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System Assessment of WUSN Using NB-IoT UAV-Aided Networks in Potato Crops

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ABSTRACT Unmanned Aerial Vehicles (UAV) are part of precision agriculture; also, their impact on fast deployable wireless communication is offering new solutions and systems never envisioned before such as collecting information from underground sensors by using low power Internet of Things (IoT) technologies. In this paper, we propose a (Narrow Band IoT) NB-IoT system for collecting underground soil parameters in potato crops using a UAV-aided network. To this end, a simulation tool implementing a gateway mounted on a UAV using NB-IoT based access network and LTE based backhaul network is developed. This tool evaluates the performance of a realistic scenario in a potato field near Bogota, Colombia, accounting for real size packets in a complete IoT application. While computing the wireless link quality, it allocates access and backhaul resources simultaneously based on the technologies used. We compare the performance of wireless underground sensors buried in dry and wet soils at four different depths. Results show that a single drone with 50 seconds of flight time could satisfy more than 2000 sensors deployed in a 20 hectares field, depending on the buried depth and soil characteristics. We found that an optimal flight altitude is located between 60 m and 80 m for buried sensors. Moreover, we establish that the water content reduces the maximum reachable buried depth from 70 cm in dry soils, down to 30 cm in wet ones. Besides, we found that in the proposed scenario, sensors' battery life could last up to 82 months for above ground sensors and 77 months for the deepest buried ones. Finally, we discuss the influence of the sensor's density and buried depth, the flight service time and altitude in power-constrained conditions and we propose optimal configuration to improve system performance.

INDEX TERMS Precision agriculture, NB-IoT, unmanned aerial vehicles, wireless underground sensor networks.

I. INTRODUCTION

Recently, using Unmanned Aerial Vehicles (UAV) in agriculture, commonly known as drones, has gained much interest. Drones can play an essential role in the Precision Agriculture (PA): from gathering images in hard-to-reach crops fields to spraying pesticides in large fields on exact locations. Similarly, also the use of drones in wireless communications has gained substantially more interest in diverse applications like supporting terrestrial cellular networks, assisting IoT (Internet of Things) applications, or being a simple end-user [1]–[4]. Recent advances in Long-Range Wide Area Networks (LPWAN) have made the usage of wireless sensors into agriculture feasible [5]–[7]. However, these are not practical to use in potato crops because plowing and harvesting can damage the sensors. As a solution, a Wireless Underground Sensor Network (WUSN) is presented as a promising way to acquire parameters from the soil [8], [9]. However, having a fixed infrastructure in large fields could lead to considerably larger distances and limitations in signal propagation. These drawbacks, in turn, lead to broken links in the network or rapid battery depletion. To overcome these downsides, we propose using a UAV to collect the data from underground sensors. This novel approach aims to reduce the transmission power and thus increase sensors' battery life. In addition, it will result in reduced implementation and

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maintenance costs in the long term, making the solution viable for farmers. This innovative methodology has not yet proposed by other authors and promises to increment the quality of potato crops and increase the production of these fields.

In this article, we propose an IoT system solution based on the usage of Unmanned Aerial Base Stations (UABS) to gather information from Underground Sensors (UGS). Its objective is to reduce the transmission power from the sensors and extend battery life. First, the study of the underground-to-aboveground (UG2AG) channel and its limitation related to power transmission is presented. Next, we evaluate the network performance based on the capacity of the wireless links, the UAV altitude and flight time, the density of the UGS, and the power consumption. As far as the authors' knowledge, there are no studies of IoT-based UABS serving underground sensors. In this innovative study, we evaluate the viability of the proposed network architecture and diverse parameters related to the capacity and life extension of the system described. We designed a simulation tool describing the network system architecture that includes a resource allocation algorithm to evaluate performance parameters. This approach differs from existing ones in the way that fixed infrastructure in large fields leads to excessive power usage from ground nodes leading to rapid battery depletion and substantial infrastructure deployment costs. Moreover, compared with actual drone solutions, image processing from on-board cameras is limited to indirect topsoil measurements rather than actual underground values. Our results show that the system architecture proposed is viable for aboveground and underground sensors. Some coverage limitations are found in wet soils that reduce the connectivity of sensors buried under 30 cm. Lastly, the battery usage of the nodes is found to last more than six and a half years in the proposed configuration.

The outline of this paper is as follows. Section II presents a survey of drone usage in agriculture and its relation to potato crops. Section III reviews technical aspects of WUSN, LPWAN technologies, and UAV-aided networks. The methodology used to describe the network architecture, the scenarios, the path-loss models, and the tool employed for the system assessment is presented in Section IV. Results are discussed in Section V, and Section VI collects the conclusions and discusses future work.

II. UNMANNED AERIAL VEHICLES IN AGRICULTURE

This section illustrates the relation between UAV in agriculture and potato crops in order to define a proper scenario for our study.

A. DRONES IN PRECISION AGRICULTURE

The role of Unmanned Aerial Vehicles (UAV) in agriculture has gained much interest in recent years [10], [11]. Precision agriculture and surveying are applications where crops are monitored with drones. They take images for the detection of weeds, pests, and pathogens, using high resolution, multispectral, or infrared cameras for later post-processing [12]. Different cases of study for precision agriculture using UAV with IoT nodes are discussed in [13]. Similarly, data monitoring through the implementation of Wireless Sensors Networks (WSN) will increase the efficiency of crop supervision, reducing data acquisition time [14]. This article is focused on the role of precision agriculture, specifically in the Wireless Sensor IoT measurement system using UAV.

B. POTATOES CROPS

Potato crops are an essential product in agriculture. In Europe, only in 2015, the fields added up to 1.6 million hectares producing an equivalent of 23 million tons of potatoes. On the contrary, the situation in Europe was much better in 2000, when the production rose to 83 million tons of potatoes [15]. This reduction of production was mainly related to the lower production rate per hectare due to unpredictable weather conditions. Moreover, in Europe, the size per field is quite small compared with non-European countries. The average in Europe is 0.8 hectare per field, with Denmark, the Netherlands, and the United Kingdom having average sizes of 20.6 hectares, 17 hectares, and 16.9 hectares, respectively. In South American countries, such as Colombia, the average field size was about 20 hectares [16]. Further, the production of potatoes is close to 2.6 million tons in 2015. High plains in Colombia with altitudes between 2000 m and 3500 m above sea level, hilly topography regions and regular rains all year round, make the country suitable for enormous potato crops [17], [18]. In this assessment, we are going to focus on 20 hectares fields.

III. NETWORK ARCHITECTURE FOR WUSN USING UAV

A network architecture definition to support agricultural applications using UAV and IoT are described here. First, the role of the WSN in agriculture is described. Second, the most relevant IoT long-range technologies are presented. Finally, the innovation of the usage of UAV as gateways and its role with IoT in agriculture is collected in the last subsection.

A. WIRELESS SENSOR NETWORKS IN AGRICULTURE

The research field of wireless sensors in agriculture to collect information from the crops has been growing actively in recent years. Several authors have done surveys in this area and have pointed out the importance of WSN in agriculture. A broad review of WSN applications is presented in [19]. In [7], a description of the main types of sensor networks and its challenges is presented, varying from terrestrial sensors to multihop underground sensors. It also describes an extensive list of sensors available in the market for agricultural applications. An introduction to WSN in precision agriculture within the study of a real soil sensor is presented in [6]. [20] presents a comprehensive study of WSN, including the wireless technologies and the energy-efficient mechanisms used in agriculture to extend sensors' battery life. An introduction to the IoT and its technologies in smart agriculture is available in [21]. A thorough description of the significant applications and technologies, including UAV, is offered in [22]. In [23], an architectural model for IoT monitoring in potato crops is presented. A practical application of WSN within a complete IoT scenario is presented in [24]. Gao in [25] introduces a QoS prediction method for IoT services in diverse scenarios.

The usage of WSN will help to determine soil parameters like humidity, volumetric water content (VWC), ground temperature, and pH level. These will determine the relation of nutrient absorption from the soil. Due to the nature of the potatoes' harvesting process, mainly through plowing, the most appropriate solution is to bury the sensors at underground depths where plowing machines could not reach and damage the sensors. In 2006, the concept of wireless underground sensors networks (WUSN) and its challenges were introduced [9]. Here the requirements of this technology and its first applications were presented. Subsequently, WUSN were gaining attention, mainly when power constrain sensors could be implemented. Yu describes the importance of WUSN and presents experimental results for an underground network with a mobile robot above ground collecting information [5]. A connectivity study of the WUSN for soil parameters is presented in [26]. Finally, in agriculture, there are mainly two types of WUSN: the ones in the topsoil (between 0 and 30cm depth) and the ones in the subsoil (under 30cm depth) where soil characteristics affect the wireless propagation differently [27]. In this study, we are studying the impact of both types of soils.

B. LOW-POWER WIDE-AREA NETWORKS TECHNOLOGIES

The usage of Low-Power Wide-Area Networks (LPWAN) wireless sensor technologies proposes several challenges to the network definition. Specifically, the definition of the underground wireless channel under the limits of low-power wireless sensors. Batteries in IoT wireless sensors are intended to last up to ten years [28], mainly if the site of the sensor is unknown or if it is placed in a difficult-to-reach spot. Two primary technologies could be used to deploy the WUSN aided by UABS, which is Narrow Band IoT (NB-IoT) and Long Range Radio (LoRa) [29]–[31].

The NB-IoT is one of three standards based on the LTE release 13 - 3GPP standard [32], in conjunction with eMTC and EC-GSM-IoT. It is the simplified version of the cellular network for IoT low power communications. The NB-IoT standard answers the need for low power transmissions, reducing the complexity of the transmitters while using channel bandwidths of 180 kHz [33], [34]. The advantages of NB-IoT include the usage of time-scheduling that allows the User Equipment (UE) to remain asleep while there is no transmission, leading to low power consumption procedures called power saving mode (PSM) introduced in the Rel 12. This characteristic allows devices to have a battery life of up to 10 years using appropriated scheduling and tracking area update (TAU) parameters. The 3GPP TR 45.820 v13 [35] defines in detail the physical and MAC layer aspects for IoT communications, including download and upload physical layer design, access procedures, and radio resource management procedures. The 3GPP TR 36.802 v13 also defines the radio requirements for NB-IoT, including frequency bands, channel arrangements, minimum receiver parameters, and coexistence prevention procedures [32].

LoRa is a physical layer technology patented by Semtech that uses a novel spread spectrum modulation based in the Chirp Spread Spectrum (CSS) [31]. LoRa, in association with the LoRaWAN (Long-Range Wide Area Network) which is the open MAC protocol defined by the LoRa Alliance, allows engineers to develop a case-specific protocol according to the specific needs of the network [36]. The most crucial advantage of LoRa incorporates a receiver sensitivity of 20 dB under the noise floor that includes interference tolerance for communication at different data rates. The different data rates are defined by the spreading factor (SF), which allows the creation of virtual channels with orthogonal codes permitting transmissions without interference if a different SF is used. As a result, for higher SF values, the data rates will be lower, resulting in more extended coverage areas of tenths of kilometers [37]. This technology is planned to work in the unlicensed bands of 433/317 or 868/915 MHz, with bandwidths of 125 to 500 kHz depending on the region and the data rate needs. All devices must support at least three subchannels of 125 kHz in the ISM EU863-870 band. Furthermore, the open architecture of the LoRaWAN protocol allows that almost anyone could deploy a LoRa network. This protocol is based in a duty cycle per subchannel, limiting the amount of transmission in the air to 1% duty-cycle; this means that a device could send a message of 1-second every 100 seconds, to avoid collision with other devices.

These two technologies are competing for the market of IoT applications with communication distances greater than 1 km. Both are designed to fulfill different requirements in the IoT market. Equally, they work in sub-1GHz frequency bands with data rates up to 50 kbps and focuses on power efficiency. However, each one has its advantages. NB-IoT outperforms in latency and provides better QoS due to the usage of a time-slotted synchronous protocol. Contrary, LoRa, could overtake NB-IoT in the transmission range and coverage, and the reduced cost of implementation [30]. Table 1 compares these technologies in the context of agricultural monitoring.

TABLE 1. Comparison parameters of LPWAN technologies.

Parameter	NB-IoT	LoRA
Spectrum	Licensed	Unlicensed
Modulation	QPSK	CSS
Bandwidth	180kHz	125-500kHz
Bit rate	56bps-43.2kbps	290bps-50kbps
Power efficiency	Medium-High	Very-High
Latency	<10 s	Up to 100x TOA
Minimum SNR	-20.0dB	-6.7dB
Peak Power Usage	430mW	110mW
Interference	Low	High
Standardization	3GPP Rel 13	De Facto

C. UNMANNED AERIAL BASE STATIONS

Unmanned Aerial Vehicles have several applications in wireless networks. Recently, the implementation of gateways into UAVs is gaining much attention among researchers. This concept is commonly known as Unmanned Aerial Base Station (UABS) when a base station (BS) is mounted on a drone to support ground communications. The applications of this model range from providing service to users in disaster scenarios, to data acquisition from IoT devices [3], [14], [38]–[42]. Mozaffari *et al.* [3] presents a comprehensive review of the usage of UAV, providing connectivity to ground devices. Also, in [43], they describe the vision of a 3D cellular network taking into account 5G network requirements. Efforts focusing on the location of UABS are addressed in [41]–[47]. This field is one of the most notorious research directions ranging from optimization of the placement based on energy, traffic or coverage to power-constrained networks. Other works like [51]–[53] include the analysis of the access and backhaul network performance. However, specific studies involving only M2M and IoT devices in agricultural scenarios are scarce. The works in [54], [55], explain a dynamic clustering methodology to support link connectivity of IoT Agricultural sensor nodes. [56] proposes a hybrid UAV-WSN to acquire data from large areas based on the movement of the UAV and WSN locations. The work in [57] discusses the relationship between the location of the UAV and energy consumption based on the sensor's transmission policy. [58] presents a multi-layer hybrid IoT–UAV–satellite architecture to optimize coverage and densification. Mignardi in [59] discusses the importance of proper trajectory design for UAV while serving NB-IoT nodes. The work in [60] introduces a multilayer UAV network for IoT applications using 5G networks. A practical LoRa deployment measuring the received signal strength (RSS) is presented in [61]. Finally, [62] reports experimental results for parameters affecting the link budget of an IEEE 802.15.4 rural IoT sensors using a UAV.

IV. METHODOLOGY

In this section, we define the system architecture for WUSN data collection through UABS. First, we describe the network parameters, and then we define the scenario. Next, we discuss the path loss for air-to-underground channels, and finally, we present our system evaluation tool.

A. NETWORK DESCRIPTION

We propose a UAV-aided network to support IoT agricultural applications and data collection, as presented in Fig 1. It is based in general architectures used in [1], [38], [44], [53]. The core network (CN) or facility, is the network part that allows access to the internet. The blue arrow describes the backhaul's direct link, which is the connection between the drone and the CN. From the CN part, connectivity can be provided through an above-roof antenna or a fast-deployable crane antenna to increase height and provide better link connectivity. The backhaul link uses LTE release 14 in the 3.5 GHz band

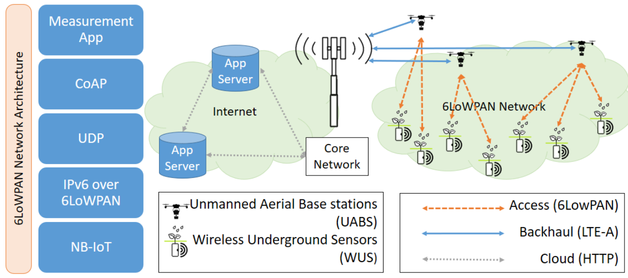

FIGURE 1. UAV-aided network architecture for IoT agricultural applications.

that could be used even in out-of-band or in-band frequency allocation [63]. This band is envisioned as a promising band because it is not broadly allocated, and its use could overcome the limited available spectrum from other bands. Specifics of the backhaul radio parameters are presented in table 2 and a detailed analysis could be found in [53]. The orange arrow describes the IoT access network. It defines the connectivity between the UABS and the ground sensors. To the best of the authors' knowledge, there is no research using an IoT gateway mounted on a UAV to collect data for agricultural ground sensors, neither using LoRa nor NB-IoT technology.

We propose to use NB-IoT due to its high tolerance to interference, well-known technology and a licensed band. These characteristics assure enhanced channelization and reduce interference to achieve better links for aboveground or underground communications [30], [33].

The access NB-IoT network consists of 36 sub-channels, each with a bandwidth of 5 kHz, for a total of 180 kHz [31]. The system uses three bitrates of 900 bps, 1.8 kbps and 3.6 kbps for an SNR of 0.5 dB, 2.6 dB and 4.9 dB, respectively [35]. Other radio parameters for the access network are presented in Table 2. The system is aware of the following

TABLE 2. Backhaul and access link budget parameters.

Parameter	Backhaul link	NB-IoT link
Frequency	3.5 GHz	716 MHz
Bandwidth	20 MHz	180 kHz
Number of used subcarriers	1 200	36
Total number of subcarriers	2 048	36
Number of Resource Blocks	100	-
Max Tx power	43 dBm	23 dBm
Antenna Gains	UABS: 5 dBi CN: 5dBi	UABS: 8dBi Ground Sensors: 0dBi
Fade margin	10 dB	7.4 dB
Interference margin	2 dB	0dB
Noise figure	5 dB	3 dB
Shadowing margin	8.2 dB	7.5 dB
CN antenna height	20m	-
Receiver Signal-to-Noise Ratio (SNR) for Modulation and Coding Scheme (MCS)	1/3 QPSK = -1.5 dB 1/2 QPSK = 3 dB 2/3 QPSK = 10.5 dB 1/2 16-QAM = 14 dB 2/3 16-QAM = 19 dB 1/2 64-QAM = 23 dB 2/3 64-QAM = 29.4 dB	1/3 π/2-BPSK = 0.5 dB 1/3 π/4-QPSK = 2.6 dB 2/3 π/4-QPSK = 4.9 dB

protocols. The physical and link layer protocols used are NB-IoT as described previously. Next, it considers IPv6 over 6LowPAN (IPv6 for Low-power Wireless Personal Area Networks) protocol to provide connectivity to a massive number of devices with constrained capabilities. The usage of open standards allows the interoperability and stability of the platform. 6LowPAN is focused on transmission time into the low-power network while maintaining connectivity with IPv6 networks utilizing i) header compression, ii) fragmentation and iii) layer-two forwarding [64]. In order to reduce the number of messages transmitted, User Data Protocol (UDP) is considered. Its headers could be compressed into the 6LowPAN header to reduce packet size. On top of UDP, the Constrained Application Protocol (CoAP) is used to support the application layer in the replacement of the Hypertext Transfer Protocol (HTTP). CoAP is designed to support application in resource-based web services with simple methods like Get, Put, Post and Delete, typical from HTTP, but simple enough for monitoring application through constrained devices [65]. Scheduling algorithms like the one offered in [66] for cloud services are not considered in this work. The above-described protocols are all designed to achieve the lower communication time for devices allowing the system to use the minimum transmission power and maximizing the system throughput.

B. SCENARIO DEFINITION

A potato field typically ranges in size from a couple of hectares to more than 30 hectares, depending on the region. Twenty hectares is the average size in Colombia and the maximum in some European countries, as described in section II.B. We consider a potato field of 20 hectares in the potato region in Colombia with low hills and small foliage to focus on the underground impact. Using a uniform distribution of sensors with 10 m spacing will sum up a total of 2000 nodes.

We will vary the number of nodes from 500 to 5000 to evaluate the impact of a flexible number. The buried depth of the sensors is varied for 0 cm, 25 cm, 50 cm and 75 cm. Fig. 2 depicts the realistic scenario of a 20 hectares field near Bogota, Colombia, where small barns are presented in orange, and uniformed distributed sensors in green.

The sensors are configured to collect climate and soil parameters like air and ground humidity, temperature, solar radiation, pH and compaction. All these variables will add a packet of 20 bytes per measurement. As described in the previous section, we include the headers for NB-IoT, IPv6/UDP compressed into 6LowPAN and CoAP protocols to account for the total system performance. We propose one measurement each hour and two flights per day, and as a result, each transmitted packet will sum up 2144 bits per device, as described in Table 3.

We propose to use a professional quadcopter able to carry a payload enough for the BS equipment for a flight time of at least 45 minutes. The MD4-100 fulfills these requirements with an average speed of 12 m/s, maximum flight time 2400 seconds, battery capacity of 17.3 Ah and voltage of 22.2 V [67]. Further, a facility deposit can support up to 10 drones, so when one is running out of battery, a new one could replace it on the serving site.

FIGURE 2. Potato field scenario used in the system evaluation.

TABLE 3. Packet description for NB-IoT system.

	Parameter	Value
	Measurement Packet size	20 bytes
	Measurements/day	24
	Flights per day	2
	Time per flight	50 (10-100)*
	Packet size	240 bytes / 1920 bits
Headers	CoAP	4 bytes
	UDP (compressed)	11 bytes
	Ipv6 over 6LowPAN	
	NB-IoT	13 bytes
	Total MTU [bytes]	268 bytes / 2144 bytes

* Values in parenthesis are variable parameters for simulations.

C. PATH LOSS MODEL

Different path loss models focus either for aerial to ground communications or for underground communications at the selected frequencies [68]–[73]. However, there is none for aerial to underground communications. Hence, we propose a mixed path loss model consisting of the sum of the above-to-ground path loss plus the underground path loss.

In [68], a two-ray model with experimental results using ZigBee is available. A path loss model at 2.6 GHz in urban scenarios accounting for the elevation angle is described in [69]. Al-Hourani *et al.* [70] offers a statistical path loss model based on the free space path loss (FSPL) model and specific environment properties. It uses ray tracing for urban and suburban scenarios were buildings and topography are included in the construction of the model. The path loss equation is presented in equation 1, where FSPL is the free space path loss from the Friss equation and N is the normal distribution from the excess path loss with a mean of μ, and standard deviation σ, as described in equation (2) where θ is the elevation angle, a and b are frequency and environment-dependent variables. We select this model based on its likeness for the evaluation tool used and for the presence of different frequencies. For the 700 MHz band in rural scenarios, the values for of Line-of-Sight (LoS) parameters for μ, a and b are 0, 11.53 and 0.06 respectively, while for No-Line-of-Sight (NLoS) are 18, 26.53 and 0.003.

$$PL_{AG} = FSPL + \mathcal{N}(\mu + \sigma) \quad (1)$$
$$\sigma = a * e^{(-b*\theta)} \quad (2)$$

The underground communication channels could be characterized by two parts, namely the ground-to-ground part and the refraction from the air-to-ground interface [26], [27]. An underground model based on electromagnetic propagation, including direct wave, reflected wave and lateral wave components, is discussed in [71]. The work in [72] proposes a path loss model considering the attenuation from soil components such as reflection, refraction and phase-shifting. In [73], an aboveground-to-underground time-domain analysis is presented, including the refraction due to the interface air-soil, based on the soil properties. Li *et al.* [74] presents a two-ray path loss model for 300 to 700 MHz considering effects such as multipath, soil composition, water content and burial depth. This model is selected for this paper for including a complete analysis of soil parameters and its impact on the propagated wave. Equation 3 describes the path loss used for underground propagation, where d is the distance in meters for the buried sensor, β is the phase-shifting constant and α is the attenuation constant of the soil. These last parameters are dependent on the dielectric properties of the soil. We use $\beta = 30.85$ and $\alpha = 1.92$ for a VWC of 5%; and $\beta = 59.83$ and $\alpha = 4.95$ for VWC of 25% using to Peplinski equations [75].

$$PL_{UG} = 6.4 + 20log(d) + 20log(\beta) + 8.69\alpha d \quad (3)$$

D. SYSTEM EVALUATION TOOL

The tool employed in this evaluation is based on the one used in [53], [76]. This tool, implemented in java, deploys a UABS-aided network. The access network uses the NB-IoT 3GPP TR 36.802 Rel 13 [32] and 3GPP TR 45.820 Rel 13 standards [35] while the backhaul uses the 3GPP TS 36.213 Rel 14 standard [77]. The novelty of the evaluation tool is the inclusion of a simultaneous radio allocation for access and backhaul links for UABSs, and the usage of hybrid path loss models for links between the UABS, the underground sensors and the facility antenna. The standard coded in the tool is following the most realistic scenario possible to integrate the aforementioned technologies in the frequency bands used [31], [78]–[80]. This tool has been experimentally validated in various research works, with results from mobile operators [76] to comparison between simulations [31] and measurement campaigns [80]. To the best of author's knowledge, there are no commercial network simulation tools that include UAV and WUSN. The algorithm of the tool is described next.

A detailed diagram of the algorithm deployed in the tool is presented in Fig 3. First, we use a realistic shape field from a known crop field to generate the serving area (Box 1). This stage includes the generation of the location of the

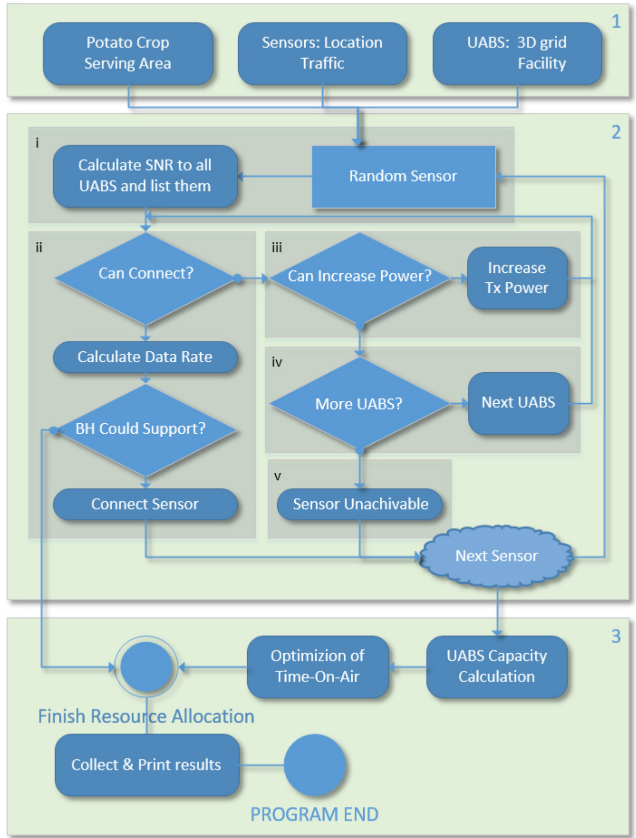

FIGURE 3. Resource allocation algorithm of the evaluation tool.

facility, the generation of the 3D flight grid for the UABS, and the uniform location and traffic parameter of the ground sensors. Second, when all the sensors are positioned, the tool initializes a random sensor resource allocation, consisting of the following steps (Box 2). *i*) The sensor calculates its path loss to all the available UABS in the 3D grid and organizes it accordingly. *ii*) It attempts to connect to the first activated UABS in the list, aiming to fulfill the required SNR. If the SNR is fulfilled, the tool calculates the data rate based on the modulation and coding scheme (MCS) (described in Table 2). It computes if the backhaul resources are available, assigning the sensor to this UABS. *iii*) If the power is not enough, it attempts increasing the transmitted power until the maximum value is achieved. *iv*) If the SNR is not fulfilled, the next UABS is evaluated following the same procedure until the sensor is allocated. *v*) If none UABS could serve the sensor, it is marked as unachievable. *vi*) The next sensors are evaluated within the same procedure from *i*-*v* until all the sensors are evaluated. Third, the UABS capacity is calculated based on the transmission airtime per sensor in each subchannel (Box 3). Therefore, an optimization method is introduced when the power of the UABS is incremented. By calculating the sensor's SNR again, we define if we can modify its data rate to adjust the UABS's resource allocation. This calculation will give a relationship between the number of nodes, the file size of each node, the modulation and coding scheme (MCS) used, the time-on-air and the number of available drones; with the capacity of the system. Finally, the tool collects all the results and print them in spreadsheet files for further post-processing and analysis.

The input files for the tool include the information of the crop field, drone specification, the access and backhaul technology parameters including radio and power constraints, and the simulation specific parameters like the number of sensors, buried depth, facility size, and flight height among others. The output files collect the statistics from served sensors, activated UABSs, access and backhaul used capacity, the power used and so on.

V. RESULTS OF SYSTEM EVALUATION

To evaluate the system described above, we consider a realistic scenario in a 20-hectares potato field in Colombia. First, we study the performance of the NB-IoT base station mounted on a UAV using the 716 MHz band. For this, we study the network performance of sensors buried at 0cm, 25cm, 50cm and 75cm, uniformly distributed. Moreover, we evaluate the impact of the flight altitude on the system performance when varying it between 20m and 200m. Next. We investigate the impact of the capacity for different flight times from 10 to 100 seconds. Following, we assess the impact of dry and wet soils into the network performance. Finally, we evaluate the power performance of the network to maximize the lifetime of the UGS. The simulation parameters are listed in Table 4.

TABLE 4. Simulation parameters.

Parameter	Value	Unit
Area Size	20	Hectares
Number of sensors	2000 (500-5000)*	Sensors
Sensor distribution	Uniform	-
Sensor data allocation	Random	-
Facility capacity	1 – Inf	UAVs
Flight altitude	100 (20-200)*	m
Flight time	50 (10-100)*	s
Sensors Depth	0, 25, 50, 75	cm
Packet size	268	Bytes

* Values in parenthesis are variable parameters for simulations.

A. WUSN DENSITY

We study the performance of the system by varying the deployed sensors' density. We vary the number of sensors from 500 to 5000 sensors, representing internode distances of 20 m to 6.5 m, respectively. First, we consider the ground sensors in dry soil at buried depths of 0 cm, 25 cm, 50 cm and 75 cm. The UABS's flight altitude is set to 100 m above the ground and a limited (one UAV) and the unlimited facility is used.

In Fig. 4a, the number of served sensors is presented. It can be seen that for an unlimited UAV facility (dotted lines), 100% of the sensors are served. When a large number of drones are at disposition, even the farthest and deeper sensors

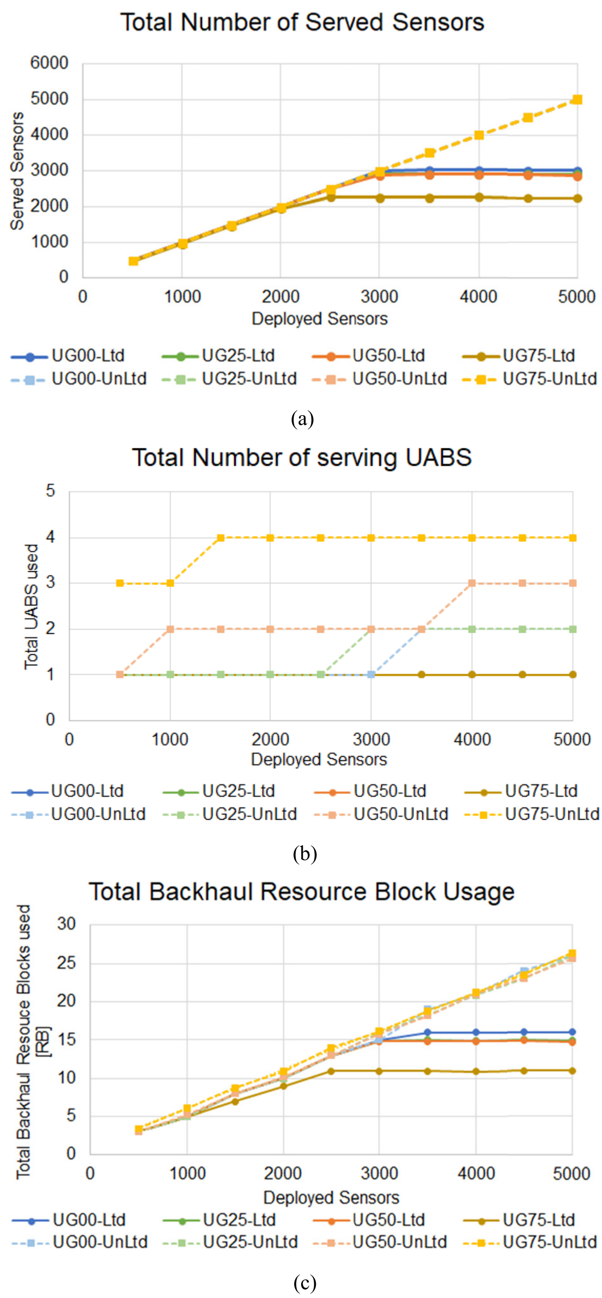

FIGURE 4. Results for sensors for wireless underground sensor network (WUSN) density analysis. (a) Total served sensors. (b) Needed unmanned aerial base Stations (UABS). (c) Total resource usage from backhaul. UGXX-Ltd/UnLtd = Underground sensor at XX (00, 25, 50, 75) cm with a limited (Ltd – continuous lines) or unlimited (UnLtd – dotted lines) facility size.

could choose a UABS that serves it and attempt to connect. In contrast, if there is only one UABS serving the field (continuous lines) limited by the UAV facility size, two phenomena occur. For ground sensors that suffer from a significant path loss, its power could be insufficient to connect to the UABS located in the center of the field. Furthermore, the maximum access capacity could be reached by the ground sensors, and it is dependent on their SNR values that affect the overall time-on-air of the ground sensors. For the three MCS used by the NB-IoT standard [35], the calculated maximum number of served nodes is 755, 1511 and 3022 for the SNR values of 0.5 dB, 2.6 dB and 4.9 dB respectively, in a 50 seconds flight time circumstance (Fig. 4a). For ground sensors (buried depth of 0 cm), the maximum number of served sensors is 3016, described in the blue line. This behavior suggests that the majority of sensors are connected using 2/3 $\pi/4$-QPSK modulation scheme. The number of served sensors slightly decreases to 2912, 2892 and 2258 for 25 cm, 50 cm and 75 cm buried depths, respectively. This happens because, at deeper distances, the nodes experience higher path losses and significant number of nodes are connected to lower modulation schemes, needing more time-on-air for its transmissions. It should be noted that the performance of 25 cm and 50 cm buried depth are quite similar despite the difference of more than 10 dB on average between its path loss calculations.

The number of required UABSs to serve the deployed sensors is presented in Fig 4b. These values are averaged through ten simulations and then rounded to the next integer value. As expected, for a limited facility (with just one UABS – continuous line) in all the scenarios, only one UABS is used. For an unlimited facility size (dotted lines), the number of needed UABSs increments with the number of deployed sensors, i.e., for above ground sensors, for more than 3000 sensors, a second UABS is needed. Besides, for buried sensors, at depths of 25 cm and 50 cm, the behaviour is quite similar, and a second UABS is needed from 2500 sensors and 1000 sensors, respectively. Finally, for the maximum depth (75 cm), three UABSs are needed from 500 sensors, increasing to four from 1500 deployed sensors.

The backhaul usage in total Resource Blocks (RBs) from the aerial network is shown in Fig 4c. The total consumption is rather small compared to the available capacity of the backhaul channel. Hence, the capacity limitation due to saturation of the backhaul channel was never reached. The simulation results indicate that less than 15% of the backhaul capacity is used even for the scenario with the highest bitrate demand. The backhaul RB usage trend is similar to the number of served sensors, although some small differences are found due to the assigned traffic rate at the side of the sensor. In particular, deeper buried scenarios (75 cm) consume fewer RBs than aboveground due to the smaller data rate assigned based on smaller SNR values. This behavior could be clarified since the UABS's RB allocation is done by requested bit rate, rather than the actual packet size–following minimum latency goals– resulting in less traffic allocated to sensors and fewer RBs assigned to the backhaul channel.

B. IMPACT OF FLIGHT ALTITUDE

For the flight altitude analysis, we vary the flight height from 20 m to 200 m for only 2000 sensors maintaining a 10 m spacing density. Following the results from Section IV.A, 2000 sensors could be served without time-on-air capacity restrictions. As a consequence, deploying 200 sensors will only be affected by the aboveground-to-underground channel comportment. The results in Fig 5a show that for an extensive facility, the number of served sensors is 100%, inclusive for deeply buried sensors. That can be served for close-by UABS locations. However, for a limited facility, the total number of served sensors decreases with lower altitudes. For example, at a buried depth of 75 cm, the number of served sensors reduces from 1991 at 200m down to 1951 at 100 m and 1741 at 20m. Instead, at 50 cm depth, 2000 sensors are served at 120m and decrease slowly down to 1947 sensors at 20 m height.

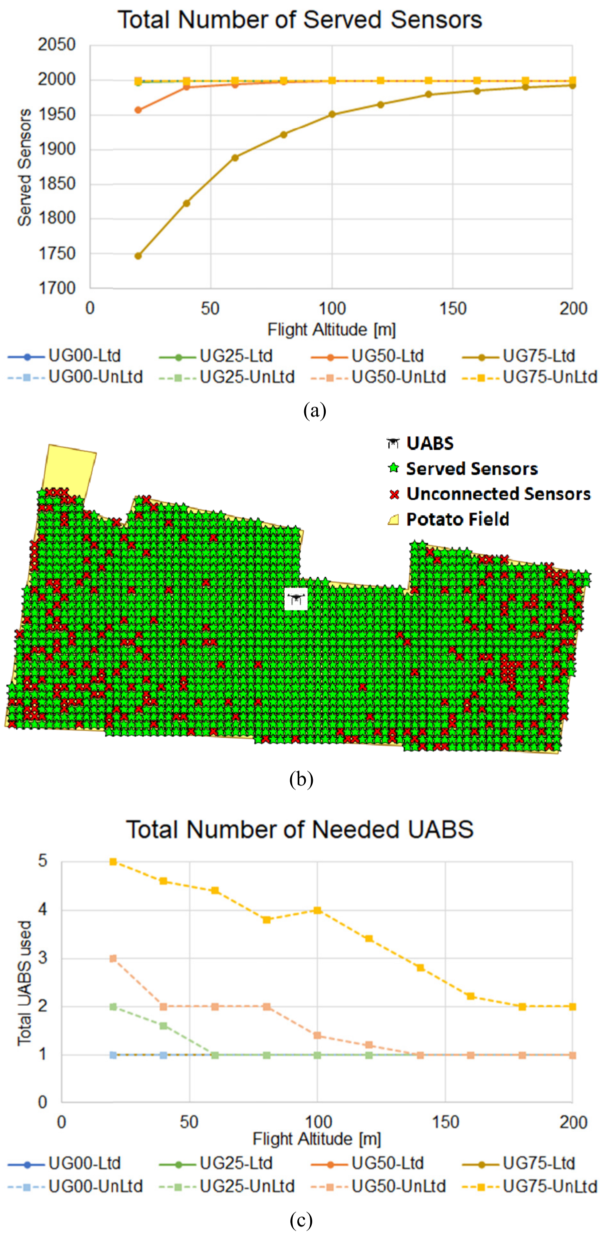

FIGURE 5. Results for flight altitude analysis. (a) Total served sensors. (b) Unconnected Sensor distribution for the worst-case scenario (c) Needed unmanned aerial base stations (UABS). UGXX-Ltd/UnLtd = Underground sensor at XX (00, 25, 50, 75) cm with a limited (Ltd – continuous lines) or unlimited (UnLtd – dotted lines) facility size.

This decrement is due to the small angle of arrival, between the UAV and the underground sensor, that increments the path loss value significantly in distant sensors. Fig 5b illustrates an example of this case for a buried depth of 75 cm, with a flight altitude of 20 m. Here, only 1747 (87.3%) sensors could be served as depicted by the green stars. The red crosses show the unconnected sensors that are too distant from the UABS in the center of the field, exhibiting a circular shape based on the omnidirectional antenna used. At smaller depths, the performance is improved, achieving 100% of connectivity at altitudes of 120 m for 50 cm, and 60 m for 25 cm. The number of required UABSs is also affected by its flying height. Fig. 5c shows that at higher altitudes, the number of needed UABSs is reduced, where optimal usage is achieved when only one UABS is needed, finding similar results from the connectivity where 140 m and 60 m are the optimal flight heights for 50 cm and 25 cm buried depths, respectively.

C. FLIGHT SERVICE TIME ASSESSMENT

Because the capacity for each user is dependent on its time-on-air (ToA), this subsection investigates the impact of the flight time on the capacity of the system. We performed simulations varying the flight time from 10 s to 100 s, with a fixed number of 2000 of deployed sensors within different buried depths (0 cm, 25 cm, 50 cm and 75 cm). First, the time behavior of the system is investigated. 3GPP rel 12 [35] states that the IoT devices can work in three modes: i) Connected Mode, where the device can receive and transmit data, ii) Idle Mode, where the device enters in sleep mode, but the BS is able to wake it and put in connected mode, and iii) Power Saving Mode (PSM), the mode with lower transmission where the radio equipment is turned off; hence no communication is available. Devices have two option for waking up from PSM. Initializing Random Access Channel (RACH) communication to move to connect mode or if the traffic is delay acceptable, wait for the Tracking Area Update (TAU) timer to wake it up. We configure the TAU to 120 s each hour. This means that all the devices have 120 s to exit from PSM mode and enter in connected mode to request RACH requests and allocations. Because the UABS only flight twice per day, when the IoT devices do not receive a response from the RACH request, they enter in PSM for the next hour. When the UABSs are flying to collect data, they have to arrive at the serving location in advance, before ground sensors start waking up, so RACH requests could be attended. Once all the IoT devices have asked for radio resources during the TAU period, the UABS allocates them through the Downlink Control Information (DCI) channel; the UABS proceeds to receive all the data from ground sensors. Details of the scheduling procedures are found in section 7.1.4 from the NB-IoT standard [35].

Fig 6 shows the flying service time, which is defined as the time when all the ground nodes are served after the allocation process. Ten seconds is sufficient time for serving 2000 ground sensors when an unlimited facility is used. Instead, when only one UABS is available, the number of served sensors increases from nearly 600 nodes at ten seconds, to 2000 nodes at 40 s. For the 75 cm buried depth, one UABS needs nearly 60 s to serve only 97.4% of the nodes. As expected, for topsoil sensors (blue lines in Fig 6), there are 11%, 7.7% and 5.5% more nodes served compared with the buried nodes at distances of 25 cm and 50 cm.

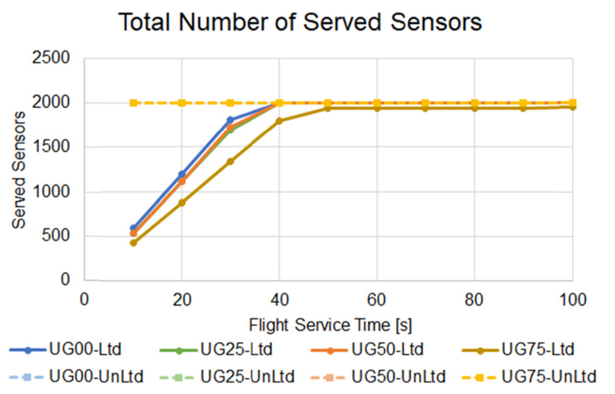

FIGURE 6. Results for flight service time for unmanned aerial base stations (UABS). UGXX-Ltd/UnLtd = Underground sensor at XX (00, 25, 50, 75) cm with a limited (Ltd – continuous lines) or unlimited (UnLtd – dotted lines) facility size.

D. WATER CONTENT EVALUATION

The impact of the wet soil on the network performance is investigated by simulating the network under dry (VWC = 5%) and wet (VWC = 25%) circumstances, at 20 m and 100 m of flight altitude and for buried depths between 0 and 1 m. Besides, the scenario consists of 500 and 2000 deployed underground sensors using only one drone. In Fig. 7, the percentage of served sensors is presented. The continuous blue line represents the percentage for 500 sensors buried in dry soil with a UABS flying at 100 m above ground level.

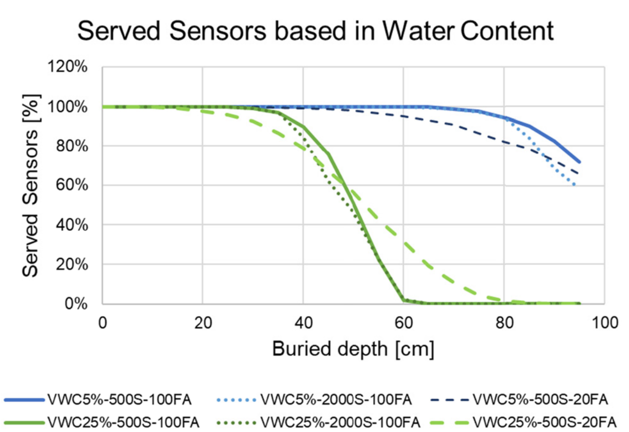

FIGURE 7. Results for water content evaluation for volumetric water content (VWC) = 5% and VWC = 25% for 500sensors and 2000sensors at 100 m and 20 m of flight altitude (FA).

The system could serve up to 500 nodes at 55 cm buried depth. Similar behavior is presented in the blue dotted line, for 2000 sensors. However, from 80 cm, the percentage decreases sharply, due to the capacity restrictions on the time-on-air for those sensors that the SNR uses the lowest MCS. When the UABS is flying at 20 m, the incidence angle affects severely, resulting in an increasing path loss and leaving more sensors disconnected. When the water content in the soil is increasing, the results are disastrous for the network performance in deeply-buried sensors.

The continuous green line in Fig 7 shows the served nodes when the VWC is 25%. From 35 cm, the percentage is sharply reduced, from 100% at 30 cm down to 0% at 60 cm depth and more. Similarly, the green dotted line shows the results when 2000 sensors are deployed. Network saturation due time-on-air could be seen between 35 and 55 cm, but after this, path losses are so significant, that service is hardly achievable. On the other hand, for the UABS flying at 20 m, the increment in the path loss due to the angle, diminishes the service from 20cm, as presented by the dashed green line.

E. POWER USAGE EVALUATION

The power usage in the IoT system is studied in two parts. The first one is the study of the power consumed by the aerial network, which includes the access and backhaul network consumption, plus the power consumption of the drone's flight [53], [81]. The second part is the study of the WUSN, in specific the life span of the deployed sensors.

In the first analysis, we review the results from flight elevation scenarios. Fig. 8a shows the mean power usage from UABS flying from 20 m to 200 m, for four different burier depths. The values are quite similar for all the scenarios, concluding that at higher altitudes, the drone needs more energy to climb higher. The results show that the drone needs approximated 125 mW for each meter increment in its flight height. Also, at higher altitudes, the NB-IoT transmission power to reach sensors and the backhaul power to reach the facility antenna should increase, increasing the overall power consumption. However, the differences in these scenarios are quite small, considering that the drone motion consumes the majority of the energy instead of the transmission power. The average power usage for the unlimited scenarios is 2 W less than the limited scenario because, in the unlimited one, the UABSs are flying close to sensors' positions hence reducing the transmission power.

Moreover, note that for 75 cm buried sensors, the power consumption is higher than the sensors above the ground. This comportment happens because buried sensors would need more transmission power on average to achieve the same MCS than sensors on the surface. For an altitude of 20 m, the average power consumption is 19.7 W +− 0.5 W and increases up to 26.3 W +− 1.5 W for 100 m flight altitude.

The second analysis consists of the evaluation of the consumption of the ground sensors and battery lifetime. Equation 4, as shown at the top of the next page, described the battery life of an NB-IoT sensor, where the lifetime,

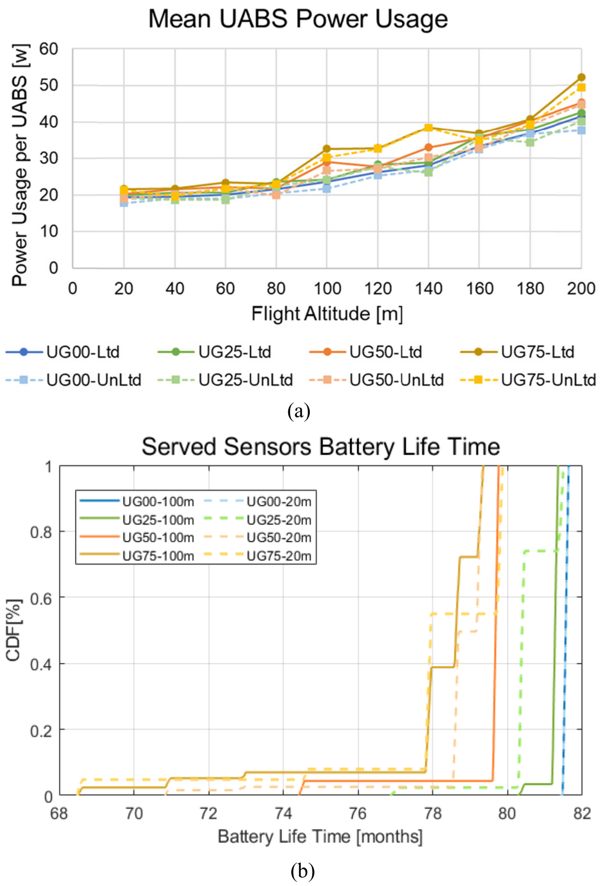

FIGURE 8. Results for power consumption analysis. (a) Mean power consumption per unmanned aerial base stations (UABS), (b) Cumulative distribution function (CDF) for average serving time. UGXX-YYm = Underground sensor at XX (00, 25, 50, 75) cm with a YY (20, 100) m flight altitude (FA). With a limited (Ltd – continuous lines) or unlimited (UnLtd – dotted lines) facility size.

in hours, is the result of the battery capacity in watts per hour, multiplied by the interval time in hours, divided by the total power consumption per transmission interval. The power consumption is the sum of products of the transmitted power by the time-on-air, the sleep power by the sleep time and the active power by the Difference Timer. All the time units should be used or converted in hours. In NB-IoT, the Tracking Area Update (TAU) is part of the PSM procedures used in the 3GPP Rel 12 standard to conserve battery.

We define the Difference Timer (Equation 5), as shown at the top of the next page, as the difference between the TAU time and the PSM cycle, where the sensor node is reachable [82]. The ToA (Equation 6), as shown at the top of the next page, and sleep time (Equation 7), as shown at the top of the next page, are calculated based on the bit rate of the sensor [32], [34], [82]. The parameters used for the sensor are described in Table 5.

We evaluate the performance of 500 ground sensors at four different depths with two flight elevations. Fig 8b elucidates the cumulative distribution function (CDF) of the battery lifetime for these scenarios. It can be seen that the

$$LifeTime\,[h] = \frac{BatteryCapacity\left[{}^{w}/_{h}\right] * TxInterval\,[h]}{P_{tx}\,[w] * ToA\,[h] + P_{sleep}\,[w] * T_{Sleep}\,[h] + P_{Active}\,[w] * T_{Diff}\,[h]} \quad (4)$$

$$T_{Diff}\,[h] = TAU\,[h] - PSM\,[h] \quad (5)$$

$$ToA\,[h] = \frac{PacketSize\,[bits]}{bitrate\,[bps] * 3600} \quad (6)$$

$$T_{sleep}\,[h] = TxInterval\,[h] - ToA[h] - TAU\,[h] \quad (7)$$

TABLE 5. Sensor power parameters.

Parameter	Value	Unit
Battery Capacity	6.8	Wh
Battery Voltage	3.6	V
Tx Interval	12	h
Sleep Power	36.0	uW
Active Power	28.8	mW
Difference time	0.0333	h

lifetime depends on the buried depth. For above-ground sensors, the batteries could last up to 81 months and decreases for deeper sensors. In the worst-case scenario, i.e., 75 cm depth, the batteries of the sensors should be changed every 77.8 months when between 10% and 40% of the sensor batteries would have been depleted. These results mean that under those conditions, the system could be operative for nearly 6.5 years. This inference is essential because a farmer could deploy the sensors in the topsoil and plant the potatoes in the organic layer above the sensors without the need for replacement them in each crop.

VI. CONCLUSIONS AND FUTURE WORK

The usage of UABSs to collect data form potato crops using underground sensors is a new subject in the precision agriculture field that needs profound research due to the versatility of drones in large fields that could reduce the need for fixed infrastructure reducing cost. Using NB-IoT as a low power technology, allow us to determine system characteristic that needs attention in the design of the monitoring system. From the simulated results, the capacity of the system is found to be related to the time-on-air of the system and the path loss between the UABS and the ground sensors. Our results show that up to 2500 underground sensors could be served for a 50 second flight time, even for 75 cm buried depths. Furthermore, using multiple UABSs could aid in serving more sensors and reduce the transmission power of the sensors. The impact of the flight altitude is primary for the buried sensor: for lower altitudes, a small angle between the UABS, the sensor and the ground, will increment the path loss and reduces the quality of the link between the ground sensor and the UABS, leading to potential uncovered sensors. However, for aboveground sensors, 60 m is an optimal altitude for single drone usage.

Also, the impact in the VWC could rapidly diminish the performance of the system leading to smaller burier depths, changing from 75 cm in dry soil down to 30 cm in wet soil, for a 100% service. Finally, the power consumption of the aerial network is highly dependent on the flight elevation and flight time, with small increments for deeply buried sensors. For the underground network, the battery life study indicated that the ground sensors could serve more than 6.5 years and depends on the buried depth, being the shortest lifetime for the deepest buried sensors.

This system assessment has included several parameters to evaluate the overall network's performance, such as the drone flight height, the buried depth of sensors, the density of sensors and the flight time. The results found in this evaluation could be applied to a different type of crops like wine and olive crops, or rice and corn crops where water contents are highly relevant. Future work will include the evaluation of a single moving UABS IoT gateway, a detailed study of the network protocol configuration, and its implications into the system behavior and comparison with other low power technologies like Low-Range Radio (LoRa). Lastly, a laboratory trial to evaluate and compare results with the proposed path loss model to validate its accuracy is part of the future work.

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