Cloud-based Wireless Sensor and Actuator System for Smart Irrigation

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Abstract

The number of devices connected to the Internet is experiencing an explosive growth. This development leads to a world with endless possibilities offered by M2M (Machine-to-Machine) communication, including the deployment of a smarter and greener planet through the use of information acquired around us. The interconnection of smart objects embedded with sensors enables this interaction with the environment according to the concept of Internet of Things (IoT). These sensors communicate wirelessly forming a Wireless Sensor Network (WSN), which performs acquisition, collection and analysis of data such as temperature and soil moisture. The almost infinite capabilities of storage and processing, the rapid elasticity and pay-per-use characteristics makes Cloud Computing an attractive solution to the large amount of data generated by the WSN. This dissertation proposes and evaluates a cloud-based Wireless Sensor and Actuator Network (WSAN) communication system to monitor and control a set of sensors and actuators to assess the plants water needs.

Keywords: Wireless Sensor and Actuator Network, Internet of Things, Machine-to-Machine, Cloud computing, Irrigation and Optimization.

1. Introduction

The World is experiencing a continuous technological development. Recent developments are enabling the deployment of miniaturized and low-cost electronics in a variety of sectors. Agriculture is surely one of them. Playing an important role in the economy of every nation, agricultural production has been experiencing the continuous improvement of its processes and techniques, which is the focus of the precision agriculture (PA) concept. The objective of precision agriculture is, by collecting real-time data from the environment, to improve products quality as well as maintaining a sustainable agriculture. To accomplish this, there is the need for optimizing the resources used in the agricultural processes, mainly in the irrigation system.

Water plays a crucial role in plants lifecycle, including germination, photosynthesis and nutrition processes [1]. Most of the times, the water provided by natural precipitation is not enough in order to provide the amount of water the plants need to grow in a healthy way. Currently, agriculture consumes about 70% of the fresh water [2]. This percentage can be decreased performing an efficient water management when it comes to irrigation. Performing Precision Irrigation, the water is applied in an efficient and optimized way, in the right place, at the right time and in the right amount. It brings wide benefits, such as water savings, money savings as well as the improvement of crop quality.

The progress of the precision agriculture passes by collecting and interpreting huge amounts of data from the field so as to understand the causes of variability and propose strategies for field management. The most important agricultural process which can be controlled and adapted to better suit the plants growth is related to irrigation. First and foremost there is the need to identify the tools used to acquire the generated data in order to be analyzed and compared. The amount of data is enormous. If this data is not organized and processed, it will become meaningless. So some of the difficulties in the adoption of precision agriculture are related to data handling and data processing [3] as well as the significant investment cost in hardware solutions to save this huge amount of data[4]. It is also very important to provide a system that is economically viable for a single farmer as well as to a big farming company.

2. Related Work

Several projects have been developed in the area of environmental monitorization. In this section some relevant architectures of projects will be described.

2.1. SensorScope

SensorScope project [5] consists of a WSN-based system for environmental monitoring. The development of such system pretends to substitute the traditionally very expensive sensing stations, by a reliable, low-cost WSN-based system. The overall architecture of this project can be seen in Figure 1. The stations transmit the data gathered in a regular basis to a sink node. The sink node forwards the data received to SensorScope Data Base, which in turn makes it available to other servers.

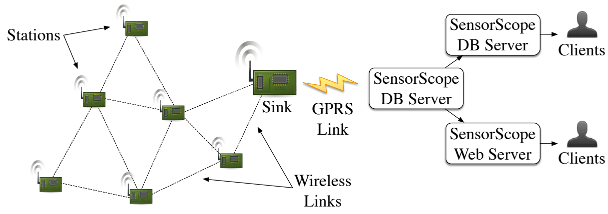

Figure 1: SensorScope Architecture, adapted from [5].

The sensor nodes used in this project are Shockfish TinyNodes. Each sensor node is placed in a sensor box, which also contains primary and secondary batteries. A sensing station is composed by a sensor node, a solar panel and environmental sensors. Each station contains up to seven sensors, capable of measuring up to nine environmental quantities: air humidity, air temperature, precipitation, soil moisture, solar radiation, surface temperature, water content, wind direction and wind speed.

In order to test the viability of this project, indoor and outdoor experimental tests were conducted. The most relevant test was the Génépi deployment. The chosen site was a rock glacier located at 2500m on the Génépi, Switzerland, being the source of dangerous mud streams during rainfall, which caused accidents by flooding the adjacent road.

A total of 16 stations were deployed in this field, with special attention in their placement, in order to acquire meaningful data. The data collected comprises rain, wind and temperature measurements. This deployment allowed to test the stations autonomy in real and rough conditions. The acquired information provided important data employed to identify the microclimate of the region, which helped predicting the evolution of the frozen soils.

2.2. A Holistic Framework for Water sustainability and Education in Municipal Green Spaces

Fazackerley et al. [6] describe the adoption of an irrigation control system deployed in a municipal green space in the city of Kelowna, Canada. This space consists on a turf landscape, which is divided in zones. A zone is a turf grass area that is watered simultaneously, controlled by valves. This system aims to determine when, and how much water, to apply at each zone. To minimize water waste, the system uses an improved adaptive irrigation algorithm that calculates the amount of water to apply in a certain zone depending on the maximum water volume that the soil can store. The end-to-end system is presented in Figure 2.

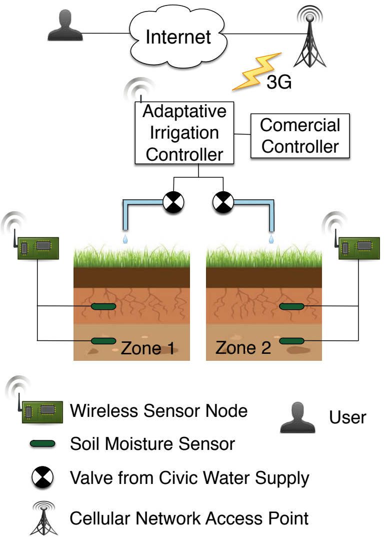

Figure 2: End-to-end System.

A wireless sensor node was deployed in each zone. Each node has two Decagon EC-5 dielectric soil moisture sensors coupled to it, as well as a wireless radio. One of the soil moisture sensors was placed in the rooting zone. The other one was placed below the rooting zone and its readings were not used in the adaptive algorithm.

The readings acquired by the soil moisture sensors are transmitted to the adaptive irrigation controller. This controller is coupled with a commercial controller, which receives remote updates used to estimate irrigation scheduling based on ET (Evapotranspiration). The commercial controller is the main controller in scheduling the watering events. However, the adaptive irrigation controller is able to override the scheduled events whenever it calculates distinct watering events.

The adaptive irrigation controller send the messages over a 3G network using TCP/IP to a central server. These messages contain soil moisture readings from each zone as well as information regarding irrigation events. Messages are stored in a database, used to provide the information to be displayed in the website. Users can consult the website in order to observe information regarding watering events, historical water content levels of each zone, as well as the total water savings experienced.

For an evaluation of water savings, the system stores both the actual watering events as well as the irrigation events only determined by the commercial controller. The total amount of water delivered based on soil moisture sensors was significantly lower than the amount of water estimated by ET based in the commercial controller. The water savings of the tested system offered 47% savings compared to the commercial controller. This work demonstrates the potential of soil moisture based irrigation over ET based irrigation.

2.3. GolfSense

Rocha et al. proposed Golfsense [7], an environmental monitoring application used to assist the irrigation management in a golf course, by constantly measuring the soil moisture state of the grass. To identify the requirements of this project, the authors utilized as a use case the Oeiras Golf & Residence golf course. This study provided information such as the behavior of a regular golf course irrigation system, as well as the mechanisms used to control the applied water. Three measuring parameters were identified: soil moisture at distinct depths, temperature at the ground level and the voltage of the batteries used to power the sensor nodes. The system's architecture is represented in Figure 3.

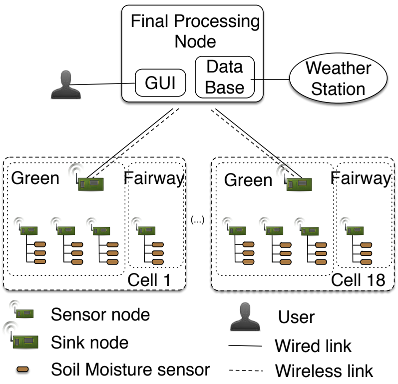

Figure 3: GolfSense system architecture, adapted from [7].

The Wireless Sensor Network is divided into cells. Each cell comprises a sink node and four sensor nodes. Three of these sensor nodes are placed in the green zone, and the remaining sensor is placed at the fairway zone. Each sensor node has 3 components: a MicaZ mote, a sensor board and EC-5 soil moisture sensors. The communication between sensor nodes is performed through IEEE 802.15.4. The sink node has the responsibility to transmit the sensor nodes readings to a final processing node (FPN).

Within a pre-defined sampling frequency, each sensor node of the network sends the measurements readings to the FPN. Readings acquired by the sensor node (soil moisture, temperature and batteries voltage) are used to estimate average values of each parameter, which will be sent to the final processing node, after the calculations. Every time a sensor nodes sends a message to the FPN, it waits until it gets a response message from the FPN.

These messages information regarding the next sensor nodes' state. Whenever the FPN receives a message from the sensor node, it checks if there is a pending irrigation order. If there is no pending order for that sensor node, the final processing node sends only the WSN configuration parameters. If a pending order for that sensor node exists, the final processing node sends, along with the WSN configuration parameters, the start and stop time of the irrigation to the sensor node.

Distinct tests have been performed in order to evaluate the accuracy of the soil moisture measurements as well as the system's ability to detect rain events. The obtained results demonstrated the usefulness of such a system in a golf course scenario.

2.4. Vineyard Computing

Vineyard Computing project [8] studied the vineyard workers' needs and priorities in order to provide a Wireless Sensor Network which could help the workers doing a better job. To do so, the authors studied workers and their practices through interviews, site tours and observational work. Through their study they concluded that the greatest variability of the parameters in the vineyard occurred during daytime, and so there should be a highest number of readings during the day and less frequently during the night. They also learned that during the winter the vineyard could be at risk because there is the possibility of frost formation.

Due to this problem, there should be frequent readings during the night and an alert system that could alert the manager whenever the temperatures were below a certain level. They observed that the workers required *actionable* data, or in other words, data that helps the workers to suggest the next step. For instance, a map that could evidence the areas of the vineyard at risk of powdery mildew (a fungal disease) calculated from temperature data readings of the vineyard over a period of time. This way, the vineyard manager could apply spray pesticides on the affected area.

The proposed architecture uses the concept of Data Mules. An overview of this system on a vineyard setting can be seen in Figure 4. Data is acquired by the sensor nodes in the vineyard every 60 seconds. These mules collect and transport data from the sensor nodes to the central database. The authors learned, from the interviews, that the workers move up and down the rows of the vineyard several times. This way, the workers could serve as “mules” by transporting a small device, which would wirelessly collect the data from the distributed nodes. Whenever the gathering device was physically close to a node, data would be transmitted, whenever new data were available.

Data mules give to the network the capability to emulate distributed nodes through the vineyard, since they do not need to communicate with its neighbours. The disadvantage of the data mules is the energy consumption, since the nodes must be awake all the time in order to detect and communicate with the data mule. Furthermore, this approach cannot be used in applications with real-time requirements (which was not the case, since vineyard managers do not need to calculate heat units immediately). The use of data mules allows the reduction of equipment costs.

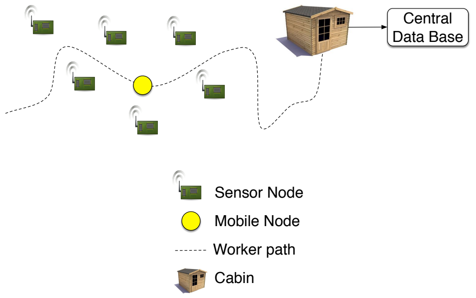

Figure 4: Data mule architecture system in the vineyard.

All the abovementioned systems are very similar regarding the wireless sensor network they comprise, except the Vineyard Computing project which uses the concept of data mules. The communication between the nodes are mainly performed using 802.15.4 or similar, whereas the communication between the sink nodes to the servers are performed through GPRS or 3G. The main difference between these systems rely on the network topology, mainly star and mesh topologies.

All the previous described systems use one or more servers to store the data they collect from the sensor nodes. The use of servers to store the required data has serious disadvantages which starts with the initial capital cost investment and the servers maintenance. Moreover as more sensor nodes are added to the network, more data is generated by them, which may cause the servers to have no space to store the information. Also, the authors of the SensorScope project highlighted the importance of saving all the raw data collected from the sensor nodes. This information can be used in the future to help the investigation of a variety of topics such as the continuous study for an optimized irrigation system or the improvement of the discovery process of plants diseases.

3. System Architecture

This work aims to be applied in a variety of distinct scenarios. Scenarios such as agriculture, greenhouses, golf courses and landscapes are a few examples in which the system described in this section can be deployed. The proposed general architecture must be modified in order to be adapted to each scenario and each situation requirements.

The architecture proposed for this project can be divided in three main components: a wireless sensor and actuator network component, a cloud platform component, and a user application component. The WSAN contains three different types of nodes: a sink node, a sensor node, and an actuator node. The cloud platform used in this project was the Sensefinity cloud platform, *Machinates*. In order to allow the user interaction with the system, a web application was developed. A representation of the proposed architecture can be seen in Figure 5.

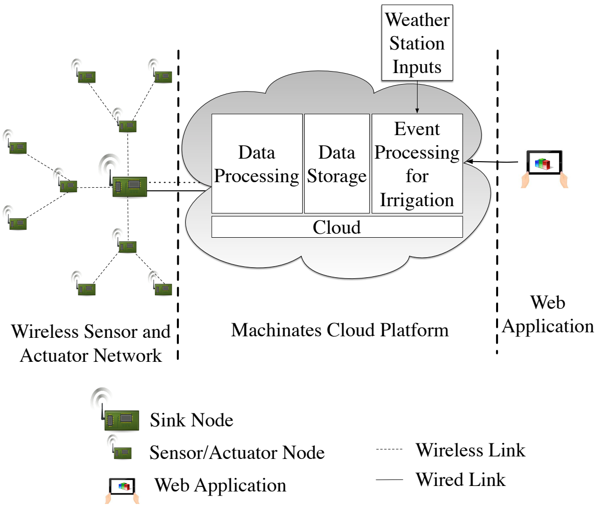

Figure 5: Proposed Architecture.

3.1. WSAN Infrastructure

Every distinct node of the network may have or not actuation capabilities. The proportion of actuators comprised in the network depends on the application scenario. In certain scenarios there is the need to have one actuator in each network node, whereas in other scenarios a single actuator can be responsible for a zone which may comprise several nodes.

Our work relies on the **cluster-tree** topology, given that this topology provides high scalability, good energy efficiency as well as reliability. Compared to the cluster-tree topology, the star topology does not provide great scalability and the mesh topology is poor in reliability and energy efficiency.

Notice that if the application scenario requires a small scale network, the star topology should be used instead. Since the nodes in this project are static, there is no need for adaptive routing. For this reason, it should be used a tree-based routing. When joining the network, the nodes establish a parent-child link. Knowing these parent-child relationships, the routing between the nodes is relatively simple. Using the cluster-tree topology, the sink node will act as the network coordinator, whereas the sensor and actuator nodes can act either as a router node and/or an end node. In order to extend the network, some nodes may be used to work only as repeaters without sensing or actuation capabilities.

The communication between the wireless nodes has to be performed by a low range communication protocol, such as ZigBee and 802.15.4. This technology is suited to this project due to its energy efficiency as well as suitable data throughput. The transmission from the sensor network to the cloud platform is performed by the sink node. The sink node must have two communication interfaces: one for the communication with the wireless nodes, and another one to the communication with the cloud platform.

Depending on the deployment scenario, the data transmission between the sink node and the cloud platform can be performed through a variety of technologies, either through a wired or wireless link. The choice of which technology to use, either wired or wireless, must be chosen according to the deployment scenario. For instance, if the WSAN deployment occurs in an agricultural field, the use of wired links is not appropriate because it may interfere with the workers activities. Regarding the wireless links, the technologies which are more appropriate for this project are either Wi-Fi 802.11 or GPRS (General Packet Radio Service). The decreasing costs of the GPRS communications, along with the deployment of the WSAN in remote zones makes this technology the better choice. In situations where GPRS connectivity is poor, the 802.11 technology could be used to send the data through a gateway.

3.2. Cloud Platform

The cloud component of this project is responsible for data storage and processing, as well as event processing regarding the irrigation algorithm. The platform has the responsibility for receiving the data from the WSAN, identifying the data sources, performing data validation as well as partitioning the data.

The actuator nodes should receive a control message in order to perform the irrigation. The decision of whether to irrigate, or not, is taken by the cloud platform. The sink node of the wireless sensor network continuously sends new measurements acquired by the sensor nodes. After the processing, the received value is compared to a threshold value, which must ensure the plants health and quality. Comparing these values it is decided if the plant in which the sensor node is located needs water.

In a regular basis, the cloud platform gets weather information from a Weather Station, capable of providing weather information regarding the region in which the wireless sensor network is deployed in. The data retrieved from the Weather Station should provide data specially regarding precipitation. Whenever the cloud platform detects that the threshold mentioned above has reached its limit, there is the need of correlation with the Weather Station data. In the case of imminent raining periods, the irrigation should not be performed. Otherwise, the cloud platform should send a control message to the wireless sensor network in order to start the irrigation in the targeted area. If the plant does not need water, the platform waits for the next measurement in order to verify once again if there is a need of irrigation.

3.3. Web Application

In the scope of this project, the web application is used to give users a textual and graphical representation of the information acquired by the wireless sensor network, which is stored in the cloud platform. This representation includes the soil moisture readings of each sensor as well as the irrigation periods.

4. System Implementation

This section details the implementation of the system's main three components in terms of technologies, hardware components and software solutions.

4.1. WSAN Infrastructure

The choice of network protocol for the WSAN fell on the proprietary SimpliciTI Protocol[9][10] developed by Texas Instruments. This protocol was chosen due to its simplicity, low-power and low system cost. SimplitiTI provides a simple protocol to implement a WSAN in a cluster tree topology by supplying APIs to easily manage messaging between devices. This protocol does not have a formal routing mechanism. However it supports the capability to create by software three logical objects: End Device (ED), Access Point (AP) and Range Extender (RE), which correspond to the End Node, Sink Node and Router Node described in the last section, respectively.

The hardware used for the implementation of the two devices known as **End Device and Range Extender** is the AA battery powered node of the eZ430-RF2500 Kit, which includes the MSP430F2274 microcontroller and the 2.4GHz CC2500 RF Transceiver, shown in Figure 6. Each ED/RE device has a soil moisture sensor connected to it.

Figure 6: Final ED/RE device.

Both ED and RE implement the same logical procedure, with the exception that the RE device also forwards the packets from other nodes to the Access Point. The logical procedure starts with the initialisation of the hardware interfaces and the network protocol, and then it performs soil moisture and battery readings with a pre-defined sampling frequency. Each time a measurement reading is performed, the devices send it to the Access Point. These devices also receive control messages from the AP, related to the modification of the measurements sampling frequency.

The initial hardware implementation for the Access Point made use of the same board of the ED/RE devices, which provided the RF radio capabilities to exchange messages within the WSAN network. This board was connected with another board (through an UART) with GPRS capabilities, designed by Sensefinity. This board includes the MSP430F5419A microcontroller and the SIM908 module. The final device developed for the Access Point device is pictured in Figure 7. This device also has the capability to control up to two distinct actuators through the use of one of the available GPIO pins of the microcontroller, for performing both the turn ON and OFF of the actuator.

Figure 7: Final Access Point device.

Having two distinct microcontrollers, there was the need to implement two distinct logical procedures. The eZ430-RF2500 board starts its logical procedure by initialising the hardware interfaces and the network protocol, and then it is responsible for receiving the measurement messages from the other network devices and forward them to the other board. The board with GPRS capabilities has the responsibility to manage the measurements messages, and send them to the cloud platform. These messages are stored in a queue waiting to be sent to the cloud.

Whenever the queue reaches a certain limit, the messages are formatted to the Columbus message format (the message format that the Machinates cloud platform understands), then encoded to base64 and finally sent to the cloud platform through HTTP. Whenever the board with GPRS capabilities receives a measurement message from the other board, it stamps the message with the current timestamp. This timestamp is provided by the on-board RTC (Real Time Clock).

When the board is initialized, it gets the timestamp information from the GPS module (included in the SIM908) in order to properly initialize the RTC with the current time. Besides sending measurement messages to the cloud platform, this board is also responsible for receiving the irrigation instructions from the cloud platform and activate or deactivate the actuator accordingly. Whenever the actuator is activated, and consequently starting the the irrigation, a control message is sent to the other network nodes in order to increase the soil moisture sampling frequency. The deactivation of the actuator also results in the modification of the sampling frequency to the previous frequency. This adaptive sampling frequency modification allows to better control the irrigation system in a way to optimize it.

4.2. Cloud Platform

Besides storing all the measurements received from the WSAN, the cloud platform is also responsible to detect whenever the plants need irrigation as well as sending messages to the WSAN in order to activate or deactivate the irrigation system. This decision making is performed through the use of two distinct pieces of information: the soil moisture measurements of the WSAN nodes and the weather station forecasts, as illustrated in Figure 8.

All the sensing nodes comprised in the WSAN send soil moisture measurements frequently, which will help the algorithm taking decisions concerning the need for irrigation. When a soil moisture message of any node has a value below the defined threshold, the service will check for the weather forecast for the next 6 hours, in order to decide whether to irrigate or not. If, in the next 6 hours the probability of precipitation is larger or equal to 50%, the system will not irrigate, otherwise, the cloud sends a message to the WSAN in order to

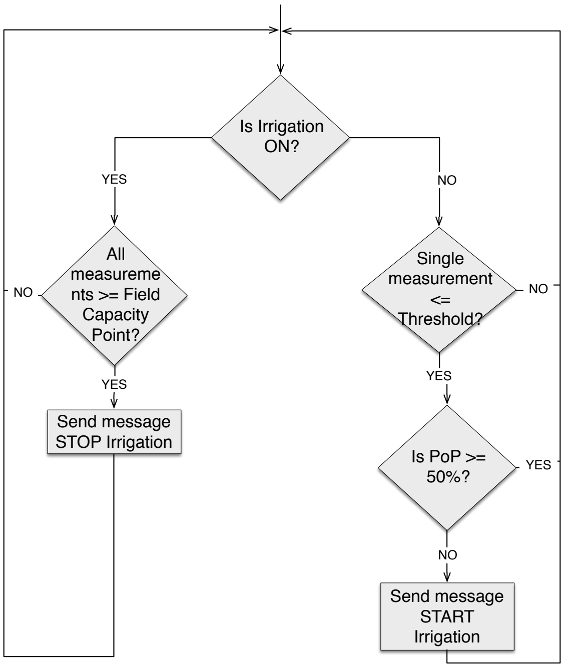

Figure 8: Irrigation Algorithm.

activate the irrigation.

The cloud is also responsible for finding the right moment to stop the irrigation. For that, whenever all soil moisture sensor of the network assumes a soil moisture value larger or equal to the defined field capacity point will specify the end of the irrigation. When this condition is assured, the cloud sends a message to the WSAN which contains an instruction to stop the irrigation.

The weather service used for fetching weather station data in this project is Wunderground[1]. This service provides the access to real-time weather information. It allows to define the available weather station closest to the location where the WSAN is deployed. The data is fetched by a *HTTP Request* and it is returned in *JSON* format.

The only data feature used in this project is the hourly forecast, which returns data such as high and low temperature, wind direction, humidity, PoP (Probability of Precipitation), among others, for the next 36 hours. For our work, it is essencial to use the PoP parameter in order to detect irrigation periods. This parameter gives the chance or likelihood of precipitation to occur in a certain area.

4.3. Web Application

The Web Application used in this work was provided by Sensefinity. The provided User Interface (UI) is based on a Model-View-Controller (MVC) software architecture. The communication between the UI and the *Machinates* platform is performed under JSON over REST.

Throught the navigation of the webapp it is possible to visualise the location of the network nodes, the historical data related to soil moisture and battery measurements as well as the PoP predictions. For the AP device there is a battery indicator in the main page which shows the battery level of that device. This functionality is not yet implemented for the nodes which sense the battery level in volts.

Print screens of two distinct pages of the used Web application can be found in Figure 9 and Figure 10.

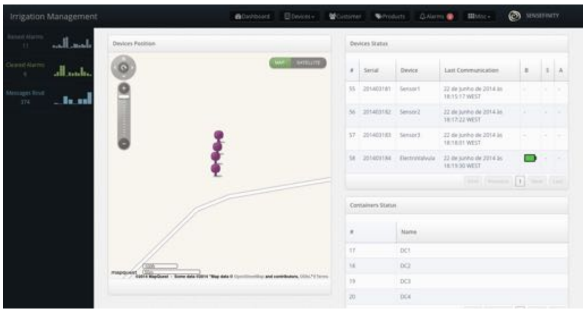

Figure 9: Print screen of the dashboard.

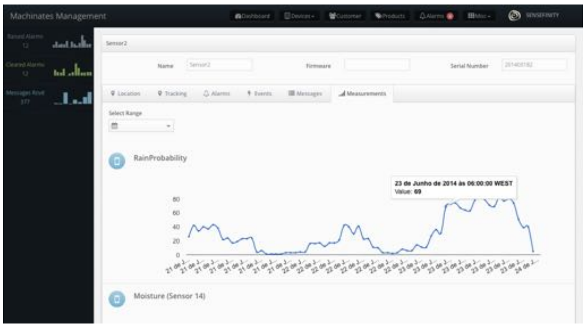

Figure 10: Print screen of the device specific menu.

5. Experimental Evaluation

In order to test and evaluate the developed system, it was deployed in a real case scenario, a local farm located near Sortelha (Guarda). For these evaluation tests a row of peach trees were available for testing the system. This row comprised 9 peach trees in which the devices were distributed. This field tests involved the use of four devices: one Access Point, two End Devices and one Range Extender following a cluster-tree topology.

Although there were 9 available trees, only 3 soil moisture sensors were used in these tests. The approximate distance between each peach tree is 3 meters. The distance between each device is pictured in Figure 11.

As for the irrigation system, before the prototype deployment it comprised a drip irrigation sys-

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[1] http://www.wunderground.com/weather/api (accessed last time on 12 April 2014)

tem which was manually scheduled. There was no frequent irrigation scheduled as the farm owner proceeded with the manual irrigation based on observation of the soil, the cultures itself, as well as the observed meteorological conditions.

The farms fields comprised a large number of different trees cultures and all these cultures were irrigated through the same irrigation system. The drip irrigation tubing comprises a 1 meter spacing between each emitter. As the spacing between the trees was approximately 3 meters, it was possible to place the emitters right near the trees stalk and above the roots. A set of drip emitter tubing connected with each other was used in the property in which the tubing beginning was connected to the public water supply. The irrigations would take place once the water tap was manually opened.

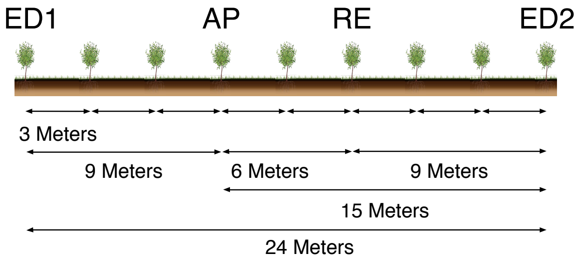

Figure 11: Distances between each network device.

The area comprising the row of the peach trees was isolated from other irrigation systems, as it was deployed an individual irrigation system for evaluating the system developed in the context of this project. This way, the irrigation system comprised the same drip irrigation system described above, but only applied in the peach trees row where this evaluation tests took place.

5.1. Experimental Setup

The experimental setup included the following:

(1) One AP device;

(2) Three devices configured as ED and RE. Two of them configured as ED and the remaining one configured as a RE;

(3) Three soil moisture sensors connected to the devices mentioned in the previous point;

(4) One drip irrigation tubing covering the entire row of peach trees;

(5) One Electrovalve controlled by the AP device. One entry of the Electrovalve connected to the public water supply, and the other one connected to the drip irrigation tubing mentioned above.

5.2. Experimental Methodology

The soil moisture sensors were paced within the tree roots about 15 to 20 cm in depth as pictured in Figure 12. It is fundamental that the readings are performed in the roots zone. It is in the roots zone that the plants absorb the needed water and nutrients for their healthy growth. Furthermore, this location enables more accurate readings due to the fact that the soil moisture sensor is not affected by external conditions such as the sunlight. Each device was fixed to the tree trunk about 1 meter from the soil due to attenuation, diffraction and reflection conditions of the soil, which may affect the signals transmission. A picture with distinct perspectives of the device with an attached soil moisture sensor can be seen in Figure 13.

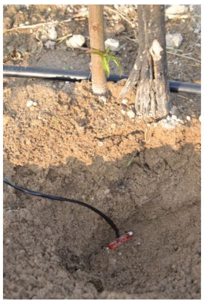

Figure 12: Soil Moisture Sensor placement.

Figure 13: ED/RE device with an attached soil moisture sensor.

As mentioned before, it was deployed an individual irrigation system only affecting the row of peaches tree. The electrovalve was directly controlled by the AP device, which means that the valve is either opened or closed following the AP commands. This electrovalve controls the water passage to the drip irrigation tubing, which covers the entire row of peaches tree.

The devices containing soil moisture sensors were configured to perform soil moisture readings every 30 minutes during non-irrigation periods and every 5 minutes in irrigation periods. The battery sampling frequency of each device was configured to 60 minutes. Regarding the parameters used for sending the measurements to the cloud platform, the AP device sends data every time the packets buffer reaches 4 or more packets, or whenever the time spent since the last data transmission exceeds 60 minutes. It was defined a threshold with the value of 400 and a field capacity point with a value of 700. The nearest weather station from the location where the experimental tests took place was located in Belmonte, within a distance of nearly 10km.

5.3. Results Analysis

Evaluation tests were taken during three consecutive days, making possible to extract results which testify the proper functioning of the developed system.

Figure 14 reports the soil moisture variations registered during this experimental tests for all the soil moisture sensors comprised in the tests.

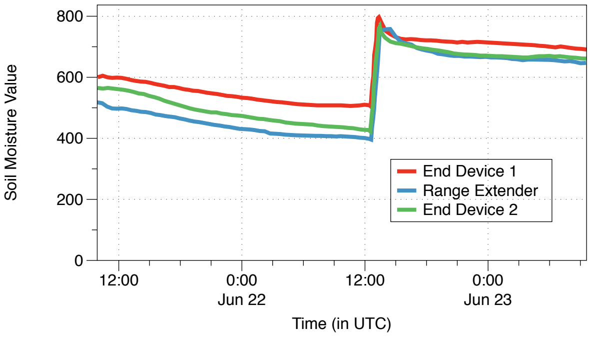

Figure 14: Soil moisture representation.

By the time the system started its proper operations, the soil sensors initiated the soil moisture readings with values comprised between 500 and 600. From here on the soil moisture readings were slowly decreasing to a point whereas there was the need of irrigation. This point in time was reached approximately 15 hours after the system has started operating.

As the soil moisture sensors were placed about 15 to 20 cm below ground, and also due to the utilized irrigation system, the variations of the soil moisture sensors were relatively slow. The soil moisture variations was slow due to the time the water needed to penetrate into the soil and reach the soil moisture sensors. This way, the irrigation system was enabled during approximately 50 minutes the point in time where all the soil moisture sensors acquired soil moisture readings above the defined field capacity point.

Even though the field capacity point had the value of 700, this value was highly exceeded by all soil moisture sensors. This may be due to the fact that even after the irrigation system was stopped, the water took more time to infiltrate into the soil, which made the soil moisture readings rise up almost until the value of 800, value exceeded by End Device 1. This shows that the system should be configured with a lower field capacity point, taking into account the time the water takes to infiltrate in the soil. For this, it would be necessary to perform a study of the soil type in order to adapt the field capacity point to the soil type.

By the time the soil moisture readings of the RE device arched values below the defined threshold, the probability of precipitation acquired from the used weather station was below 50% for the next 6 hours. Which meant that there was no probability of precipitation for the next 6 hours and so the irrigation system had to be activated in order to apply the needed irrigation.

These experimental tests occurred during summer time. During this period, according to the observed weather conditions, the fields comprised in the farm were manually irrigated by the farms owner. As stated before, our system was isolated from the remaining irrigation systems which were used to irrigate the remaining fields in the farm. During these experimental tests, the remaining fields were manually irrigated by the farms owner once a day with a duration of approximately one hour.

If our system was not deployed, the peach trees used in our tests would be irrigated following the same scheme as the other remaining fields. Which means that the fields would be irrigated 3 times in a period of 3 days with a total of 3 hours of irrigation. Our system allowed to conclude that the fields were suffering from over irrigation. Using our system the field was only irrigated once within a period of approximately 50 minutes. This demonstrates the success of our system regarding the irrigation efficiency and ultimately water savings.

It is possible to estimate the amount of water savings during the experimental tests. Each dripper comprised in the drip irrigation tubing issues approximately 2,3 liters per hour. The peach trees row comprised 9 trees with a dripper right above each tree. The total amount of water issued by the 9 drippers during the irrigation of 50 minutes is approximately 17,25 liters. Without the use of our system, with a total of 3 hours, the water used would be approximately 62,1 liters. Our system delivered about 72% less water than the typical manual irrigation process.

Given the fact that these experimental tests occurred in a time interval of 3 days, it was not possible to evaluate the quality of the peach trees used in our tests. With longer experimental tests it would be possible to assess if the trees quality was still maintained.

As mentioned before, the Access Point device sent messages to the cloud platform every time the buffer reaches a total of 4 or more messages. The time between the measurements acquisition and the time the measurements arrive at the cloud platform is variable. After sending a set of messages to the cloud, the next measurement stored in buffer will remain there until 3 more messages arrive. This way, this first message will have a greater delay time relatively to the next 3 messages. The last message received at the AP device (before the sending process is started) has this way the lowest delay time since acquisition. The processing times for all messages at the cloud platform are all similar. This processing time is obtained by calculating the time interval since the received message passes from the *Created* state to the *Processed* state. These statistics take into consideration the measurements received in each hour in a 12 hour time interval.

A graphical representation of the Mean values and the Standard Deviation of communication time for each hour of operation is represented in Figure 15.

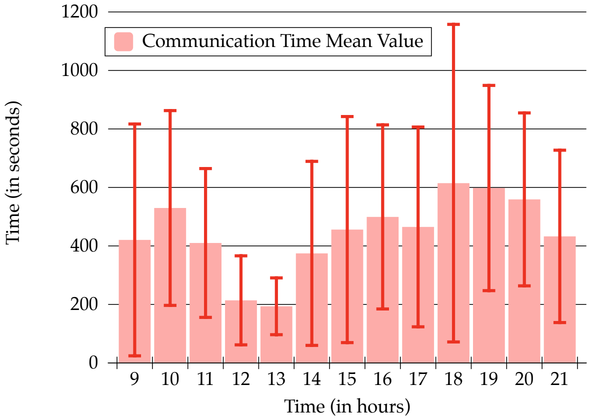

Figure 15: Mean Values and Standard Deviation of the Communication time for each hour.

The mean value of the Communication Time for all the operational hours represented in the last figure is 443 seconds ($\sim$ 7,38 minutes). In both periods of analysis, concerning 12 and 13h, the mean value of the communication time is lower than the remaining hours due to the fact that in this period of time the irrigation system was turned on and so the soil moisture measurements were taken each 5 minutes. This means that the Access Point device sends more often messages in these two periods given that the buffer reaches the pre-defined value faster.

As expected, the standard deviation values are very high, some of them really close to the correspondent mean value. This is expected since the time between acquisition and the time the message is received by the cloud platform is not the same for every message, as explained above. During this time sample, the message with the largest communication delay arriving at the cloud platform took about 1877 seconds ($\sim$ 31,3 minutes). The message with the lowest time took approximately 1,25 minutes. In resume, the communication delay is dependent on the measurements sampling frequency, since a higher frequency implies the buffer gets full more rapidly, and hence a smaller transmission delay.

Figure 16 depicts the graphical representation of the mean values of the processing time for each hour of operation.

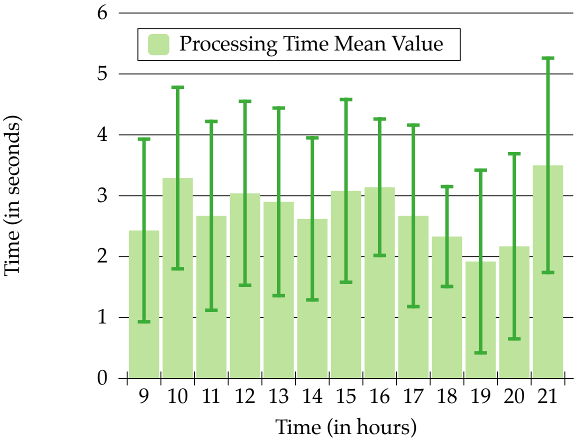

Figure 16: Mean Values and Standard Deviation of the Processing time for each hour of operation during experiments.

During this time sample, the processing time was low, never exceeding 6 seconds. Additionally, there is no statistically significant difference between the periods when the cloud platform received more messages (in irrigation periods) and the remaining periods of analysis.

The soil moisture sampling frequency is higher during irrigation periods because it is desirable to have more feedback information during these periods, and so the soil moisture measurements should arrive at the cloud platform faster than in periods of non irrigation. Indeed, it is crucial that the amount of time the irrigation system is turned on must be minimized. To further investigate the impact of sampling rate on communication delays, it was selected a continuous sampling of soil moisture measurements both in irrigation and non irrigation periods. In Figure 17 is represented a graph containing a comparison of 20 continuous samplings for each case (irrigation and non irrigation).

As expected, the communication time for messages during irrigation periods is much smaller

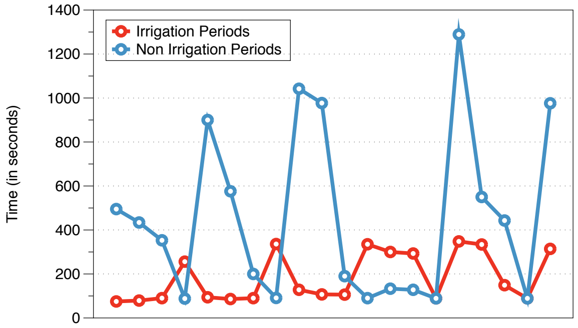

Figure 17: Comparison of communication times between periods of irrigation and non irrigation.

than in non-irrigation periods.

The mean value for periods of irrigation was approximately 3,08 minutes, whereas in periods of non irrigation was about 7,61 minutes. For the experimental tests performed in this dissertation under the conditions mentioned above, the sampling frequency of the soil moisture measurements was found to be appropriate. This is due to the irrigation method used, a drip irrigation system, which takes more time to do the irrigation at a very slow pace. If other irrigation system was used, the sampling frequency during periods of irrigation would had to be adapted, possibly with a higher sampling frequency.

6. Conclusions

Through the study and investigation of literature related to the interconnected field studies of Internet of Things, Machine-to-Machine and Wireless Sensor and Actuator Networks, it was possible to identify that besides its continuous developments in the last couple of years, there is still a huge problem regarding the generated and collected data. Being cloud computing a recent resource providing approach, the main work developed within the context of the paradigms presented above was not properly integrated with the possibilities that a cloud computing platform could offer.

This work aims to lead the integration of such systems with the attractive features offered by cloud computing. When developing such system for the agriculture use case, it was essential to understand the soil and water dynamics. A comprehensive study of such topics was performed which allowed us to have a clearer vision of the plants water needs and how this information could be helpful in the development of our system. Besides the monitorization performed related to the soil and water, in order to assess the plants water needs for its proper and healthy development, it was also important to assess the possibility of natural resources' usage optimization. In this context it was introduced the integration of weather forecast parameters which could allow a better optimisation of the used natural resources.

A first prototype of our system was developed, using the hardware components and the cloud computing platform provided by Sensefinity. Besides the functional tests performed, it was possible to validate the correct behaviour and performance of the developed system. For that, the prototype was tested in a real case scenario, which validated the successful collection of soil moisture measurements, the correct behaviour of the developed irrigation algorithm as well as the remaining features developed. With the development and consequent tests on a real case scenario, it was possible to identify some limitations of the developed system. The main limitation is related to energy consumption. It was clear that the the current scheme is not able to last as long as it should. In addition, there is the need to have a better comprehension of the distinct soil types, the distinct cultures and irrigation methods applied, as these factors influence the optimisation of the water savings. The collaboration with a soil and cultures expert would be highly appreciated to better assess the soil water needs.

The first exposure of our prototype in a real case scenario allowed to validate the correct behaviour of the developed system, as well as to identify possible improvements to be added to the current developed work. This possible improvements will be described in the next section.

6.1. Future Work

The development of a system such as the one presented in this work presupposes the continuous upgrades, enhancements and the addition of new features. Some of the enhancements and features presented in this section were envisioned during the course of the systems development, while others were discovered during the tests performed in the real case scenario. The possible additions and enhancements are described hereafter.

Improvement of the battery life time will allow deployment system during long periods of time.

Improvement of the irrigation algorithm to do a better use of the natural resources as well as maintaining the plants health and its proper growth. A careful study of the soil and cultures allows the proper definition of the thresholds used to know the exact moments where the irrigation should be turned on and off. Also, the addition of other parameters coming from the weather forecast reports would help the irrigation decision making.

Modification of the sampling frequencies in the Web Application and let the cloud platform command the notifications of this modifications to the WSAN.

Implementation of a safety mechanism for the actuators used in the irrigation system. Although situations of communication loss between the WSAN and the cloud platform should be rare, there is the need to prevent the actuators for not turning off the case the network does not received the instructions from the cloud platform to stop it.

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