An overview on IoUT and the performance of WiFi low-cost nodes for IoUT Applications

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GLOBECOM 2020 - 2020 IEEE Global Communications Conference | 978-1-7281-8298-8/20/$31.00 ©2020 IEEE | DOI: 10.1109/GLOBECOM42002.2020.9348057

Abstract— **It is evident that the Internet of Things (IoT) is a technology that is not only already being implemented but it is also going to be part of our everyday life in many aspects regarding our homes, workplace and the cities we live in. As the concept of IoT evolves, new terminologies are being developed to specify certain characteristics of the IoT network. The Internet of Underground Things (IoUT) is an example of these new terms, considering, in this case, the soil medium. IoUT is then separated from IoT in the fact that the requirements of underground communications and the underground nodes are different from those in regular IoT networks and, therefore, IoUT should be studied separately. However, as IoUT is a new concept, there are not many studies available. Therefore, in this paper, an overview of the IoUT concept and the most important conclusions that have been reached on this topic is presented. Furthermore, transmission experiments between underground and above-ground low-cost WiFi nodes deploying them at different depths, heights, and distances to determine the suitability of the currently available low-cost nodes for this new IoT concept have been performed. The results show that the optimal height is 1.5 meters and the optimal depth is 20 cm. Furthermore, the connection was able to reach distances up to 10 m. Lastly, an underground transmission decision-making algorithm for soil monitoring nodes in precision agriculture has been provided.**

Keywords— IoUT; Wi-Fi; RSSI; agriculture; low-cost.

I. INTRODUCTION

The main objective of the Internet of Things (IoT) is to establish the connection between devices to automate and control processes that are carried out on a daily basis. The scope of IoT has varied and, as the years go by, its applicability increases. Cisco [1], predicts that M2M connections will grow 2.4-fold, from 6.1 billion in 2018 to 14.7 billion by 2023. There will be 1.8 M2M connections for each member of the global population by 2023. The increase, in their use, is due to the decrease in the costs of the devices and the means of transmission of the observed information.

Fig. 1 shows a schematic of the connectivity between the different elements that make up the IoT. In it, it can be seen that there are not only person-person and person-machine connections, but machine-machine connections are established as well. The establishment of optimal communications, between the different elements that make up the IoT system, is essential for its implementation to be carried out. For this, different cases must be studied in the different areas where the IoT will be applied. In general, a common network infrastructure will not be necessary to connect the devices. Furthermore, the networks connecting the devices will be short-range and complex.

Today, IoT applications for Smart Homes, Smart Cities, Smart Agriculture, eHealth, Environmental monitoring, Energy management, Manufacturing, Transportation, Internet of Military Things (IoMT), etc., can be found. The increase in the world population, estimated at 31% in 2050 [2], makes evident the need for a 72% increase in natural resources and food [3]. To achieve such a significant percentage increase, it is necessary to apply the new agricultural techniques provided by Smart Agriculture. Using Precision agriculture (PA), agricultural needs can be properly assessed. To have great precision in the predictions, it is necessary to do an adequate monitoring of the soil conditions. By applying new models such as the Internet of Underground Things (IoUT) or the Internet of Underwater Things, the use of underground and submarine sensors can be facilitated.

According to Vuran [4], IoUT consists of sensors and communication devices, partly or completely buried underground for real-time soil sensing and monitoring. Underground communications can be performed both by wired and wireless technologies. Wireless technologies are based on acoustic waves, electromagnetic waves (EM), magnetic induction (MI) and, visible light communication (VLC) while the wired technologies use coaxial cable and optical fibers [5]. When using IoUT, if EM is emitted, there are scenarios where the sensors are buried under a cultivated field, and the communication is performed between buried nodes, between some of the buried nodes and nodes or surface wireless devices that collect the signal emitted by the buried node, and the nodes or surface wireless device that send the signal via WiFi to other points. Therefore, the requirements of the soil medium and its characteristics should be considered for the design of an IoUT network. For that purpose, there are path loss prediction models specific to the underground channel [6].

Many coverage studies and models have been done for IEEE 802.11 in indoor environments [7-8], however, that is not the case for underground mediums.

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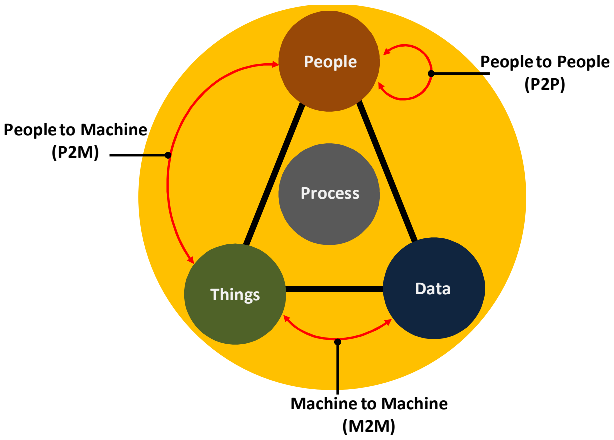

Fig. 1: Connectivity between the different IoT elements.

In this work, an overview of the current state of IoUT is presented. Also, transmission experiments have been performed between an underground node and an above-ground Access Point (AP) where different burial depths and different AP distances and heights were considered. To carry out the experiments, EM wireless technology was used. Moreover, they were carried out with low-cost nodes, capable of transmission through IEEE 802.11 standards.

The remainder of this paper is organized as follows. Section 2 presents an IoUT overview. The testbed description is explained in Section 3. The results are discussed in Section 4. The underground wireless communication proposal is presented in Section 5. Lastly, Section 6 draws the main conclusions and future works.

II. IoUT OVERVIEW

In this section, an overview of the concept of IoUT and its characteristics is provided.

IoUT is an IoT network comprised of at least one underground device with communication capabilities. In the case of the Over The Air (OTA) communication among the above-ground things, the communication can be affected by weather conditions, irrigation, and crop growth. Therefore, these aspects should be considered. On the other hand, underground communication has other requirements such as adapting the transmission parameters to be able to transmit through the soil considering its changing conditions.

The architecture of IoUT applications may be comprised of static and moving elements such as machinery, drones, sensing nodes, radios, and cloud [4]. These elements should be integrated and can be utilized for both real-time sensing and automation.

The underground things are embedded systems with sensors for monitoring and a communication module. Underground things should be encapsulated in waterproof and weatherproof materials to avoid damages in the equipment from weather, animals, or machinery. They are powered by batteries, solar panels, or a combination of both and are expected to be low-cost. Underground things are deployed in large numbers to perform sensing in multiple places of the field. Base stations have a larger cost and are usually deployed at buildings or weather stations. They have access to more power as they have higher requirements.

The machinery and vehicles utilized on the field can carry mobile sinks to gather the information from underground things as they move through the field. UAVs and robots can be employed as well for this purpose. The data is usually forwarded to a cloud service for its storage and analysis.

Fig. 2 shows a possible IoUT deployment for agriculture. However, there is no unified or standard IoUT architecture due to the different demands of the sectors that can employ this technology. One of the sectors that could benefit from IoUT is agriculture. In agriculture, IoUT is generally used for real-time sensing of soil moisture, ph, presence of organic matter, the composition of the soil, and nutrients [4]. It is also utilized for yield monitoring, precision planting, geolocation, map generation, soil sampling, drones, VRT, and auto steering. The usage of all these elements allows applications to divide the field into different areas according to the conditions of the field. Another sector is that regarding oil and natural gas extractions and transport. Oil and gas reservoirs can benefit from IoUT applications to perform temperature and pressure sensing and to detect pipe and gas leaks. However, localization is necessary to determine the position of the underground nodes. Nasir Saeed et al. resolved this problem using isometric scaling [9] and CRBL (Cramer Rao Lower Bound) in the closed-form to perform 3D localization as opposed to the existing two-dimensional solutions. Lastly, seismic exploration is another one of the uses of IoUT [5]. It differs from other uses such as agriculture in the required burial depth of the node.

The wireless communication in IoUT systems can be performed among underground elements, among above-ground things, and between underground and above-ground elements. The latter one is not symmetric because of the soil-air interface. Vuran et al. determine the communication range for underground communication to be 12 meters [4].

The characteristics of the soil as the communication medium is the principal aspect to consider in IoUT. The parameters that characterize the underground channel are the propagation of electromagnetic waves, soil composition, water content, the multipath effect, and burial depth [10]. Furthermore, when the transmission is performed among underground things, the communication is performed through a direct wave, a reflected wave, and a lateral wave with a path that proceeds along the soil surface. The latter one is the wave with the highest contribution to the received signal power [11].

The behavior of the signal in the 0.3-0.9 GHz band was studied to perform underground channel propagation models [10]. The results show that the effects of the reflected wave decrease with increases in burial depths, being negligible at depths higher than 2 meters. Therefore, for burial depths up to 2 meters, a two-path model should be used and for depths from 2 meters on, a single-path model can be considered.

Regarding the distance between the nodes, the higher the distance, the higher the path loss. Furthermore, when the signal is reflected on the soil-air surface, its phase is changed and, when aggregated with the direct signal, ripples can happen. Another aspect to consider is the lack of uniformity of the soil. As the soil surface is not uniform and smooth both reflection and refraction occur. The multi-path effect can occur as well due to roots, stones, and air, resulting in random values of the phase and amplitude of the signal. Lastly, L. Li et al. conclude that the operating frequency and the soil composition are the key aspects for successful underground

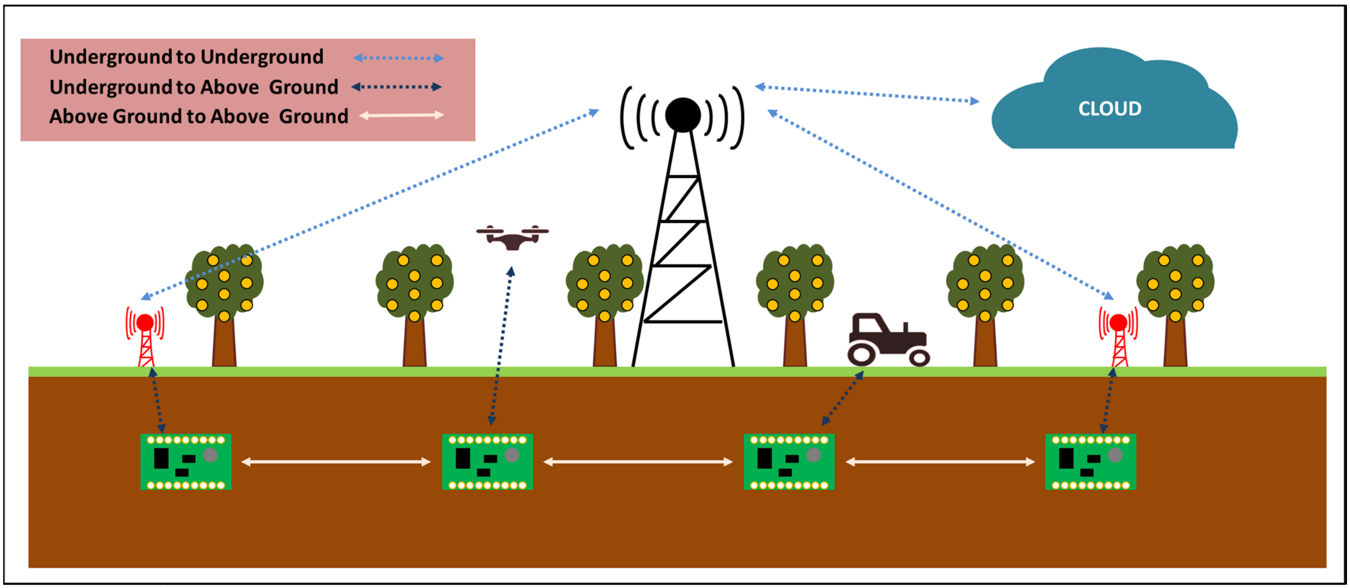

Fig. 2: Example of IoUT using EM.

wireless communication and the existence of an optimal burial depth that minimizes the path loss for each operating frequency [10].

Several technologies have been studied to be utilized for wireless underground communications [5]. Electromagnetic signals have low ranges, are very susceptible to interferences and attenuations, and have lower data rates. Acoustic communications are less susceptible to interferences in comparison to EM waves. It has high coverage ranges and low data rates. Mud pulse has medium interferences and attenuation, a high coverage range, and low data rates. Magnetic induction has a medium coverage range, data ranges of kbps, and low interferences and attenuation. Lastly, VLC has low interferences but high attenuation. It has a medium coverage range and data rates of kbps.

N. Saeed et al. utilized magnetic induction to establish wireless communication between underground things for oil and gas reservoirs [9] to perform 3D localization. The results show that the channel and parameters such as transmission power, error variance, coil size, and the number of underground things affect the localization accuracy. The performance is improved by increasing the number of turns in the coils, the transmission power, and the number of anchors. When the ranging error variance stays between 10 and 30%, the proposed solution is robust, but higher values are not accurate. In summary, the proposed solution is able to improve the localization accuracy by 30%. However, M. C. Vuran et al. determine that magnetic induction is not an option for IoUT systems [4].

A. Salam et al. studied the effects of soil type and moisture on the quality of wireless communication among the Underground Things [11]. From experiments performed both indoors and outdoors, results showed that lower soil moisture led to an increase of the channel capacity by 180%. Adapting the sub-carrier bandwidth to the soil conditions led to increases in capacity ranging from 56% to 136%. From experiments performed with sandy soil, silt loam soil, and silty clay soil with a system bandwidth of 20 MHz for all soils, the achieved capacity was 233 Mbps for sandy soil, 195 Mbps for silt loam soil, and 178 Mbps for silty clay soil. Furthermore, when studying the changes in capacity when increasing the distance from 50 cm to 100 cm, a decrease of 22 % was detected in sandy soil, a decrease of 29% in silt loam soil, and a decrease of 27% in silty clay loam soil. The water holding capacity of the soil is the principal soil parameter in the attenuation of electromagnetic waves. The higher the clay content of the soil, the higher the EM attenuation due to the small pore size. Moreover, the signal travels through both soil and air, with their respective conductivity and permittivity values and through multiple paths. This results in an increase in the delay spread as the distance increases, obtaining less coherence bandwidth. Lastly, distance is another parameter that determines the channel capacity. Experiments were performed with antennas buried at 20 cm of depth in silty clay loam soil using an empirical antenna bandwidth of 20 MHz. Results showed a decrease from 678 kHz to 411 kHz in the coherence bandwidth when the distance was increased from 50 cm to 12 m, and an increase in the number of subcarriers from 30 to 49.

Regarding the future challenges of IoUT, N. Saeed et al. commented on the difficulty in deploying IoUT nodes and accessing them for activities such as battery replacement [5]. Therefore, batteries should have a high enough capacity to reduce as much as possible the need for accessing the nodes and, the utilized protocols should implement energy-efficient functionalities. Furthermore, the nodes can get damaged if digging activities are performed. Another aspect is the transmission range that can be obtained in wireless underground communications, which is reduced due to the attenuation caused by the characteristics of the soil. Security in IoUT is not a topic that has been thoroughly studied yet. The physical security of the nodes is one of the security aspects that have to be considered as the nodes must be protected from the corrosion, machinery, and digging activities. Furthermore, regarding cyberattacks, the interest in blockchain has been increasing. There are also problems regarding scalability and robustness. N. Saeed et al. also comment on the use of Software Defined Networks and cloud and fog computing to optimize data traffic, analysis, and data storage.

III. TESTBED DESCRIPTION

In this section, the performed testbed is presented.

The diagram of the testbed is presented in Fig. 3. As it can be seen, there were four nodes placed at the depths of 10, 20, 30, and 40 cm, as in our previous work [12]. However, in these sets of experiments, we have measured the RSSI with the AP located at heights of 50, 100, 150, and 200 cm. As in [12], there were four ESP8266 Mini D1 [13] nodes buried in the soil inside a protective box. All nodes utilized their built-in antenna. They were taped to the base of the box to avoid undesired movements when burying the boxes. The AP was moved horizontally away from the place the nodes were buried in 1-meter intervals, moving the platforms as shown in Fig. 4.

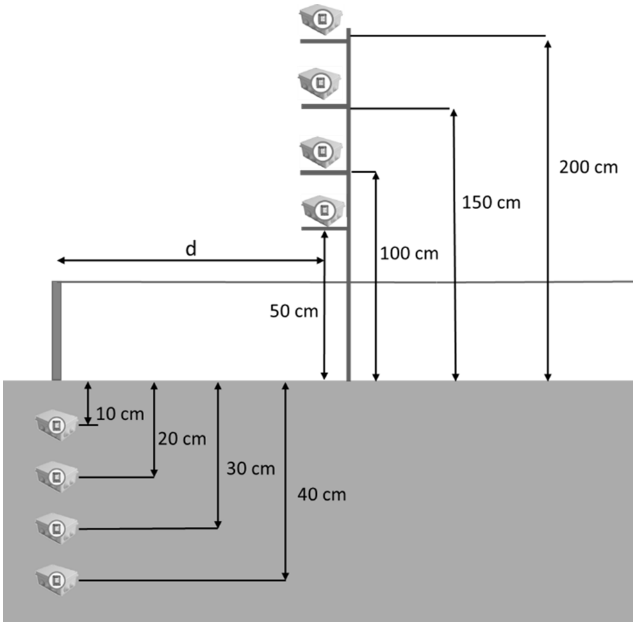

Fig. 3: Diagram of the testbed.

To ensure no other networks produced interferences, a preliminary experiment was performed to determine if there were other networks in the area. Furthermore, there were no residences in the area. The nodes were placed in the same hole at different depths and the soil was slightly compacted. Moreover, the soil had a high content of sand. The area has a Mediterranean climate and the surrounding fields are utilized as citrus plantations, as it can be seen in Fig. 5.

Fig. 4: Field where the experiments were performed.

Fig. 5: Field where the experiments were performed.

IV. RESULTS

In this section, the results from the coverage experiments performed between an underground node and an above-ground AP at different depths and heights are presented.

The RSSI values for each depth and each AP height are presented in the following figures. The measures at each height and length were taken five times and the average was calculated for each case.

Fig. 6 presents the RSSI obtained from the node buried at 10 cm of depth. As it can be seen, the signal was able to reach 10 meters of length the node getting disconnected from the AP. The good quality RSSI signal values reach a length of 2 meters for a height of 1.5 meters. This height is also the best for the range between -70 and -80 dBm. Furthermore, there is a noticeable difference between the quality of the signal below and above the height of 1 meter. For the heights below 1 m, acceptable signal quality only reaches the 2-meter mark. However, for heights above 1 meter, it reaches up to 7 meters of length. For the RSSI values between -80 and -90, the maximum distance is up to 7 meters for heights below 1 meter and up to 9 meters for height above 1 meter.

The RSSI obtained from the node buried at 20 cm of depth is presented in Fig. 7. In this case, there is a similar pattern to that of the node buried at a depth of 10 cm. However, the signal reaches 9 meters of length before getting disconnected. 1 meter less than in the case of the node buried at 10 cm of depth. However, it is important to remark that acceptable RSSI values reached up to 8 meters, 2 meters more than the node situated above. Good signal quality values reached a similar distance. Lastly, the signal reached RSSI values between -80 and -90 dBm further than in the previous case for the AP located at heights below 1 meter.

Fig. 8 presents the RSSI obtained from the node buried at 30 cm of depth. The reduction of the quality of the signal is evident with the node buried at this depth. No good-quality signal values were obtained. The signal was able to reach up to 7 meters of length before disconnecting. Furthermore, the signal was considerably better for heights above 1 meter, with acceptable RSSI values up to 6 meters of length.

Lastly, Fig. 9 presents the RSSI obtained from the node buried at 40 cm of depth. Similar to the node located at 30 cm of depth, the signal was able to reach 7 meters before getting disconnected. However, acceptable RSSI values only reached the 3-meter mark.

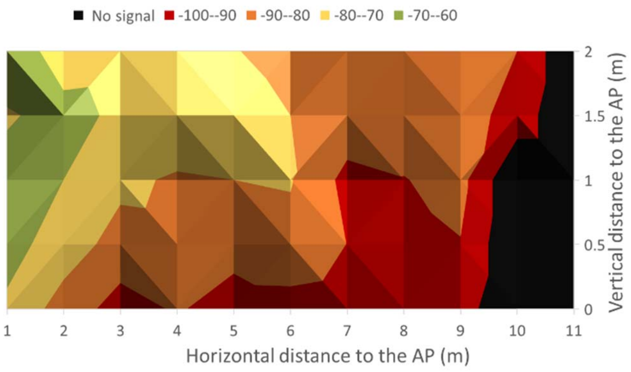

Fig. 6: RSSI at 10 cm of depth.

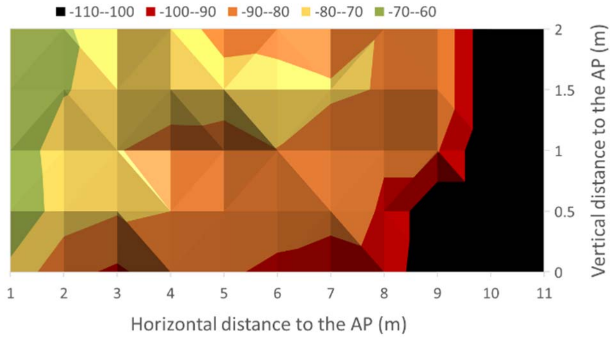

Fig. 7: RSSI at 20 cm of depth.

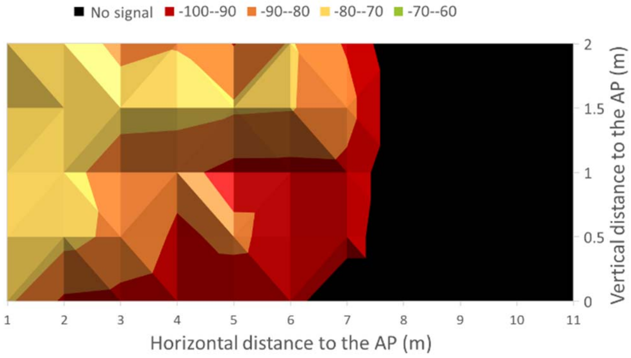

Fig. 8: RSSI at 30 cm of depth.

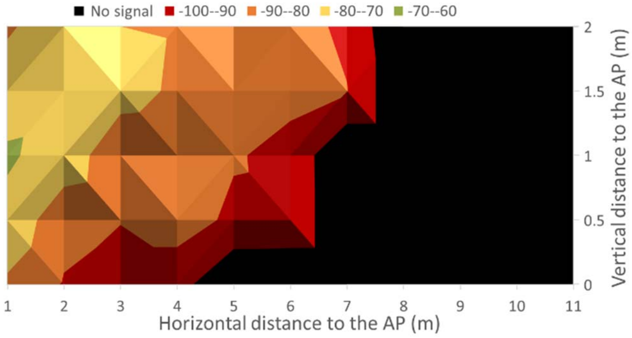

Fig. 9: RSSI at 40 cm of depth.

V. UNDERGROUND WIRELESS COMMUNICATION

With the experiments performed in the previous section, the best transmitter depth-receiver height for underground-above-ground communication has been determined. In this section, a data transmission decision technique is going to be presented according to the characteristics of the underground transmission.

The propagation loss caused by the soil and the received power can be determined by the modified Friis model [6,10]. In our previous work [12] this approach was employed adding the effects of the humidity in the air, Lambient-humidity, of the area where the measures were performed, which has a value of 0.006 dB. Obtaining (1), for the received power Prx (dB). Equation (2) shows the transmitter power at 1 m, Ptx-1m (dB), which has a value of -59.857 dBm for the nodes employed in the experiments. In both (1) and (2), the distance is expressed in meters.

$$P_{rx} = P_{tx-1m} - 20 * \log d - L_{soil} - L_{ambient-humidity} \quad (1)$$

$$P_{tx-1m} = 20\ \log_{10} d + 20\log_{10}(f(Hz)) + 20\log_{10}\left(\frac{4\pi}{c}\right) \quad (2)$$

The attenuation caused by the soil is expressed in (3). The dielectric constants (μ,ε) should be obtained from testing the soil at the laboratory as they may vary greatly according to its content of clay, sand, and silt. The attenuation constant is expressed in (4) and the penetration depth is $d=5.31*10^{-3}$ ($\sqrt{(\varepsilon')}\ /\ \sigma$).

$$L_{soil} = 20\log\left(\sqrt{\mu_r\varepsilon_r}\right) + 8.69\alpha d \quad (3)$$

$$\alpha = \frac{1}{5.31 * 10^{-3} * \frac{\sqrt{\varepsilon'}}{\sigma}} \quad (4)$$

As the dielectric constants may be difficult to obtain, D. W. Sambo [6] proposed a Complex Dielectric Constant (CDC) prediction model based on the Mineralogy-Based Soil Dielectric Model (MBSDM) which utilizes clay content, soil moisture, and wave frequency and is valid for frequencies between 45MHz and 26.5GHz. In other to measure soil moisture, D. W. Sambo et al utilized the YL-69 sensor [6]. This sensor is one of the most common low-cost soil monitoring sensors on the market and it is utilized by many of the IoT irrigation proposals available in literature.

One of the key functionalities of precision agriculture systems is soil monitoring. Soil monitoring nodes are the elements more susceptible of being deployed underground in an IoUT system. These nodes incorporate sensors to monitor soil humidity, temperature, ph, and nutrients. Particularly for irrigation systems, nodes such as the Arduino UNO or the Node MCU are the most utilized in scientific papers. Considering the extended use of low-cost nodes for IoT precision agriculture systems, as high soil moisture values lead to high signal attenuation in underground communications, the decision-making process regarding the transmission of the data gathered by soil monitoring IoUT nodes can be improved making use of the soil moisture values provided by the sensors.

The decision-making algorithm is presented in Figure 10. After obtaining the information from the sensors, the humidity threshold (Hth) is evaluated. According to the selection of the settings performed by the user, humidity values are divided into three different ranges as it is exemplified in Figure 11. If the value of Hth is 3, then the humidity of the soil is high, and the data is stored. Then, if the value stored at the variable that indicates the time of the last transmission (TLT) surpasses the maximum time the node can stay without forwarding any data (Max Time), the urgent transmission (UT) flag is activated. If the maximum time has not been surpassed, the node goes into sleep mode. If the value of the humidity threshold is 2, the settings of the transmission mode (TM) are checked. A value of 1 indicates the default mode and the value 0 indicates the energy-saving mode. When the normal mode is activated and the value of the humidity threshold is 2, the transmission power (TP) of the antenna is set to high (value 1). The high setting depends on the characteristics of the utilized antenna and should be specified at the preliminary set-up. This is done to increase the quality of the signal that reaches the receiver when there are medium levels of soil moisture. Then, the urgent transmission flag and the counter of the last transmission time are set to 0 and the node goes to sleep. Lastly, if the humidity threshold is set to 1, the transmission power of the antenna is set to default, and the data is forwarded. In this manner, the soil monitoring node is able to decide when and how to transmit the gathered data according to the moisture levels of the soil.

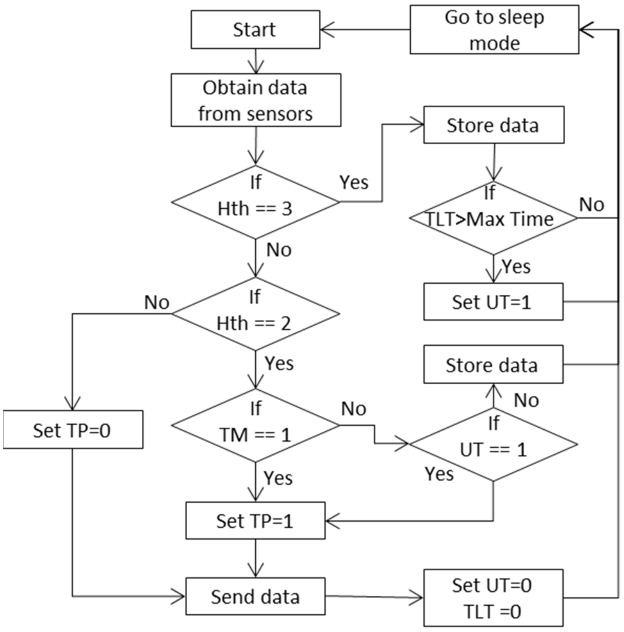

Fig. 10: Underground transmission decision-making algorithm.

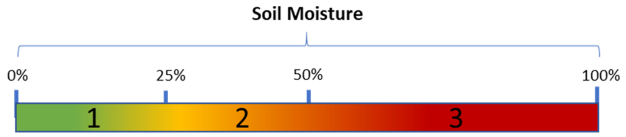

Fig. 11: Humidity threshold example from soil moisture values.

VI. CONCLUSION AND FUTURE WORK

As IoT evolves, new concepts are being developed. One of these new forms of IoT is IoUT. IoUT considers the soil as the communication medium between some of the elements of the networks, specifically, those deployed underground. In this paper, an overview of the concept of IoUT and the current conclusions that have been reached on this topic was provided. Transmission experiments between underground and above-ground low-cost WiFi nodes were performed as well. The nodes were positioned at different burial depths, and the receiver was deployed at different distances and heights. The results showed the optimal depth is 20 cm and the optimal height was 1.5 m. The connection was available up to distances of 10m. Lastly, an underground transmission decision-making algorithm for soil monitoring nodes in precision agriculture was provided.

As future work, experiments with other available wireless technologies will be performed to determine which one of the actual available EM wireless technologies would be the most suitable for IoUT.

ACKNOWLEDGMENT

This work has been partially supported by the European Union through the ERANETMED (Euromediterranean Cooperation through ERANET joint activities and beyond) project ERANETMED3-227 SMARTWATIR and by the European Union with the “Fondo Europeo Agrícola de Desarrollo Rural (FEADER) – Europa invierte en zonas rurales”, the MAPAMA, and Comunidad de Madrid with the IMIDRA, under the mark of the PDR-CM 2014-2020” project number PDR18-XEROCESPED.

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