	VWC, Clay proportion, wave frequency.	Reflection + Refraction

using Peplinski, it is based on MBSDM for a better CDC prediction, thus a more accurate path loss model. Furthermore, the MBSDM is derived for a larger number of soil samples than in Peplinski and it is based on the powerful Generalized Refractive Mixing Dielectric Model (GRMDM) [29]. The real and the imaginary parts of the CDC depend on the refractive index n and the normalized attenuation coefficient k of the moist soil [17].

Despite its better accuracy than the other path loss models, the MBSDM Modified Friis as defined is not suitable for real WUSN application. For example, in an application such as precision agriculture in which sensor nodes can be buried at different depths. Another limit of these presented path loss models is that they are not able to consider the different communication types presented in Section 2. In order to address these issues, we improve the MBSDM Modified Friis like shown in Section 4.

B. Mixing path loss models

Contrary to underground path loss models, mixing models are designed for UG2AG and/or AG2UG communications.

1) ZS Free Space-Modified Friis based models

Most of the mixing path losses in WUC adds to the free space path loss, the loss due to underground communication. Sun et *al.* [30] propose a path loss model for UG2AG and AG2UG communications. To achieve it, authors add to Free Space and Modified Friis models, the loss due to Soil-Air and Air-Soil refraction for UG2AG and AG2UG communications respectively. The resulting path losses are given in (11) and (12). Where θ is the incidence angle of the wave, ε' is the dielectric constant, L_{ug} and L_{ag} are the conventional Modified Friis (5) and the free space [21] path losses respectively.

$$L_{UG2AG} = L_{ug} + L_{ag} + 10log\frac{\left(\sqrt{\varepsilon'}+1\right)^2}{4\sqrt{\varepsilon'}} \qquad (11)$$

$$L_{AG2UG} = L_{ug} + L_{ag} + 10log\frac{\left(cos\theta\sqrt{\varepsilon'-sin^2\theta}\right)^2}{4cos\theta\sqrt{\varepsilon'-sin^2\theta}} \qquad (12)$$

Similar to Modified Friis and the NC Modified Friis, the model proposed by Sun et *al.* [30] does not consider the wave phenomena that can occur at different burial depth such as the loss due to wave reflection. However, the added refraction loss neglects the effect of the loss factor ε'' of the wave in soil and

in practice, the incidence angle cannot be easily obtained in real *in-situ* application.

2) XD Free Space-Modified Friis based models

Another mixing model for prediction of signal loss in UG2AG/AG2UG communications is proposed by Dong et *al.* [31]. Their approach is quite similar to the one proposed by Sun et *al.* [30], however, for UG2AG, the authors neglect the loss due to the wave refraction. This is because the signal travels perpendicularly from a higher density medium (soil) to a lower density one (air). Furthermore, for AG2UG communication, the loss due to refraction L_r depends on the refractive index of the soil n (13). In order to give an approximate value, Dong et *al.* assume that the signal incidence angle is zero degree, thus, the maximum power path taken by the signal. ε' and ε'' are the dielectric constant and the loss factor respectively. The resulting path losses for UG2AG and AG2UG communications are resumed in (14) and (15).

$$L_r(dB) = 20log\left(\frac{n+1}{4}\right); \ n = \sqrt{\frac{\sqrt{(\varepsilon')^2+(\varepsilon'')^2}+\varepsilon'}{2}} \qquad (13)$$

$$L_{UG2AG} = L_{ug} + L_{ag} \qquad (14)$$

$$L_{AG2UG} = L_{ug} + L_{ag} + L_r \qquad (15)$$

The overall path loss models are resumed in Table I in terms of the communication types, the CDC prediction approach, the needed input parameters and the additional losses are taken into account.

IV. PROPOSED MODEL

This section describes the proposed Wireless Underground Sensor Network Path Loss for Precision Agriculture called WUSN-PLM.

A. Problem statement

Despite a large number of path loss models for WUSN fields, there is any path loss models design for the 03 communication types to the best of our knowledge. Furthermore, the problem of accuracy and computation issues remain relevant in this research field. To find a tradeoff between accuracy and lower real *in situ* measurements, we designed the WUSN-PLM presented in the following sections.
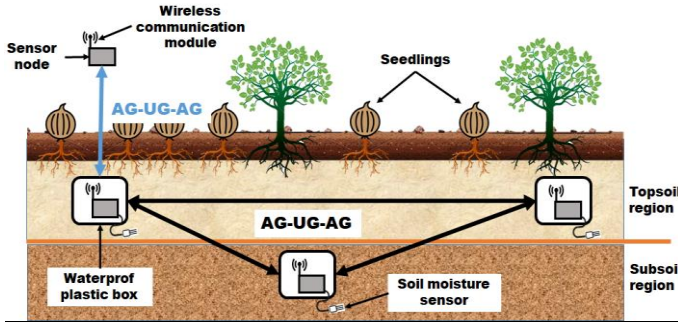
Fig. 2. Design of wireless underground communications.

B. Wireless Underground Communications

The proposed WUSN-PLM considers the underground parts (topsoil and subsoil) because in agriculture the topsoil region or the subsoil can be ploughed before planting seeds or young plants. We classified the buried depth into two locations: *top_depth* and *sub_depth*. They denote the buried depth at topsoil (15cm to 30cm) and subsoil (more than 30cm) regions respectively.

In order to protect the electronic components from the water of other deteriorations, all the node components except sensors are put inside a plastic waterproof box that contains air. Thus, during the communication between two buried nodes (UG2UG), the wireless signal will successively cross the air inside the sender box, the ground and the air inside the receiver box (Figure 2). A buried node can communicate with another node located above the ground (UG2AG). Then, for that case, the wave crosses the air inside the box of the buried node, the ground that separates the buried node and the surface, and finally the air up to the receiver node. For the communication between an above ground node and a node placed under the ground (AG2UG), the scenario of wave propagation is slightly similar to UG2AG. In our model, the 03 communications types presented in Section 2 become AG2UG2AG (Figure 2).

C. Path Loss Computation

The proposed model WUSN-PLM (16) is divided into two forms WUSN-PLM#1 (17) and WUSN-PLM#2 (18) for topsoil and subsoil regions respectively. For the topsoil region, the reflection effects due to ground surface proximity are added like [12] given by the equation (17). In subsoil regions, these effects are avoided, WUSN-PLM is resumed to (18).

$$\text{WUSN} - \text{PLM(dB)} = L_{d1}(dB) + L_{ug}(dB) + L_{d2}(dB) \quad (16)$$

$$\text{WUSN} - \text{PLM}_{\#1}(dB) = \phi + 20log\left(\sqrt{\frac{2R}{1+R}}\right) + 40log(f) \quad (17)$$

$$\text{WUSN} - \text{PLM}_{\#2}(dB) = \phi + 40log(f) \quad (18)$$
$$\phi = -288.8 + 20log(d_1.d_2.d_{ug}.\beta) + 8.69\alpha d_{ug}$$

Where d_1 and d_2 are travelled distance in the aboveground region (air) by the wave; d_{ug} denotes the underground distance. For the communication between two buried nodes, d_{ag1} and d_{ag2} are the distance travelled by the signal inside the waterproof box. However, for a smaller distance (less than 1 m), the signal loss in free space can be neglected [11]. The α and β values are based on predicted ε' and ε'' values like
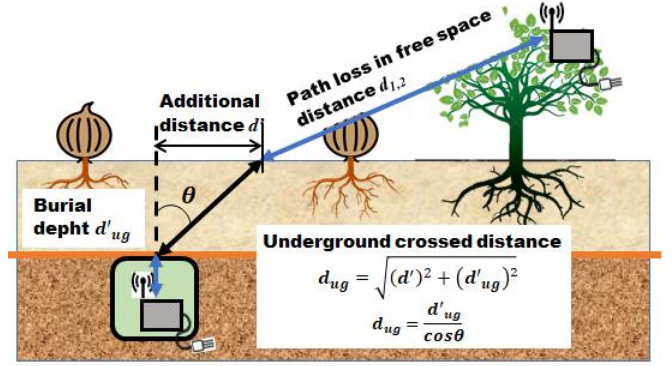

Fig. 3. UG2AG and AG2UG path loss designing.

in the MBSDM Modified Friis model [17]. In the case of AG2UG communication, d_{ag1} will represent the distance between the above ground node and the soil surface. For UG2AG communication, d_{ag2} is the height of the buried node relative to the ground surface.

For fully underground communications, d_1 and d_2 are considered as the plastic waterproof width. Thus, they represent the distances travelled by the wave on the air inside each box. The underground distance between the two nodes is d_{ug}. Since at the topsoil region (*top_depth*), the wave reflection phenomenon is observed, we consider the loss due to reflection. The resulting path loss is resumed by WUSN-PLM#1 (17). However, for *sub_depth*, the reflection phenomenon is neglected, then the path loss becomes WUSN- PLM#2 (18).

For UG2AG communications, the sender is located below the ground and the receiver above the surface of the ground. d_1 is the distance travelled by the wave in the transmitter box, d'_{ug} denotes the buried depth and d_2 is the travelled distance in free space by the EM wave. The underground distance d_{ug} crossed by the wave is related to the burial depth d'_{ug} and the critical angle θ (Figure 3). Furthermore, when the soil is dry, the critical angle $\theta \approx 15°$ and for moist soil it is slightly equal to 30° like it is shown in [11]. Thus, if the transmitter is located at the *top_depth*, the overall path loss is expressed according to (17). Whereas, if the transmitter is located at the *sub_depth* the path loss is expressed through (18).

The path loss for AG2UG communications is slightly the same as the path loss in UG2AG. Meanwhile, for this kind of communication, additional attenuation caused by refraction L_r (13) is considered as it is shown by Dong et *al.* [31]. Furthermore, if the receiver is located at *top_depth* and *sub_depth*, the corresponding path loss becomes WUSN'-PLM#1 (19) and WUSN'-PLM#2 (20) respectively.

$$\text{WUSN}' - \text{PLM}_{\#1}(dB) = \text{WUSN} - \text{PLM}_{\#1} + L_r$$

$$\text{WUSN}' - \text{PLM}_{\#1}(dB) = \phi + 20log\left(\sqrt{\frac{2R}{1+R}}.\left(\frac{n+1}{4}\right).f^2\right) \quad (19)$$

$$\text{WUSN}' - \text{PLM}_{\#2}(dB) = \text{WUSN} - \text{PLM}_{\#2} + L_r$$

$$\text{WUSN}' - \text{PLM}_{\#2}(dB) = \phi + 40log\left(f.\sqrt{\frac{n+1}{4}}\right) \quad (20)$$

V. EXPERIMENTATIONS

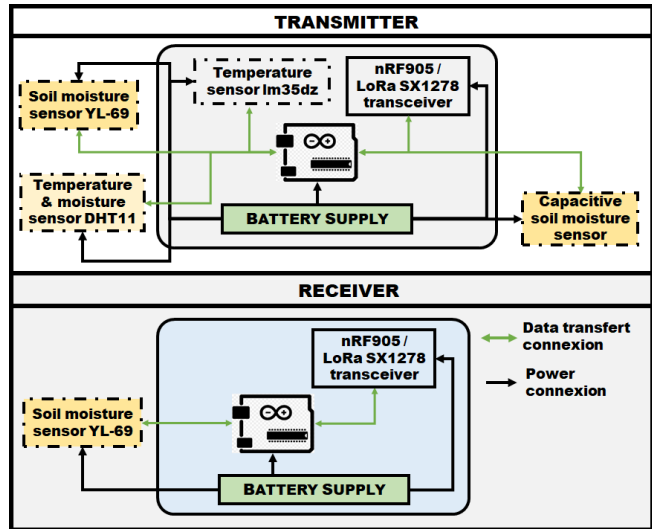In this section, the experimentations processes are presented.

Fig. 4. Transmitter and receiver sensor nodes

TABLE II
CHARACTERISTICS OF TRANSCEIVERS

Transceivers	TX power (dBm)	Sensitivity (dBm)	Antenna gains	Maximum PL(dB)
nRF905	+10	-100	2dB	114
SX1278	+17	-121	2.5dB	143

The nodes used during the tests, the experimental field and the methodology are described in details.

A. Sensor nodes

In order to evaluate the path loss, we designed a transmitter and a receiver, both based on Arduino UNO (Figure 4).

The two nodes are powered by a 9V input. In order to sense the soil moisture and the temperature, the transmitter has four different sensors: a sensor LM35DZ to measure the temperature inside the box; a soil humidity sensor YL-69 and a capacitive soil moisture sensor resistant to corrosion; a DHT11 sensor is fixed outside the box in order to give the temperature and the humidity of the soil around the box. Contrary to the transmitter, the receiver node has only the soil moisture sensor YL-69. Except for the Arduino board, the transceivers, the batteries and the sensor LM35DZ from transmitter node, all other components are put outside a plastic box like the MoleNet [32]. The plastic box used in our model has a truncated square pyramid form with 13cm height. In order to achieve wireless communication between the nodes, we used pairs of nRF905 and LoRa SX1278 transceiver both working at 433MHz frequency.

The nRF905 and SX1278 transceivers parameters are found in Table II. The Path loss is computed according to the transmitted power P_t, the received power P_r and the antenna gains G_t and G_r.

$$PL(dB) = P_t(dBm) + G_r(dB) + G_t(dB) - P_r(dBm) \quad (21)$$

From Table II and (21), the maximum acceptance path loss for nRF905 and SX1278 transceivers is 114dB and 143dB respectively. In other words, for the nRF905 transceiver, if the path loss is greater than 114dB, the receiver will not get an incoming packet. However, if the signal attenuation is lower than this threshold, a node receives a new packet.

TABLE III
SOIL CONFIGURATIONS AT THE EXPERIMENTAL FIELD (UCAD) [31-32]

Name	Sand (%)	Clay (%)
Sandy clay #1	82.9	7.6
Sandy clay #2	95.3	3.3

B. Experimental field

We conducted our experimentations at the botanic garden of the University Cheikh Anta Diop of Dakar, Senegal (Figure 5). A 450m^2 area for an onion's plantation is considered; the present soil is a sandy clay type in which the clay proportion increase with the depth. Before putting the onion plants under the ground, the soil is ploughed beforehand on the first 20cm of the topsoil region (Figure 5a). Then, a drip irrigation system is installed and young onion seedlings are planted two days after the soil ploughing, thus, the soil is enough soft (Figure 5b and Figure 5c). From Figure 5d and Figure 5e, the buried transmitter (green lid) and receiver (red lid) at different depth are presented. They are separated from each other by a certain distance in meter. The average distance between two onion plants of the same line (irrigation pipe) is 15cm and the distance between two lines is 50cm (Figure 5f).

In order to have the clay and the sand portions of the area around the experimental field, we considered previous measurements conducted by [33-34]. From these studies, sand and clay portions of sandy clay soil in Dakar could be grouped into two types, as shown in Table III. Thus, because of the non-uniformity of these portions along the experimental field, both types of sandy clay are furthermore considered for the conducted experiments and tests.

C. Methodology

We have considered two scenarios for our measurements: Scenario #A when the soil is dry (Figure 5a) and Scenario #B for moist soil (Figure 5b and Figure 5c). On dry soil, there is no presence of moisture due to the heat released by the sunlight and the wind have dried the soil so that the soil moisture is around 0 %.

For each scenario, the distance between the transmitter and receiver nodes varies between 5m, 10m, 15m and 20m. On each distance, the buried depth of nodes changes from the ground, 15cm, 20cm, 30cm and 40cm (Figure 6). The three types of communication presented in Figure 1 are considered in both topsoil and subsoil regions. Moreover, depths located at the first 30cm are considered as *top_depth* region and beyond 30cm, they are considered as *sub_depth*.

The transmitter sends 170 packets to the receiver, each sent packet has 32-byte size and the interval between two transmissions is fixed to 02 seconds in order to avoid the latency due to sensor measurements. The structure of a radio packet in the nRF905 transceiver is presented in Figure 7, the Cyclic Redundancy Check (CRC) is used to detect errors in the received data. During each round, we get the different values of the DHT11 sensor (temperature and humidity), LM35DZ temperature, YL-69 soil moisture, capacitive soil moisture and the id of the current packet. The six sensed values are stored inside the transmitter EEPROM. Therefore, the packet thus constituted is sent to the receiver by the pure ALOHA communication scheme. At the receiver side, the node listens to any incoming packets from the transmitter. If it receives a
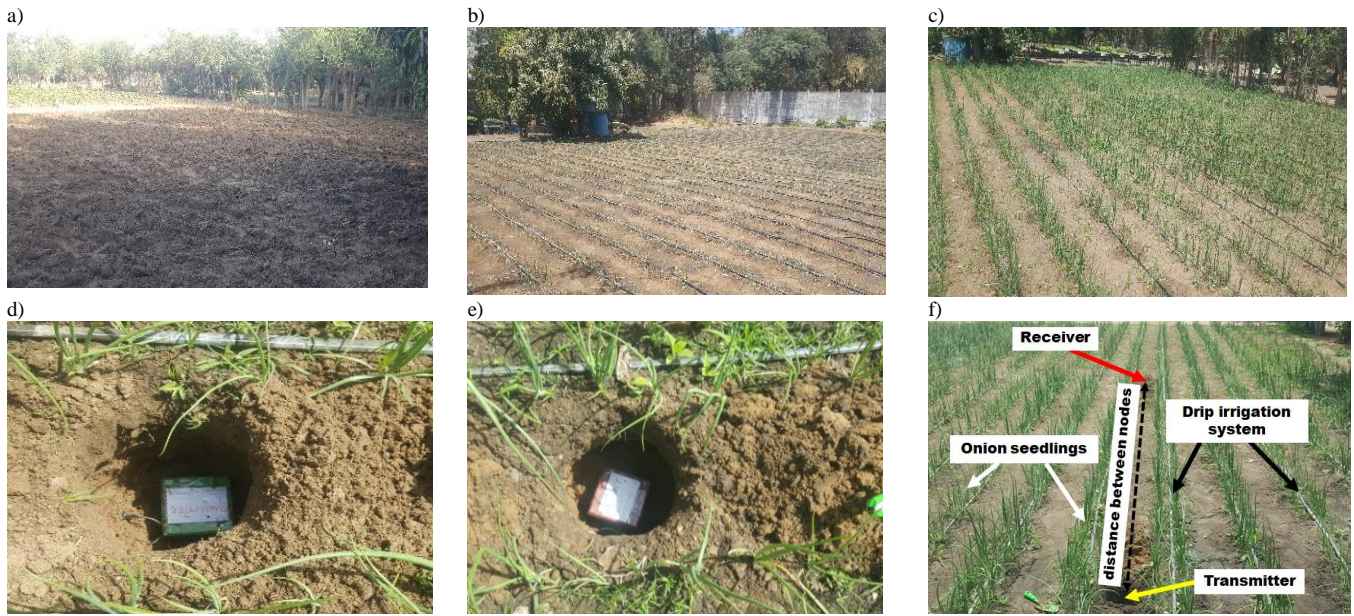
Fig. 5. Experimental fields at the botanic garden of the University Cheikh Anta Diop (UCAD), Senegal.
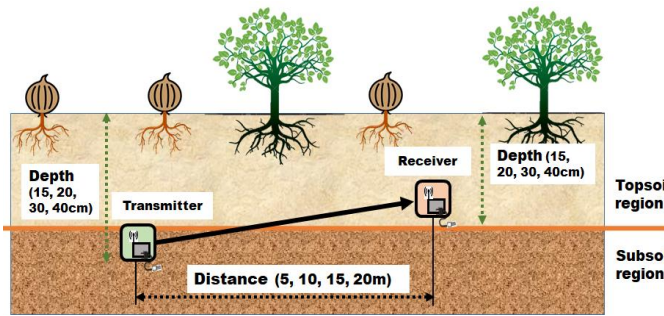

Fig. 6. Methodology of measurement process.

Fig. 7. Packet structure

packet, it gets the sensed value of its YL-69 sensor and stores it with the id of the received data on its EEPROM. Thus, we have an overview of the soil moisture between the transmitter and the receiver nodes at each round. The transmitter code and the receiver code are available on GitHub. The communication processes of nodes are resumed in Figure 8.

In order to evaluate the path loss prediction on each model with the nRF905 transceiver, we define the following classes:

- Positive or Received class: the predicted path loss is less or equal to the maximum path loss of the transceiver (114 dB) from Table I. In other words, the receiver node is able to get a packet sent by a transmitter node.
- Negative or Not received class: here, the computed path loss by the proposed approach is more than the maximum path loss of the transceiver. The receiver does not get incoming packets sent by the transmitter.

Moreover, according to the previous classes, we consider the 04 well-known metrics:

- True Positive (TP) : is a correct result when an approach successfully detects or predicts the positive class of an observation;
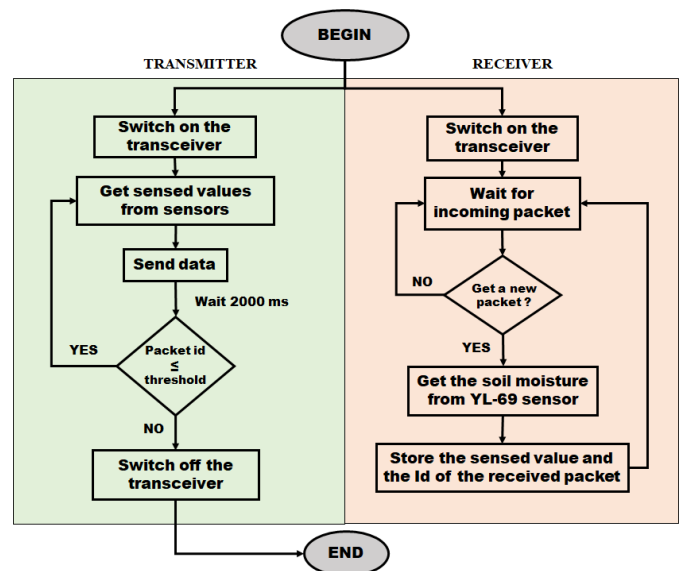

Fig. 8. Overview of communication between transmitter and receiver

- True Negative (TN) : is a correct estimation when the approach successfully predicts a negative class;
- False Positive (FP): is an error when predicting a positive class
- False Negative (FN) : is an error when the approach does not successfully predict the negative class;

Furthermore, the number of good predictions is GP (TP+TN) and the amount of bad predictions is BP (FP+FN). GP gives the number of cases in which the prediction is equal to the observation. BP is simply the number of cases where the prediction is different from the observation.

VI. RESULTS AND DISCUSSIONS

We evaluate the proposed WUSN-PLM on two scenarios: #A for dry soil and #B for moist soil. For each scenario, the soil configurations presented in Table III are considered. Furthermore, in each scenario, we evaluated and compared the

TABLE IV
COMPARISON OF UG2UG PATH LOSSES IN SCENARIO #A.

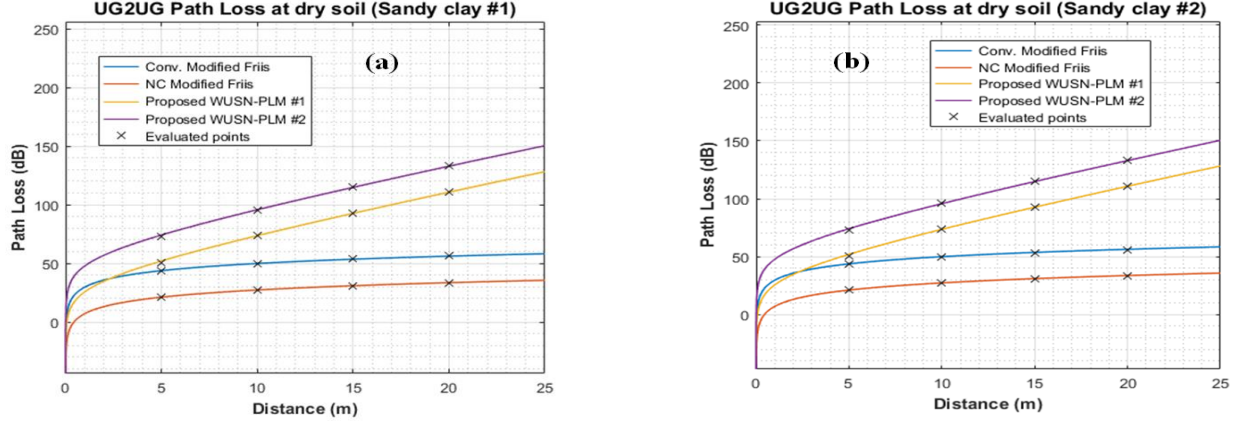| Location	Conventional Modified Friis				NC Modified Friis				Proposed approach (WUSN-PLM)				Overall observations
	TP	TN	FP	FN	TP	TN	FP	FN	TP	TN	FP	FN	
top_depth	24	0	8	0	24	0	8	0	24	0	8	0	**32**
sub_depth	12	0	4	0	12	0	4	0	12	4	0	0	**16**
Total	**36**	**0**	**12**	**0**	**36**	**0**	**12**	**0**	**36**	**4**	**8**	**0**	**48**

Fig. 9. Path losses comparison on Dry soil. (a) is the path losses for sandy clay#1 soil whereas, (b) is the path losses for sandy clay#2 from Table III.

presented path loss models according to the type of communication.

A. Dry soil (Scenario #A)

The path losses for UG2UG WUC for dry soils (0% of moisture) are shown in Figure 9, where the distance crosses by the wave inside the plastic boxes is set to 13cm ($d_1 = d_2$) and can be neglected. Path losses in Sandy clay#1 (Figure 9a) and in Sandy clay #2 (Figure 9b) seem to be identical; this is because both soil samples are sandy clay with a high concentration of sand. Moreover, we conclude that, the clay portion in dry soil does not highly affect the signal attenuation in the same soil type (sandy clay).

From Figure 9, the Path losses on Conventional and NC Modified Friis have the same evolution; this is because both are based on the Peplinski derivations to predict the value of the CDC. Meanwhile, due to wave reflection phenomenon introduced by NC Modified Friis, the resulting path loss is slightly lower than the conventional Modified Friis. The path loss evolution on the proposed approach is different from the other path loss models since it is based on the accurate MBSDM for predicting the CDC. Nevertheless, the proposed approach additionally considers the presence or the absence of the wave reflection in soil according to the burial depths. Thus, we observed that the path loss at *sub_depth* (WUSN-PLM$_{#2}$) is greater than the path loss on *top_depth* (WUSN-PLM$_{#1}$).

To evaluate the UG2UG communications in each model for scenario #A, the number of TP, TN, FP and FN are compared based on the 48 measurements made. From Table IV, it is observed that the Conventional Modified Friis and the NC Modified Friis have the same results: $36GP$ ($36TP$ and $0TN$). However, our proposed model obtained the best prediction with $40GP$ ($36TP$ and $4TN$) and $8BP$ ($8FP$ and $0FN$). All the BP of our proposed approach are located in the *top_depth* and are caused by the wave interferences that appear in this region during reflection phenomenon but neglected by the authors of [11].

In order to evaluate the performance of each approach, we calculate their precision (*PRE*) and their accuracy (*ACC*) according to (16). *PRE* simply stands for how consistent results are when measurements are repeated whereas *ACC* is used to describe the closeness of a measurement to the true value. Conventional and NC Modified Friis have the same performance, thus their corresponding precision and accuracy are the same (75%). *PRE* is equal to *ACC* in both approaches because all the *GP* are only *TP*; therefore, they are not able to predict the negative class (not a packet reception). However, the proposed WUSN-PLM obtained highest performance with 81.81% precision and 83.33% accuracy. The proportion of negative observations well predicted known as selectivity (*SEL*) and the ratio of correct prediction called sensitivity (*SEN*) are also evaluated according to (22). Likewise, the precision and the accuracy, our proposed path loss model has the best efficiency with a perfect Sensitivity ($SEN = 1$) and 0.33 selectivity. Furthermore, the same results are obtained for both sandy clay soils which configurations are presented in Table III.

$$
\begin{aligned}
PRE(\%) &= \frac{TP \times 100}{TP+FP} \\
ACC(\%) &= \frac{(TP+TN) \times 100}{TP+TN+FP+FN} \\
SEN &= \frac{TP}{TP+FN} \; ; \; SEL = \frac{TN}{TN+FP}
\end{aligned}
\tag{22}
$$

Knowing that the Conventional Modified Friis and NC Modified Friis are designed only for fully UG2UG communications, we compare and evaluate our proposed model WUSN-PLM to the mixing path losses models presented in subsection B of Section II. To evaluate ZS path loss for AG2UG communication, we assume the incidence angle to be null. Thus, the transmitted power is the maximum as in the XD path loss model.

For UG2AG communication, the predicted path loss models in scenario #A are presented in Figure 10. As for UG2UG
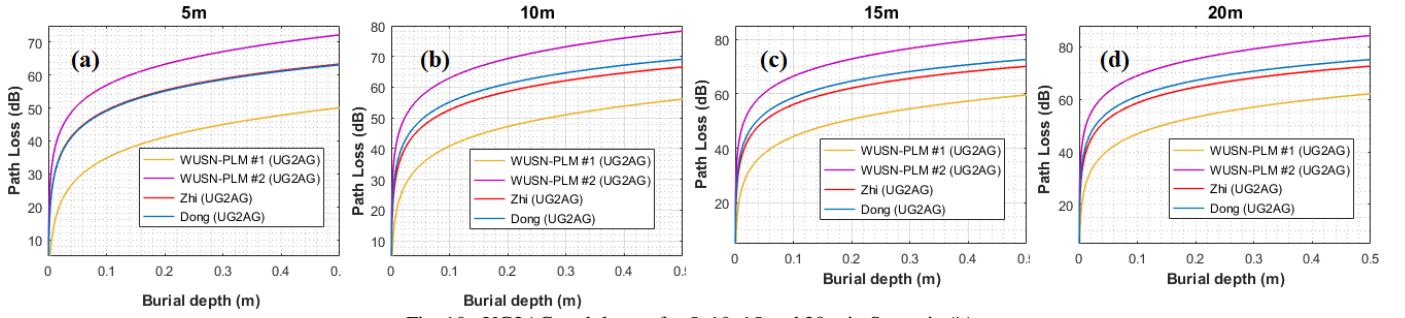
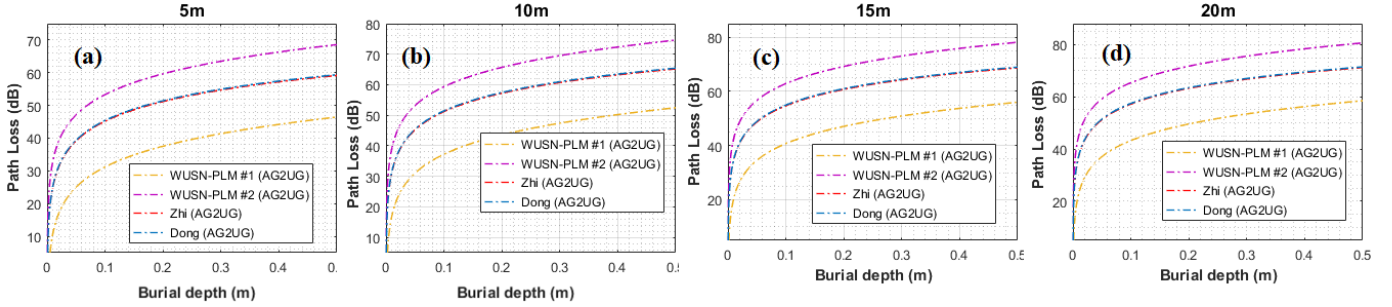Fig. 10. UG2AG path losses for 5, 10, 15 and 20m in Scenario #A.

Fig. 11. AG2UG path losses for 5, 10, 15 and 20m in Scenario #A.

TABLE V
RESULTING CONFUSION MATRIX OF ZS, XD AND WUSN-PLM PATH LOSS
FOR UG2AG AND AG2UG IN SCENARIO #A.

		Observation	
		Received	Not received
Prediction	Received	16 TP	0 FP
	Not received	0 FN	0 TN

TABLE VI
OVERALL CONFUSION MATRIX OF WUSN-PLM IN SCENARIO #A.

		Observation	
		Received	Not received
Prediction	Received	68 TP	0 FP
	Not received	0 FN	12 TN

TABLE VII
PERFORMANCE EVALUATION OF WUSN-PLM IN SCENARIO #A

Precision (PRE)	Accuracy (ACC)	Sensitivity (SEN)	Selectivity (SEL)	Balanced Accuracy (bACC)	MCC
89.47%	90%	1	0.33	66.67%	0.55

communication, the path loss evolution in UG2AG type is the same despite the type of sandy clay soil used. We observe that the path loss models slightly increases with the burial depth and the distance between the nodes (Figure 10a, Figure 10b, Figure 10c and Figure 10d). Thus, there is a positive association between the path loss and the burial depth; and between the path loss and the distance between transmitter and receiver sensor nodes for UG2AG communications. Path loss predicted values of ZS and XD models can be confused for the low linear distance between transmitter and receiver (Figure 10a). However, the signal attenuation for 10, 15 and 20m linear distance between nodes, the ZS and XD path losses are closed each other. This is because both have slightly the same core and are based on Conventional Modified Friis and Free Space models.

Moreover, the expected path loss on each presented model seems to be lesser than the threshold path loss value of the transceiver nRF905 (114dB). Thus, in all the cases presented here, the communication between the transmitter (located under the ground) and the receiver (located on the ground surface) is reliable in the scenario #A independently of the burial depths of sensor nodes (up to 40cm) and for linear distance lesser or equal to 20m. To evaluate UG2AG these path loss models, 16 observations (12 in *top_depth* and 4 in *sub_depth*) have been made for each model. All the path loss models for UG2AG communications have the same perfect result in Scenario #A, the resulting confusion matrix is presented in Table V. All the presented proposed approach obtained a perfect score with 16TP. Thus, they obtained 100% of accuracy and precision with perfect sensitivity ($SEN = 1$) in Scenario #A.

The comparison of the path loss models in AG2UG for each linear distance (5, 10, 15 and 20m) is given in Figure 11. Contrary to UG2AG communications, ZS and XD path loss models are identical for all the linear distance. This is because both consider a zero angle of incidence; the maximum power is therefore considered to be transmitted. Furthermore, the calculated path losses in scenario #A for AG2UG communication are identical either for sandy clay #1 or for sandy clay #2 soil. As with UG2AG communication, the path loss for AG2UG is less than the maximum path loss acceptable by the nRF905 transceiver, which means that all sent packets are received despite the position of the nodes. The evaluation process of these models for AG2UG communication is similar to UG2AG evaluation process. However, for the WUSN-PLM, the computation of the predicted path loss is based on (19) and (20) for *top_depth* and *sub_depth* regions respectively. The resulting confusion matrix for each path loss model is identical to the confusion matric for UG2AG communication (Table V) with 16TP. Then, they have perfect accuracy ($ACC = 100\%$), precision ($PRE = 100\%$) and sensibility ($SEN = 1$).

80 measurements have been conducted in scenario #A in order to evaluate our proposed path loss (Table VI) and only 48 measurements for the other existing path loss models since these are latter only designed for fully UG2UG communication.

In order to evaluate the correlation between the prediction and the observation in WUSN-PLM, we used the *Matthews*

TABLE VIII
CONFUSION MATRICES OF PATH LOSS MODELS FOR UG2UG COMMUNICATIONS IN SCENARIO #B.

		Observation					
		Conv. Modified Friis		NC Modified Friis		WUSN-PLM	
		Rcv.	Not Rcv.	Rcv.	Not Rcv.	Rcv.	Not Rcv.
Pred.	Rcv.	9TP	6FP	13TP	9FP	2TP	0FP
	Not Rcv.	9FN	48TN	5 FN	45TN	16 FN	54TN

TABLE IX
OVERALL CONFUSION MATRIX OF WUSN-PLM IN SCENARIO #B.

		Observation	
		Received	Not received
Prediction	Received	20 TP	5 FP
	Not received	8 FN	27 TN

TABLE X
OVERALL PERFORMANCE EVALUATION OF WUSN-PLM IN SCENARIO #B.

PRE	ACC	SEN	SEL	F1 Score	MCC
80%	78.33%	0.71	0.84	75.47%	0.56

TABLE XI
CONFUSION MATRICES OF PATH LOSS MODELS FOR UG2UG COMMUNICATIONS (SCENARIO #A AND SCENARIO #B).

		Observation					
		Conv. Modified Friis		NC Modified Friis		WUSN-PLM	
		Rcv.	Not Rcv.	Rcv.	Not Rcv.	Rcv.	Not Rcv.
Pred.	Rcv.	81TP	30FP	85TP	33FP	74TP	16FP
	Not Rcv.	9FN	48TN	5FN	45TN	16FN	62TN

TABLE XII
PERFORMANCE EVALUATION OF PATH LOSS MODELS FOR UG2UG COMMUNICATIONS (SCENARIO #A AND SCENARIO #B).

	PRE	ACC	SEN	SEL	bACC	MCC	AUC
Conv. Modified Friis	72.97%	76.79%	0.9	0.62	75.77%	0.542	0.831
NC Modified Friis	72.03%	77.38%	0.94	0.58	76.07%	0.350	0.871
WUSN-PLM	82.22%	80.95%	0.82	0.79	80.85%	0.62	0.9

Correlation Coefficient (*MCC*). Additionally, since the positive and the negative classes have different size (positive class is larger than the negative class), the *balanced accuracy* (*bACC*) is more suitable than the accuracy ACC (23). The positive value of MCC means that the proposed approach is better than a random prediction and therefore the correlation between the prediction of the path loss and the observation is good ($MCC = 0.55$). The overall performance evaluation of the proposed approach is resumed in Table VII.

$$bACC(\%)=\frac{(SEN+SEL)\times100}{2};$$
$$MCC=\frac{TP.TN-FP.FN}{\sqrt{(TP+FP).(TP+FN).(TN+FP).(TN+FN)}}$$
(23)

B. Moist soil (Scenario #B)

1) nRF905 transceiver

For moist soil configuration (scenario #B), the soil moisture portion varies according to each sensor measurement. In order to evaluate the path loss, we analyse each case and their corresponding parameters. Due to the table size, the evaluation of path loss models on UG2UG in moist soil for 5m and 20m linear distances is presented in Appendix A1. From the 18 observations of Appendix A1, the proposed WUSN-PLM obtained the highest precision (100%) and selectivity (1) for both sandy clay configurations.

Moreover, the same measurements in Appendix A1 are conducted for 10m and 15m between the transmitter and the receiver. Thus, 36 comparisons have been observed in each soil (sand clay #1 and sandy clay #2). By observing the two types of soil, path loss predictions on the Conventional and the NC Modified Friis are different despite the same type of soil (sandy clay). This observation reveals that a minor change of the sand or clay portions would highly affect these path loss models. Thus, the use of Conventional and NC Modified Friis is possible only for a uniform soil type in which sand and clay portions are the same. Contrary to Conventional and NC Modified Friis, WUSN-PLM gave the same prediction either for sandy clay #1 and sandy clay #2. Then, this path loss can be

used for the same soil type despite a slight difference in sand or clay portions along the field.

However, due to the inaccuracy of the low cost soil moisture sensor (YL-69) [17], [35], we consider an error margin of ±3% on the soil moisture value. In order words, for the underground communication at 20cm depth (20 to 20), and by considering the distance between nodes to 5m, the measured moisture was 44% (Appendix A1). Thus, by applying the ±3% margin, we assume that the exact value of the soil moisture is between 41% and 47%. Despite the ±3% margin error of the soil moisture sensor device, the predictions presented in Appendix A1 no longer change. Thus, the prediction of the path loss can be done with the proposed model regardless of the use of a low cost sensor. Table VIII shows the corresponding confusion matrices of each path loss model for the 72 observations (36 in each sandy clay) made in full UG2UG communication. The NC Modified Friis obtained a higher number of *TP* whereas the proposed WUSN-PLM had the best amount of *TN*.

Furthermore, as in Scenario #A, we compared our proposed path loss model in UG2AG and AG2UG communications to ZS and XD path loss models. Appendices A2 and A3 resume the evaluation of mixing path loss models for UG2AG and AG2UG respectively. For each communication type, 12 observations are conducted based on the measured soil moisture. During UG2AG communications in Scenario #B (Appendix A2), each path loss model obtains 75% precision and accuracy. As in Scenario #A, the recall or sensitivity is perfect ($SEN = 1$). In addition, the presented path loss models have an average balanced accuracy ($bACC = 50\%$). Thus, based on our data set, these path loss models have the same performance regardless of the scenarios in sandy clay #1 and sandy clay #2.

For AG2UG communication (Appendix A3), ZS and XD path loss models have the same results ($10TP$ and $2FP$). Both obtained 83.33% precision and accuracy for AG2UG communication, however, their corresponding recall is perfect ($SEN = 1$) in Scenario #B. Nevertheless, the proposed WUSN-PLM outperforms ZS and XD models with a perfect prediction ($10TP$ and $2TN$). It obtained 100% Accuracy, precision and balanced accuracy, its correlation between prediction and observation is perfect ($MCC = 1$).
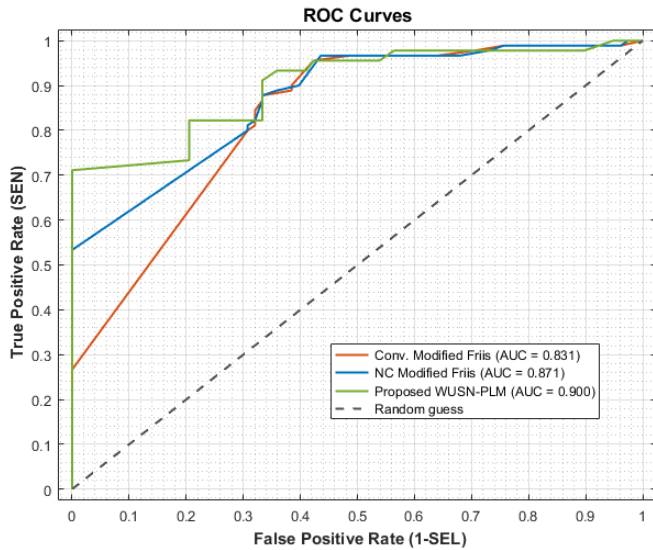
Fig. 12. ROC curves comparison for UG2UG communications.

TABLE XIII
PERFORMANCE EVALUATION OF PATH LOSS MODELS FOR UG2AG
COMMUNICATIONS (SCENARIO #A AND SCENARIO #B).

	PRE	ACC	SEN	SEL	bACC	MCC
Path loss models	89.28%	89.28%	1	0	50%	/

The overall performance evaluation of our proposed WUSN-PLM in Scenario #B (UG2UG, UG2AG and AG2UG) is resumed in Table IX and Table X. Since the proposed approach gives the same results for sandy clay #1 and sandy clay #2, 60 tests were conducted in each soil type. The corresponding observations are presented in Table IX. From the 60 observations, our proposed obtained $47GP$ ($20TP$ and $27TN$). The corresponding precision and accuracy in Scenario #B are 80% and 78.33% respectively.

Nevertheless, since the size of the negative class is higher than the size of the positive class (32 and 28 respectively), the *F1 score* is considered according to (24) instead of the balanced accuracy ($bACC$). Thus, the prediction reliability of the proposed approach despite the size of observed classes is 75.47% with a good correlation of 0.56 between the prediction and the observation (Table X).

$$F1\ Score(\%) = \frac{2 \times TP}{(2 \times TP + FP + FN)} \times 100 \qquad (24)$$

In order to compare the path loss models in UG2UG communications (scenario #A and scenario #B), 168 observations have been conducted in sandy soil. The corresponding confusion matrices are given in Table XI in which the size of the observed positive class is higher than the size of the observed negative class, i.e. 90 and 78 respectively. The proposed WUSN-PLM obtained the highest number of GP ($74TP$ and $62TN$). The Conventional Modified Friis performed the worst prediction with the highest number of BP ($9FN$ and $30FP$) directly follow by the NC Modified Friis ($38BP$).

Table XII resumes the performance evaluation for UG2UG communications of the different path loss models presented in Section 3. The WUSN-PLM obtained the best precision and accuracy of 82.22% and 80.95% respectively. Meanwhile, the

TABLE XIV
PERFORMANCE EVALUATION OF PATH LOSS MODELS FOR AG2UG
COMMUNICATIONS (SCENARIO #A AND SCENARIO #B).

	PRE	ACC	SEN	SEL	bACC	MCC
ZS / XD Models	92.85%	92.85%	1	0	50%	/
WUSN-PLM	100%	100%	1	1	100	1

TABLE XV
CONFUSION MATRIX OF WUSN-PLM IN SCENARIOS #A AND #B FOR EACH
SANDY CLAY CONFIGURATION.

		Observation	
		Received	Not received
Prediction	Received	88 TP	13 FP
	Not received	8 FN	31 TN

TABLE XVI
OVERALL PERFORMANCE EVALUATION OF WUSN-PLM IN SCENARIOS #A
AND #B FOR EACH SANDY CLAY CONFIGURATION.

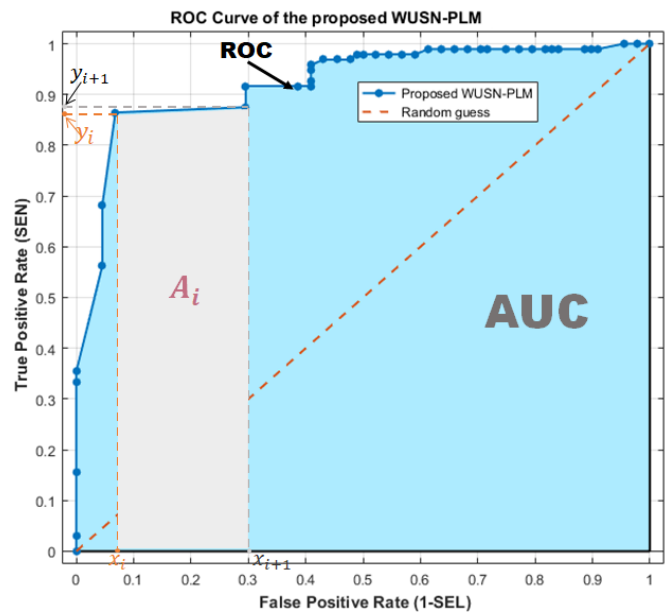| (PRE)	(ACC)	(SEN)	(SEL)	(bACC)	MCC	AUC
87.13%	85%	0.92	0.70	81.06%	0.64	0.92

Fig. 13. ROC and AUC of the proposed WUSN-PLM.

Conventional and NC Modified Friis performed the worst precision and accuracy. Moreover, despite the 77.38% accuracy in NC Modified Friis, we observe that, the correlation between its prediction and the observation is worst with the lowest *MCC* (0.35). In summary, the path loss in UG2UG communications regardless of the soil moisture is better predicted by WUSN-PLM. Due to the unbalanced size of classes (received and not received classes), the balanced accuracy is considered. Like the other metrics, the proposed path loss obtained the highest precision ($PRE = 82.22\%$), accuracy ($ACC = 80.95\%$), selectivity ($SEL = 0.79$), correlation between prediction and observation ($MCC = 0.62$) and balanced accuracy ($bACC = 80.85\%$). However, the WUSN-PLM performed the worst sensitivity (0.82) because it badly predicts the positive classes. This can be caused by the wave interferences neglected at top soil region by [11]. Despite the worst sensitivity, the proposed WUSN-PLM is more suitable than the Conventional and the NC Modified Friis.

Additionally, in order to evaluate the trade-off between the true and the false positive rate independently of the transceiver
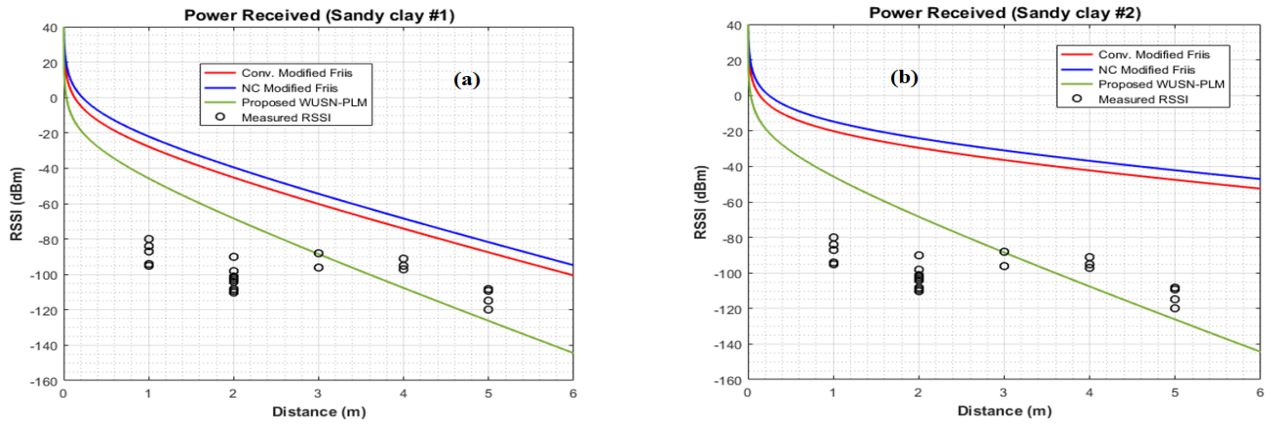
Fig. 14. Received power at soil moisture between 19 and 21% in Sandy clay #1 (a) and in Sandy clay #2 (b). The communication is UG2UG at a burial depth between 30 and 40 cm.

type, we use the *Receiver Operating Characteristic* (*ROC*) curve. It is used to evaluate a prediction model through graphical representation and regardless of the fixed threshold used to separate the positive and negative classes (reception and loss of an incoming packet). By varying the value of the maximum path loss bearable by transceiver from 0 dB to 1150 dB with a step of 10dB, the resulting *ROC* curves of each approach are presented in Figure 12. We observe that the *ROC* curves are all above the random guess. However, the proposed WUSN-PLM seems to be more above the random separation than the Conventional and NC Modified Friis. The value of the *Area Under Curve* (*AUC*) is calculated according to the trapezoidal rule describe in (30). The highest *AUC* value is obtained by the proposed WUSN-PLM (0.9) follow by the NC Modified Friis (0.871). The Conventional Modified has the lowest *AUC* (0.831).

The performance evaluation of the mixing path loss models in UG2AG communication (Scenario #A and Scenario #B) is given in Table XIII. Each of them gets 89.28% precision and accuracy, the balanced accuracy is average ($bACC = 50\%$).

The overall performance evaluation of mixing path loss models in AG2UG communications (Scenarios #A and #B) is resumed Table XIV.

From Appendices A2, A3 and above evaluation, we observe that the prediction in both sandy clay soils is similar. Thus, the proposed WUSN-PLM is more efficient for UG2AG and AG2UG communications than the presented mixing path loss models in the same soil type regardless of the slight variation of sand and clay portions.

Additionally, despite the assumed ±3% error given by the sensor moisture device, the amount of *GP* no longer changes from Appendix A2 and Appendix A3.

The total number of observations conducted in each sandy clay soil was 140 (80 in scenario #A and 60 in scenario #B) for our proposed approach. From these observations, our proposed WUSN-PLM obtained a total of 119 *GP* (88*TP* and 31*TN*) and 21*BP* (13*FP* and 8*FN*) like it is shown in Table XV. According to these observations, its corresponding performance evaluation is shown in Table XVI. It has very good precision and accuracy (87.13% and 85% respectively), moreover, despite the different sizes of the observed classes, the proposed approach obtained a very good balanced accuracy (81.06%). Furthermore, the

correlation between predictions and the real tests is high ($MCC = 0.64$), then our proposed model can be used for all the different types of communication (UG2UG, UG2AG and AG2UG) with very high sensitivity ($SEN = 0.92$) and selectivity ($SEL = 0.70$).

Like for the evaluation of UG2UG communications, we evaluate the trade-off between the true and the false positive rate in our proposed path loss for all the communications types by the corresponding *ROC* curve presented in Figure 13. The computation of *AUC* is also based on the trapezoidal rule, thus, the area A_i of a trapezoid i delimitated by points x_i and x_{i+1} from Figure 13 and the *AUC* are given in (25). Where y_i denotes the sensibility according to the false positive rate x_i and n is the number of trapezoids used ($n = 41$). The calculated value of the *AUC* presented in Table XVI shows that the proposed model has 92.28% change to distinguish positive class (reception of a packet) from the negative class (not packet reception) independently of the communication types (UG2UG, UG2AG and AG2UG).

$$A_i = \frac{(y_i + y_{i+1})}{2} \times (x_{i+1} - x_i); \quad AUC = \sum_{j=1}^{n} A_j \quad (25)$$

2) SX1278 LoRa transceiver

More experimentations are conducted at moist soil in order to check between the presented path loss models which are closer to real data for UG2UG communications regardless of the previous number of *GP* and *BP*. To achieve it, we replaced the previous nRF905 transceivers by a pair of LoRa transceiver SX1278 (Table I). Contrary to nRF905 transceiver, the SX1278 transceiver allows getting the received signal (RSSI) of an incoming packet. The same operating frequency (433MHz) of the nRF905 transceivers has been considered in the SX1278 transceivers. Additionally, we evaluated and compared the received power P_r according to the link budget equation (21). We conducted several measurements at 30-40cm burial depth (*sub_depth*) for measured soil moisture between 19 and 21%. Figure 14 gives the predicted power received in each path loss models and the different RSSI measurements get by SX1278 transceiver. 21 RSSI measurements have been obtained for the distance between the transmitter and the receiver nodes.

In order to evaluate the different path loss models, we used the *Root Mean Square Error* (RMSE), the *Mean Absolute Error* (MAE) and the *Mean Absolute Percentage Error* (MAPE) (26).

TABLE XVII
EVALUATION OF APPROACHES ACCORDING TO GAP INDICATORS FOR SANDY CLAY SOIL WITH MOISTURE BETWEEN 19 AND 20%.

Location	Conv. Modified Friis			NC Modified Friis			Proposed WUSN-PLM		
	RMSE	MAE	MAPE (%)	RMSE	MAE	MAPE (%)	RMSE	MAE	MAPE (%)
Sandy clay #1	50.403	47.641	48.405	55.885	53.406	54.216	32.753	29.427	30.121
Sandy clay #2	68.441	67.979	68.150	73.800	73.371	73.585	32.761	29.416	30.112

For a total of n measurements, p_i and o_i are respectively the predicted and the observed values for the measurement i. From Table XVI, NC Modified Friis has the worst accuracy than other approaches despite its good performance obtained with the nRF905 transceiver (Table XVII).

$$MSE = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(p_i - o_i)^2}$$
$$MAE = \frac{1}{n}\sum_{i=1}^{n}|p_i - o_i| \tag{26}$$
$$MAPE(\%) = \frac{100}{n}\sum_{i=1}^{n}\left|\frac{p_i - o_i}{o_i}\right|$$

Moreover, the NC Modified Friis has 53.406 and 54.216 MAE, thus the highest MAPE 54.216% and 73.585% for sandy clay #1 and #2 respectively. The RMSE, MAE and MAPE values in Conventional Modified Friis are close to these of NC Modified because they are based on slightly a same model. Furthermore, the value of RMSE, MAE and MAPE in Conventional and NC Modified Friis highly vary from one sandy clay soil type to another, therefore, a slight variation of clay and sand proportions in soil would negatively affect the prediction of the path loss in these models. The proposed WUSN-PLM outperforms the Conventional and the NC Modified Friis with a lowest RMSE, MAE and MAPE regardless the type of sandy clay soils. Thus, the predicted values of the WUSN-PLM are closer to real observations than the existing path loss. In order words, similar to results of Table XVII, our proposed path loss is more accurate for UG2UG wireless communication than the existing approach on an application of precision agriculture.

VII. CONCLUSION AND FUTURE WORKS

In this paper, we designed the Wireless Underground Sensor Network Path Loss Model for precision agriculture called WUSN-PLM. To achieve it, we first simplify the underground communication types to a generic model designed for precision agriculture. We integrated the accurate CDC prediction approach called MBSDM to our WUSN-PLM as in our previous work. The proposed model takes into account the three types of wireless communication (UG2UG, UG2AG and AG2UG) known in the WUSN field. Moreover, for each communication type and the node location, we consider phenomena like the wave attenuation or the wave refraction. To evaluate and validate the WUSN-PLM, intensive experimentations have been conducted in a real environment with two different pairs of wireless transceivers (nRF905 and LoRa SX1278). The resulting comparison has shown that the proposed WUSN-PLM outperforms the other approaches with the overall highest amount of *Good Prediction GP* (*TP* and *TN*) in dry soil (scenario #A) and in moist soil (scenario #B) for different communication type. Additional experiments are conducted in fully UG2UG communication in order to compare the errors of the predicted power received and the real measured RSSI. The evaluation shown that for UG2UG communication, our proposed approach has the lowest RSME, MAE and MAPE (32.7, 29.4 and 30.1 respectively).

As future works, we plan to extend our model to other WUSNs applications like ecological monitoring, finding of persons after natural disasters like earthquakes or floods. Furthermore, since the traditional WSN nodes have several constraints due to their limited resources, a path loss model adapted to their constraints with a low computation and memory need is planned.

APPENDIX

A1 – UG2UG path losses comparison in moist soil (5m and 20m).

Distances and communication			Moist. (%)	Convent. Modified Friis		NC Modified Friis		WUSN-PLM	
				#1	#2	#1	#2	#1	#2
5 m	top	15-> 15	40	FN	TP	TP	TP	FN	FN
		15-> 20	11	TP	TP	TP	TP	TP	TP
		15-> 30	41	FN	TP	TP	TP	FN	FN
		20-> 15	46	FN	TP	TP	TP	FN	FN
		20-> 20	48	TN	FP	FP	FP	TN	TN
		20-> 30	47	FN	TP	TP	TP	FN	FN
		30-> 15	72	FN	TP	FN	TP	FN	FN
		30-> 20	25	TP	TP	TP	TP	FN	FN
	sub	30-> 30	18	FP	FP	FP	FP	TN	TN
20 m	top	15-> 15	74	TN	TN	TN	TN	TN	TN
		15-> 20	53	TN	TN	TN	TN	TN	TN
		15-> 30	37	TN	TN	TN	TN	TN	TN
		20-> 15	66	FN	FN	FN	FN	FN	FN
		20-> 20	44	TN	TN	TN	TN	TN	TN
		20-> 30	66	TN	TN	TN	TN	TN	TN
		30-> 15	72	TN	TN	TN	TN	TN	TN
		30-> 20	25	TN	TN	TN	TN	TN	TN
	sub	30-> 30	18	TN	TN	TN	TN	TN	TN

A2 - UG2AG path losses comparison in moist soil.

Distances and communication		Moist. (%)	ZD Path Loss		XD Path Loss		WUSN-PLM	
			#1	#2	#1	#2	#1	#2
5 m	15-> gnd.	29	TP	TP	TP	TP	TP	TP
	20-> gnd.	48	TP	TP	TP	TP	TP	TP
	30-> gnd.	90	TP	TP	TP	TP	TP	TP
10 m	15-> gnd.	72	TP	TP	TP	TP	TP	TP
	20-> gnd.	22	FP	FP	FP	FP	FP	FP
	30-> gnd.	68	TP	TP	TP	TP	TP	TP
15 m	15-> gnd.	20	FP	FP	FP	FP	FP	FP
	20-> gnd.	66	TP	TP	TP	TP	TP	TP
	30-> gnd.	58	FP	FP	FP	FP	FP	FP
20 m	15-> gnd.	17	TP	TP	TP	TP	TP	TP
	20-> gnd.	81	TP	TP	TP	TP	TP	TP
	30-> gnd.	39	TP	TP	TP	TP	TP	TP

A3 - AG2UG path losses comparison in moist soil.

Distances and communication		Moist. (%)	ZD Path Loss		XD Path Loss		WUSN-PLM	
			#1	#2	#1	#2	#1	#2
5 m	gnd.-> 15	91	TP	TP	TP	TP	TP	TP
	gnd.-> 20	40	TP	TP	TP	TP	TP	TP
	gnd.-> 30	66	TP	TP	TP	TP	TP	TP
10 m	gnd.-> 15	50	TP	TP	TP	TP	TP	TP
	gnd.-> 20	66	TP	TP	TP	TP	TP	TP
	gnd.-> 30	65	TP	TP	TP	TP	TP	TP
15 m	gnd.-> 15	67	TP	TP	TP	TP	TP	TP
	gnd.-> 20	71	TP	TP	TP	TP	TP	TP
	gnd.-> 30	73	FP	FP	FP	FP	TN	TN
20 m	gnd.-> 15	95	TP	TP	TP	TP	TP	TP
	gnd.-> 20	41	TP	TP	TP	TP	TP	TP
	gnd.-> 30	64	FP	FP	FP	FP	TN	TN

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