A three-tiered architecture based on IEEE 802.15.4 and Ethernet for precision farming applications

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***Abstract*—This paper proposes a three-tiered network architecture to support precision farming applications over large cultivated fields. The hybrid network combines IEEE 802.15.4 Wireless Sensor Networks, operating in a multichannel mode, with Switched Ethernet. The network design has to fulfill several objectives, such as, achieving a tradeoff between energy saving for battery-operated devices and timeliness of precision farming applications over large areas, while providing scalability, robustness and cost efficiency. The work presented in the paper is based on real-world specifications provided by end users, i.e. qualified farmers, during a comprehensive investigation and requirement analysis phase. The paper first discusses the constraints that drive the network design and then presents the three-tiered architecture. Finally, the performance of the network, obtained through OMNeT++ simulations, are discussed.**

Keywords*—IEEE 802.15.4 Wireless Sensor networks; Multichannel communications; Switched Ethernet; Precision farming.

I. INTRODUCTION

Precision farming deals with the application of technological equipments to improve yield quality or to decrease costs or risks in production. In particular, precision farming provides the means for observing, assessing and controlling agricultural practices. According to the crop production process they address, precision farming applications may deal with [1][2]:

- Sensing of growth conditions, sampling various measurable parameters to monitor the progress of the agricultural products;
- Manuring, differentiating the manuring of products placed in different areas;
- Irrigation, distributing the right amount of water when needed;
- Plant protection, coping with pests, plant diseases, weeds and other parasites that damage the crops;
- Harvesting, collecting information used by Decision Support Systems to choose the best time for harvesting;
- Fleet control, improving the timing performance of farm tractors when crossing over fields, using satellite systems (GPS).

This paper proposes a three-tiered network architecture to support precision farming applications over large cultivated fields. The proposed network combines two wireless tiers based on the IEEE 802.15.4 protocol with a Switched Ethernet backbone. Such a network is able to comply with multiple design challenges. Among them, energy saving for battery-operated devices, support for soft real-time constraints of precision farming applications, the ability to cover large areas, combined with scalability, robustness, and cost efficiency.

The research work here reported starts with a state-of-practice analysis on the precision farming techniques used in the Eastern Sicily territory. The analysis has a twofold aim. First, to identify the state-of-the-art technology and its limitations, with reference to the specific crops of the considered area and the way they are cultivated. Second, to derive the application requirements to be taken into account in the design of the new network architecture. The study encompasses many aspects. Among them, the number and type of sensors to be used, their density, the distance to be covered on the field, the installation and maintenance costs, the temporal constraints and the energy consumption of the supported applications. In addition, indications are collected about the new features that qualified farmers consider useful, such as, the network ability to provide a mobile user, equipped with a handheld device, with the data relevant to a given area of interest.

The second step of the work is to investigate on network architectures able to match the requirements of the precision farming application under study. In this work, different architectures are considered and the pros and cons of each option are evaluated. The outcome of the analysis is that a three-tiered hybrid network offers more advantages than the other solutions considered. The work then focused on the design of the three-tiered network. For each tier, the choice of the most suitable protocol, operating mode, and communication algorithm is addressed, included the local queue management algorithms.

The third and final step of the work is to assess the compliance of the envisaged architecture with the requirements of precision farming applications. To this aim, a simulation model based on the OMNeT++ tool and the results of several tests performed in different operating conditions are presented.

The paper is organized as follows. Sect. II presents the results of the requirement analysis. Sect. III addresses possible network architectures for the application considered in this work and discusses the rationale behind the choice of a three-tiered hybrid network. Sect. IV describes the network design, while Sect. V presents experimental evaluations. Finally, Sect. VI concludes the paper and outlines future work.

II. REQUIREMENT ANALYSIS

In the territory under study, the most common crops are watermelons, oranges, cherry tomatoes, lemons, potatoes, and tomatoes. All these crops are cultivated in greenhouses, with the support of sensors and devices for monitoring and control of irrigation and manuring processes. The investigated farms are all equipped with a weather station to monitor humidity, temperature, wind speed, and rainfall. Some of these variables are also measured inside greenhouses.

The most sophisticated sensors found in our analysis are:

- Sensors to measure soil chemical, physical, biological and mineralogical properties from a distance of approximately less than 2 meters above the soil surface.
- Sensors to detect weeds or diseases in order to appropriately apply protection agents. They are based on spectral color analysis techniques and textural properties of leaves.
- Yield sensors, including mass flow meters, volume flow meters, impact sensors.

Interviews with qualified farmers allowed us to acquire the requirements of the precision farming applications relevant to the addressed environments. From such requirements, the constraints to be imposed on the communication architecture were derived. They are summarized in the following list.

Traffic types and requirements

- Most of the traffic is generated by the periodic monitoring of environmental variables.
- Data sampling must be done within a defined time window and sampled data has to be delivered within its validity interval. This traffic is considered soft real-time.
- Critical conditions such as devices failures or out of range measurements require timely notification. Some alarms have higher priority than periodic samples.
- Throughput is not an issue for these applications, as the amount of exchanged data, and their transmission periods, do not impose a significant workload on the network.

Network requirements

- Sensors position shall change over time, following the seasons, due to crops rotation.
- Energy saving policies should be enforced to extend the nodes lifetime.
- Network scalability is an issue, especially over large areas.
- Technological solutions able to offer low-cost installation and maintenance are especially sought.
- Standard protocols and devices are preferred over proprietary ones to avoid the need for specialized personnel.
- Support for various traffic classes and Quality of Service management has to be provided.

In Table I the network requirements are summarized.

TABLE I. NETWORK REQUIREMENTS

End-to-end Delays	< 60s
Throughput	Low
Coverage	High
Reliability	High
Scalability	High
Energy saving	High
Cost	Low

In this context, Wireless Sensor Networks (WSNs) are suitable and promising candidates. In particular, they are the most appropriate solution for the sensor network on the field, as cabling does not allow sensors to be easily moved. Moreover, sometimes is not even feasible to deploy cables on the ground, as they could be damaged by humidity and agricultural machinery crossing the field.

In addition, WSNs feature many desirable properties that match the network requirements discussed before, such as:

- The ability to embed multiple sensors in a single node and to easily move them over the field.
- Support for data aggregation and low duty-cycles to save energy and provide for long battery duration.
- Scalable architectures.
- Availability of cost-effective standard technologies, (e.g., IEEE 802.15.4 [3]) that are widely-known and accepted.
- Support for QoS management, according to the IEEE 802.1Q [4].

III. INVESTIGATED ARCHITECTURES

In this section, multiple design options for a precision farming network able to fulfill the requirements described in Sect. II are considered and compared.

A. *Two-Tiered Fully Wireless network architecture*

Fig. 1 shows a two-tiered, fully wireless network architecture in which multiple WSNs, compliant to the IEEE 802.15.4 and Zigbee standards, are connected to an IEEE 802.11 backbone.

In this architecture, each sensor sends its data to the PAN Coordinator of the relevant WSN, which acts as a gateway towards the IEEE 802.11 [10] backbone. All the gateways send the data received from the WSNs to a concentrator, called a Sink, which stores and manages the collected data.

This fully wireless architecture offers some advantages, such as low deployment and maintenance costs, as there is no need for a wired infrastructure. However some drawbacks are also found:

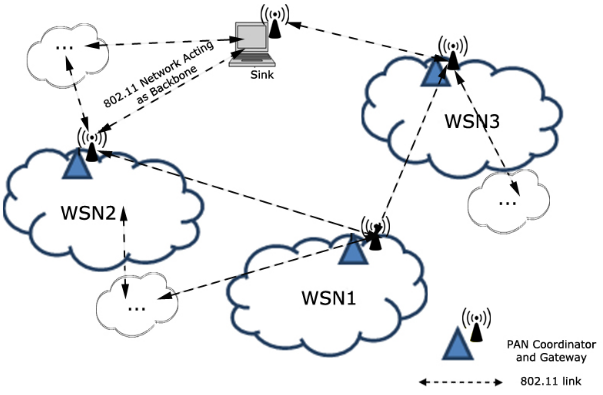

Fig. 1. Two-tiered, fully wireless architecture

- Collisions are likely to occur both in the IEEE 802.11 tier and in the IEEE 802.15.4 tier, due to the CSMA/CA mechanism. As a result, packet loss may be experienced..
- High overhead introduced by the IEEE 802.11 protocol (e.g., message acknowledgement, large control fields, Request-to-Send/Clear-to-Send mechanisms), that is not appropriate when short messages are transmitted.
- Unpredictable transmission delays of the CSMA/CA-based medium access policy, due to collisions.
- Higher errors and interference probability compared with wired networks.
- IEEE 802.11 gateway nodes would unlikely be battery-powered. Line power is more suitable to maintain the network connectivity.

Suitable solutions could be envisaged to cope with these drawbacks, but most of them come at the expense of interoperability (i.e. proprietary protocols) or are not scalable.

B. *Two-tiered wired/wireless architecture*

Fig. 2 shows a hybrid two-tiered wired/wireless architecture. The lower tier is composed of multiple WSNs in which sensor nodes transmit their data to the relevant PAN Coordinator. In the highest layer, a wired network connects the PAN Coordinators (that act as gateways for their WSNs) to a Data server and to the End-user workstations. Each PAN Coordinator manages its own WSN and forwards the sensor data to the Data server through the wired backbone. The network architectures investigated in [6], [7], and [8] adopt a full-duplex Switched Ethernet, as it provides high bandwidth and collision-free communications, while the solution in [5] proposes a CAN network.

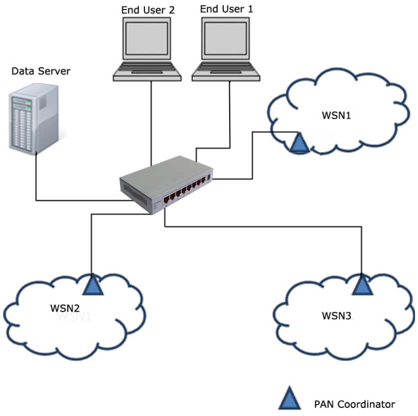

Fig. 2. Two-tiered wired/wireless architecture

The two-tiered wired/wireless architecture offers several advantages, as wired networks are more robust to interference than wireless networks and can also be collision-free (e.g. a Switched Ethernet), thus providing for higher reliability than the fully wireless architecture. However, a drawback of this solution is the need for long wired network segments which not only entail high costs, but also raise problems, as it is not always possible to deploy cables over long distances on the cultivated fields, as wires can be damaged (by weather conditions, by agricultural tractors, etc.).

C. *Three-tiered wired/wireless architecture*

Fig. 3 shows the basic model of the three-tiered wired/wireless architecture that is proposed in this paper to exploit the advantages of the previously investigated architectures while minimizing their drawbacks.

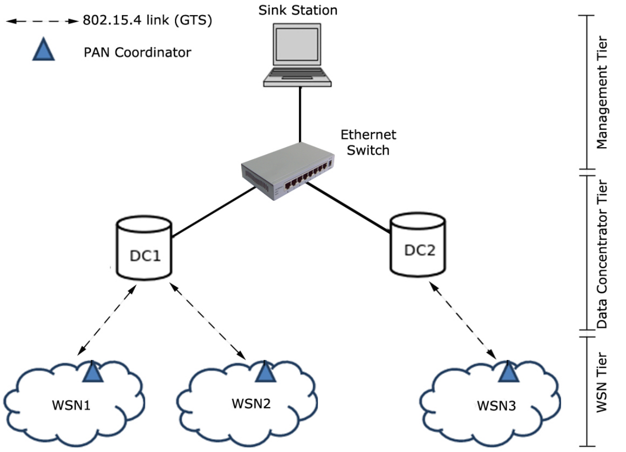

Fig. 3. Three-tiered wired/wireless architecture

The lowest tier consists of one or multiple WSNs, with star or cluster-tree topologies, based on the IEEE 802.15.4 protocol. The PAN Coordinators of each WSNs communicate with a middle tier, also based the IEEE 802.15.4 protocol thanks to its energy efficiency, that is made up of a number of Data Concentrators (DCs).

To cover large areas, multiple DCs are foreseen in the middle tier. The DCs are “smart” devices that are in charge of collecting and storing the data received from the lower tier. Moreover, DCs are connected to the network-wide Sink station by a Switched Ethernet network that is used to transmit processed data or aggregated data (average, maximum, etc.). The proposed architecture also allows handheld devices to connect to the DCs, thus enabling an operator to inspect the data collected over a given area.

The proposed architecture, as compared with the solution discussed in Subsect. A, provides higher reliability and bandwidth, thanks to the wired tier. Moreover, if compared with the two-tiered hybrid architecture in Subsect. B, the proposed architecture requires shorter cables, as the wired tier has only to cover the distance between the DCs and the Sink, thus overcoming the drawbacks discussed in Subsect. B.

Communications between the WSNs PAN Coordinators and DCs only occur in the Guaranteed Time Slots (GTSs), the mechanism provided by the IEEE 802.15.4 standard for collision-free transmissions. This choice provide for determinism, while limiting the maximum number of PAN Coordinator to the maximum number of GTS, i.e., 7 [3]. This is not an issue, as the total number of DCs can be increased to cope with larger networks. In addition, handheld devices can be connected to the DCs using the Contention Access Period (CAP), without interfering with the communications between the PAN Coordinators and the DCs.

Summarizing, the advantages of the proposed three-tiered architecture are the following:

- Scalability: Each DC is able to support data collection from multiple WSNs.
- Fault tolerance: If a single DC goes down, not all the WSNs become unreachable, but only those that are connected to the faulty DC.
- Less cabling: Thanks to the switch, the amount of wired connections is limited, to the benefit of cost and ease of management.
- Data Pre-processing: Sensor data coming from the WSNs are pre-processed by the DCs, which are smart nodes provided with computational capabilities. As a result, only aggregated data (e.g., average, maximum, minimum, etc.) are sent to the Sink Station, thus reducing both the network traffic and the computational load on the Sink Station.

In order to further improve the network scalability in the lowest tier, the multichannel approach proposed in [12] for the IEEE 802.15.4 protocol is adopted. Such an approach, as shown in [12], can be implemented on Commercial Off-The-Shelf (COTS) devices.

A potential limitation of the proposed architecture could be the low datarate of the wireless connections. However, our requirement analysis showed that precision farming applications do not require high datarates (e.g., a sensor sends data with a period typically ranging from 15 min to 1 hour).

Table II shows a comparison between the investigated architectures, based on the extent to which they match the network requirements. While large coverage is provided by both the three-tiered wireless/wired and the fully wireless architectures, it is limited for the two-tiered wired/wireless architecture, for two reasons:

- The cable length is limited to 100 meters without repeaters.
- For each WSN, a cable to connect the PAN coordinator and the switch is required.

TABLE II. COMPARISON BETWEEN THE INVESTIGATED ARCHITECTURES

	Two-Tiered Fully Wireless	**Two-tiered wired/wireless**	**Three-tiered wired/wireless**
Coverage	High	Low	High
Reliability	Medium	Medium	High
Scalability	Low	Medium	High
Energy saving	Medium	High	Medium

IV. ARCHITECTURE DESCRIPTION

The proposed network architecture includes the WSN tier, followed by the Data Concentrator tier and, on top of this, the Management tier. These tiers are described in the following.

A. WSN Tier

Each WSN is composed of sensors equipped with a communication module (from 1 to 5 sensors per node). Sensors in this tier acquire samples, with typical sampling periods from 15 min to 60 min, while the data samples size is between 2 and 4 bytes. Sensor nodes are distributed over a sensing area, in which each node collects and routes the data and send them to the PAN coordinator. The WSN tier is based on the IEEE 802.15.4 [3] and Zigbee [9] protocols, and three types of nodes are found:

- Leaf Nodes (LNs): They collect sensor data and send them to the parent node.
- Router Node (RNs): The function of these nodes, that are available only in cluster-tree topologies, is routing the data coming from the low-level nodes.
- Coordinator Nodes (CNs): Each CN is the PAN Coordinator of one WSN. It receives data from all nodes and sends them to the Data Concentrator (DC). CNs are equipped with a second transceiver to communicate with the DC.

In the proposed architecture, the following types of messages are envisaged:

- Sample Messages: Data messages scheduled according to the Rate Monotonic algorithm [11].
- Alive Messages: These messages are periodically sent by RNs or CNs when these nodes have nothing to transmit, to notify the parent nodes of their normal operation.
- Dead-node Messages: These messages are sent from the RNs or CNs that do not receive messages from a leaf node, to notify the upper levels that a Leaf Node is not transmitting any more.
- Threshold Messages: These messages indicate that a sensor exceeded some threshold.

Both Alive Messages and Dead-node Messages are 3 bytes long (at the Application level) and are sent only when necessary. As a result, the overhead introduced by these messages is not significant.

The network topologies foreseen for the lower tier of the proposed architecture are star and cluster-tree. In the star topology, shown in Fig. 4,

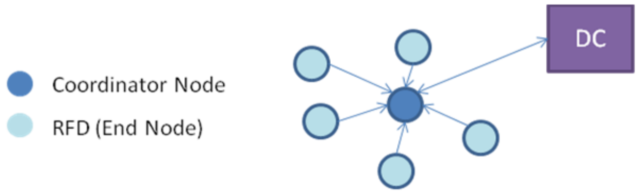

Fig. 4. Star Network

each Leaf Node is associated with a CN and sends data in the CAP using the slotted CSMA/CA protocol. The CNs forward messages to DCs in a FIFO way, only Threshold and Dead-node messages are transmitted with high priority.

In the cluster-tree topology, as it is shown in Fig. 5, the network has a hierarchical structure. Leaf Nodes can be connected to a Coordinator or a Router Node and communicate during the CAP. Router Nodes can be connected to other RNs or to a CN. Each RN communicates with the parent node in a GTS so as to have a collision-free and predictable channel. Communication is collision-free as, when the data arrives to RNs from LNs, it is forwarded during the GTS.

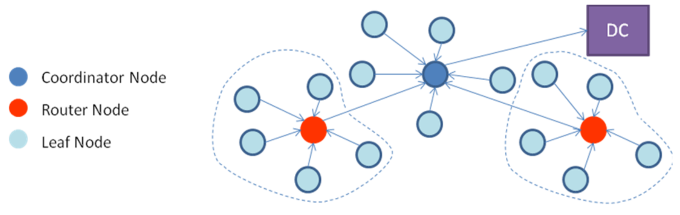

Fig. 5. Cluster-tree network

In a cluster-tree topology, routers periodically generate beacon frames to synchronize the nodes belonging to their cluster. Without suitable scheduling policies, beacon frames from different routers might collide. The typical solution to avoid collision is represented by time-division approaches, in which each coordinator schedules its superframe during the inactive period of the other coordinators. In this work, collisions are avoided by means of a multichannel approach that overcomes the limitations of time division approaches, which do not scale well and do not support contention-free transmission in the GTSs. Conversely, in the multichannel superframe scheduling presented in [12] and adopted in this work, RNs communicate with parent nodes and child nodes on different channels. To enable adjacent clusters to communicate although they use two different channels for their inter-cluster communications, scheduling of adjacent clusters is divided into two alternate timeslices, so that when a coordinator schedules its superframe, the adjacent coordinators are prevented from scheduling theirs.

For instance, in the topology shown in Fig. 6, each router has a reserved channel and timeslice (TS) to schedule its superframe. During TS1, R1, R4, R2 and R6 transmit their superframes at the same time on different channels, to acquire data from their child nodes. After transmitting the superframe, each router switches to the parent's channel and waits for the parent's superframe that will be transmitted during TS2. The process will continue until the end of the major cycle (that coincides with the largest superframe, i.e., the largest Beacon Interval).

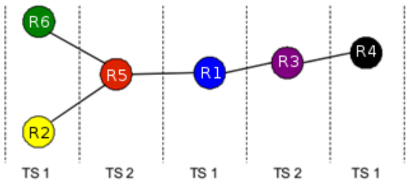

Fig. 6. Scheduling the clusters in alternale timeslices (TS1 and TS2)

B. *Data Concentrator Tier*

The Data Concentrator tier connects the WSN tier with the Management tier. Its function is collecting and pre-processing the data acquired from the WSNs, maintaining a database of the samples transmitted by the sensors, and allowing the connection of handheld devices for data monitoring purposes. Multiple DCs are required to improve reliability in case of faults and to limit wiring as well.

DCs receive data from the Coordinator Nodes in the CFP of the superframe with a GTS for each CN. A maximum of 7 CNs can be connected to one DC. Communication with mobile nodes is allowed in the CAP. Connection with the sink is realized by a full-duplex Switched Ethernet network.

C. *Management Tier*

The management tier periodically sends requests to the DCs to receive data sampled from a single sensor during a time window, or aggregated values acquired from all sensors.

Alive messages and Dead-node messages are directly received without any request from the DCs. Farm control is realized in this tier: For instance, if the soil is found dry, irrigation procedures are activated.

V. EVALUATION OF THE PROPOSED ARCHITECTURE

To assess the performance of the proposed network architecture, a simulation model was implemented with the OMNeT++ simulation tool [14] using the INET-MANET framework [15]. The INET-MANET model of IEEE 802.15.4 was extended to enable cluster-tree topologies and Multichannel Superframe Scheduling [12]. The Management Tier was not simulated, as the Ethernet backbone is predictable and able to meet communication requirements. Multiple queues were implemented, up the MAC layer module, to allow messages prioritization. The aim of the simulation is to assess packet delivery, delays, energy consumption, and scalability.

Table III summarizes the simulation parameters values that remained constant in both scenarios. Path loss coefficient and signal attenuation threshold were chosen as in [13].

TABLE III. SIMULATION PARAMETERS

Superframe Order	3
Beacon Order	5
Path loss coefficient	2
Signal attenuation threshold (dBm)	-85
Battery Capacity (mAh)	2400
Simulation time (hours)	24

A. *Scenario 1*

The first scenario, depicted in Fig.7, refers to a network with 3 clusters, each one composed of a Router Node with 12 Leaf Nodes. Each Leaf Node contains three sensors, with sampling periods and payload shown in Table IV.

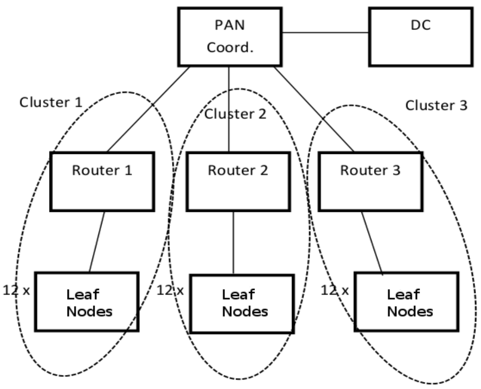

Fig. 7. Two-level WSN in the first scenario

TABLE IV. SENSOR PARAMETERS

	Sampling Period	Payload Size	Workload
Sensor 1	25 min.	2 bytes	3.8 bit/s
Sensor 2	40 min.	3 bytes	
Sensor 3	60 min.	4 bytes	

Depending on the sensor, the minimum sampling time varies from 25 to 60 min, and the payload from 2 bytes to 4 bytes. These are real values, as they were directly provided by the end users. The overall workload, 3.8 bps, was calculated using formula (1).

$$workload = N \cdot \sum_{i=1}^{SN} \frac{PacketSize_i}{GenPeriod_i} \qquad (1)$$

where:

- N is the number of leaf nodes
- SN is the number of sensors for each node
- $PacketSize_i$ is the packet size (in bit) for the i-th sensor with the addition of the Sample Message header
- $GenPeriod_i$ is the generation period (in seconds) of the i-th sensor.

The calculated duty cycle is equal to the 25% of the Beacon Interval which, in this scenario, has a duration of 491.52 ms. This value has been set in order to allow nodes to sleep for long periods, for the sake of saving energy.

The measured values are the distribution of successfully delivered packets for Leaf Nodes, the distribution of delivered packets for the entire cluster, and the mean delay distribution. In the following figures, all these values are expressed as a percentage.

Fig. 8a shows that the distribution of successfully delivered packets for LNs is quite high. In fact, most of the leaf nodes experienced a success percentage between 95% and 98%, and as many as the 25% of them (i.e., 9 out of 36 nodes) successfully sent all the packets.

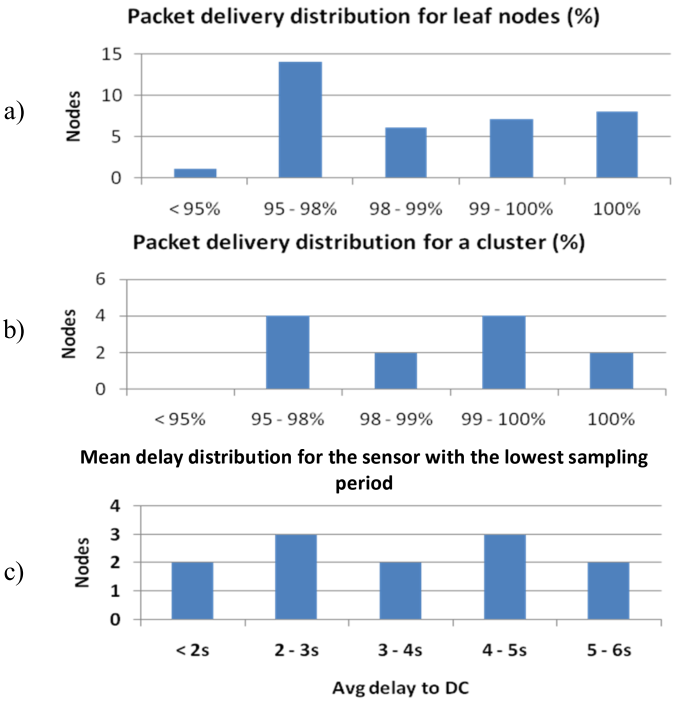

Fig. 8. Simulation Results for Scenario 1. Fig. 8a: Packet delivery distribution for leaf nodes. Fig. 8b. Packet delivery distribution for a cluster. Fig. 8c: Mean delay distribution for the sensor with the lowest sampling period.

The observed failure percentage is very low. Failures occurred when the maximum number of allowed retransmissions was exceeded. No queues overflow was observed during the simulation.

Fig. 8b shows that the distribution of successfully delivered packets for cluster 1 is always beyond 95% and is therefore quite high. Similar results were obtained for the other clusters.

Fig. 8c shows the average delay distribution for the sensor data that are sent to the DC from the nodes connected to a router. The sensors here considered are the most critical ones, i.e., the ones with the lowest sampling period (25 minutes). The figure shows that the mean delivery delay for such sensors is always below 6s. This value is fully compatible with the requirements of the supported precision farming applications. The delays values for the other sensors data (i.e., those with 40 min and 60 min sampling period), which are not shown here for the sake of brevity, are always lower than 7 s and 8 s, respectively, so they match their application requirements as well. We also obtained the energy consumption during 24 hours of network operation, assuming a typical 2400 mAh battery, as the one in [16], using the battery module embedded in INET-MANET. The energy consumed in this scenario during 24 hours is 0.40% for LNs, 0.69% for RNs, respectively.

B. Scenario

In the second scenario, depicted in Fig.9, there are 3 Level-1 Router Nodes, with 1 Level-2 Router Node and 15 Leaf Nodes each. The resulting network therefore consists of two clusters, Level 1 and Level 2, respectively, as shown in Fig.9.

As in Scenario 1, each Leaf Node contains three sensors, whose sampling periods and payload are the same as those in Table II. Due to the increased number of nodes, here the

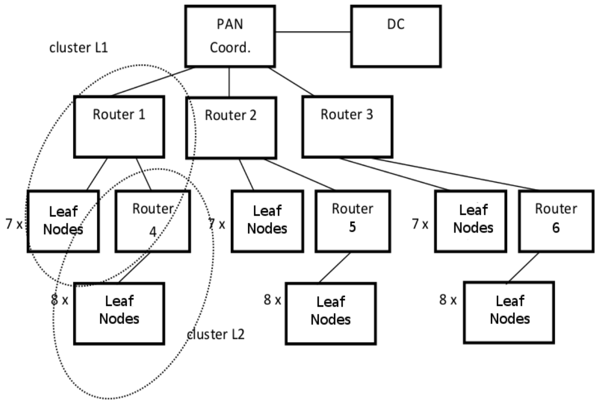

Fig. 9. Three-level network in the second scenario

workload is 4.76 bps. Fig. 10a shows that the packet delivery percentage significantly increases, as in this scenario, although the overall number of nodes is higher, the number of nodes in each cluster is lower as compared with Scenario 1.

Fig.10b shows that the average delay also increases, as there are more hops from source to destination than in Scenario 1. However, even in this case, the delays are fully compatible with the requirements of the supported precision farming applications. In this scenario, the energy consumed during 24 hours of operation is 0.40% for LNs, 0.69% for Level-1 RNs and 0.73% Level-2 for RNs. The reason for delay values of 6-8 seconds is the long Beacon Interval that provides a superframe period of 491.52 ms, so a retransmission requires at least this amount of time for each hop in the WSN tier.

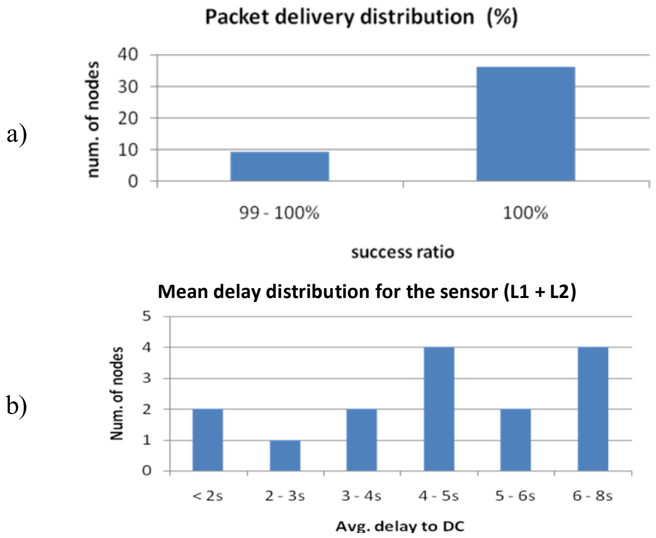

Fig. 10. Simulation results for Scenario 2

VI. CONCLUSIONS AND FUTURE WORK

The three-tiered architecture here proposed proved to be suitable for precision farming applications, as it allows for covering long distances with affordable costs and the quality of service provided to the different applications meets the requirements.

Moreover, simulations under different operating conditions reported mean delays that never exceed 25 seconds, a very good value for these applications, and battery duration up to 4 months, a quite reasonable value, as human operation in greenhouses is not an issue. Scalability is also achieved, thanks to the combination of the cluster-tree topology with multichannel superframe scheduling. Reliability is acceptable as, thanks to the presence of multiple DCs, in case of faults only a portion of the network will be unreachable, and human intervention can be promptly triggered by the envisaged alert mechanisms (Alive messages and Dead-node messages). On the reliability side, there is still room for improvement and this will be the subject for future work. The approach presented in this work requires a careful network planning, because of the use of timeslices, which have to be re-calculated every time a major network re-deployment is needed. However this does not affect the network scalability, as such major re-deployments in precision farming are not performed on a daily basis, but only seasonally. Another direction for future research will be how to exploit the novel features introduced by the recent IEEE 802.15.4e amendment in our architecture.

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