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Implementation of an Interactive Environment With Multilevel Wireless Links for Distributed Botanical Garden in University Campus

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ABSTRACT In this contribution, an end to end system to enable user interaction with a distributed botanical university campus garden is designed, implemented and tested. The proposed system employs different wireless links to collect data related to different bio physiological parameters of both the vegetation mass and the surrounding environment. Detailed analysis of these multilevel communication links is performed by using deterministic volumetric wireless channel estimation and considering underground, near ground and over ground radio propagation conditions. An in-house developed technique enables accurate wireless channel characterization for complete campus scenario considering the multiple link types and all its composing elements. Node definition and network topology is thus obtained by wireless channel analysis of over ground, near ground and underground communication for both 868 MHz and 2.4 GHz Wireless Sensor Networks in an inhomogeneous vegetation environment. Connectivity to enable user interaction as well as for telemetry and tele-control purposes within the campus is achieved by combining ZigBee and LoRaWAN transceivers with the corresponding sensor/actuator platforms. Coverage studies have been performed in order to assess communication capabilities in the set of multiple underground/near ground/over ground links, by means of deterministic channel analysis for the complete university campus location. Measurement results in lab environment as well as full system deployment are presented, showing good agreement with deterministic simulations. Moreover, system level tests have been performed over a physical campus cloud, providing adequate quality of experience metrics. The proposed solution is a scalable system that provides real time trees status monitoring by a cloud-based platform, enabling user interaction within a distributed botanical garden environment in the university campus.

INDEX TERMS The Internet of Things, wireless sensor network, LoRaWAN, university garden, radio channel model, smart agriculture, 3D ray launching.

I. INTRODUCTION

Wireless Sensor Network (WSN) are being actively adopted as enablers for context monitoring within multiple applications and scenarios, such as environmental pollution [1], power grids [2], public safety [3] and agriculture [4]. However, the deployment of WSNs in applications focused in vegetation monitoring is challenging, considering inherent restrictions in terms of energy source availability, form factor and limited computational capacity [5]. In this sense, one

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of the main difficulties is to insure a reliable connection between nodes, especially in dense vegetation environments. The presence of foliage in the communication path has a direct impact in wireless communication system Quality of Service (QoS) values. This generally leads to node densification to increase coverage levels, especially in large areas, resulting in additional costs. Discrete scatters such as randomly distributed leaves, twigs, branches and tree trunks can cause attenuation, scattering, diffraction and absorption of the radiated waves. This severely constrains the design of wireless communication systems in inhomogeneous vegetation environments, given by the effect of foliage or multipath dispersion, among others [5]–[9].

In order to provide communication capabilities within large coverage areas, wireless sensor networks provide moderate cost, flexible topology and constrained energy consumption. Among WSNs, LoRaWAN (Long-Range Wide-Area Network) is a long range, low power wireless platform that has become one of the main technologies for Internet of Things (IoT) networks worldwide [10], [11]. The works in [12]–[14] present the use of LoRaWAN technology in precision agriculture, especially in automate irrigation systems, climate and soil parameters monitoring. Moreover, in [15], [16] present LoRaWAN based smart sensing systems for environmental monitoring.

In parallel, universities have been more aware with global warming and climate change issues, making more efforts to promote sustainability. The first step universities take toward sustainability is campus greening. Thus, campus landscape management is important for a green and sustainable campus [17], [18]. Campus Sustainability Assessments as Green Metric provide the result of online survey regarding the current condition and policies related to Green Campus and Sustainability in Universities all over the world [19]. Greenery has been even identified for stress reduction and emotional state balance in students [20]. In this context, the use of WSNs can provide more information about the state the green zones of the campus, not only for monitoring, but also for on-campus botanic tours in a more amenable fashion [21]. Considering the characteristics of a university campus in terms of size and the existence of multiple distributed sites/buildings, long range, low power platforms such as LoRaWAN enable telemetry, tele-control and interactive communication systems.

The performance of systems that rely on WSNs depends on radio channel characterization and on whether vegetation is present or specific requirements in terms of underground or near to ground communications are required. In the literature, a ray-based model for scattering by tree branches has been developed in a pre-existent ray-tracing tool, validated with measurements results in campus scenario [22]. LoRa LPWAN measurements have been performed in IIUM campus to study the contribution to the path loss of five tree types for propagation channel modelling [23], and an IoT based system for water quality monitoring using WSN and RFID is deployed in the campus area of the University Sains Malaysia [24]. However, no references have been found which explore the complete set of underground, near ground and over ground communication links.

Since trees monitoring requires measurements of various eco-physiological/biological parameters (e.g., stem water content, quality/quantity of foliage, soil parameters), sensors should be placed in specific locations as a function of vegetation type in order to obtain accurate readings. Different approaches have been described, such as a system for measuring the vegetation Leaf Area Index with ZigBee based WSN technology [25], a tree health condition monitoring system via LoRaWAN [26] or a NB-IoT based tree health monitoring system [27].

System deployment within this complex scenario requires accurate propagation modeling capabilities for underground, near ground and over-ground links, for both Line of Sight (LoS) and Non-Line of Sight (NLoS) cases. Therefore, it is compulsory to perform radio propagation analysis when deploying a WSN. The works in [28]–[30] analyse the effect of soil and present link quality characterization for underground to underground and underground to above ground communication. The possibility of using magnetic induction communication for wireless underground sensor network designed for irrigation control is addressed in [31]. The works in [32]–[34] present near-ground radio channel propagation in the presence of vegetation. Furthermore, path loss models for wireless sensor nodes deployed in short and tall grass environments are presented in [35], [36]. The works in [37]–[41] present wireless propagation measurements and path loss models for WSN in forest environments. Table 1 summarizes the research works related to the use of wireless communications in vegetation environments.

In this work, a distributed system implemented to enable user interaction with the distributed botanical garden at the university campus of the Public University of Navarre (UPNA) is presented. Node design and network deployment are optimized by means of detailed wireless propagation analysis considering complex operation conditions in underground, near ground and over ground communications. To this aim, specific characterization and simulation models have been implemented in the framework of an in-house implemented deterministic volumetric ray launching simulation tool, previously tested in different scenarios, including vegetation [42], [43]. In this way, coverage relations are obtained for each communication link type. To our knowledge, it is the first time to propose and test the characterization of all the communication link types (underground, near ground and over ground) by means of deterministic techniques.

Experimental and system level validations with the implemented testbed have been carried out at the UPNA campus, located in the city of Pamplona, Spain.

As a final stage, a monitoring distributed wireless system has been implemented for the UPNA campus botanical park in addition to the multilevel underground, near-ground and over-ground wireless link assessment. Thus the system is

TABLE 1. Related work.

Ref	Aim of the work	Description	Technical Specifications
[22]	Ray-based model for scattering by tree branches has been developed in a pre-existent ray-tracing tool.	The measurements have been performed in a campus scenario in Belgium and have been compared with simulations where several trees were present alongside the propagation environment.	Freq: 3.8 GHz BW: 200 MHz TX power: 23 dBm
[23]	Determination of foliage effect in terms of attenuation and its contribution to path-loss and link budget calculations.	The measurement tests of different scenarios for both LOS and NLOS links have been performed in IIUM campus (International Islamic University Malaysia).	Technology: LoRa Freq: 915 MHz BW: 125 KHz TX power: 20 dBm
[24]	IoT based system implementation by embedding RFID system, WSN platform and IP based communication into a single platform for water quality monitoring.	The WSN nodes have been deployed at the lake in the campus area of University Sains Malaysia (USM), using the 920 MHz Digi Mesh protocol to surpass the signal attenuation in vegetation area.	Technology: RFID, ZigBee Freq: 920 MHz TX power: 18 dBm Android mobile app; real-time display: pH value, sensor node ID and timestamp.
[25]	Determination of crop Leaf Area Index	The proposed system is a useful method for collecting ground crop LAI in flexible time and space, measuring the vegetation canopy parameters by the remote sensing.	Technology: ZigBee
[27]	A tree health monitoring system based on NB-IoT is proposed to guide arborists and to prevent potential hazards, such as soil erosion and climate warming	The principle of this system is to transmit the data of the environmental characteristics around the trees by NB-IoT network and to analyze the data using the K-nearest neighbors (KNN) classification method.	Technology: NB-IoT
[32]	Narrowband radio channel model under near-ground conditions, applied to a smart agriculture in 5G-IoT bands.	A measurement campaign has been carried out using identical directional antennas in agriculture fields with three types of ground: soil, short and tall grass.	Technology: ZigBee Freq: 868 MHz, 2.4, 5.8 GHz TX power: 17 dBm (2.4 GHz)
[33]	Continuous-wave power measurements for determining expected range for IoT D2D communication systems in rural areas.	Measurements have been performed over a long-range (around 2.5 km) in a forest environment with low elevation antennas. The measurement data have been compared with existing foliage excess loss models.	Freq: 917.5 MHz BW: 1 KHz TX power (amplified): 40 dBm
[34]	Vegetation attenuation models for WSN planning and deployment in scrub forest, mango plantation and guava plantation.	A short-range, near to ground received signal strength measurements have been performed for precision agriculture and plantation management applications.	Freq: 915 MHz, 2.4 GHz TX power: 17 dBm
[35]	Experimental path loss models for natural short- and tall-grass terrain environments, for WSN in similar scenarios.	The empirical models are compared with the theoretical models to demonstrate their inaccuracy in predicting the path loss between sensor nodes deployed in natural grassy environments.	Technology: ZigBee Freq: 2.4 GHz TX power: 18 dBm
[36]	Signal attenuation evaluation based on RF measurements for WSN deployed in an extended grass environment.	The measurements carried out without obstructions and compared with theoretical models.	Technology: ZigBee Freq: 1925 MHz
[37]	Peer-to-peer propagation analysis for various vegetation environments and wireless network frequencies.	A power measurement campaign has been performed along six different scenarios in order to obtain data enough to adjust the propagation studies predictions.	Freq:2.4GHz, 3.5GHz, 5.8 GHz BW: 3 MHz TX power: 15-19 dBm
[38]	Optimum model identification for WSN deployment at 5G frequencies in forest environments.	The measurements values have been acquired in a forest area of Jim Corbett National park in India to compare with the empirical foliage attenuation models.	Freq:15GHz, 28GHz,3 8 GHz
[39]	Forest monitoring system based on WSN, empirically evaluated by measuring RSSI.	The measurements have been carried out in two different types of forest: heterogeneous tropical forest and homogeneous pine forest.	Technology: ZigBee Freq: 2.4 GHz TX power: 18 dBm
[40]	Near-ground attenuation model in a forest environment in the European region and compares against already suggested propagation models.	The study is important in the context of military communications, emergency networks and environmental monitoring systems.	Freq: 485 MHz Bandwidth: 300 KHz
[41]	Review of radio wave propagation through the forest is presented, with a focus on propagation loss evaluation.	It proposes to experimentally determine the impact of daily humidity changes on the RF signal attenuation and explore the effects of rain on the forest environment path loss exponent.	Technology: ZigBee Freq: 868 MHz TX power: 0 dBm
This work	In this contribution, an end to end system for interaction with a distributed botanical university campus garden is presented.	Different technologies are combined for an optimal coverage/cost balance within a huge scenario. Measurements and analysis have been performed on multilevel communication links, considering underground, near-ground and over-ground conditions. Measurement results compared to deterministic simulations using an in-house 3D Ray launching Simulator.	Technology: LoRaWAN and ZigBee Freq: 868 MHz, 2.4 GHz TX power: 14 dBm (LoRaWAN), 25 dBm (ZigBee 868 MHz) 17 dBm (ZigBee 2.4 GHz) Real-time tree monitoring/guiding app for user interaction. Interactive Garden Monitor Platform for telemetry and tele-control purpose

divided into multiple/seven ZigBee-based zonal collection networks which gather the information provided by the sensors deployed on trees, and a LoRaWAN campus-wide communication network which sends the information of each ZigBee network to a central gateway.

The system is completed with the implementation of a real-time tree monitoring application, a cloud-based architecture, and a physical cloud infrastructure, all of the set allows performing in depth tests and analysis on campus premises. In Fig. 1, it is shown a schematic overview of the different tasks developed, as well as the results obtained in this work Fig. 1.

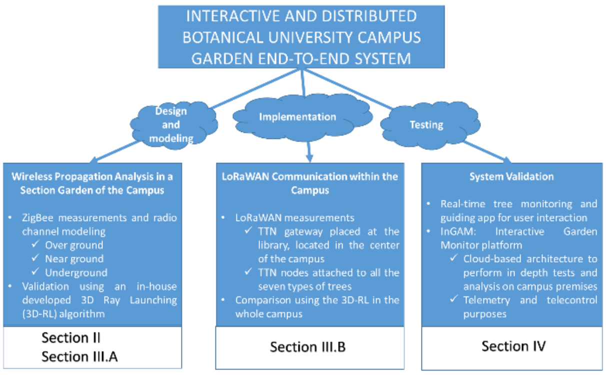


FIGURE 1. Schematic overview of the tasks developed in relation with the design, implementation and analysis of the proposed UPNA Smart Campus system.

The paper is organized as follows. Section II describes wireless channel characterization for near ground, over ground and underground links. Section III presents the link analysis applied to provide wireless system planning, for LoRaWAN and ZigBee network nodes. System validation and end to end data transmission are discussed in Section IV. Concluding remarks are offered in Section V.

II. UNDERGROUND, NEAR-GROUND AND OVER-GROUND WIRELESS CHANNEL ASSESSMENT IN CAMPUS ENVIRONMENT

With the aim of optimizing both the design and deployment of the proposed distributed system, wireless channel analysis for the complete UPNA campus must be performed to determine coverage distributions thus providing the initial wireless system planning. In this section, once presented the campus scenario, the multiple level wireless link types are studied: underground, near-ground and over-ground links. Link types are defined based on the wireless node transmitter antenna height.

A. CAMPUS ENVIRONMENT UNDER ANALYSIS

The UPNA campus covers approximately a surface of 170000 m^2 and a volume of over 5.1 million m^3. It has one central building, one library building, seven department buildings and elements such as sitting benches and hundreds of trees. In fact, it contains 99 different species, a variety of different trees and a dozen relevant shrub species [44]. This vegetation mass harmonically surrounds the campus buildings and is distributed in various landscaped areas, with the aim of conforming a distributed botanical garden. As shown in Fig. 2, the campus is divided into five main parks: the Park of Navarre, the English Park, the Asian and European Park, the American, African and Oceanic Park and finally the *Rectorate* Park.

FIGURE 2. Location of the five parks that conform the distributed botanical garden at the Public University of Navarre.

In this work, the seven main types of trees distributed in five of the total parks within the campus are considered: Yew trees, pine trees, olive trees, holly trees, arbutus trees, magnolias trees and holm oak trees. The tree types can be easily recognized because each one grows next to a university department building that bears its name. This setting constitutes a distributed botanical garden aimed to promote dissemination of agroforestry knowledge [44].

B. 3D RAY LAUNCHING SIMULATION TOOL

With the aim of providing in depth understanding of the behavior of the multilevel wireless links present in this complex environment, a 3D-RL algorithm has been employed. The 3D-RL algorithm has been implemented in-house, based on Geometrical Optics (GO) and Geometrical Theory of Diffraction (GTD), optimized with hybrid simulation techniques in order to reduce computational cost. As an example, the garden surrounding the *Los Tejos* building has been analyzed and the simulation scenario implemented. The scenario has 110 m in length, 31 m width and 15m height. Fig. 3a shows a real picture of the scenario, and Fig. 3b shows the 3D-RL simulation scenario.

All the existing elements at the garden such as trunk trees, foliage, streetlights and grass have been taken into account in order to obtain accurate radio propagation estimations. To this extent, the frequency dispersive characteristics of the dielectric constant and conductivity of the materials for the specific operation frequency have been taken in consideration. Table 2 presents the material properties

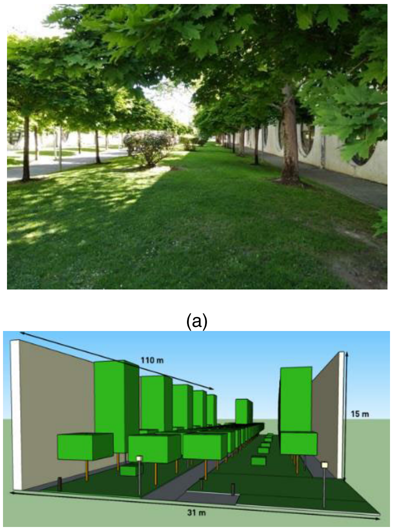


FIGURE 3. Garden scenario for simulation in the 3D Ray Launching Simulator (a) real view and (b) schematic view.

TABLE 2. Material properties for the 3D ray launching simulation.

Parameter	Permittivity (ε_r)	Dielectric constant (σ) [S/m]
Trunk tree	1.4	0.021
Tree foliage	(1)	(2)
Air	1	0
Brick wall	4.44	0.11
Grass	30	0.01

(dielectric constant and conductivity) of all the elements considered.

The dielectric constant ε_r and conductivity σ of tree foliage varies with humidity h as per (1) and (2):

$$\varepsilon_{rfoliage} = 137h^3 - 69.688h^2 + 23.385h + 1.4984 \quad (1)$$

$$\sigma_{foliage} = 1.1541h^3 - 0.5489h^2 + 0.1669h - 0.0004 \quad (2)$$

For this study, 20% humidity level has been considered. Simulation results have been obtained for the complete scenario volume. As an example, RF power distribution planes for different receiver heights are presented in Fig. 4, for both 2.4 GHz (ZigBee) and 868 MHz (LoRaWAN) bands. In order to simulate near ground and over ground conditions, two different transmitter antenna heights were conf: 0.1m and 1.1m. Simulation parameters have been chosen to agree with the measurement equipment setup, which will be analyzed in the following subsection.

C. NEAR-GROUND AND OVER-GROUND WIRELESS LINK ASSESSMENT

As a first step to perform the analysis of the multiple communication link types, over-ground and near-ground propagation conditions were considered, since accurate measurements of tree's eco-physiological/biological parameters requires sensors placed at different height on the tree. Therefore, the multiple positions of the nodes leading to the different link types have been included in the wireless channel analysis.

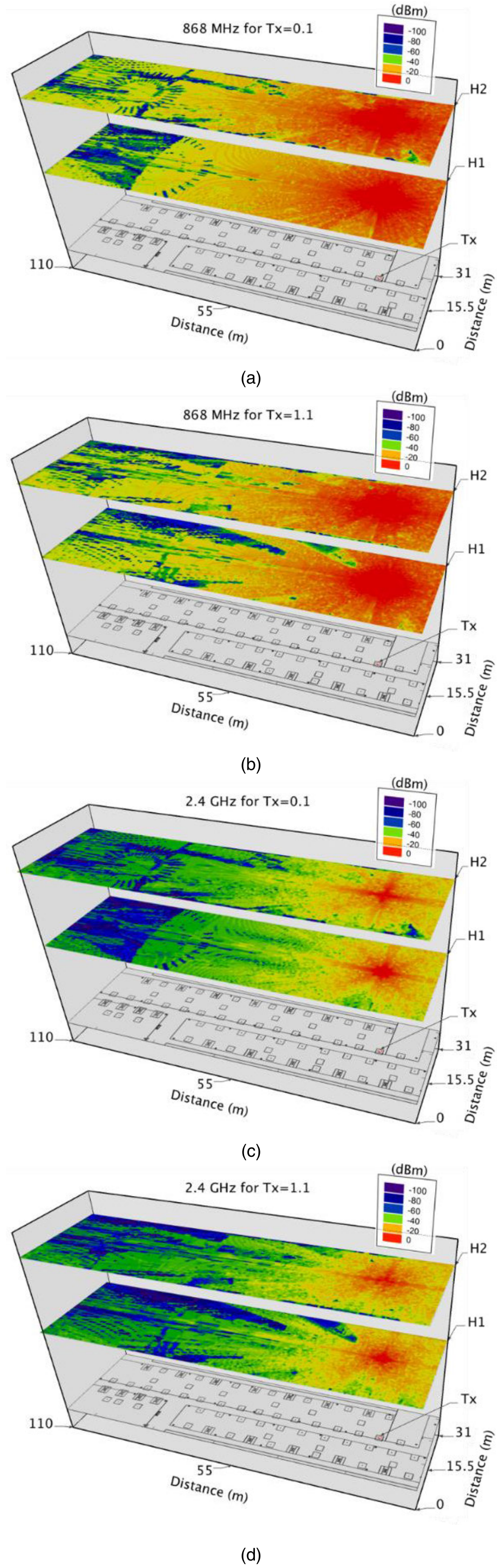


FIGURE 4. Estimated RF power level distributions for 868 MHz for (a) Tx = 0.1m; (b) Tx = 1.1m; and for 2.4 GHz for (c) Tx = 0.1m; (d) Tx = 1.1m.

Received power and Received Signal Strength Indicator (RSSI) values have been measured while transmitter nodes were placed at different heights T_x of 0.1m and 1.1m from the ground, corresponding to usual operating conditions of devices in near to ground and over the ground locations, respectively. Both transmitters were communicating with both receiver nodes placed at the same heights resulting in a near-ground to near-ground communication, near-ground to over-ground communication, over-ground to near-ground communication and over-ground to over-ground communication schemes. Measurements have been performed along both LoS and NLoS link paths, as it is schematically shown in Fig. 5a. Thus, these experiments will determine communication QoS parameters between nodes attached to trees in *Los Tejos* garden (see Fig. 5b). The distance between two trees in the same row is approximately 6.5m, and the distance between two rows is 9.5m. *Los Tejos* was chosen owing to the complexity of the scenario in terms of vegetation density and location. Nodes were placed over, near and under the ground.

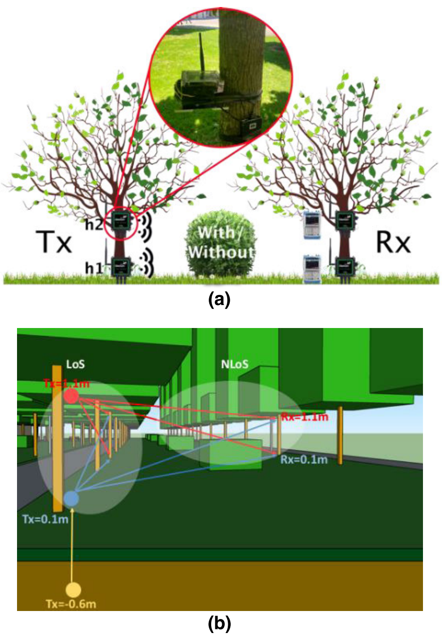


FIGURE 5. (a) Details of the measurement setup for the near ground and over the ground communication links. (b) 3D-RL view of over-ground, near-ground and underground communication links considered in the scenario under analysis.

Wireless channel measurements have been performed using Libelium 868 MHz nodes, 2.4 GHz ZigBee nodes and a voltage-controlled oscillator (VCO) tuned at 2.4 GHz. Transmitted power of the ZigBee nodes was 25 dBm at 868 MHz and 17 dBm at 2.4 GHz. Received power measurements have been performed with an Agilent N9912 Field Fox portable spectrum analyzer.

For the received power measurements at 2.4 GHz, an omnidirectional antenna has been connected to the VCO with a transmit power of 8.38 dBm. The RSSI has been measured using Libelium ZigBee nodes operating at 868 MHz and 2.4 GHz. Receiver sensitivity of the ZigBee nodes was -112 dBm at 868 MHz and -102 dBm at 2.4 GHz.

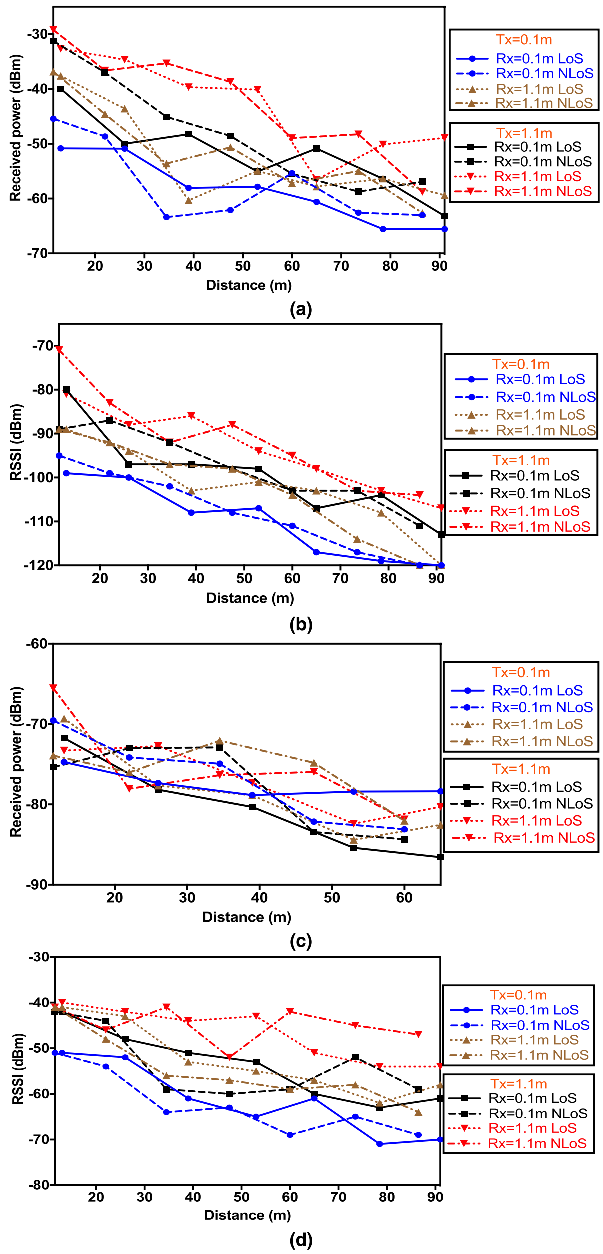


FIGURE 6. (a) Received power and (b) RSSI (dBm) at different Tx and Rx heights for 868 MHz; (c) and (d) the same for 2.4 GHz.

Fig. 6 shows the received power and RSSI results for both transmitter and receiver placed at 0.1m and 1.1m from the ground, for LoS and NLoS path cases. It can be seen that over ground to over ground links exhibit the highest received power level, given by lower obstruction in such links. Measurements have been performed at a maximum distance of 65m in the case of 2.4GHz (Fig. 6c), to avoid unwanted effects of detected interferences in the 2.4GHz ISM band.

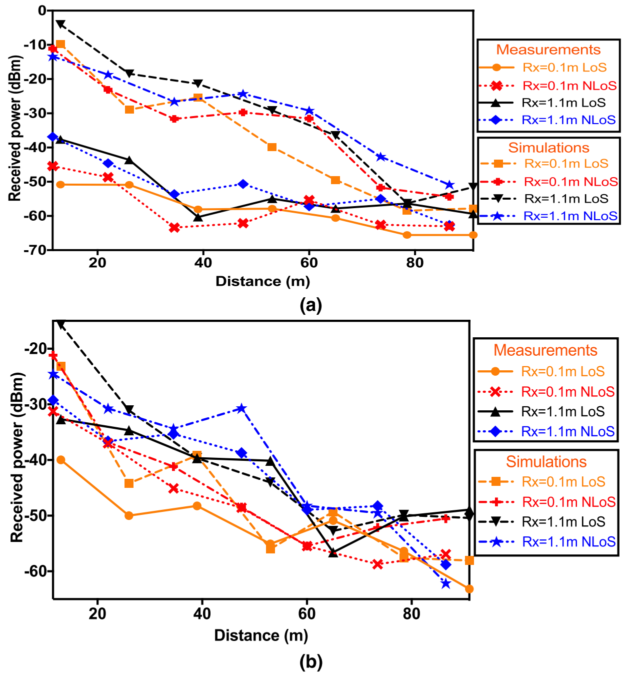


FIGURE 7. Comparison between the measured and the simulated results for 868 MHz radio frequency; (a) for Tx = 0.1m, and (b) Tx = 1.1m.

Once the measurements were carried out, simulations were performed, in order to validate the presented 3D-RL tool. For that purpose, simulation and measurements results at 868 MHz are compared in Fig. 7. Both heights of $T_x = 0.1$ m and $T_x = 1.1$ are included.

Table 3 summarizes the measurements vs. simulations results, with the obtained mean error and standard deviation.

TABLE 3. Measurements vs. simulations comparison for near-ground and overground communication at 868 MHz.

T_x (m)	R_x (m)	Link	mean error x (dB)	Standard deviation σ
0.1	0.1	LoS	19.97	12
		NLoS	23.89	9.63
	1.1	LoS	21.8	12.68
		NLoS	22.11	6.5
1.1	0.1	LoS	5.18	5.88
		NLoS	3.9	3.69
	1.1	LoS	2.75	6.32
		NLoS	2.24	3.79

Mean error values for received power estimations are given by using equation (3):

$$x = \frac{\sum_{i=1}^{n} |P_{mi}[\text{dBm}] - P_{si}\,[\text{dBm}]\,|}{n} \tag{3}$$

with P_m the measured received power, P_s the simulated received power and n the number of the measurement points.

As it can be observed in Table 3, higher errors occur when the transmitter (Tx) is placed on the ground (i.e. 0.1m) while lower errors appear when the transmitter is placed over-ground (i.e. at 1.1m height). These errors are further reduced in the case of over-ground to over-ground communication links (Tx and Rx at height of 1.1m. Large deviations in the estimation of received power levels mainly at closer distances to the transmitter as well as in the case of transmitter locations in near-ground configuration. This is given by the fact that near ground communications are influenced by phenomena such as surface wave coupling, which are not intrinsically considered following deterministic physical optics approach. Moreover, the implemented ground model considers a macroscopic homogeneous soil layer with dispersive material properties considered for a specific humidity level. Finally, a thin homogeneous grass layer has been implemented. Effects such as non-homogeneous soil/humidity distributions and small-scale diffraction and scattering effects from individual grass filaments increase average error values and will be considered in future models.

D. UNDERGROUND WIRELESS LINK ASSESSMENT

The use of underground nodes is required for soil parameters measurement (e.g., moisture levels, scatterer density such as roots, rocks, etc.), which have a direct influence on tree health assessment. Radio propagation measurements have been performed to characterize communication links between a node placed underground and a node placed on the ground surface. In order to obtain accurate results, a container of 50/50/50 cm full of soil has been used, as depicted in Fig. 8.

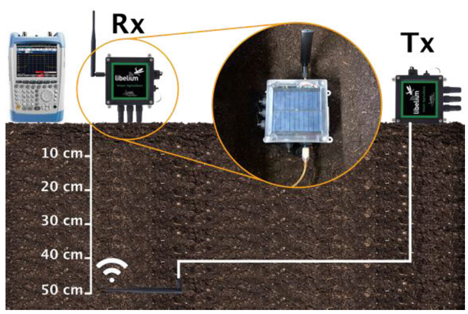


FIGURE 8. Schematic view of the measurement setup implemented for the underground link.

Received power, Delta RSSI (the difference between the received power and the RSSI), path loss and received packets in terms of the difference between the RSSI for propagation in both soil and air have been measured. Measurements were obtained for increments of 10 cm under the soil up to 50 cm of distance between the underground transmitter node and the receiver which is placed on the soil, as shown in Fig. 8. Measurement results are depicted in Fig. 9 plots.

The results show that high losses are present at short distances, mainly given by the power extinction rate and the impedance mismatch between the node antenna and the surrounding soil medium. Impedance mismatching depends on the frequency dispersive dielectric constant values but also on the location conditions of the antenna/soil interfaces,

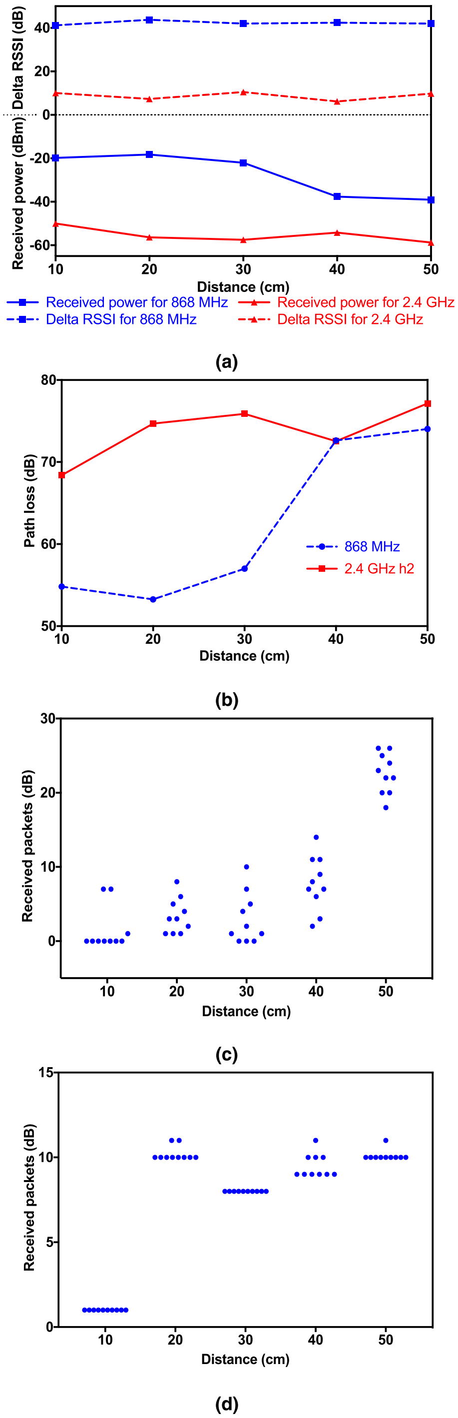


FIGURE 9. **(a) Received power and Delta RSSI at 868 MHz and 2.4 GHz, (b) path loss at the same frequencies, (c) difference between the received packets RSSI for propagation in both soil and air at 868 MHz and (d) 2.4 GHz.**

which, in turn, also impact on both matching conditions (similar to the case of radome location with respect to an antenna radiating surface, owing to the existence of a stationary wave condition) and on the inter symbol interference [45], [46]. Path losses are within the range of 55 dB to 72 dB at 868 MHz and in the range of 68 dB to 76 dB at 2.4GHz (see Table 4). Differences in losses can also be due to other factors, such as the surface wave coupling, which in the case of near ground communication are more relevant as operational frequency decreases, usually below the UHF/microwave range, out of the scope of the transceivers employed in this work. Another critical factor of influence is the transmitted waveform which should be specifically designed to counteract the effects of frequency dispersion to provide larger links [46]. Finally, although the measured losses for the underground links are high, it is important to note that the received RF power levels at 50cm distance/depth are greater than the sensitivity thresholds of the nodes, and therefore, adequate to enable a communication link between the underground and near-ground nodes, where all the transmitted packets are received.

TABLE 4. **Path loss range for underground communication.**

Frequency range	Path loss (dB)	
	Min	Max
868 MHz	55	72
2.4 GHz	68	76

III. IMPLEMENTATION OF THE DISTRIBUTED WIRELESS SYSTEM FOR THE MONITORING OF THE BOTANICAL PARK

Once the different wireless link types involved in the presented environment have been assessed, this section describes the radio planning tasks that validate the deployment of the LoRaWAN devices for the monitoring system of the botanical park of the UPNA campus.

FIGURE 10. **Schematic view of the simulation scenario implemented to analyze the campus botanical monitoring system, in which each one of the LoRaWAN/ZigBee sub-networks is presented.**

Due to the large size of the scenario to be covered, and the high number of wireless nodes that are necessary to monitor all the trees and shrub species, two differentiated wireless networks are proposed. On the one hand, since the area covered by the flora is extensive, instead of a unique network, several sub-networks have been proposed, based on ZigBee technology (see Fig. 10). ZigBee technology provides the possibility of having a large number of nodes within the same network (up to 65,000), therefore, the high number of present flora elements can be monitored in each sub-network, while at the same time allows scalability. ZigBee also allows mesh topology, which makes the network more robust against wireless link falls. Therefore, this study has focused on the LoRaWAN network, since its star topology needs point-to-point evaluation (beside the presence of obstacles such as buildings), while ZigBee's mesh topology and the distances between ZigBee devices within a single sub-network are short and do not require extra radio planning tasks.

While ZigBee can be considered as a medium range wireless technology (which if low power consumption is wanted, the range becomes much shorter), a long range wireless technology has been proposed in order to send/transport the collected information of all the ZigBee sub-networks to a centralized gateway. For that purpose, three different technologies were assessed: NB-IoT, SigFox and LoRaWAN. All of them provided good coverage on campus, but even if LoRaWAN is the only one that needs the deployment of gateways (see Fig. 10), we opted for LoRaWAN because it does not require extra costs for the provided service after the deployment of the network, while SigFox and NB-IoT solutions require fee payments.

The proposed LoRaWAN wireless network has been evaluated as follows. The 3D-RL simulation tool has been employed to obtain an optimized deployment for the LoRaWAN gateway. Once a placement for the LoRaWAN gateway is obtained based on simulations, LoRaWAN communication measurements between each garden with a specific tree type (where the ZigBee sub-networks are deployed) and the LoRaWAN gateway within the campus (the central node in Fig. 10) have been performed. As in the ZigBee case, different node heights have been considered. Received packets, RSSI and SNR were measured.

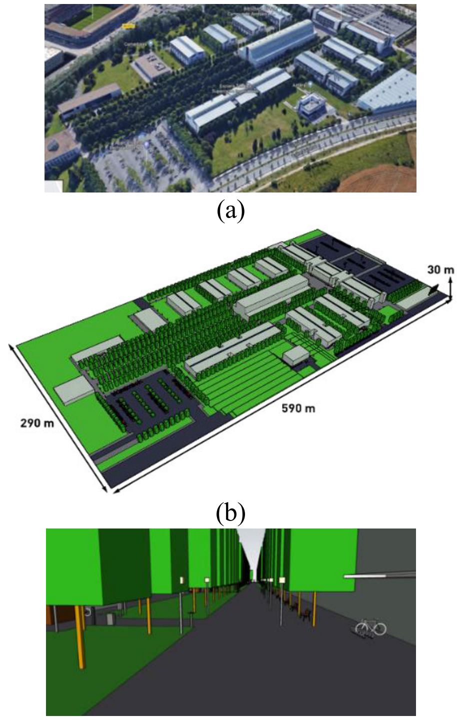
A. 3D RAY LAUNCHING FOR LoRaWAN

In order to provide full campus connectivity, the local sub-networks operate in conjunction with campus wide networks. Therefore, an additional deterministic radio planning study has been performed to obtain information about the feasibility of the proposed WSN for the whole campus. A view of the complete schematic campus model developed for the simulations is illustrated in Fig. 11. The campus of the Public University of Navarre scenario dimensions are 590 m long, 290 m width and 30 m height.

All the existing elements at the campus, such as trunk tree, foliage, streetlights, grass, benches, vehicles, and metallic elements, have been considered, making a simulation volume of 5.1 million m^3. Table 5 presents the frequency dispersive material properties of the elements within the campus scenario.

Fig. 12 illustrates the coverage maps for receivers placed at different heights $H_1 = 2$ m, $H_2 = 4$ m and $H_3 = 6$ m from the ground, and transmitters placed at *Los Tejos* building in Fig. 12 (a) and *Las Encinas* in Fig. 12 (b), at a height of 1.1 m from the ground. It is worth noting that results have been obtained for the complete simulation volume, although they are represented in bi-dimensional constant height cut-plane for the sake of clarity. *Los Tejos* and *Las Encinas* buildings simulations results were chosen because of their locations within the campus context.

Results show that coverage distributions at the height of 4m are better than the two other heights for both transmitters. Thus, placing the gateway at 4m from the ground provides higher received power levels and hence, communication link quality metrics with the nodes. Fig. 13 shows the coverage intersection of both transmitters. The results from transmitters placed at other buildings are compatible with this conclusion.



(c)

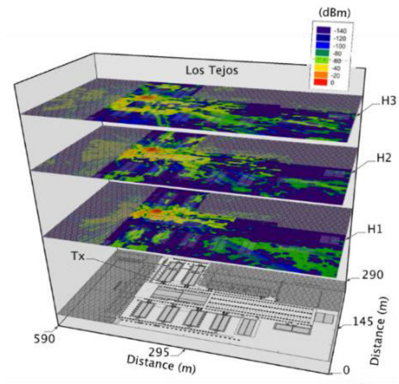
FIGURE 11. Campus scenario for simulation in the 3D Ray Launching Simulator (a) real view and (b) schematic view and (c) a zoomed part of the scenario.

TABLE 5. 3D RL material properties for the campus scenario.

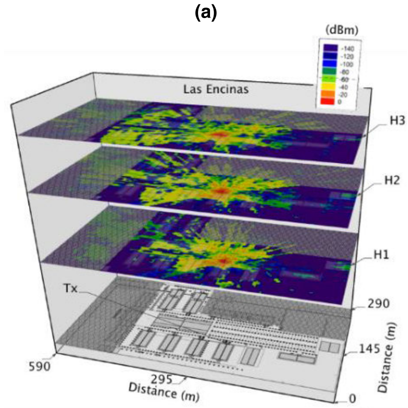
Parameter	Permittivity (ε_r)	Dielectric constant (σ) [S/m]
Metal	4.5	37.8×10^6
Plastic	8.5	0.02
PVC	4	0.12
Asphalt	5	0.7
Glass	6.06	0.11

B. LORAWAN MEASUREMENTS

In order to analyze and validate LoRaWan system deployment, The Thing Network (TTN) nodes have been attached to trees from all the seven types within the campus. Measurements have been conducted with the TTN nodes placed on the ground and at a height of 1.1m from the ground.



(a)



(b)

FIGURE 12. Estimated RF power distribution planes obtained by 3D RL at different heights for a transmitter placed at (a) *Los Tejos* building, and (b) *Las Encinas* building.

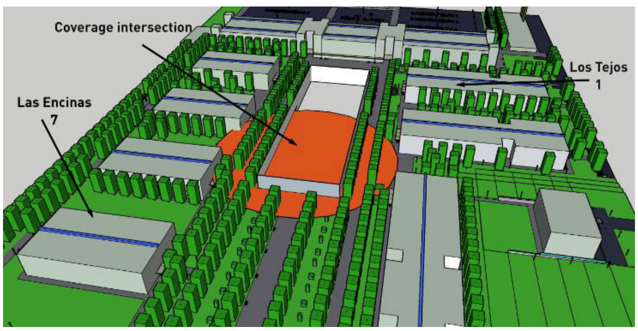


FIGURE 13. Coverage intersection for transmitters placed at *Los tejos* and *Las Encinas* buildings.

The transmitted power and the sensitivity of the TTN nodes are 14 dBm and −148 dBm respectively. Following the simulations results and Fig. 13, the TTN gateway has been placed at the library, which is located at the center of the campus for an optimal communication link with all the deployed nodes. Fig. 2 illustrates the locations of the TTN nodes and gateway and Fig. 14 shows the deployed devices for the measurement campaigns.

Received packets, RSSI and Signal-to-Noise Ratio (SNR) results have been obtained from direct communication between the TTN nodes in order to perform physical layer as well as preliminary system level validation. Fig. 15 depicts the results achieved for different node locations, placed at both 0.1m and 1.1m from the ground, and the gateway placed at 4m from the ground.

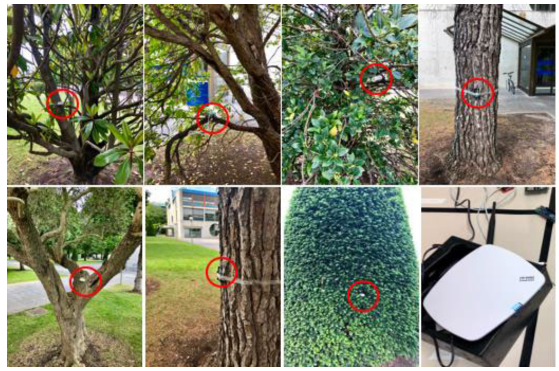


FIGURE 14. LoRaWAN system campaign: location of the different nodes within the campus, as well as the TTN gateway.

The results show that received power level are in general higher in over ground conditions, with an RSSI average difference in the order of 5-8dB between near ground and over ground links, consistent with losses given to ground/signal interaction. These results lead to improved performance in quality of experience metrics, such as those given by SNR and percentage of successful received packets. Hence, transceiver location within near ground leads to increased losses, which must be considered in the deployment phase to perform adequate coverage analysis and hence, optimal node location.

IV. SYSTEM VALIDATION AND APPLICATION DEVELOPMENT

Once a complete model for the different communication links within the distributed campus garden has been developed, a real scenario in terms of end users for trees monitoring within the campus has been tested for system validation. System validation is given by wireless communication between the sensor nodes and the Cayenne platform. The sensor nodes are communicating with the coordinator via ZigBee. Then, the coordinator sends data to the TTN gateway via LoRaWAN technology. The collected data is sent to the Cayenne platform for storage and display. A schema of all the communication steps for system validation is illustrated in Fig. 16.

Users can check the real time data of the tree parameters or revise the history of the last hour, day, week, month or year using cayenne's webpage or application, which is available on both Apple and Android. Fig. 17 illustrates some of the platform features.

After successful communication tests, a purpose specific application has been implemented. The developed application is divided into two main services, monitor and guide, as shown in Fig. 18. The monitor part is dedicated in the first place to gardeners and campus staff for data

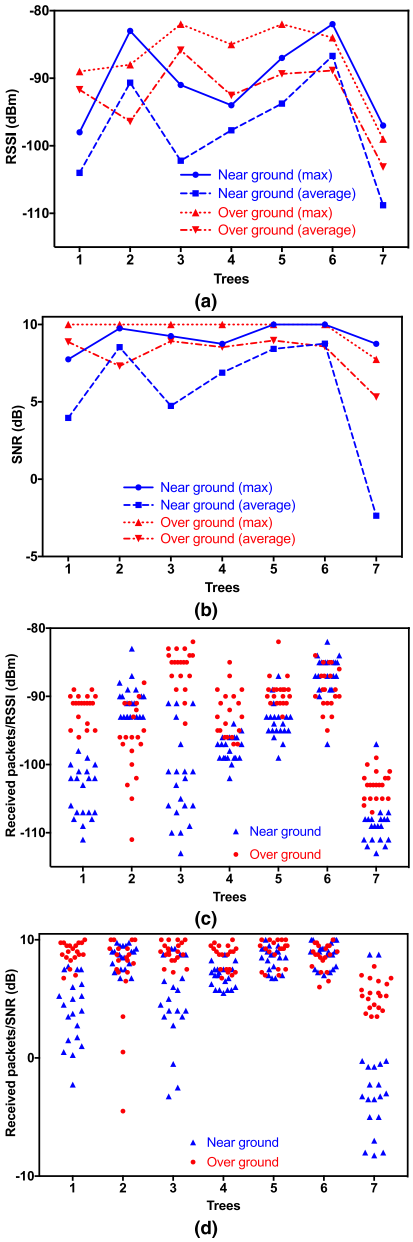


FIGURE 15. Near ground and over ground TTN nodes to gateway results: (a) RSSI, (b) SNR, (c) received packets/RSSI and (d) received packets/SNR.

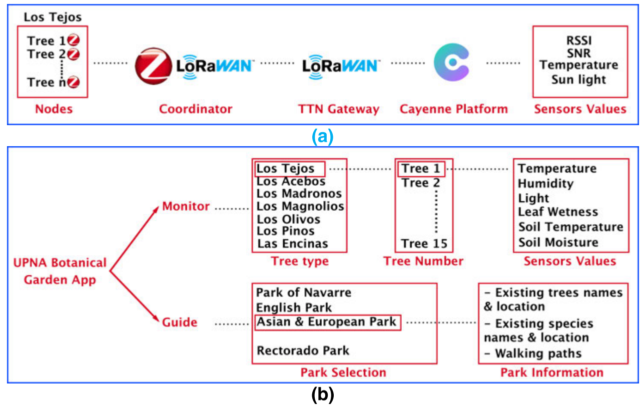


FIGURE 16. (a) Functional diagram of the measurements system; (b) Developed application blocks and features.

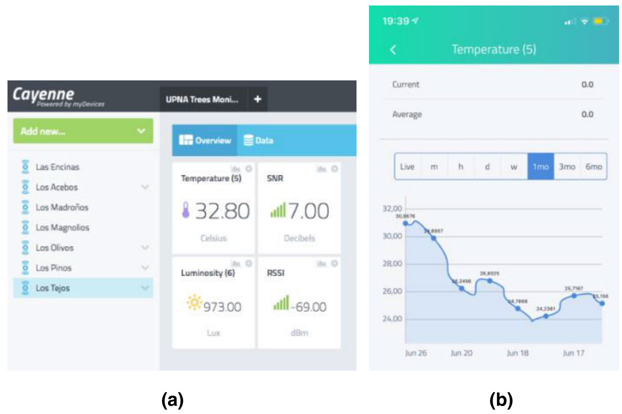


FIGURE 17. (a) End user platform for trees monitoring; (b) Temperature history plot for the mobile application.

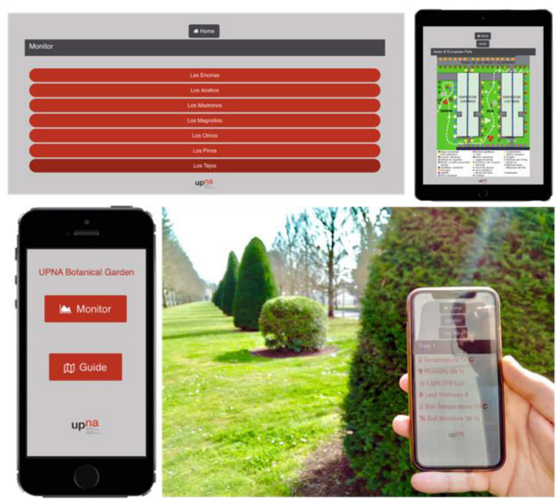


FIGURE 18. The developed UPNA Botanical Garden application, compatible with desktop, Tablet and mobile platforms. Bottom right, a picture of real time tree data monitoring within the UPNA campus.

analysis and decision making. To contribute directly to sustainability in green campuses and water saving. By selecting the desired tree type, user can select the exact tree number for sensors information display. For each tree, user can read the following sensor data: Air temperature and humidity, sun light, leaf wetness, soil temperature and moisture.

Moreover, the application guides new students and visitors through the gardens of the campus through the guide section. By selecting the desired park, visitors can see a schema of the park, containing the names of all the existing trees and species with its location at the park. Also, a walking path for assuring a valuable experience for visitors. For an easy use, the application is compatible with mobile, Tablet and desktop, as it is shown in Fig. 18.

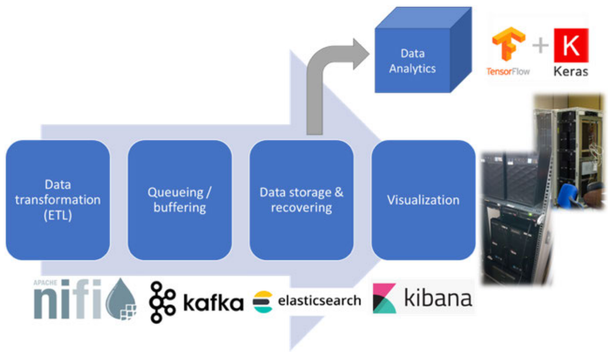


FIGURE 19. Platform architecture and network hardware employed for the UPNA Botanical Garden application integration.

In addition to the Cayenne environment, a specific platform called InGaM (Interactive Garden Monitor) has been developed for monitoring the campus garden of the Public University of Navarre. This platform, whose architecture is depicted in Fig. 19, is based on Apache and Elasticsearch's components. Data collected by the WSN network can be injected directly into the platform, or it can be imported as often as desired from the Cayenne platform. In addition, the platform allows importing meteorological information from the national and regional meteorological networks [48], [49], in addition to municipal [50] and regional geographical open-data [51].

Data harvesting may be heterogeneous in terms of data model, so Apache Nifi allows data transformation and provides ETL functionalities (extract, transform and load) to ensure the arrival of quality, consistent and standardized data in the NGSI-LD data format to the platform. According to the data source, the data is distributed into message queues managed by the Apache Kafka component, which allows the use of the publish/subscribe paradigm. Data recovery, previously structured by Nifi and arranged by Kafka, is stored by means of the Elasticsearch component. Finally, visualization is provided by the Kibana component. All the components (Nifi, Kafka, Kibana and elasticsearch) are well-known and widely used software components. As a parallel learning mechanism, there is a data analysis module based on Python, Keras and TensorFlow, which enables fast experimentation with deep neural networks. Currently, InGaM has just accomplished its implementation and validation phase, and as enough data is harvested, data analysis will begin.

V. CONCLUSION

In this work, an interactive and distributed botanical university campus garden end to end system is proposed. Deterministic wireless channel analysis has been performed, considering a full set of communication links that includes underground, near ground and over ground communications. Precise coverage estimations for the complete volume of a very large and complex scenario, such as UPNA campus have been obtained, for communication links at 868MHz and 2.4GHz frequency bands. The results have allowed the deployment of the sensor nodes, employing ZigBee protocol and data communication links, based in LoRaWAN. Simulation along with measurement results indicate the differences and limitations within the different communication links under analysis, establishing the maximum link distance for each one of underground, near ground and over ground link types. System level validation has been performed, initially on a Cayenne platform and afterwards a purpose specific dual application and in-house implemented cloud-based architecture. Measurement results show the viability of the system in terms of communication link availability as well on the successful reception of both telemonitoring data (for asset management) as well as those related with visitor interaction. Future work is foreseen in higher levels of sensor integration, as well as in interoperability of the data management system at operational level with the Pamplona Smart City platform.

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