Practical Design of a WiFi-based Wireless Sensor Network for Precision Agriculture in Citrus Crops

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Abstract: Agriculture is one of the most important economic sectors in the world. On the one hand, most of its importance resides in the food that is produced. On the other hand, this sector employs millions of people in the world both directly and indirectly. The introduction of Internet of Things (IoT) solutions for crop monitoring and management was the next step to improve the quality of the product, the quantity in the production, and to reduce the use of resources such as water. In this paper, a practical design of a WiFi-based Wireless Sensor Network (WSN) for citrus crop monitoring is presented. A mathematical model is obtained from the results of practical tests performed with low-cost devices for different height configurations of both the Access Point (AP) and the emitter according to the distance. The maximum coverage for the AP for each configuration is obtained as well. The results show the number of sensor nodes necessary to monitor the field according to its extension, and the number of APs needed to provide coverage for all the nodes deployed on the citrus field for each configuration. This way, a tool for the design of WSNs to monitor citrus plots is provided.

1 INTRODUCTION

Agriculture is one of the strongest economic sectors in the world, employing over one-third of the population on the planet (Perri, 2017). Furthermore, many families depend on it, where often the entire family is employed in this sector. This is more evident in developing countries where agriculture is the key to the survival of people. Agriculture is also related to sustainability and human rights issues such as water scarcity, contamination due to chemical fertilizers, child labor, or the contamination of the products caused by the usage of untreated wastewater and polluted water for irrigation. These aspects are raising the concern of both farm workers and consumers, leading varied organizations to take action to improve these problems.

As the focus on sustainability increases, the United Nations has established a set of sustainable development goals for 2030 (UN, 2022) to raise awareness of some aforementioned aspects. Eight of the 17 proposed goals can be related to agriculture and how it can be optimized and be more sustainable using technology. The first goal associated with agriculture and its concerns is the second goal, which is focused on wasting less food and supporting local farmers. The sixth goal is focused on avoiding wasting water, which in precision agriculture can be accomplished by the implementation of smart irrigation systems (Garcia et al., 2020). Furthermore, the seventh goal is focused on energy efficiency. Precision agriculture Internet of Things (IoT) systems can implement energy efficiency algorithms and use solar panels to power the system to reduce energy consumption and obtain green energy. IoT precision agriculture systems can also be part of the eighth goal of creating job opportunities for the youth as new job opportunities would be designed to manage these systems. The ninth goal is Industry, Innovation, and Infrastructure investment. The eleventh goal is focused on Sustainable Cities and Communities, and IoT precision agriculture systems can be tied to this

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topic. There are papers focused on urban farms. Moreover, the twelfth foal is focused on Responsible Consumption and Production. This goal can be applied to both the materials used in the hardware of the precision agriculture system and the optimization of the resources used in the fields. Lastly, the fifteenth goal is centered on Life on Land and protecting the environment. This can be achieved by focusing on making agriculture more sustainable.

As mentioned before, IoT technologies can aid in achieving the goals proposed by the UN in the sector of precision agriculture. Moreover, with the increase in the production of low-cost sensors, it is possible to implement low-cost precision agriculture solutions for developing countries to aid farmers and aid in achieving sustainable agriculture. As a result, most of the papers on intelligent systems for agriculture are produced in countries with high dependence on this sector and low income for the farmers, such as India, which produced 57.5% of the papers on smart irrigation for precision agriculture in the world (Garcia et al., 2020). Furthermore, most of the papers employed low-cost sensors to ensure their affordability, increase the chance of these systems being deployed, and help farmers improve the quality of both produce and their work life.

However, there is a crucial aspect to consider regarding the access of the precision agriculture system to the internet. Fields are often far from populated areas and do not have access to the cabled infrastructure of a service provider. Therefore, wireless communication presents itself as a solution to provide communication to remote locations.

WiFi is a very popular wireless communication technology for IoT systems in precision agriculture; its coverage range allows Arduino microcontrollers to receive information from the different nodes distributed through the crop field. The use of applications and smartphones will enable the farmer himself to know in real-time the situation of the area and be able to make sustainability decisions when necessary, for example, in the use of irrigation water, and fertilizers, among others. Some studies show that the signal between nodes varies according to the height at which the node is located. In (Garcia et al., 2021), the results show that the lower the size, the better the signal quality. In addition, it is taken into account that the vegetation density varies with the quality and strength of the WiFi signal.

Considering all these issues, this paper presents a practical design of WIFI-based wireless sensor networks for precision agriculture in citrus crops. To do that, we based on our mathematical model in previous practical experiments with low-cost Wi-Fi nodes. Our practical design will estimate the number of sensors and access points (APs) we will need to cover a field with different sizes for different conditions.

The rest of the paper is organized as follows. Section 2 presents the related work. A general description of WSNs is presented in Section 3. Section 4 describes the mathematical model in which our practical design is based. The final results of our practical design are shown in Section 5. Finally, the conclusion and future work are presented in Section 6.

2 RELATED WORK

This section presents some works based on WiFi connections to send data in different types of crop fields. In addition, with the data collected through the use of sensors (temperature, humidity, water level, pH...), the farmer is informed of the situation of the field, which allows him in real-time to be able to know the needs of the crop and make decisions.

Firstly, it is important to perform a good design in the network deployment to ensure the correct operation. For example, Brinkhoff et al (Brinkhoff et al., 2017) studied the propagation characteristics of the 2.4 GHz WiFi signal in natural outdoor agricultural crop environments using field data. As a result, they established that crop growth status was much more significant in determining signal strength than weather conditions, with signal strength declining by 8 dB in a cotton field and 20 dB during the season. dB in a rice field. Another example of wifi practical deployment is presented by Yang et al., (Yang et al, 2022). This paper addressed the problem of mold affecting wheat in storage. They developed a low-cost, non-intrusive, and non-destructive detection system by implementing the use of Wi-Fi devices. They demonstrated the feasibility of using WiFi Channel Status Information (CSI) amplitude for mold detection in stored wheat. Finally, they established the MiFi system, a radial basis function (RBF) neural network-based detection model, and mold detection.

Additionally, those designs are frequently used in specific applications such as the following ones:

In 2018, (Mei-Hui Liang et al., 2018) proposed a dynamic monitoring method for China's production greenhouses. This is because until then, artificial means were being used, which used cables. The automatic monitoring methods were based on the 485 bus or the CAN bus, presenting particular problems. For this reason, and to alleviate these problems, dynamic monitoring based on Wi-Fi is proposed. To do this, through the sensor of the designed greenhouse, the light intensity of the greenhouse, humidity, and temperature were taken remotely. They developed a software and hardware system for data collection from the greenhouse via Wi-Fi. They had the system running for seven days, and the results obtained were highly accurate. In that same year, (Mahmud et al., 2018) established a system based on carbon dioxide, humidity (both MQ135), and temperature (DHT11) sensors. These parameters are necessary for cultivating mushrooms since they cannot grow at temperatures below 25ºC or above 33ºC, hence their importance. This work focuses on developing an automatic environmental control system that allows the farmer to optimally control crop conditions. The sensors are connected to the ESP8266 Wi-Fi module to become IoT (Internet of Things) sensors that send a large amount of data to the Internet for monitoring and evaluation. The irrigation system is thus capable of turning on or off depending on the climatic conditions in which the crop is found.

On the other hand, in 2020, several authors presented studies related to WiFi connection and agriculture. (Rawi et al., 2020) used the Arduino microcontroller, which captures, processes, and subsequently analyses the data from the previously connected sensors. The utilized sensors were used to establish soil parameters. They used the humidity, pH, and soil inclination sensor. This study arose from the need to be able to monitor palm oil fields remotely. This type of oil is one of the staple products of Malaysia. In this way, the production of this type of crop can be controlled because the quality of the oil depends vitally on the quality of the soil. This allowed the farmer to control his cultivation since the data obtained was sent via WiFi to the cloud database for registration, and, in addition, it was displayed in real-time on a graph using ThingSpeak. Sreeja et al. (Sreeja et al., 2020) in that year developed an intelligent agricultural monitoring system to be able to provide water and air to the crop. They carried out an innovative method based on IoT, which consisted of three sensors (pH, water level sensor, and soil humidity), a WiFi module, and a DC motor. The data obtained from the sensors and stored and processed by the microcontroller were sent to the IoT platform via WiFi connection. The values obtained are sent to a registered mobile through the GSM modem. In addition, they established that if the value of the sensor exceeded the specified threshold, it would send a notification to the farmer's mobile. This system allows the farmer, in real-time, to know the state of the crop field. In this case, it was used for rice production fields. And finally, (Saini et al., 2020) showed an IoT platform based on NodeMCU (which has built-in WiFi) and ThingSpeak. The work shown develops an intelligent agricultural monitoring system to alleviate the problems that farmers face concerning irrigation. With this development, the farmer is helped to control the irrigation of his field from a computer or his smartphone. In addition, if the value is below what is established, an email will be sent so that the farmer can take the necessary measures. It allows real-time monitoring of such essential parameters for the crop as humidity and temperature directly involved with the need or not to irrigate. In this way, it is intended to optimize water resources.

In the year 2021, Lloret et al. (Lloret et al., 2021) developed a sensor network based on WiFi communication for a flood irrigation system. With this, they established the opening and closing of the gates for the irrigation water. They selected different sensors to obtain atmospheric parameters (temperature, humidity, and rainfall), water parameters (salinity, water height, and water temperature), and soil parameters such as humidity. These sensors were installed in a natural environment to evaluate the correct functioning of the system. In addition, they developed an application for the user. The data taken by the sensors were collected and helped the farmer himself manage the irrigation of his fields.

3 WSNs FEATURES AND TOPOLOGIES

This section describes a brief description of the main characteristic of a WSN and the typical topologies we can find in applications, such as precision agriculture.

3.1 Overall description of a WSN

WSNs are based on low-cost and low-consumption devices (nodes) that are capable of obtaining information from the environment that surround them. The collected information can be locally processed and communicated through wireless links to a central coordination node. Additionally, these nodes can have different roles. While some of them can be only in charge of collecting data, others can act as a network element required to forward the messages transmitted by more distant nodes to the coordination center. A WSN is composed of numerous spatially distributed devices, which use sensors to monitor several parameters including temperature, sound, vibration, pressure, movement, or contaminants. Sensors can be fixed or mobile.

The devices used to measure these parameters are usually autonomous units that consist of a microcontroller, a power source (commonly a battery), a radio interface that depends on the technology used, and finally, digital and analog inputs/outputs to which sensors can be connected.

Due to battery life limitations, nodes are built considering, among others, energy constraints, and they generally spend a lot of time in a low-power consumption, i.e., sleep mode. WSNs have self-restoring and self-organizing capabilities, that is, if a node fails, the network will find new ways to route data packets. In this way, the network will remain alive as a whole, even if an individual node fails. Self-diagnosis, self-configuration, self-organization, self-restoration, and repair capabilities are properties that have been developed for this type of network to solve problems that were not possible with other technologies.

Possible applications of sensor networks include:

- Smart agriculture.
- Industrial automation
- Smart and automated homes
- Video surveillance
- Traffic monitoring
- Monitoring of medical devices
- Monitoring of weather conditions
- Air traffic control
- Robot control

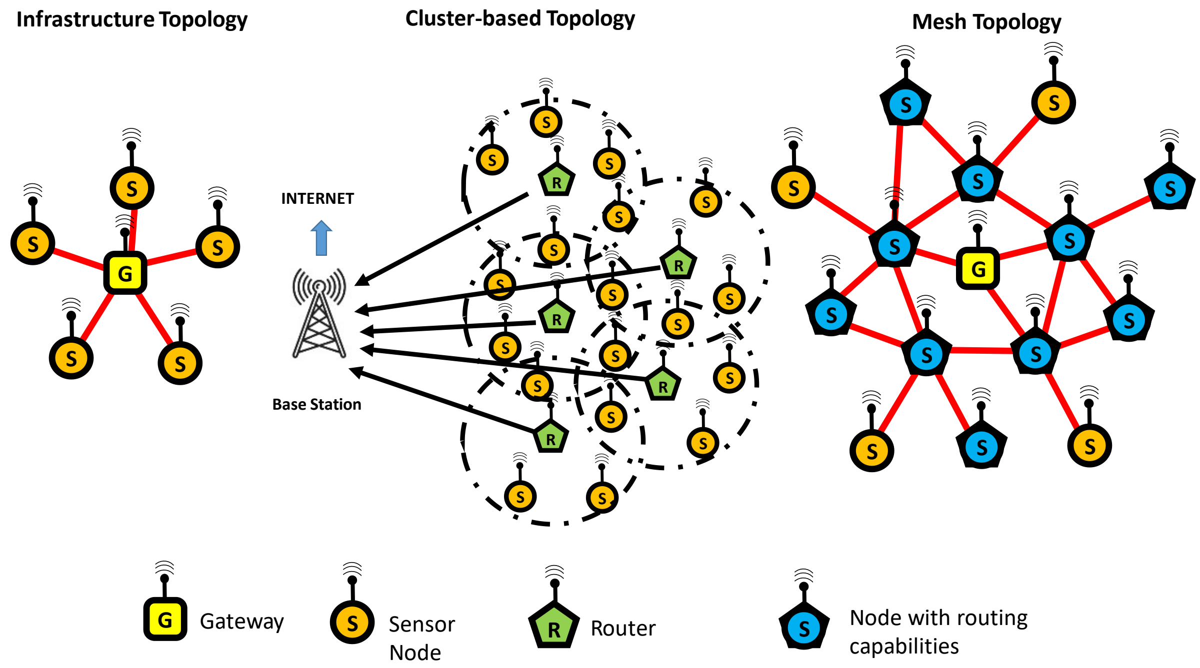

Figure1: Topologies used in WSNs.

3.2 Typical WSNs topologies

Sensor networks are characterized by being unattended networks with a high probability of failure (in the nodes, in the topology), usually built ad hoc to solve a very specific problem (that is, to run a single application). For this reason, the topology of a WSN is a critical design factor that depends a lot on its deployment in the crops to be monitored.

In order to design a topology, it is commonly used mesh networks. However, it is possible to work with more simple topologies such as an infrastructure (star topology) topology where the center of the star is the gateway (See Figure 1). This gateway device acts as a communication bridge to a wired network.

The cluster-based topology combines the benefits of the previous one to give intermediate fault tolerance, but with greater scalability and energy efficiency. It is appropriate for medium-scale applications that use battery-powered nodes. This topology organizes the nodes into logical groups called clusters where each router, including the base station, forms a cluster and it is therefore known as a cluster head. The end nodes associated with a particular cluster head belong to its group, and all their transmissions are controlled by the cluster head. The base station is identified as the root of the network and forms the initial cluster. With this topology, the life of the batteries can be extended using a mechanism that establishes cyclic periods in which the radio of the nodes is turned on or off.

4 MATHEMATICAL MODEL

In this section, the coverage models obtained from the results of the experiments performed with low-cost devices on citrus fields are presented.

The tests were performed in orange fields with devices deployed at different heights and distances. The Access Point (AP) was deployed at heights of 0m, 0.5 m, and 1 m. The emitter was located at heights of .5 m, 1 m, 1.5 m, and 2 m. The results from these tests were published in our previous work (Garcia et al., 2021), as well as the employed methodology and the description of the utilized devices. The following models present the theoretical received power for each of the combinations of AP height and emitter height. For an emitter height of 0.5m, the equations of the theoretical models with the AP located at 0m, 0.5m, and 1m are (1), (2), and (3) respectively. Where *d* is the distance in meters.

$$P_{rx-0m}(dBm) = -39.25 - 11.24 \ln d \quad (1)$$

$$P_{rx-0.5m}(dBm) = -38.54 - 8.303 \ln d \quad (2)$$

$$P_{rx-1m}(dBm) = -57.47 - 1.899 \ln d \quad (3)$$

The models for the emitter height of 0.5m and each of the AP heights are equations (4), (5), and (6).

$$P_{rx-0m}(dBm) = -41.77 - 10.71 \ln d \quad (4)$$

$$P_{rx-0.5m}(dBm) = -47.68 - 4.124 \ln d \quad (5)$$

$$P_{rx-1m}(dBm) = -43.43 - 8.337 \ln d \quad (6)$$

Equations (7), (8), and (9) present the models for the combinations with an emitter height of 1.5m.

$$P_{rx-0m}(dBm) = -49.199 - 12.08 \ln d \quad (7)$$

$$P_{rx-0.5m}(dBm) = -39.336 - 9.037 \ln d \quad (8)$$

$$P_{rx-1m}(dBm) = -50.89 - 7.516 \ln d \quad (9)$$

Lastly, the models for the emitter height of 2m are equations (10), (11), and (12).

$$P_{rx-0m}(dBm) = -42.851 - 12.02 \ln d \quad (10)$$

$$P_{rx-0.5m}(dBm) = -40.715 - 10.26 \ln d \quad (11)$$

$$P_{rx-1m}(dBm) = -47.002 - 8.008 \ln d \quad (12)$$

According to the previous models, the theoretical coverage of the utilized low-cost AP devices in a field of citrus trees, including the losses caused by the vegetation from the trees is presented in Figures 2, 3, and 4. Figure 2 presents the results for the AP deployed on the ground. As can be seen, the best coverage is obtained for the lower emitter heights as there is little vegetation density.

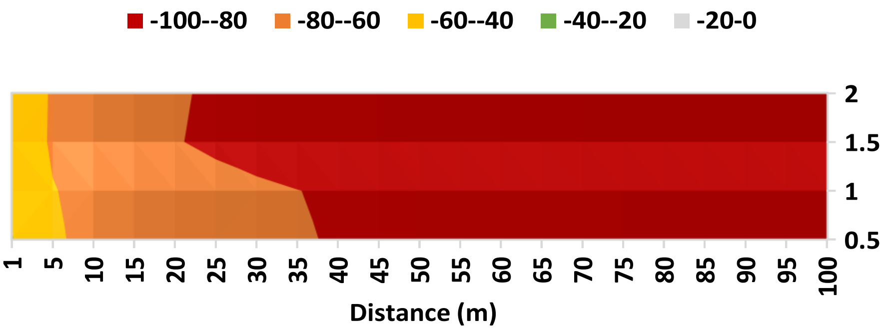

Figure 2: Coverage of AP deployed at a height of 0m for each of the emitter heights.

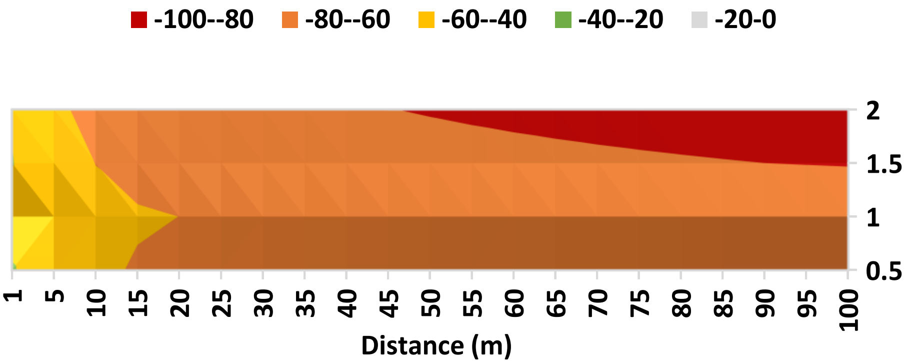

Figure 2: Coverage of AP deployed at a height of 0.5m for each of the emitter heights

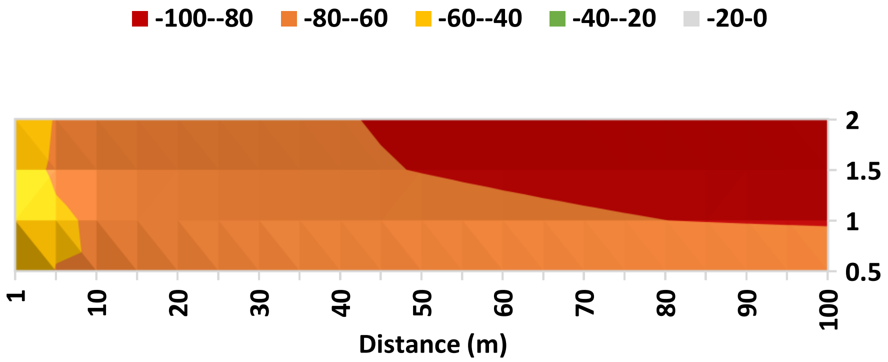

Figure 3: Coverage of AP deployed at a height of 1m for each of the emitter heights.

Table 1: Maximum coverage for each configuration of AP and emitter height.

	Emitter height			
AP Height	0.5 m	1 m	1.5 m	2 m
0 m	38	36	22	22
0.5 m	100	100	90	47
1 m	100	81	46	43

The coverage for the AP height of 0.5m according to the theoretical models is provided in Figure 3. As can be seen, the increase in height has led to better coverage. However, the best results remain for the medium to lower emitter heights.

Lastly, Figure 4 presents the coverage for the AP height of 1 m. In this case, the coverage is again reduced, in comparison to the previous AP height, and the best results are obtained for the lowest emitter heights.

Considering the data presented in the previous figures and selecting -80 dBm as the lowest admissible received power, the coverage in meters of the APs for each configuration is presented in Table 1.

5 RESULTS

This section presents the results of the number of devices that need to be deployed to provide coverage on citrus fields of varied dimensions. These results have been obtained considering the node density, the area to be covered, and the coverage provided by the devices at different heights as presented in the previous section.

Figure 5 presents the number of sensor devices required to monitor the expanse of a field of the dimensions displayed on the X-axis according to node densities of 1 node per 5 m^2, 10 m^2, 50 m^2, and 100 m^2. The selection of the node density will depend on the functionalities and accuracy desired for the design of the crop monitoring system.

The AP devices need to gather information from the number of sensor devices shown in the previous figure. The number of AP devices needed to cover the field for the emitter height of 0.5m and the three options of AP heights is presented in Figure 6. As it can be seen, the number of necessary AP devices of these are located on the ground increases substantially as the area increases. However, for both heights of 0.5m and 1m, the device requirement is considerably less.

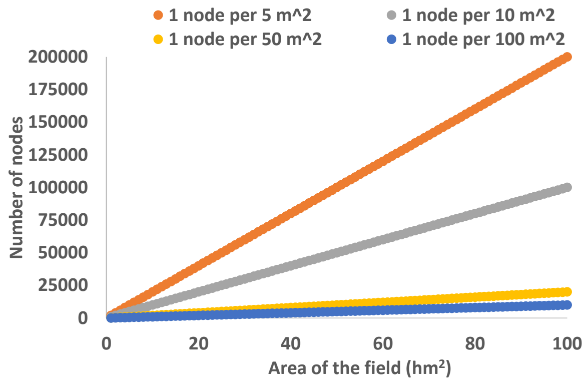

Figure 5: Number of nodes per area of the field.

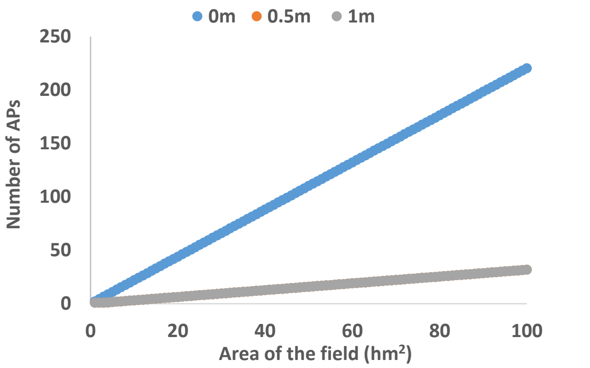

Figure 6: Number of APs per area of the field for the emitter at 0.5 m.

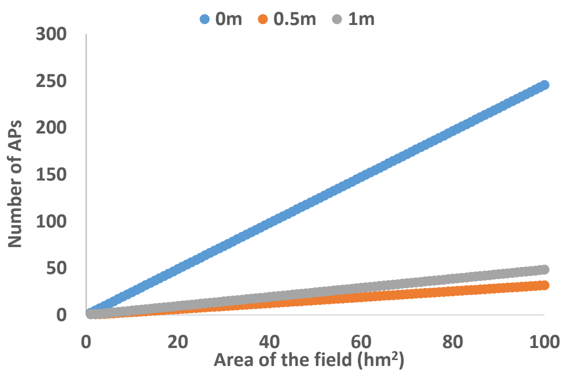

Figure 7: Number of APs per area of the field for the emitter at 1 m.

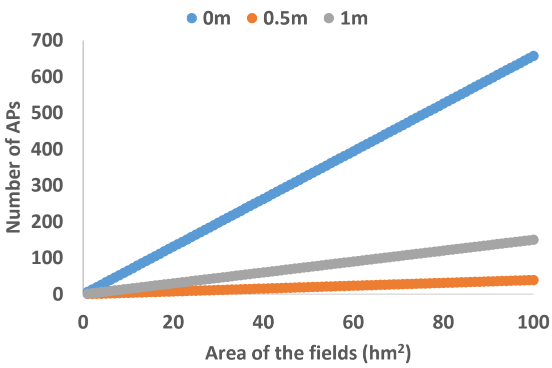

Figure 8: Number of APs per area of the field for the emitter at 1.5 m.

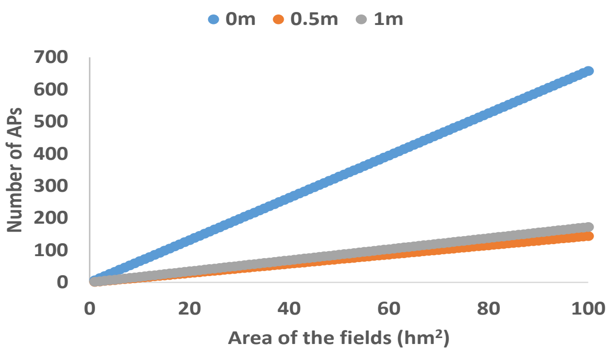

Figure 9: Number of APs per area of the field for the emitter at 2 m.

The results for the number of AP devices necessary when the emitter is placed at a height of 1 m are presented in Figure 7. As can be seen, there is an increase in the number of devices needed to provide coverage compared to the previous case. Furthermore, there is a slight difference between the AP heights of 0.5 m and 1 m, with the first one being the best option.

Figure 8 presents the results for the emitter height of 1.5 m. The number of necessary APs to provide coverage is increased once again compared to the previous case. Furthermore, the difference between the number of devices needed with the AP located at a height of 0.5 m or 1 m is more differentiated as well, with the first one being the best option.

Lastly, Figure 9 presents the results for the emitter height of 2 m and the different configurations of AP height. For the AP height of 0m, the results are similar to those of the previous case. However, for the higher AP heights, the number of necessary devices is increased. Though the difference between the 0.5 m and 1 m AP heights is reduced compared to the previous figure.

6 CONCLUSION AND FUTURE WORK

Agriculture is a key element to the economy and well-being of the population in the world. WSNs were incorporated into the agricultural fields as a way of improving both the produce and the amount of the utilized resources. In this paper, a practical design for WSNs in citrus plots based on WiFi wireless technology is presented. The mathematical model for different configurations of the heights of the APs and the sensor nodes is provided. Furthermore, the results of the number of devices needed to monitor the field and to provide enough coverage were obtained as well for each configuration.

In future work, tests with deployments of LoRa-based WSNs for agriculture will be performed to provide the tools for the design of this type of network.

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