Multi-layer Fog Computing Framework for Constrained LoRa Networks Intended for Water Quality Monitoring and Precision Agriculture Systems

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Abstract: As the population of the world keeps increasing, it is necessary for the agriculture to adopt technologies that improve the production and optimize re-sources such as water. This has been done by introducing IoT devices, which has led to smart agriculture or precision agriculture. However, due to the remoteness of the fields, the communication of these devices needs to be per-formed with technologies such as LoRa that has limitations on the amount of data and the number of messages that can be forwarded. Furthermore, as there is no connection to the electric grid, optimizing the energy consumption is a necessity. In this paper, we present a multi-layer fog computing framework for a water quality monitoring and precision agriculture system. Data aggregation techniques are applied at the algorithms provided for the different layers to reduce the amount of data and the number of messages forwarded to the data center so as to improve the performance of the constrained LoRa network and reduce the energy consumption. Furthermore, the added decision-making provides fault-tolerance to the system if the connection to the Data Center is not available. Simulations were performed for different functioning modes. Results show a reduction of the 80% in the amount of transmitted data and a reduction of 85.33% in the number of for-warded messages for the most restrictive functioning mode.

1 INTRODUCTION

The adoption of technologies that optimize agricultural production is necessary to be able to feed the world population, which is constantly increasing. Furthermore, the climatological and environmental problems threaten the future of the agricultural production as well. The fourth industrial revolution, Industry 4.0, has also reached agriculture resulting in the term Agriculture 4.0 (Industry 4.0 in Agriculture: Focus on IoT aspects., 2020). Fundamentally, it is about applying ICT (Information and Communication Technology) techniques to agriculture. According to De Clercq et al. (2018), the application of Agriculture 4.0 will no longer depend so much on the use of water, fertilizers, and pesticides, as they will be used in minimal quantities. Furthermore, it will even be possible to cultivate in arid areas and use clean and abundant resources such as the sun or seawater.

Smart agriculture incorporates the contributions of both capital and high technology, making it possible to grow food accurately while being clean and sustainable. For all the previously mentioned reasons, the use of the Internet of things (IoT) applied to agriculture is increasing day by day.

One of the biggest concerns, when deploying IoT devices is their power consumption. Currently, when

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applied to agriculture, most of the time they are installed in areas where it is not possible to connect the device to the electricity grid. For this reason, devices and technologies with minimal energy consumption are often used. To achieve this, in the field of communications it is ideal to use technologies such as Low-Power Wide-Area Network (LPWAN).

Among the LPWAN technologies, we can highlight Long Range (LoRa) (LoRa Alliance, 2020), due to its low cost, long range, and the use of license-free bands. The main problem that can be found is that the information transmitted through the air must be as optimized as possible to reduce as much as possible what is known as "time on air" or "airtime", that is, the time necessary to transmit the message from the sender node to the receiver (gateway). The more time utilized for data transmission, the greater the saturation of the frequency and greater energy consumption; therefore, it is vital to keep the payload of the transmissions as low as possible.

Greenfield defines and differentiates Fog Computing and Edge Compu-ting. When using Fog Computing a decentralized network structure is employed in which resources, including data and applications, will be found somewhere between the data source and the Cloud (Fog Computing vs. Edge Computing: What's the Difference?, 2016). By using Edge Computing, intelligence is brought into individual hardware systems such as sensors. Using Edge Compu-ting, the source devices are already in charge of filtering data. Redundant data and even false positives can be removed depending on the architecture.

In our work we present the proposal of a multi-layer fog computing framework for a precision agriculture and irrigation water quality monitoring system. Which has been designed to be implemented in two areas. One of the control zones are the canals that transport the irrigation water, where the salinity or turbidity levels of the water are observed, and if any of the two parameters exceeds a threshold, an alarm is forwarded. The other zone is that of the crop fields, where parameters such as soil moisture and soil salinity will be observed. Through our proposal, decision-making, regarding the actions to be carried out to achieve optimal irrigation of the crops, will occur in nodes located near the sensor nodes. Furthermore, data aggregation is performed to adapt to the constrained LoRa network. In this way, the energy consumption will be reduced by filtering the data and reducing the number of messages sent to the data center. The proposed framework will provide the system with fault tolerance capabilities as well, eliminating the need of depending on continued computations at the Data Center.

The remainder of this paper is organized as follows. Section 2 presents the related work. The multi-layer fog computing framework description is explained in Section 3. The simulation results are carried out in Section 4. Finally, Section 5 draws the main conclusions and future works.

2 RELATED WORK

The introduction of several layers to the edge and fog computing architecture provides many benefits compared to the classic cloud architecture. Gia et al. (2019) discuss these benefits applied to smart systems in remote areas. At these areas, the chosen communication technology, such as LoRa, has a low bandwidth and performing the analysis and decision-making activities at the edge allows providing more functionalities. The presented architecture has an edge, a fog and a cloud layer and performs image compression based on CNNS. Results show 67% of data size reduction with less than 5% of decompression errors. Guardo et al. (2018) also presents a fog computing framework with two tiers intended for precision agriculture. The first tier is comprised of the sensing nodes and the second tier is the gateway. Both tiers perform data filtering and analysis to reduce the amount of data forwarded to the Cloud. The LoRa and MQTT protocols were utilized for communication. The authors expected a reduction in cost, a waiting times and load balancing as a result of implementing the proposed architecture.

On the other hand, conventional fog computing networks have some challenges as well. Chang et al. (2017) present a fog computing infrastructure called In-die Fog in order to solve some of these challenges. With Indie Fog, the authors aim to provide a solution that can be implemented with consumer devices eliminating the need and the restrictions of the devices owned by the service provider. Furthermore, fog computing reduces latency and provides communication and computation efficiency. Indie fog can be implemented in an integrated manner, where the router incorporates a virtual machine to perform computations, or in a collaborative manner, where a computer is connected to the router. However, other devices such as smartphones or vehicles can also be used as fog devices. Wang et al. (2019) designed a multilayer system for edge computing. The architecture is comprised of three layers being the edge device, the Access Point and the Cloud Center. The authors divide the system into a blocking and a nonblocking state. Results showed a minimization of recovery time for the block-ing state and reduced latency for the nonblocking state. Another multi-tier architecture was presented by Chekired and Khoukhi (2018). The authors also present the Simulated Annealing Algorithm to determine the best allocation. A probabilistic model is utilized to determine and improve the efficiency of the presented architecture. The simulation results show that a reduction of 35% in response time can be obtained utilizing the 3-tier architecture instead of the flat architecture. For the case of the 2-tier topology, a 20% reduction was obtained. Regarding offloading, a reduction of 30% was obtained for the 3-tier topology, outperforming other designs. Lastly, an improvement in performance was obtained as well utilizing multi-tier architectures.

Although some work has been done in (Guardo et al., 2018) regarding fog and edge computing in agriculture, it only considers the fields and a small number of devices. In this paper, the concept is extended and applied to both the fields and the canals that provide water to the fields so as to determine the quality of the water. Further-more, data aggregation algorithms are provided for the layers of the framework that perform fog computing.

3 MULTI-LAYER FOG COMPUTING FRAMEWORK DESCRIPTION

In this section, our multi-layered fog computing proposal for a precision agriculture and irrigation water quality monitoring system is presented.

The deployment of the water quality monitoring system for irrigation purposes and the precision agriculture system is presented in Figure 1. The Canal Area is comprised of a series of subcanals in a comb shape where the biosorption pro-cess for water purification is performed. The Field Area is where the fields are situated. These fields can be further divided into different zones to apply different processing to each of the areas and have a more detailed overview of the state of the plants. The Urban Area is the zone where the Gateway is located and connected to the Data Center. There are clusters of sensing nodes at each subcanal and deployed on each zone of the fields, with a cluster head for each cluster. Actuator nodes are deployed as well at each subcanal to manage the gates to the biosorption process and to control the amount of water for the irrigation of the fields. Furthermore, the cluster head forwards the data to the aggregator of their Area. Then, the aggregator forwards the data to the Gateway destined to the Data Center. The CH nodes and Actuators at each Zone are detailed at Table 1. The system is scalable, and more zones can be added when necessary. If monitoring more fields is necessary, more gateways could be added so that the data transmission is divided into the deployed gateways and a bottleneck scenario is avoided.

The architecture of the system is presented in Figure 2. The architecture is com-prised of the following layers:

- Layer 1: The first layer is the layer comprised of the sensor and actuator nodes. These devices forward all data to the next layer and do not perform any computations. The data acquisition is performed at different frequencies depending on the selected settings. These settings are the Research Mode, the Advanced Farmer Mode and the Regular Farmer Mode. Table 2 presents the characteristics of each mode. For the case of the actuators, the actions are performed when the message with the new action is received. Then, a message with the new state of the actuator is forwarded to the data center.
- Layer 2: This layer is comprised of the Cluster Head nodes. These nodes receive the data from the sensing nodes and perform the first data aggregation process detailed by the Algorithm 1. For the Canal Area, these nodes evaluate the quality of the water by considering the values obtained by all the nodes at the cluster. The CH node receives the turbidity or salinity levels from the sensor nodes of the cluster. The outlier values are discarded. This is performed by calculating the variance σ_i^2 and determining if it surpasses the Th_{sigma2} threshold. Then, the CH compares all the received values using the $C_{Positive-var}$ variable to obtain a final result of the salinity or turbidity levels of the water. If the turbidity or salinity surpasses the $Th_{variable}$ threshold, an alarm is forwarded to the next layer. For the case ofthe CH nodes of the field area, the same process is performed with soil moisture and soil salinity. That way, the Aggregator nodes at layer 3 and the Data center are able to determine if the variations in the calculations due to water stress or salinity should be applied when determining the necessary amount of water for irrigation.

- Layer 3: This layer is comprised of the Aggregator nodes. These nodes receive the data from each of their areas, being the canal area or the field area. This node performs the decision-making process that determines the actions of the actuator of their areas. At the canal area, the Aggregator node sends a message to the actuator node of the specific canal to open or close the gates. At the field Area, the Aggregator node calculates the water requirements for a time frame of one month and forward the actions to the Actuator when irrigation is required. The data exceeding the time frame of one month is deleted from the storage system of the Aggregator node. The data is aggregated as detailed in Algorithm 2 and forwarded to the data center when the data forwarding timer is reached so the user can access the history of all the variables. According to the state of the actuators in the Canal Area and the selected settings, the amount of data forwarded to the data center varies.
- Layer 4: This layer is comprised of the gateway. This node will store all the data in the rare case the Data Center or the connection to the data center is down. This layer does not perform data aggregation nor performs computing as all the necessary data aggregation and computation has been performed on the lower layers.
- Layer 5: This layer is comprised of the Data Center. The data center stores all the data and processes the information to perform analysis and predictions on water quality, water requirement and quality of the soil, among others.

By providing a multi-layered fog computing functionality to the topology of the water quality monitoring and precision agriculture system, the obtained benefits are twofold. On the one hand, it provides the system with fault-tolerance capabilities by providing autonomy to each of the layers of the architecture in case any of the elements of the network gets damaged or stops functioning and the decision made at the Data Center cannot be forwarded. This is a key aspect considering the tree topology of the system. On the other hand, it reduces the energy consumption by filtering the data and limiting the number of messages that are forwarded to the data center. This reduction in data and messages also helps to reduce the collisions that may be caused when different LoRa nodes transmit at the same time. It also allows the system to meet the duty cycle requirements of LoRa. However, it is important to consider that in our proposal, a multi-hop LoRa network is considered thus protocols such as the ones in (Liao et al., 2017) are utilized instead of LoRaWAN. While the use of WiFi results in more energy consumption than using communication technologies with similar coverage such as ZigBee, WiFi is often used due to its convenience, accessibility and low price of the devices. Nonetheless, the presented proposal would lead to a reduction in energy consumption if ZigBee was utilized as in (Truong et al., 2021).

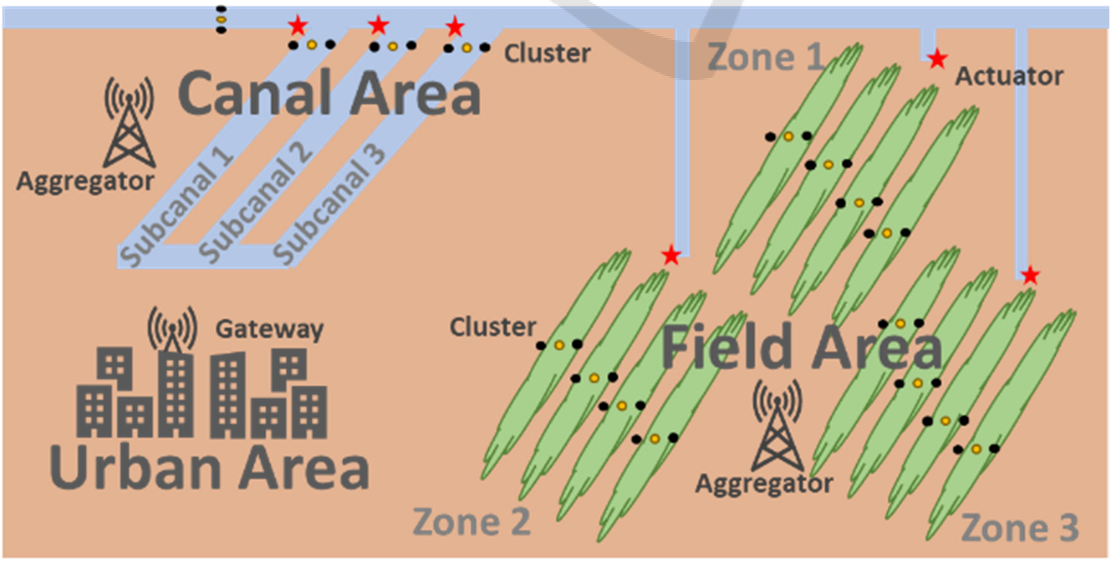

Figure 1: Water quality monitoring and precision agriculture system.

Table 1: CH nodes and Actuator nodes at each Zone.

Zone	CH	Actuator
Main canal	CH 1 Canal Area	Actuator Node 1 &2
Secondary Canal 1	CH 2 Canal Area	Actuator Node 3 &4
Secondary Canal 2	CH 3 Canal Area	Actuator Node 5 & 6
Secondary Canal *n*	CH *n*+1 Canal Area	Actuator Node 2*n*+1
Biosorption Output	CH *n*+2 Canal Area	Actuator Node 2*n*+2
Field Area Zone 1	CH 1 Field Area	Actuator Node Field Area 1
Field Area Zone 2	CH 2 Field Area	Actuator Node Field Area 2
Field Area Zone *m*	CH *m* Field Area	Actuator Node Field Area *m*

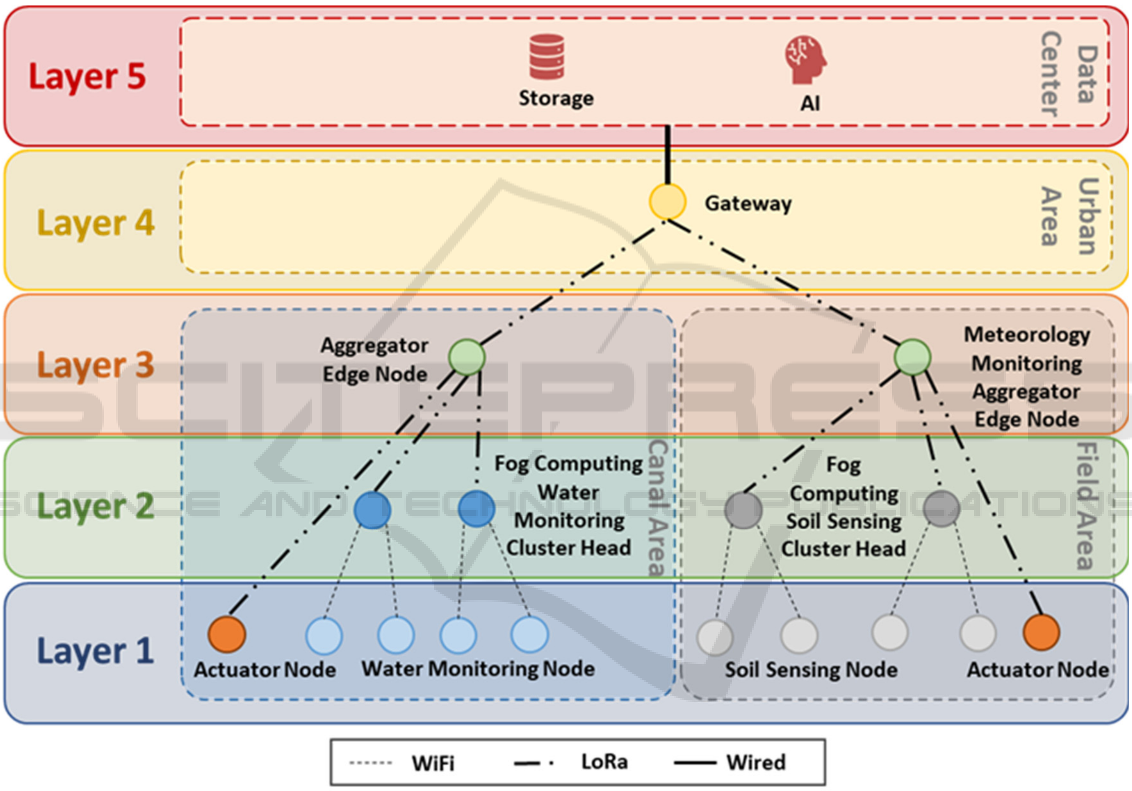

Figure 2: Multi-layered fog architecture of the precision agriculture and irrigation quality monitoring system.

Table 2: Data forwarding and aggregation settings.

Settings	Data Acquisition Frequency	Data Aggregation	Data Forwarding Frequency
Research Mode	10 minutes	Data driven aggregation at layer 2	4 times a day + Alerts
Advanced Farmer Mode	30 minutes	Data driven aggregation at layer 2 and layer 3	2 times a day + Alerts
Regular Farmer Mode	1 hour	Data driven aggregation at layer 2 and layer 3	Once a day + Alerts

Algorithm 1: Data Aggregation at layer 2.

Gather data from the sensors of the CH node
Receive the data from the *n* sensors of the cluster
    for each variable *var* **do**
        for each node *i* in the cluster **do**
            $\sigma_i^2 = \frac{\sum_1^j (s_j - s_i)^2}{n}$
            if $\sigma_i^2 > Th_{sigma2}$ **then**
                Discard data from sensor *i*
            end if
            If $V_i > Th_{variable}$ **then**
                $C_{Positive-var} = C_{Positive-var} + 1$
            end if
        end for
        if $C_{Positive-var} \geq {}^{3n}/_{2}$ **then**
            Add the average of the value for the variable V_{Avg} to *Alert-Payload* string
        else if $V_{Avg} > Th_{variable}$ **then**
            Add the average of the value for the variable V_{Avg} to the *Alert-Payload* string
        else
            Store aggregated data V_{Avg}
        end if
    end for
    if there is data on the *Alert-Payload* string **then**
        Send Alert message with the content of *Alert-Payload*
    end if
    if timer for data forwarding has been reached **then**
        Forward stored aggregated data
    end if
End

4 SIMULATION RESULTS

In this section, the results of the simulations for amount of forwarded data and number of forwarded packets are presented. As the collision management is not part of the scope of this paper, it is assumed that there are no collisions.

The Canal area is comprised of four clusters that forward the data to one aggregator node. There are eight actuator nodes in this area. For the Field area, three zones were considered with three clusters per zone, one aggregator node which is an agrometeorological station as well, and three actuator nodes. The sensing nodes and the CH nodes communicate through WiFi. The CH nodes and the Aggregator nodes communicate through LoRa at the EU 863-870 frequency band, with a bandwidth of 125 kHz and a spreading factor of SF8. This LoRa settings allow a maximum payload of 222 Bytes including the LoRa header.

The data forwarded by each layer to the next layer of the hierarchy on the Regular Farmer Mode is presented in Figure 3 a) and b). The algorithms allow reducing substantially the amount of data forwarded by the higher Layers to the Data Center with an 83% for layers 1 and 2 and an 80% when the data forwarding timer is reached. Furthermore, a reduction of 69% in the transmitted data at the forwarding time is obtained compared to not performing data aggregation. This reduction in the forwarded data leads to a reduction in the energy consumption of the devices as the higher energy consumption is produced when data is transmitted.

At the Advanced Farmer Mode, as it can be seen in Figure 3 c) and d), the amount of forwarded data is decreased due to the data acquisition frequency of 30 minutes. The state of the Actuator nodes keeps being forwarded each hour. Thus, there is a fluctuation in the amount of data forwarded each time the timer is reached. Furthermore, the data is aggregated at Layer 3 as well and the data is forwarded to the data center twice a day. With this mode, compared to not performing data aggregation, a reduction of 60% was achieved when the forwarding time is achieved. With data aggregation, a reduction of 66% of the forwarded data was obtained compared to the Research mode. The reduction reached a 76% at the times where the states of the actuator are forwarded.

Algorithm 2: Data Aggregation and decision-making at layer 3.

```
Update Actuator decision making rules from the Data Center
Receive data from the devices in layer 2.
Receive Actuator State
if Canal Area Alert received then
    Forward Action message to the required actuator so as to open the gates of the biosorption canal closest to the
    CH node that activated the alarm
    Forward Alert message destined to the Data Center
end if
if Field Area Alert received then
    Store Alert for further processing
    Forward Alert Message destined to the Data Center
end if
if data_forwarding_timer is reached then
    if Research Mode then
        if all gates are closed then
            Add the data from the Main Canal to the Payload string
        else
            Add data from all CH nodes at canal area to the Payload string
        end if
        Add data of the CH nodes at the field area to the Payload string
    else if Farmer Mode then
        Add data of the Main Canal and the Biosorption Output to the Payload
        for each field area do
            for each Zone at Field area do
                Calculate average of the variables measured by all CH nodes at the same zone
            end for
        end for
        Add average data of the field zones to the Payload
    end if
    Forward message with the data stored at the Payload string
end if
If water_requirement_calculation_timer is reached then
    For each zone in field area do
        if water_stress alert && Salinity alert received then
            Calculate water requirements with water-stress and salinity modifications
        else if water_stress alert received then
            Calculate water requirements with water-stress modifications
        else if Salinity alert received then
            Calculate water requirements with salinity modifications
        else
            Calculate water requirements
        end if
        if irrigation_day is true then
            Forward Action message to the actuator nodes of each area with the amount of water needed for the next
            irrigation
        end if
    end for
end if
End
```

The Researcher mode performs the data acquisition process each 10 minutes and thus, the high amount of forwarded data (See Figure 3 d) and f)). As it can be seen, the nodes in Layer 1 forward all the data to the CH nodes in Layer 2. The state of the Actuator nodes is forwarded each hour. The Researcher Mode obtains a reduction of 35% at the forwarding times compared to not performing any data acquisition. In this case, no data aggregation was performed at Layer 3. Furthermore, there is a water salinity alarm on the first day. At the times the data forwarding timer is reached, the data forwarded nearly reaches 20000 Bytes for an hour.

Regarding the number of forwarded messages, for the Regular Farmer mode, the number of forwarded messages remains between 39 and 55 messages per hour (See Figure 4 a) and b). With an 85.33% of reduction at peaks compared to the Researcher Mode and 29% compared to not performing data aggregation. This mode is optimal for remote areas as it would allow other LoRa settings with more re-strictions regarding the number of messages that can be forwarded by each de-vice. Furthermore, it would not be detrimental to the farmer as the calculations of the irrigation requirements only need one measure of each variable per day except for the meteorology data were the maximum and minimum values of temperature and relative humidity are necessary.

At the Advanced Farmer Mode, the number of messages oscillates between 78 and 83 messages per hour except for the first hour with 53 messages (See Figure 4 c) and d)). The reduction of messages at the peaks is 68,67% compared to the Researcher Mode and 21% compared to not performing any data aggregation.

The results of the Researcher Mode are presented in Figure 4 e) and f)). Between 234 and 249 messages are forwarded per hour except when the system is firstly activated where 53 messages are generated. As it can be seen, the hierarchical structure of the framework allows reducing the number of forwarded messages at each layer.

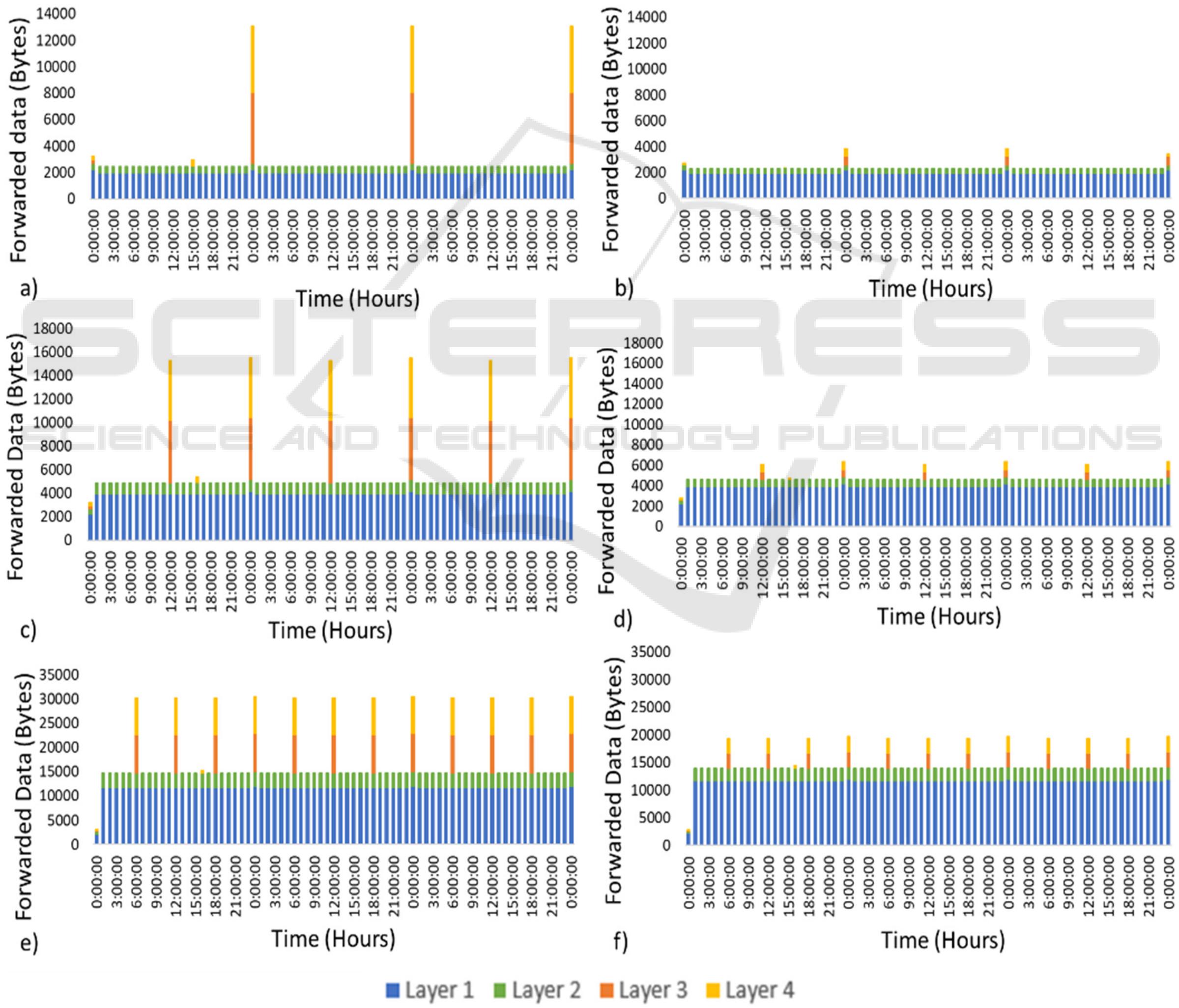

Figure 3: Data forwarded by each layer at the a) Regular Farmer Mode without data aggregation, b) Regular Farmer Mode with data aggregation, c) Advanced Farmer Mode without data aggregation, d) Advanced Farmer Mode with data aggregation, e) Researcher Mode without data aggregation and Researcher Mode with data aggregation.

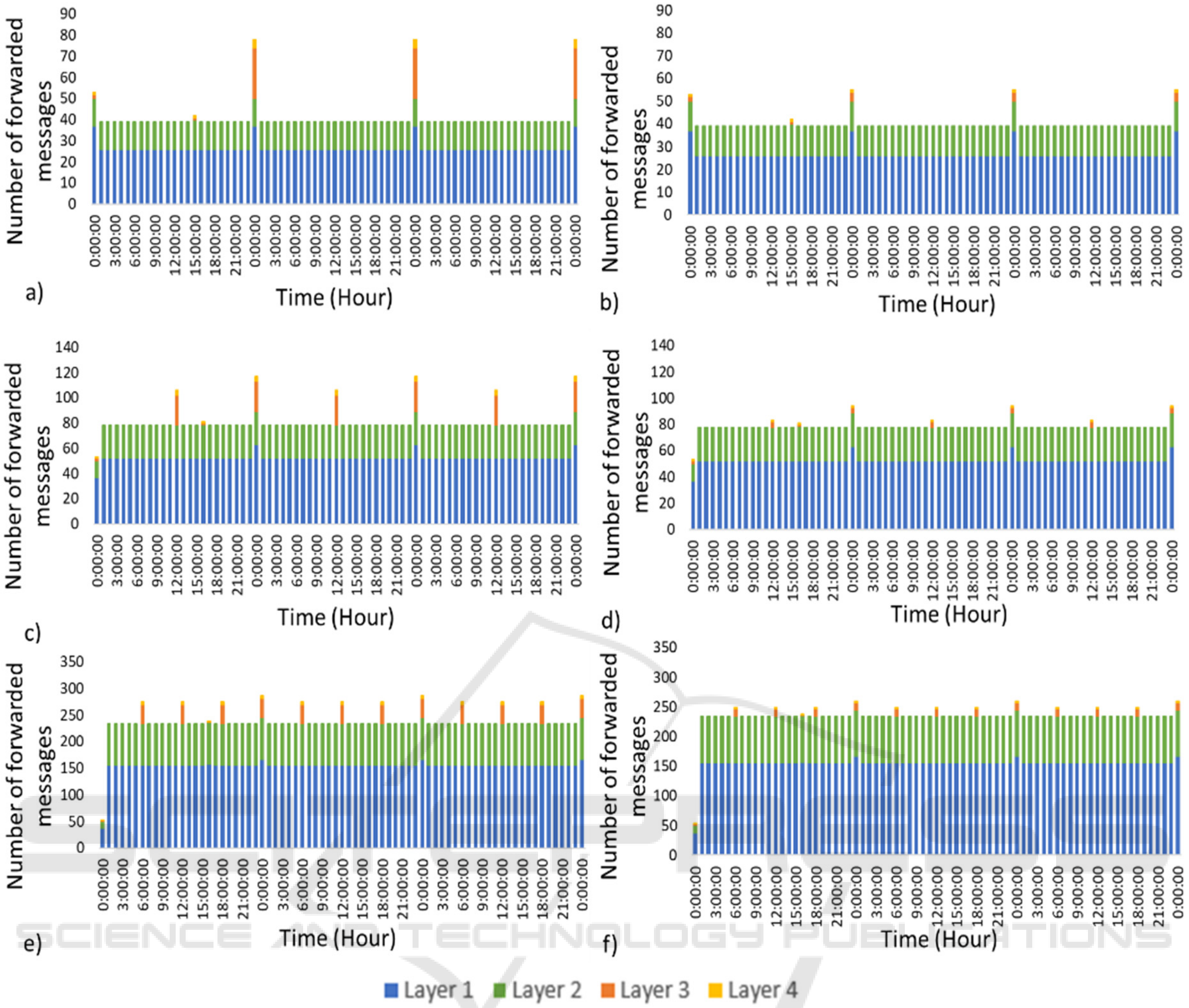

Figure 4: Number of messages forwarded by each layer at the a) Regular Farmer Mode without data aggregation, b) Regular Farmer Mode with data aggregation, c) Advanced Farmer Mode without data aggregation, d) Advanced Farmer Mode with data aggregation, e) Researcher Mode without data aggregation and Researcher Mode with data aggregation.

Furthermore, a reduction of 9% of the messages at the peaks compared to not performing data aggregation was achieved. This is important regarding LoRa as there is a limitation in the number of messages that can be forwarded due to the duty cycle. Other LoRa settings would not support the Researched Mode. This is a key aspect if longer distances need to be reached as higher spreading factor values would be necessary and thus, the number of messages that could be forwarded would decrease.

5 CONCLUSION AND FUTURE WORK

The introduction of IoT technologies in agriculture has led to the optimization of the food production and resources such as water. However, as precision agriculture systems often need to be deployed on remote areas, technologies such as LoRa must be employed. But these technologies introduce restrictions on the amount of data that can be forwarded and the number of messages that can be transmitter per device due to the duty cycle. Furthermore, the impossibility of connecting the devices to the grid also introduces energy consumption constrictions, which is tied to the performed data transmissions. In this paper, a multi-layer fog computing framework for water quality monitoring and precision agriculture has been presented.

Two algorithms for data aggregation and decision-making have been provided as well. These algorithms also provide fault-tolerance to the network providing certain levels of autonomy in case the connection with the Data Center is severed.

The simulation results show a reduction in the amount of forwarded data for the Advanced Farmer Mode and the Regular Farmer Mode of 66% and 83% respectively. Furthermore, a reduction of 68.67% in the number of messages was obtained for the Advanced Farmer Mode and of 85.33% for the Regular Farmer Mode. These results also lead to a reduction in energy-consumption as the most energy is consumed when transmitting data.

As future work, other forms of gateways so as to add another layer of fog computing in networks that present other types of constrictions will be considered such as the use of drones for precision agriculture as a mobile gateway like in (García et al., 2020).

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