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ENAC/TELECOM/ReSCo, Toulouse, France
{juliette.garcia@recherche.enac.fr, alain.pirovano@enac.fr, mickael.royer@enac.fr}

Abstract. In this paper we address routing in the context of segmented wireless sensor networks in which a mobile entity, known as MULE, may collect data from the different subnetworks and forward it to a sink for processing. The chosen settings are inspired by the potential application of wireless sensor networks for airport surface monitoring. In such an environment, the subnetworks could take advantage of airport service vehicles, buses or even taxiing aircraft to transfer information to the sink (e.g., control tower), without interfering with the regular functioning of the airport. Generally, this kind of communication problem is addressed in the literature considering a single subsink in each subnetwork. We consider in this paper the multiple subsinks case and propose two strategies to decide when and where (to which subsink) sensor nodes should transmit their sensing data. Through a dedicated simulation model we have developed, we assess and compare the performance of both strategies in terms of packet delivery ratio, power consumption and workload balance among subsinks. This paper is an intermediate step in the research of this problem, which evidences the benefit of storing the information on the subsinks and distributing it among them before the arrival of the MULE. Based on results, we provide some information on further works.

Keywords: Wireless Sensor Network · Segmented network · Routing.

1 Introduction

A Wireless Sensor Network (WSN) is composed of a set of sensing devices, each able to collect information from the environment and transfer it to the others using wireless capabilities. The data gathered by the sensor nodes is sent to a node called sink for processing. These properties make WSNs deployment easier and quicker than for wired based solutions. Sensor nodes have the ability to determine paths to transfer information among them and to adapt in case a node is lost (e.g., due to failure or battery depletion). However, these have a limited communication range that only allows them to establish direct contact with nearby nodes. Due to this limitations, sometimes the network becomes segmented (i.e., a network composed of multiple isolated subnetworks). This scenario often appears when the sensing field is too large to be exhaustively covered by a fully connected WSN or when there are physical constraints on the field (e.g., buildings, rivers, etc).

In this paper we consider the routing problem in the context of a segmented WSNs. To address this problem, an existing solution relies on mobile nodes that pick up data from the subnetworks along their path and forward it to the sink. This type of entities are known as Mobile Ubiquitous LAN Extensions (MULEs) [1]. The role of MULE can be played by vehicles or drones for instance. Those could be entities traversing the area with the sole purpose of data transfer (controlled data collection), or entities non-devoted to the operation of the communication network (opportunistic data collection). In this paper, we focus on opportunistic data collection. As it advances on its way, a MULE can successively get in contact with several nodes belonging to the same subnetwork. In this paper, those nodes are named subsinks. A strategy to assign a destination subsink to each sensor node has to be defined. In addition, a suitable routing protocol must be chosen to define the multi-hop path between each sensor and the selected subsink.

In this paper, we compare two strategies to decide when and where (to which subsink) sensor nodes should transmit their sensing data. Firstly, in the frame of a so-called *Reactive strategy*, gathered information is retained by each sensor node until the MULE visits the subnetwork. Then, each sensor node sends all gathered data only to the subsink in contact with the MULE. Results obtained with this strategy encourage to investigate an alternative method. Hence, we developed a second strategy called *Proactive strategy*. A relevant subsink for each node is proactively selected and the data sent progressively as collected, even if none of the subsinks has detected a MULE. In this way, the information will be stored only in the nodes that will have contact with MULE, that means, in the subsinks. We remark that the value of the paper is not in the routing strategies applied but in the results of computer simulations that evidence, through comparison of both strategies, the benefit of storing the information on the subsinks and distributing the information among them before the arrival of the MULE. Our results are based on a simple example case in which the subnetwork has a grid structure. However, this case is sufficient to conclude about the potential benefit of the two actions previously mentioned.

The remaining of this paper is organized as follows: Section 2 presents the application case that motivated this study and a description of our research problem. Section 3 discusses previous developments found in the literature related to our research. In Section 4 we present the Reactive strategy and then, in Section 5 we describe the Proactive strategy. The performance of both strategies is assessed in Section 6 through simulations. Finally, conclusions and further research directions are provided in Section 7.

2 Motivation Case and Problem Description

This work is inspired by the process of Airport Surface Area Surveillance (ASAS), which encompasses the set of strategies and techniques used to control operations in both, movement areas (taxiways and runways) and non-movement areas (aprons and aircraft parking spots) of an airport. ASAS procedures may involve both critical monitoring for short term decision making (e.g. detection and removal of foreign objects placed on a runway) and non-critical monitoring for long term decision making (e.g. control of pavement temperature and noise levels along and around runways). Nowadays, airports conduct ASAS procedures using regular visual inspections performed by ground personnel. This approach presents strong limitations. Notably, it requires stopping regular activities on the area under inspection and its effectiveness may be naturally affected by human factors. We propose an alternative and automated solution based on WSNs. This innovative approach is expected to be easy to deploy in a short delay and totally customized considering the environment, in addition to provide the ability to survey several types of events or parameters at a relatively affordable cost.

To transfer critical data we assume the use of long range radio communication technologies (e.g., LoRa [2]). This type of technology allows direct communication between any sensor node and the destination sink at a high energy cost for the sensor. Long range communication technologies are limited to relative low data transfer rates, so this solution should be suitable for the sending of critical data that are expected to be rare. Non-critical measurements are tolerant to delays in the order of minutes or even hours for some of them. Thus, the collection of information of this type from the different subnetworks by means of MULEs seems to be a reasonable approach. In the context of airports, the role of data MULE could be played by already operating airport service vehicles, buses or even by taxiing aircraft, all this in an opportunistic way.

We further assume that the system is aware of the nodes that will be potentially in contact with the MULE , but not of the time at which the contact will be effective. Thus, data transfer to the MULEs must be done in an opportunistic way (i.e., using the occasion each time a MULE gets in contact). As we assume that the set of subsinks is known and fixed, the MULE will always visit the same group of nodes for a given subnetwork at any time. In our airport application case, for instance, this setting may reflect a scheme where subsinks are located along or by the side of runways and taxiways. Each sensor node must send its data to the subsinks that will forward the packets to the MULEs later. Depending on the distance separating each sensor and the subsinks, such a transfer could be done via direct, or more often, multi-hop paths. The solution approaches proposed here decompose the problem for each subnetwork into: a) selecting to which subsink and when a sensor node should send its data; and b) building routes among resulting pairs.

Solution strategies will use a classic 5 layer WSN model as base. The application protocol is responsible for the decision about to which subsink and when a sensor must send data, while the routing protocol defines an appropriate path between sensor nodes and subsinks.

3 Related Work

The literature contains several approaches to address the routing problem in Segmented Wireless Sensor Networks (S-WSNs). Main differences lie on the degree of control that the communication system is assumed to have over the MULEs. Some studies assume that the communication system determines both, the routes and schedule of the MULEs (see e.g., [3],[4] and [5]). Some other studies consider the setting where the MULES are non-controlled by the communication system. In those cases the proposed methods are often based on opportunistic data collection (i.e., taking advantage of not known a priori visits of a MULE). In the remaining of this section we focus on this latter approach.

The type of path that MULEs follow under the opportunistic data collection scheme can be classified as random or fixed. If the path varies from one visit of the MULE to the other and thus, the set of nodes that get direct contact with the MULE at each visit vary too, we classify the trajectory as a random path. In contrast, if at each visit the MULE gets contact with the same set of nodes, the trajectory is considered as a fixed path. This type of trajectory is often subjected to the layout of traffic lanes present in the environment.

The fixed path scenario is addressed in [6] and [7] with the particular assumption that the network topology and MULE's path are such that only one sensor node is able to get direct contact with the MULE (i.e., there is only one subsink per subnetwork). As such an assumption is often limiting, we consider in our study several subsinks per subnetwork. In the frame of the current state of the art and in accordance with our airport use-case, we propose two solution strategies for this problem with predefined and multiple subsinks per subnetwork.

4 Reactive Strategy

In the reactive strategy, the system starts by building suitable paths from each sensor node to each subsink. Then, sensor nodes start collecting and storing data. Meanwhile, the MULEs travel in the surroundings of the network and periodically emit beacons to make subsinks aware of its presence. Once a subsink receives a beacon, it sends a message to the sensor nodes to inform them that it is in contact with the MULE. At this point, the sensor nodes start sending their data packets to the subsink using the previously defined paths. Finally, data is forwarded from the subsink to the MULE. If the MULE advances on its path and gets contact with another subsink, this last propagates a new message to update the destination subsink. Then, data transfer is redirected to the new destination subsink using the routes built at the beginning. During this updating process, if the former destination subsink retains data from other sensor nodes, it starts transferring it to the new destination subsink as all the other sensor nodes do.

This strategy is called *reactive* as the selection of the destination subsink for each sensor node and the subsequent transfer of gathered data are tasks triggered by an event: the reception of the message indicating that a subsink is in contact with the MULE. The core functions of this strategy are implemented in the network and application layers of the WSN node communication architecture. Those functions are listed below.

4.1 Network Layer Protocol

Routing Paths Establishment to Reach the Subsinks : when the system goes into operation each subsink builds a directed acyclic graph (referred to as tree hereon for concision) connecting itself to every other node in the subnetwork through the shortest path. In our study, the tree for each subsink is built using the IPv6 Routing Protocol for Low-Power and Lossy Networks (RPL [8]), a protocol standardized by the Internet Engineering Task Force (IETF). As most other shortest-path oriented methods, RPL works for a generalized cost that could be defined, for instance, in terms of time, distance, energy consumption, or number of hops. Here we assume that the cost is given by the number of hops.

4.2 Application Layer Protocol

We called this protocol Reactive Origin Destination Matching (R-ODM).

Notify Contact with the MULE: each MULE declares its presence to its nearby nodes by periodically broadcasting one-hop beacon messages. Once a subsink receives a beacon, it notifies all the nodes in the subnetwork that it is in contact with the MULE. It is done using short advertisement messages (ADVs) which cross the network through the minimum cost paths included in the RPL trees. To do that, we use a broadcast technique called Parent Flooding, proposed in [9]. This procedure starts from the root of the RPL tree (a subsink), which broadcasts the ADV packet. Nodes that receive the ADV packet only broadcast it if the node who sent it is its parent in the RPL tree. Otherwise the node does not broadcast the ADV. This way, the ADV packet is propagated through the network using efficient routes in the RPL tree avoiding loops.

Sending of Information: when a node receives an ADV, it starts sending its gathered information. To do so, the node sends the data to its parent on the RPL tree whose root is the subsink in contact with the MULE.

Notify Lost Contact with the MULE: when a subsink loses communication with the MULE, the former sends an ADV to all the network to indicate the other nodes its status has changed and the nodes stop sending packets to it. The procedure to notify lost contact uses the minimum cost paths provided by RPL.

Change of Subsink: when a new subsink receives a beacon from the MULE, it must notify the entire subnetwork its new status. This operation is also performed by means of ADVs that travel through RPL trees. Once all nodes get aware of the new destination, data transfer is redirected to it. If a subsink loses contact with the MULE but has still information stored, it forwards it to the new destination subsink. If the MULE has left the subnetwork, the subsink retains it for a future visit of a MULE.

5 Proactive Strategy

To overcome some deficiencies of the reactive strategy, we propose a new approach called proactive strategy. Its objective is to mitigate the packet storm that occurs when a MULE gets contact with the subnetwork and to improve the load balance between subsinks. To do so, we propose two main changes compared to the previous strategy. Firstly, each sensor node must choose in advance a destination subsink before the MULE gets contact with the subnetwork. In this paper, we use a simple heuristic rule for that end: each sensor node must select the closest subsink in terms of hops as destination. This information is given by RPL since a tree is built for each subsink based on the number of hops. Secondly, each time a sensor collects information, it does not store it locally but sends it to its chosen subsink.

As for the reactive strategy, the core functions of the proactive strategy are implemented in the network and application layers of a 5 layer WSN architecture.

5.1 Network Layer Protocol

Construction of Routes to Reach any Subsink : each subsink builds a tree connecting to every node in the subnetwork using RPL as in the reactive strategy. This way, each node will be aware of the number of hops required to reach its destination subsink.

5.2 Application Layer Protocol

We called this protocol Proactive Origin Destination Matching (P-ODM)

Selection of the Subsink and Sending of Data: each node selects the subsink closest to it, that is, the subsink reachable in the lowest number of hops. Each time a node gathers new information, it forwards it immediately to its destination subsink.

6 Simulations and Results

6.1 MULE's Functioning

The way the MULE works does not have any impact on the reactive nature of the first solution strategy. In fact, the functioning of the MULE is exactly the same for both solution strategies. In both approaches, MULE's functioning requires a particular protocol in the application layer, responsible of: i) the delivery of periodic beacons to alert the subnetworks about the presence of the MULE; and ii) the storage of data received from the subsinks.

Application Layer Protocol

Sending of Beacons: each MULE broadcasts periodically beacon messages to warn nearby subsinks that it is close. When a subsink receives a beacon, the application layer protocol and network layer protocol for sensor nodes work together to transfer the data to the MULE.

Data Storage: this application allows the MULE to store information received from the subsinks in order to transfer it to the sink later.

6.2 Setup for Simulations

The performance of the reactive and proactive strategies was evaluated through computer simulations performed on the discrete event simulator OMNeT++ 5.2 [10]. The protocol stacks implemented for the sensor nodes and the MULE mainly differ at the application layer. Both architectures are based on the well-known IEEE 802.15.4 for the physical and the data link layers. Similarly, RPL is a control plane protocol specially designed for wireless networks with memory, power or processing constraints. It requires the use of IPv6 as data plane protocol. As data applications are tolerant to delay, UDP was chosen for the transport layer. Most of these protocols were already available in libraries of OMNeT++. However, RPL was not available, so we had to develop it. We also implemented the R-ODM and P-ODM protocols, required by the reactive and proactive strategy respectively, as well as the applications which simulate the collection of data for each sensor node. Those applications are detailed below.

Data Collection to be as representative as possible of the airport monitoring application, each sensor has to collect data using two strategies: in a periodic way or based on a threshold.

Periodic Data Collection: this function simulates the data collection in *almost* equally spaced periods of time (e.g. sense noise levels each $\sim$10 minutes). Each time data is collected, it is passed to the R-ODM or P-ODM protocol (depending on the used strategy) to proceed with its transfer to the subsink.

Data Collection based on Thresholds: as the previous approach, this function simulates data collection in almost equally spaced periods of time (e.g. collect pavement temperature levels each $\sim$10 minutes). Each time data is collected, it is checked to determine if the sensed variable exceeded a predefined threshold assigned by the user (e.g., pavement temperature of 40°C). If this is the case, the data packet is forwarded to the R-ODM or P-ODM protocol (again, depending on the used strategy). Otherwise, the data is discarded.

Simulation Parameters We consider a scenario with a single MULE and a subnetwork composed of 50 sensor nodes. Among all the sensor nodes, 10 are subsinks while the other 40 remain out of the communication range of the MULE. We modeled a rectangular grid-like subnetwork with 5 rows and 10 columns, covering a rectangular area of dimensions $500 \times 1000\,\mathrm{m}$. This may correspond, for instance, to a section of a grass area between runways and taxiways in an airport (see Figure 1).

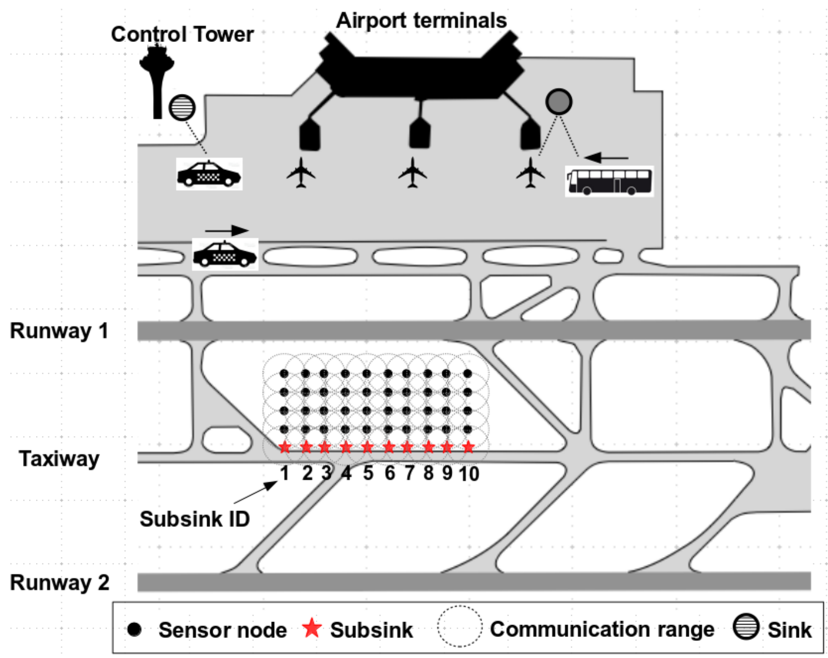

Fig. 1. Deployment of the subnetwork considered in the experiment for an ASAS case.

The speed of the MULE is fixed constant at $30\,\mathrm{km\,h^{-1}}$. The MULE gets contact for the first time with a subsink after 30 minutes of simulation, along which the sensors are collecting information. After that first contact, the MULE keeps advancing at constant speed, parallel to the row of subsinks. Given the MULE's speed, there is a time-lapse of two minutes of continuous direct contact with at least one subsink and then the simulation stops (see Figure 2). During the whole simulation, the MULE sends beacon messages at a constant rate of 1 message each 2 seconds. The transport of packets by the MULE and the sending of them to the sink are not considered in this paper since the MULE's route is not controlled by the communication system. On the other hand, we do not consider packet exchanges between sub-networks using the MULE since the final destination of the data is the sink. The Standard IEEE 802.15.4 protocol is setup with a bitrate of 250 kbps, a communication range of 100 m and a maximum queue length of 100 packets. Acknowledgement messages are activated and the maximum number of transfer attempts is fixed in 7. After that, a *loss due to collision* is registered and the message is dropped.

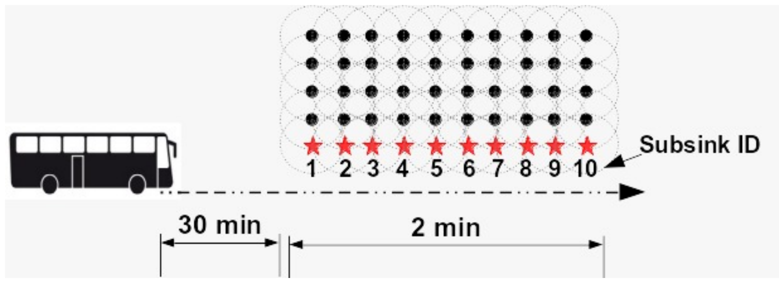

Fig. 2. Trajectory of the MULE in the experiment.

For the data collection, the periodic function and the one based on thresholds are assigned each, two variables to sense. In all cases, the first measurement at each node is performed at a random instant uniformly distributed in $[1, 5]$ sec from the beginning of the simulation. From that moment and on, the time between measurements is uniformly distributed between 0.9 and 1.1 min. The function based on thresholds uses a random number uniformly distributed between 0 and 1 to determine if a given measurement should be sent to the MULE. The decision threshold is fixed in 0.8 so that in average, 20% of measurements performed by the function based on threshold are transferred.

The memory capacity for each node was set in 1 MB, taking as a reference a TelosB sensor [11]. This type of sensor is often used in WSN to simultaneously monitor multiple variables such as temperature, humidity and light intensity. This sensor works with AA rechargeable batteries, which could provide the sensor with up to 16,000 J of energy. As our main interest was to compare the performance of the reactive and proactive strategies, we chose large enough (but realistic) parameters that would not cause neither energy depletion nor memory overflow issues in our scenario.

Finally, in the R-ODM Protocol, ADVs and data packets are sent by each node with a delay uniformly distributed between 0.04 and 0.05 s and between 0.02 and 0.03 s respectively, to mitigate collisions. No aggregation approach (as those used in [12]) is considered in the proposed strategies to keep the comparison as simple as possible.

6.3 Results

The results of the reactive and proactive strategies are presented below. Because we used randomness in the selection of some parameters, we ran 30 simulations and calculated mean/standard deviation. We evaluated the proposed strategy in terms of three performance metrics:

Packet Delivery Ratio (PDR): percentage of data packets received by the MULE out of the total number of packets sent by all the sensor nodes. The PDR for the reactive strategy over the 30 runs was in average 45.73%, with a standard deviation of 8.58%. The main cause of packets loss was the queue overflow, accounting for 83.1% of the losses. The remaining losses were caused by data collisions. The reactive strategy is highly susceptible to queue overflow due to the fact that on this approach, all sensors node have the same destination subsink at the same time. This converts nodes around the destination subsink into bottlenecks, as they are included in the shortest paths between several sensor nodes and the subsink. Packet collisions and queue overflow took place during: i) the transfer of data from one subsink to another, and ii) the massive transfer of data from the sensor nodes to the first set of subsinks when the MULE arrived to the subnetwork. In the proactive strategy, both problems are mitigated as there is no communication among subsinks, data is sent at the subsinks as soon is collected before the arrival of the MULE and data is distributed among them. This way, localized congestion spots are avoided. Table 1 shows the positive impact on the PDR by using the proactive strategy. The standard deviation of the PDR shows that the proactive strategy is also considerably more stable in this performance measure than the reactive strategy.

Table 1. Comparison of reactive and proactive strategy in terms of PDR and PC.

	Performance metric	**Mean**	**Standard deviation**
Reactive strategy	PDR (%)	45,73%	8%
	Energy (Joules)	203	1.02
Proactive strategy	PDR (%)	98,10%	0.13%
	Energy (Joules)	198	0,36

Power Consumption (PC): total amount of energy used by all the sensor nodes. On the one hand, this measure is correlated with the length of the routes (number of hops) to reach the destination. Results in Table 1 show that the reactive strategy causes in average greater PC. In the reactive approach, the destination subsink is assigned without considering the distance separating it from the sensor nodes. In contrast, the proactive approach performs optimally in this aspect, as that strategy uses the nearest subsink as destination for each sensor node. On the other hand, the PC is related to congestion issues such as a high number of transfer attempts to avoid loss of packets due to collisions; problems that are mitigated in the proactive strategy. Similarly to the PDR, the standard deviation of the PC for the reactive strategy is bigger, which indicates less stable performance.

Subsink Load (SL): average over the 30 runs, of the percentage of packets received by each subsink out of the total number of packets received by all the subsinks. Figure 3 shows the SL for each of the 10 subsinks for each strategy.

Results show a strong imbalance in the SL for the reactive strategy. Under this approach, there is a large amount of data stored at the sensor nodes when the MULE reaches the subnetwork. This data corresponds to 30 minutes of sensing. When the MULE gets in contact with the subnetwork, all that information is sent to the first subsink. This last sends as much data as it can to the MULE, but the contact time with the MULE is too short to transfer all stored data. Therefore, it had to redirect data to the second subsink and so on. In fact, it forwards 54.38% of the information it receives to the other subsinks. The remaining 45.61% is sent to the MULE. This indicates that the first subsink is overloaded. The large amount of data progressively shrinks as it moves forward in the subsinks line. The consequences of the first subsink being overloaded are: i) this subsink consumes more energy than the other nodes in the network, since it often has to forward arriving packets to the subsink in contact with the MULE; and ii) this subsink increases the probability of collision of a packet as some packets are forced to cover unnecessarily large paths to reach its location.

Unlike the results obtained with the reactive strategy, the proactive approach shows an almost perfect balance in the number of packets received by each subsink (see Figure 3). This is the result of the even assignment of sensor nodes to subsinks, which helps to reduce the number of bottleneck nodes, and thus, the amount of dropped packets by queue overflow and collisions.

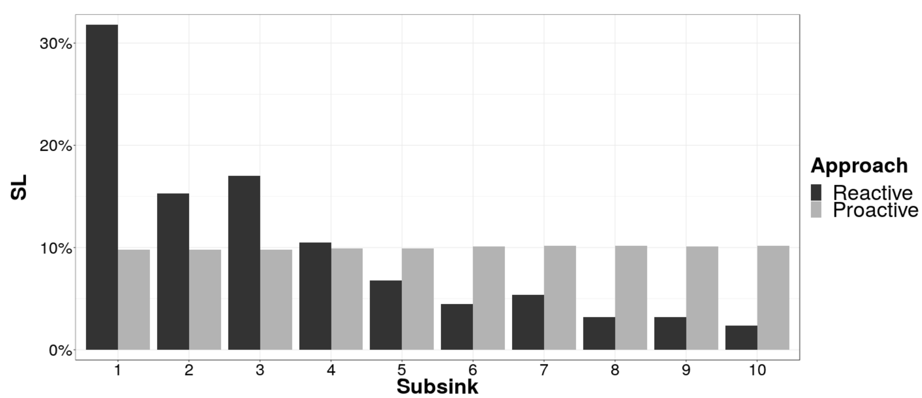

Fig. 3. Subsink Load for each strategy.

We remark that our simple heuristic rule for proactive strategy offers good results in our case. This, due to the grid-like structure of the network considered and the fact that each sensor node generates the same amount of data. More sophisticated assignment rules should be applied in order to reach comparable results if the network presents other type of structure or if data collection is not homogeneous among sensor nodes.

7 Conclusions and Further Works

This paper aims to investigate routing and forwarding in segmented wireless sensors networks. Data collected in each subnetwork must be forwarded to the final destination, the sink, where they will be processed. Existing mobile nodes, such as vehicles, are involved in an opportunistic way to act as intermediate nodes between the subnetworks and the sink. These properties match with the considered use case of wireless sensor networks for airport surface monitoring. As the forwarder vehicles follow existing lanes, nodes that could be in contact with them in each subnetwork are fixed and considered as subsinks.

Firstly, we propose and assess the performance of a reactive approach. In this case, the sending of collected data from the sensor nodes to the relevant subsink is triggered by the fact that the subsink is in contact with a MULE. This approach offers poor results in terms of packet delivery ratio caused by many collisions around the subsink in contact with the MULE. Then, to mitigate this problem, we propose a simple proactive approach based on the assumptions of a regular grid topology with homogeneous nodes in terms of generated data traffic. Here, the relevant subsink selection for each sensor node and then the progressive sending of data packets to this subsink are anticipated. The obtained results show that the proactive approach avoids the congestion observed with the reactive approach, ensuring better results in terms of packet delivery ratio, subsink load and power consumption.

This study is a preliminary step whose results justify the development of a more complex methodology which uses strategies as storing and distribution of information among the subsinks, in networks with random structure. In this direction we are continuing this investigation. The new approach could be based on heuristic mechanisms (e.g., Ant Colony Optimization) taking into account multiple performance criteria and also the frequency of MULEs' visits to improve the routing strategy. To the best of our knowledge, this kind of methodology has never been considered in such a context.

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