Reality-proof activity scheduling for energy-efficient wireless sensor networks

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Abstract: A straightforward idea to prolong wireless sensor networks network lifetime is to schedule activities of nodes, that will turn into either Active or Passive states during the deployment. Several papers proposed solutions to turn Passive a large subset of nodes. However, only few of those provide information on how to translate this activity state in reality. In this paper, we further improved several activity scheduling mechanisms by introducing a new activity state called Sensing-Only. This new sensor node state concerns formerly Active nodes, all the more reducing the size of this subset. In addition, radio usage being the sensor nodes main source of energy depletion, we also provide a realistic translation of activity states by adjoining to each of those a specific configuration of the medium access control layer. Finally, we validate our approach both by simulation and experimentation over a large set of real sensor nodes.

Keywords: WSNs; wireless sensor networks; energy-efficiency; activity-scheduling; duty-cycling.

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1 Introduction

In order to collect information about remote or hostile environments, battery powered sensing devices are now being deployed over areas of interest. Nodes must organise themselves into a wireless sensor network (WSN) that is dedicated to a specific monitoring application. In order to have this commitment pursued over a long period of time, the emphasis has been put on energy-efficiency of these wireless sensors. Energy-preserving mechanisms have gained much attention from both researchers and engineers in the field (e.g., medium access control, routing of sensed data toward the sink stations) (Anastasi et al., 2009), leading to dedicated communication stacks for specific monitoring applications.

In this paper, we consider WSN operated to ensure that any physical point of the target area can be sensed by at least one running sensor (i.e., area coverage), yet guaranteeing the existence of communication paths from every sensor to at least one of the sink stations (i.e., connectivity). In this context of energy conservation, connected area coverage is achieved by a subset of Active nodes, so that the remainder limit their own energy depletion by entering a sleeping state. In other words, activity scheduling consists in switching nodes between Active and Passive modes, therefore significantly reducing overall energy consumption and extending network lifetime.

Although turning a great proportion of nodes into a low-power sleeping mode already improves energy-efficiency (Choi et al., 2012), lots of contributions remain sub-optimal as this *Active/Passive* logical division does not finely reflect the role that each node should take on. For instance, the node redundancy among active nodes may remain far too large for a routing task, thus allowing some of them to stop participating in the multi-hop communications (Mérindol et al., 2009). In this article, we illustrate this possibility by introducing a *Sensing-Only* state. Nodes entering this state are no longer forced to relay the communications of others, as they only care about their own outgoing data. This state regroups nodes only required to ensure full coverage of the area of interest, and whose presence is not necessary to provide full connectivity of the network. Defining which nodes could enter this state is similar to a maximum leaf spanning tree (MLST) for data collection, thus being NP-complete (Galbiati et al., 1994). We therefore follow several leads and show how much energy could be gained from such enhancements in the large set of existing contributions. The first one uses a local approximation of the minimum spanning tree (MST) (Li et al., 2004) while the second relies on routing roles assigned through a gradient-based structure (Khadar et al., 2009).

Then, we can observe that several options have been proposed to give life to the concept of passivity of a sensor node. Some studies propose to completely switch off nodes in this state (Gupta et al., 2006a; Gallais et al., 2008), thus assuming scheduled or synchronised wake-up mechanisms at some point, other proposing to reduce their sensing frequency (Choi et al., 2012). However, only few of those have been experienced (Yang and Heinzelman, 2009), with unsatisfactory results (e.g., only little energy gain).

In order to maximise the energy gains, we aimed at modifying the components that are the closest to the main source of energy consumption. In response to the observation that the radio component is responsible for most of the energy depletion (Akyildiz et al., 2002), we here decided to consider fully asynchronous mechanisms at the MAC layer and allowed for self-configuring sensors, making decisions solely based on their 1-hop neighbourhood and their activity state defined during the activity scheduling process.

We demonstrated the feasibility and performances of our contributions via a thorough study, both by simulation and experimentations. Special care is given to some critical points such as network lifetime. A campaign of long-term experiments allowed us to underline some specificities (e.g., precise energy consumption), observable in realistic experimentations only. These experiments helped us to confirm the extension of network lifetime or stability, hardly estimable otherwise.

The remainder of this paper is organised as follows: Section 2 presents related work. Section 3 details the required backgroud on activity scheduling. Section 4 introduces our novel *Sensing-Only* activity state and presents our scheme to assign to each of those a specific MAC configuration. Section 5 presents the evaluation of our contribution conducted through simulation, and Section 6 details our experimentation over two 240 node testbeds. Section 7 concludes this paper and discusses the results.

2 Related work

2.1 Activity scheduling

The connected area coverage problem has been intensively studied. Both centralised and localised solutions have been proposed. The following papers deal with activity scheduling within a WSN and target full area coverage by connected sets of *Active* nodes. Thus, each solution aims to reduce the subset of *Active* nodes, yet preserving initial area coverage and connectivity of the network.

In Yan et al. (2003), for each sensor able to cover a given physical point, a list of other sensors also able to cover it is maintained, in a priority order. All sensors covering the same point then set time schedules for the monitoring task. In this solution, the complexity of the signalling traffic induced by decision making in such a cooperative manner is nontrivial. This scheme was further extended to address cases where overflow between time schedules occurs (Lu and Suda, 2008).

A randomised algorithm was proposed in Yener et al. (2007). Based on a Markov model, this algorithm allows each node to probabilistically turn off while ensuring strong guarantees for both coverage and connectivity. Still, this solution requires a new analysis when considering non homogeneous settings. In other words, exact neighbour information is required to ensure coherent node behaviour. This assumption hardly holds in reality as the neighbourhood is subject to many modifications (e.g., mobility, failure).

Some papers also consider the area coverage problem from another angle. In Zhou et al. (2009), instead of determining a subset of nodes to remain active, each node adapts its sensing and communication radii, to fit area coverage and connectivity requirements. To do so, each node computes the Voronoï diagram and the relative neighbourhood graph (RNG) of the topology consisting of its direct neighbourhood and itself. The required activity radius is then set as the maximum between the maximal distance in the Voronoï cell of the node and the longest adjacent edge of the local RNG. By doing so, the area remains fully covered by the whole set of nodes, but only with limited activity radius. Note that, for all these reasons, we decided to implement this contribution for our performance evaluation.

In Gupta et al. (2006b), centalised and distributed mechanisms are proposed to determine a subset of active nodes. The distributed one, called DGA for Distributed Greedy Algorithm, works as follows. A single node is selected to transmit its location to the whole network via an advertisement message. Upon reception, a node will answer to it by attaching its coordinate. Each node relaying this message will also attach its own coordinates. Then, the deciding node will consider the coverage of all candidates and their corresponding paths to select one node to remain *Active*. This newly selected node will then iterate the operation, and so on until all points of the area are covered. This mechanism emulates the behaviour of centralised algorithms in a distributed fashion by broadcasting the selection messages over the network. Although the number of messages might be prohibitive in a real-life deployment, its efficiency in terms of active nodes involved makes it a valuable candidate for comparison in our simulation campaign.

We propose two localised solutions that, although remaining sub-optimal, perform well and require only very limited communication overhead. Unlike most existing proposals, our mechanisms are very scalable and turn out to be very stable. Moreover, their apparent simplicity makes them perfectly appropriate for constrained devices, and thus ideal for real WSN deployments.

2.2 Activity states translations

Activity scheduling is primarily meant for energy savings. This role is guaranteed by assigning to *Passive* nodes an energy-preserving mode. Up to now, very few activity scheduling contributions have proposed a way to give life to such mode in reality.

Most of those (Gupta et al., 2006a; Gallais et al., 2008) simply suggest to turn *off Passive* nodes until the next activity decision round. This method is optimal in terms of energy consumption, as every non-vital electronic component (e.g., sensors, radio) will be turned *off* as well. Yet, this solution requires a wake-up scheduling mechanism, as the node will have to be turned *on* again for the next decision round. Most of the time, it induce precise time-synchronisation between nodes, in order to ensure that all *Passive* are awaken altogether to perform their next activity decision. Otherwise, some nodes may have to take their decision based on incomplete information, which may lead to severe underachievements in the activity scheduling process.

In Choi et al. (2012), a realistic approach for *Passive* mode translation is proposed. It suggests to adapt the applicative layer depending on the considered activity state. While *Active* nodes send their readings normally up to the sink, *Passive* nodes divide by two their transmission frequency. This method ensure that *Passive* nodes remain reachable at any moment. This way, no wake-up scheduling mechanism is required. By reducing the overall traffic load, the networks performances (e.g., latency) are improved. However, this technique has only little effect on energy consumption, as the radio idle-listening is the main cause for energy wastage.

In Yang and Heinzelman (2009), the authors investigate single-layer and multi-layer passivity schemes for Directed Diffusion (Intanagonwiwat et al., 2003). They investigate the performance of making sensors sleep at the routing and MAC layers simultaneously, with and without cross-layer coordination. The proposed passivity scheme displays interesting simulation performances, improving throughput and data delivery ratio for dense networks. Yet, energy consumption of the proposed schemes were not evaluated. Since the main aim of activity-scheduling techniques is energy efficiency, the interest of the proposed schemes can not be clearly identified

3 Background and assumptions

In this section, we provide the required background on activity scheduling, by detailing the mechanisms we rely on for determining a subset of *Active* nodes.

3.1 Activity scheduling

In our case of study, each sensor node is considered able to retrieve precise information about a certain area in its vicinity. Activity scheduling mechanisms aim at preserving global sensing coverage of the area of interest, performed by only a subset of nodes called *Active*. The remaining nodes, called *Passive*, are then put in an energy-saving mode. In addition to area coverage criterion, the subset of *Active* nodes must also preserve global connectivity of the network, so that each of them can send its readings at any moment up to the sink. The problem of finding a minimal set of such sensors already is NP-hard even without the connectivity requirement (Guha and Khuller, 1998). In order to improve network lifetime (i.e., the period during which no node fails from battery exhaustion) the sensor nodes can alternate their activity mode (*Active*, *Passive*) simply by launching several activity decision rounds at regular interval.

3.2 Determining Active node sets

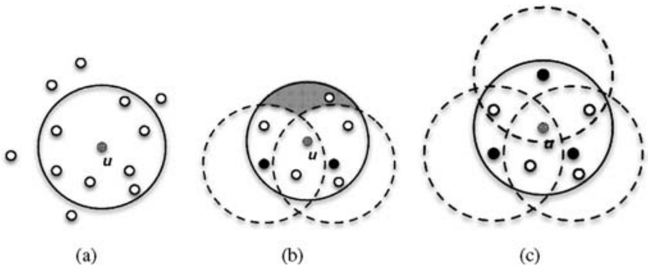
We base our contribution on two of the four algorithms presented in Gallais et al. (2008), especially because of the very low communication overhead they induce. These mechanisms, respectively referred to as Positive-Only (PO) and Positive-Retreat (PR) work as follows. Every node u in the network selects a timeout TO. Once this timeout expires, u evaluates its own coverage and its neighbourhood connectivity, based on received decisions made by neighbours with shorter timeouts. This coverage test is positive if and only if u is fully covered and its direct neighbours are connected. This step ensures connected area coverage. If u gets *Passive*, no message is sent. If *Active*, u sends an activity announcement. This solution is referred to as Positive-Only (PO). Nodes with higher timeout values that receive the message from u will consider u during their coverage evaluation. If any sensor u has decided to be *Active* while additional coverage is provided by other nodes with longer timeouts, u can change its decision. Once a new timeout expires, if u is covered then it sends a *retreat* message. This solution is referred to as Positive-Retreat (PR). Considering the proportion of involved sensors, the PR algorithm is optimal regarding the knowledge we assume at each deciding node as detailed in Property 1.

Property 1: The Positive-Retreat variant is optimal regarding the available knowledge at every node. Indeed, no *Active* sensor is useless as it would have otherwise turned into a *Passive* mode upon later notifications of *Active* node decisions, provided that timeout are kept unique over the whole set of nodes.

Proof: Let us figure out a node u that would have decided to remain *Active* and whose presence would be useless. If u did not receive any activity message, then no *Active* sensor belongs to its vicinity. If some messages were received from nodes that fully cover the sensing area of node u, then node u would have decided to retreat. □

The general principles of PO are exposed in Figure 1. After expiration of its timeout and if no neighbours have signalled themselves, u must remain *Active* to cover its sensing area itself. It also has to send an activity message to its neighbourhood (see Figure 1(a)). Else, if neighbours signaled during the timeout period do not cover the sensing area of u, it also has to remain *Active* and signals itself (see Figure 1(b)). On the contrary, if neighbours signaled during the timeout period do cover its sensing area, u can enter *Passive* mode without signalling its presence (see Figure 1(c)). PR adds a second decision, similar to the one previously described, but advertises its neighbourhood only if it decides to enter *Passive* mode. Pseudo-code describing the functioning of PO and PR are respectively in Algorithms 1 and 2.

Figure 1 Activity scheduling over the network: (a) if u has not listed any neighbour after expiration of its timeout; (b) if listed neighbours of u does not cover its sensing area and (c) if listed neighbours of u cover its sensing area



Algorithm 1: `Positive-Only` algorithm

```
begin
    wait(RANDOM_TIMEOUT);
    if fully_covered then
        status == Passive;
    else
        status == Active;
        send_broadcast(ID, position, status);
    end
end
```

Each signalling message therefore contains the coordinates of the emitting node and indicates its type (i.e., positive or retreat). Note that the later a node decides, the higher the probability to become fully covered by a connected set of nodes. Several timeout computation schemes have been proposed. These methods induce very few messages as knowledge comes with activity decision making. To ensure homogeneity of node usage over the network, and thus increase network lifetime, the process can be restarted locally at regular intervals (called rounds) so that another subset of *Active* nodes will be determined. Topology changes (e.g., node mobility) can be addressed similarly. The timeout value can also be balanced in order to favour some nodes (e.g., depending on the participation to previous rounds). In the present paper, we increased the random timeout of nodes during the Activity scheduling phase, depending on the number of round participated.

Algorithm 2: `Positive-Retreat` algorithm

```
begin
    wait(RANDOM_TIMEOUT);
    if fully_covered then
        status == Passive;
    else
        status == Active;
        send_broadcast(ID, position, status);
    end
    wait(RANDOM_TIMEOUT);
    if fully_covered then
        status == Passive;
        send_broadcast(ID, position, status);
    else
        status == Active;
    end
end
```

3.3 Summary and discussion

In order to implement our contributions, we selected two activity scheduling mechanisms to rely on: PO and PR. Both PO and PR allow to determine a subset of *Active* nodes that preserves the global sensing coverage of the area of interest. The main advantage of these solution relies in their low computation, their limited overhead (at most 1 control message per *Active* node for PO, and 2 for PR), and the fact that they require local information only.

Each variant can be used depending on the deployments characteristics. Indeed, while PO requires less overhead than PR, it also induces larger sets of *Active* nodes. Yet, with PR, the loss of a *retreat* message may disrupt the protocol general functioning, some *Active* nodes being potentially unaware of some other node retreat. PR could thus be favoured as long as the loss rate does not reach a certain threshold, yet to be defined in real experimental conditions.

4 Contributions

In this section, we first introduce a new activity state called *Sensing-Only*. This new sensor node state concerns formerly

Active nodes, all the more reducing the size of this subset. This way, it improves further more the activity scheduling mechanisms depicted in the previous sections. In addition, given that the radio usage is the sensor nodes main source of energy depletion, we also provide a realistic translation of activity states by adjoining to each of those a specific configuration of the medium access control layer.

4.1 Introduction of a Sensing-Only state

The localised solutions described in the previous chapter lead us closer to minimum *Active* node sets needed to achieve connected area coverage. It was recently shown in Mérindol et al. (2009) that, among these *Active* nodes, some could spare themselves the trouble of participating in the routing process without endangering the information relaying toward the sink. Indeed, although the sensing coverage is optimal regarding the available knowledge at each decision making node, ensuring the connectivity of the *Active* node set is made through a restrictive local criterion (i.e., every node should be covered by a connected set of neighbours) and therefore leaves much room for further reductions of nodes participating in the multi-hop communicating process.

In consequence, we introduced a new intermediate state, called *Sensing-Only* (SO). The set of *Sensing-Only* nodes is constituted of nodes that do not participate in the routing process and only transmit their own information up to the sink. These nodes can sleep for longer periods of time without undermining the network performances (e.g., delay, packet reception rate). This way, they reduce their overhearing of other transmissions, thus saving an important amount of energy. Indeed, receiving a message is usually at least as costly as sending one in considered hardware (Akyildiz et al., 2002) and happens far more often, considering the multi-hop nature and the average densities of common WSN. Finding the maximal subset of nodes unnecessary to guarantee the connectivity of the network can be summarised as finding its MLST, which is a NP-complete problem (Galbiati et al., 1994). Thus, we propose several local approximations in order to obtain as many *Sensing-Only* nodes as possible.

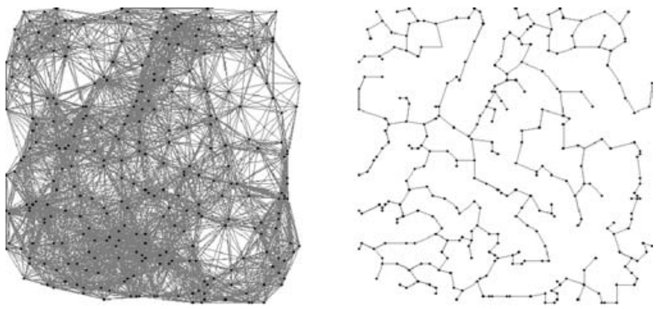
As for PO and PR, we here focus on localised solutions, targeting efficiency and portability on systems with restricted capabilities such as wireless sensor nodes. An easy way to identify the subset of *Sensing-Only* is to rely on a Directed Acyclic Graph (DAG). Many routing protocols in WSN are based on the construction of such structures (Intanagonwiwat et al., 2003; Khadar et al., 2009), notably the IETF RPL routing standard (Winter et al., 2012). When using a routing DAG, finding the subset of *Sensing-Only* nodes is straightforward. Indeed, every node having no *son* in the routing tree (i.e., farther to the sink than itself) can be added to the subset of *Sensing-Only* nodes. In such case, no additional control message is required. Else, a virtual DAG construction should be specifically performed for the *Sensing-Only* subset identification. Among all localised DAG-construction approaches studied, we decided to focus on two of those, selected for their low overhead, good performances and realism.

4.1.1 Determination of the Sensing-Only subset using LMST

Our first approach to determine a subset of *Sensing-Only* nodes uses a local approximation of a MST. As locally finding the MST of a topology is known to be a NP-complete problem, we propose to approximate it by using the local minimum spanning tree (LMST) algorithm proposed in Li et al. (2004). In this method, each node u computes the MST of the topology (i.e., its neighbours and itself). Then, a message is sent from u to every neighbour v if there is an edge between u and v. If both nodes agree on the existence of the edge, it is added to the resulting topology.

From this approximation, we can underline a subset of *Sensing-Only* nodes. Indeed each node having only one outgoing edge (and then only one neighbour) is located at a dead-end of the LMST, and is of no use in the multi-hop communication. These leaf nodes can consequently change their state to *Sensing-Only* and stop participating in multi-hop communications. The construction of the LMST itself theoretically requires $O(n)$ messages, and an average of three messages per nodes. An example of initial WSN and resulting MST approximation topologies are respectively provided in Figure 2(a) and (b).

Figure 2 Tree approximation using a LMST: (a) initial topology and (b) resulting topology



(a) (b)

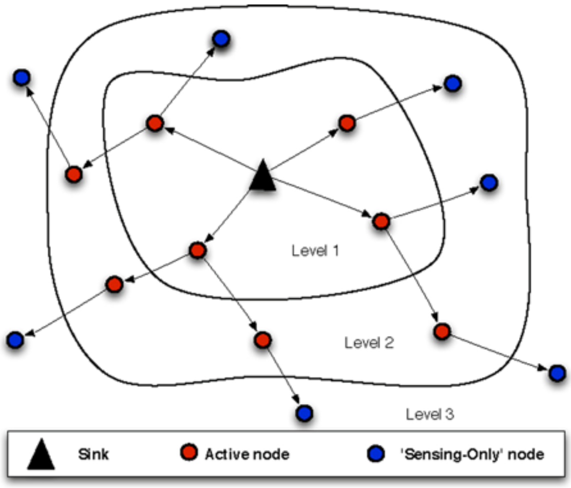
4.1.2 Determination of the Sensing-Only subset using a gradient construction

We also consider using a gradient construction (Khadar et al., 2009) to characterise our subset of *Sensing-Only* nodes, as it is one of the most lightweight and efficient localised solution found in the literature. The gradient construction allocates a rank and a father identification number to each node of the network. That rank represents the minimal distance to the sink in terms of number of hops, while the father is a direct neighbour that is closer to the sink.

The sink initiates the gradient construction by sending its rank (i.e., 0) to its direct neighbours. Upon message reception, if a node has not chosen a position in the gradient yet, it takes the received rank plus one. It also selects the source of the message as its father, and retransmits its newly chosen rank and father to its direct neighbours. Else, if a rank has already been selected but is strictly superior to the newly received one plus one, the latter is chosen as the new rank and the emitters

ID as the father. Finally, a gradient construction message is sent to direct neighbours using the newly chosen rank and ID. Thus, the gradient structure is initiated by the sink and then built recursively. By simply overhearing these construction messages, a father node can easily identify its sons, and take it into account for its activity decision. Yet, to compensate the instability of wireless communications, we consolidated this mechanism by sending an acknowledgement message after each father change. The gradient construction process is depicted in Figure 3 and Algorithm 3.

Figure 3 *Sensing-Only* subset using a gradient (see online version for colours)



Algorithm 3: Gradient construction forwarding process

begin
    rank = Ø;
    father = Ø;
    while *Reception of packet P* **do**
        if *P.rank + 1 < rank* **then**
            rank = P.rank + 1;
            father = P.ID;
            $send_{broadcast}(ID, rank)$;
        else
            Drop P;
        end
    end
end

Through this construction, a subset of *Sensing-Only* nodes can be characterised. Indeed, each node being the father of at least one of its direct neighbours is here considered as necessary to guarantee the global full connectivity of the network. Inversely, a node which is not the father of any of its direct neighbours is considered as not necessary to the connectivity, and can then switch in *Sensing-Only* mode.

Note that this solution keeps low overhead (theoretically $O(n)$ messages) and that the gradient construction can be later used for routing purposes. Indeed, at the routing layer, next-hop node is selected among neighbours with lower ranks.

4.2 *Activity scheduling facing the reality*

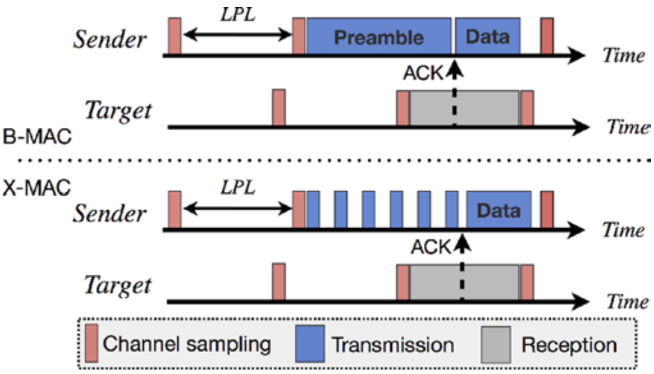
Several options have been proposed to give life to the concept of passivity of sensor nodes. Several contributions suggest to completely switch off nodes in this state (Gupta et al., 2006a; Gallais et al., 2008). Yet ideal in terms of energy preservation (the consumption of a node turned off being minimal), this method supposes scheduled or synchronised wake-up mechanisms at some point, so that *Passive* nodes are turned on again for the next decision round. Yet, such mechanisms engender high overhead and are hardly scalable (Sivrikaya and Yener, 2004).

Other contributions suggest to reduce the sensing frequency of *Passive* nodes (Choi et al., 2012). In such cases, their readings are sent up to the sink half as often as *Active* nodes. This solution reduces traffic load over the network, thus improving performances (e.g., delay, losses), but has only limited impact on energy consumption. Plus, it still requires *Passive* nodes to send data, while unnecessary to perform full coverage of the area of interest. In consequence, we propose in this section a novel approach for reducing *Passive* and *Sensing-Only* nodes energy consumption. This approach consists in adapting the MAC layer configuration depending on activity states.

In typical sensor nodes, the radio component is the main source of energy wastage (Anastasi et al., 2009). In order to reduce energy consumption, most WSNs MAC protocols thus spare their radio usage by alternating active and sleep periods of the radio. In this paper we focus on preamble sampling MAC protocols for their scalability and good performances, and also because synchronised protocol engender additional control traffic and are hardly scalable (Sivrikaya and Yener, 2004). In such protocols, this task is performed by sampling the channel for incoming messages at regular interval, and remaining asleep otherwise. The time interval between two consecutive channel samplings is called low-power-listening (LPL). When a node is willing to send a packet, a preamble must be transmitted beforehand. This preamble must be longer than the target node LPL, in order to ensure that the latter is awake at the moment of the transmission. These principles govern the general functions of the B-MAC protocol (Polastre et al., 2004). In X-MAC (Buettner et al., 2006), the preamble is split into multiple strobes containing information about the source node. Each of these strobes can be acknowledged, so as to reduce the effective preamble length. Preamble sampling MAC protocols represent the vast majority of MAC protocols actually deployed for WSNs (Cano et al., 2011). Figure 4 depicts the general principles of B-MAC and X-MAC.

The LPL value bears a strong influence on networks performances. Indeed, a low LPL allows each node to handle more traffic and reduces delays and losses. Yet, it also increases idle-listening, leading to increased energy consumption. On the contrary a longer LPL reduces energy consumption, at the cost of increased delays and loss-rate. Symmetrically, *Active* nodes are required to handle the networks load at best, while *Passive* and *Sensing-Only*, which do not take part in the routing process, can focus on energy efficiency. Thus a specific MAC configuration can be attributed to each node depending on its activity state and reflecting its very needs. *Active* nodes will favour low LPL values, while *Sensing-Only* and *Passive* nodes will be attributed configuration with longer LPL values.

Figure 4 B-MAC and X-MAC preamble sampling MAC protocols (see online version for colours)



This technique presents several advantages. First, it allows *Passive* and *Sensing-Only* nodes to save energy by affecting their main source of energy depletion, radio idle listening state. Also, it prevents these nodes from being disconnected from the whole network. Indeed these nodes are still reachable. *Active* nodes wishing to contact one of them simply have to extend the preamble length of their transmission. This way, no scheduled or synchronised wake-up mechanisms is required.

4.3 *Summary and discussion*

In this section, we first introduced an intermediate activity state called *Sensing-Only*, that concerns formerly *Active* nodes. The *Sensing-Only* subset is constituted of nodes that do not participate in the routing process and only transmit their own information up to the sink. Thus, these nodes can sleep for longer periods of time without undermining the network performance, all the more reducing the average energy consumption of the network. We also described two different techniques to identify this subset, one using an LMST and the other one relying on a gradient construction.

Then, we proposed a new approach to give life to the concept of passivity of sensor nodes. Given that the radio communication is responsible for most of the energy depletion in WSNs, we suggested that *Passive* and *Sensing-Only* nodes change their MAC configuration to a more energy efficient one. To do so, *Sensing-Only* and *Passive* nodes can increase their LPL length. This method allows *Sensing-Only* and *Passive* nodes to significantly reduce their energy consumption, without the need for scheduled or synchronised wake-up mechanisms. Indeed, nodes in these states are still reachable and can thus receive control messages. Special care is taken while assigning specific MAC configuration (i.e., LPL and preamble length) to each activity state set, as a pair of nodes with different MAC configurations may be unable to communicate with each other.

5 Simulation evaluation

The results presented in this section were obtained from simulations. Simulations allowed us to compare the performances of our propositions with several other mechanisms, extracted from recent literature. It also helped us to evaluate our mechanisms in conditions that could not be met otherwise (e.g., complete control of the radio propagation, ability to precisely monitor any event).

The 95% confidence interval is always provided, as proof of the reliability of our measurements. Only topologies initially connected were considered, thus preventing us from using too sparse topologies. The sink is never taken into account in the following evaluation, being in essence always fully active.

5.1 *Simulation setup*

Simulations were performed using the WSNet event-driven simulator (Fraboulet et al., 2007). This WSN simulator provides various MAC and radio propagation models that allowed us to intensively test our propositions under realistic assumptions while being able to have full control on the runs.

We assume up to 600 static sensor nodes to be deployed according to a Poisson point process of intensity $\lambda > 0$ over a 50×50 m square area, creating a connected network. However, we also made simulations over heterogenous topologies (i.e., with densities varying strongly over the network) with results of the same order.

All presented results are about topologies of *Active* nodes that cover as large an area as the whole set of nodes. For each parameter, 100 simulations were performed. A sensing area is modeled as a disk of radius fixed at 10 m, while the communication model follows a log-distance pathloss rule.

We selected area coverage as our applicative model. A node u evaluates its coverage by discretising its sensing area (using a 900 point regular grid) and is said to be covered as soon as every point can be sensed by at least one *Active* sensor. Note that points outside the target area should not be considered in order to limit border effects in our experimental results. This discretisation step was set in order to remain as close as possible from exact computation schemes, as well as light enough to be computed by constricted components such as sensor nodes.

Note that our results were obtained by simulating realistic conditions such as X-MAC (Buettner et al., 2006) layer and log-distance pathloss propagation for instance. Simulation parameters are exposed in Table 1.

5.2 *Evaluation of activity scheduling mechanisms*

Firstly, we evaluated activity scheduling schemes on which we rely, via a simulation campaign. To do so, we compared it with two existing contributions from the literature, Distributed Greedy Algorithm (DGA) (Gupta et al., 2006a) and a Voronoï-based scheme (Zhou et al., 2009) (see Section 2). The results of this comparative study are displayed in Figure 5.

Table 1 Simulation parameters

Simulation parameters	*Value*
Density	From 10 to 60
Considered area	50×50 m
Sensing radius	10 m
MAC layer model	X-MAC (Buettner et al., 2006)
Antenna model	Omnidirectional
Interferences	Orthogonal
Radio propagation	Log-distance pathloss

DGA works in a distributed fashion, and recursively constructs a covering and connected topology by adding *Active* nodes, all remaining nodes being set in *Passive* state. This approach constructs the final topology from the sink.

The Voronoï-based solution uses an approximation of the Voronoï diagram and a RNG, to adapt both sensing and communication range. Yet solving the area coverage problem from a different angle, this solution displays good performances among other area coverage contributions. Moreover, it works in a fully localised fashion, and requires only few control messages.

As shown in Figure 5(a), both Positive-Only and Positive-Retreat mechanisms perform better than the Distributed Greedy Algorithm (DGA). Moreover, while in DGA the size of the subset of *Active* nodes increases with network density, both PO and PR remain very stable. Finally, while DGA requires messages to be broadcasted to the whole network at each step, PO and PR are completely localised and only require one message per *Active* node in the resulting topology for PO and a maximum of two messages for each *Active* node in the resulting topology for PR.

Figure 5(b) shows the comparison between our solution and the Voronoï-based mechanism. While this solution tends to adapt sensing and communication of each node of the network, our propositions determine a subset of nodes to remain *Active*. Thus, with PO and PR, communication and sensing radii can either be null or maximal. The Voronoï-based solution outperforms PO on low-density topologies only. In all other cases, both PO and PR turn out to be more effective.

We also quantified the maximum overhead required by each solution, in term of control messages. The overhead induced by DGA is strongly related to the network density. Indeed, the complexity of DGA in term of control messages is as follows : $O(3 \times (log\ n \times d))$ with n the number of nodes in the network and d the network density (Gupta et al., 2006a). For its part, Voronoï induces exactly 2 control messages per node in the network. Indeed, 1 message is needed to ensure the network connectivity by using a relative neighbourhood graph (RNG, as introduced in Li et al. (2004)), and 1 message to ensure the area coverage through a Voronoï graph. On the other hand, PO and PR respectively induce 1 and 2 control messages at most per node, as demonstrated in Section 3. In our simulation conditions, PO induced at most 0.6 message per node in the network, and PR at most 0.8.

This comparative study underlines the performances of PO and PR. Both outperform major activity scheduling contributions, yet performing in a fully localised fashion with little communication overhead. Among existing activity scheduling literature, these mechanisms thus prove to be valuable candidates to rely on. However, the proportion of induced *Active* nodes is not the only essential parameter to evaluate the performances of activity scheduling solutions. Another important evaluation metric in WSN is the period during which no node fails from battery exhaustion. This period is referred to as network lifetime.

Selecting some nodes to enter *Passive* state can not, by itself, provide precise information on corresponding network lifetime. Indeed, *Active* nodes will not be concerned by the mechanism, and thus the first node failure is likely to occur after the same time interval. A straightforward idea to compensate this effect is to re-launch PO or PR at regular intervals. Each process is called *round*. Activity scheduling timeout window will then be pondered by the number of rounds a node participated in.

For the following simulations, 25 rounds were performed. As demonstrated in Figure 6 for PO and Figure 7 for PR, this mechanism allows to increase substantially the lifetime, except for particularly low-density networks. Indeed, each node participates only to a reduced proportion of rounds, increasing network lifetime accordingly. With PO, the most participative nodes will be *Active* in 18 of the 25 rounds with a 300 node initial topology, and 15 with a 450 node topology, corresponding to an increase of respectively 28% and 40% of network lifetime. With PR, we observe an increase of 40% and 66% of network lifetime respectively for 300 and 450 node initial topology. Note that the denser the initial topology, the lower the maximal number of participations, and then the longer the network lifetime.

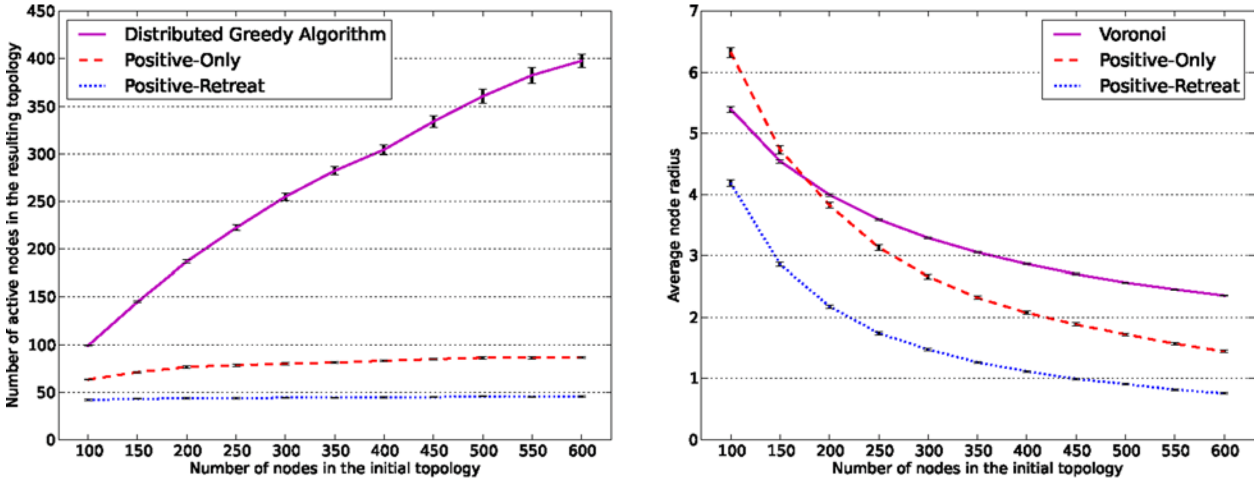
The results listed above show that both Positive-Only and Positive-Retreat require little knowledge and communication overhead and allow increased lifetime of sensor nodes in the network. These reasons led us to select both these mechanisms as the basis to the introduction of our new *Sensing-Only* state. We investigated the efficiency of two different schemes in order to identify the subset of nodes likely to enter *Sensing-Only* state.

5.3 Determination of a Sensing-Only subset of nodes

At first, we evaluated the performances of LMST mechanism introduced in Li et al. (2004) and described in Section 4.1.1. With this scheme, an approximation of the Minimum Spanning Tree is built. Each node of the resulting topology with a single outgoing edge is called a leaf, and is located at a dead-end of the routing tree. Thus, each leaf belongs to the subset of *Sensing-Only* nodes. Figure 8 displays the proportion of fully *Active* and *Sensing-Only* nodes observed while using both activity scheduling mechanism and the LMST construction. As depicted in Figure 8(a), approximatively a fifth of *Active* nodes enter *Sensing-Only* state while using PO. Similarly, while using PR and LMST (see Figure 8(b)), a third of the nodes composing the initial topology are set to *Sensing-Only* state.

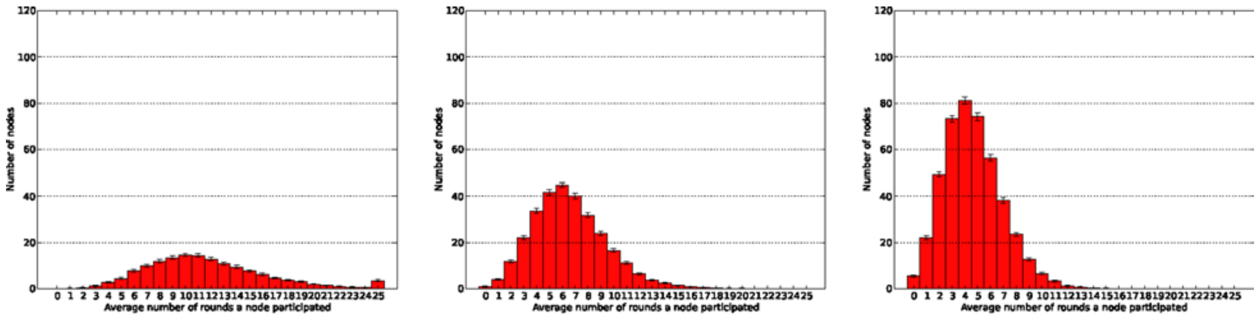
Similarly, we evaluated the performances of a gradient construction on the proportion of leaf nodes in the network. Figure 9 shows the proportions of fully *Active* and *Sensing-Only* nodes in the network, when using a gradient construction.

Figure 5 Comparative study of activity scheduling mechanisms: (a) comparison with DGA and (b) comparison with Voronoï-based solution (see online version for colours)



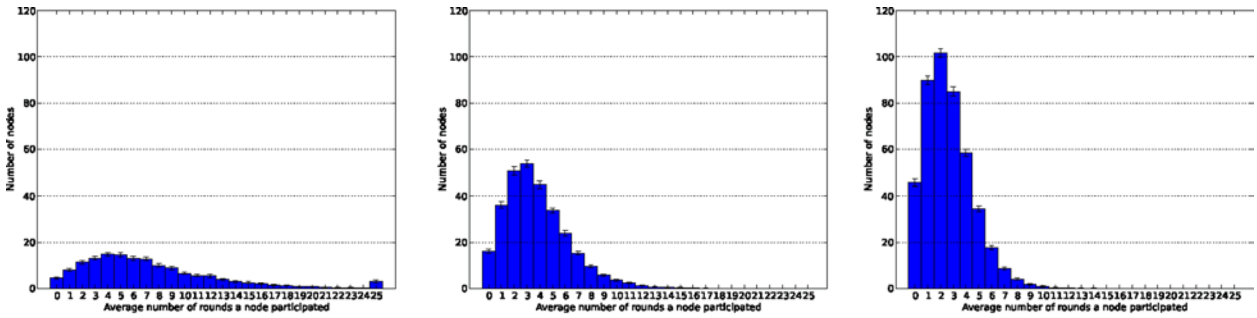
(a) (b)

Figure 6 Impact of regular computation of Positive-Only on activity periods: (a) 150 node topology; (b) 300 node topology and (c) 450 node topology (see online version for colours)



(a) (b) (c)

Figure 7 Impact of regular computation of Positive-Retreat on activity periods: (a) 150 node topology; (b) 300 node topology and (c) 450 node topology (see online version for colours)



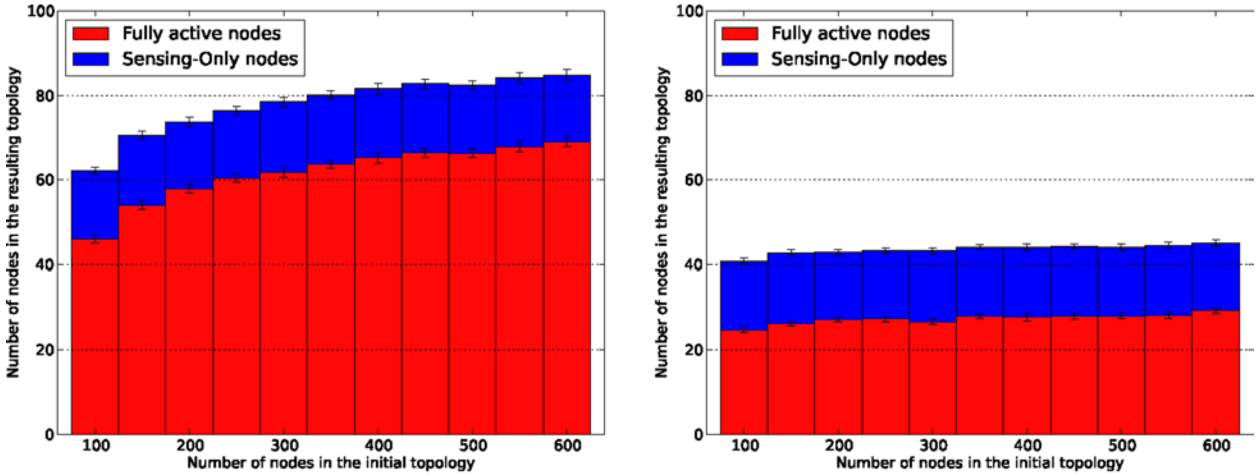
(a) (b) (c)

The results demonstrate that the gradient enables more than half the *Active* nodes of the network to be placed in *Sensing-Only* mode when coupled with PO (see Figure 9(a)) and more than a third when coupled with PR (see Figure 9(b)). Note that, in addition to the good performances obtained in this context, the gradient construction only requires few messages (i.e., an average of one message per *Active* node) and relies on very few information (e.g., no position information needed). This makes it particularly suitable for real WSN deployments.

5.4 Simulation conclusion and discussion

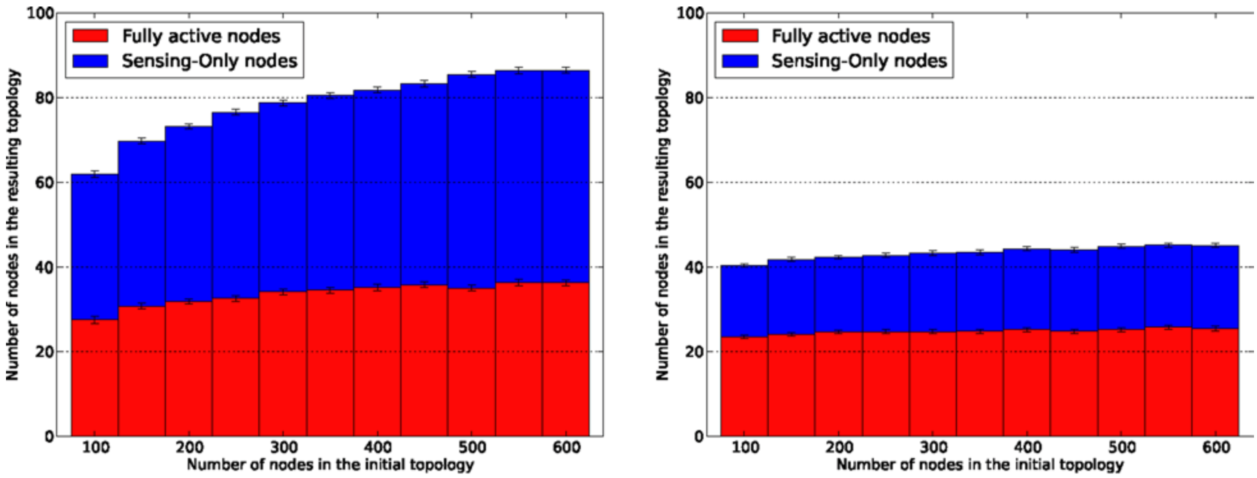
We led a simulation campaign with very realistic assumptions such as the use of the energy-efficient X-MAC protocol, log distance pathloss and orthogonal interferences. Our results confirm the important reductions of *Active* nodes obtained by both Positive-Only and Positive-Retreat mechanisms, allowing to outperform recent contributions in the field. These lightweight mechanisms rely on local information only and induce very little overhead, contrary to some

Figure 8 Determination of *Sensing-Only* set using a LMST: (a) Positive-Only mechanism and (b) Positive-Retreat mechanism (see online version for colours)



(a) (b)

Figure 9 Determination of *Sensing-Only* set using a Gradient construction: (a) with Positive-Only mechanism and (b) with Positive-Retreat mechanism (see online version for colours)



(a) (b)

other popular propositions from the literature. In addition, they allow an important network lifetime increase. The results listed above led us to select Positive-Only and Positive-Retreat as valuable candidates to base our further contributions on, and to thoroughly evaluate in realistic experimentations.

On top of those, the introduction of a *Sensing-Only* state allows as much as a half of the *Active* nodes to cut their radio off in reception, thus preventing overhearing and reducing energy depletion. Among all the mechanisms considered to identify a subset of *Sensing-Only* nodes, two were investigated in this paper, this choice being governed by their realism (e.g., only local information and few control messages required). The gradient structure, which only requires an average of one message per *Active* node and no prior neighbourhood knowledge, displays the best performances in simulations, and we decided to conduct a real large-scale experiment as detailed in the following section.

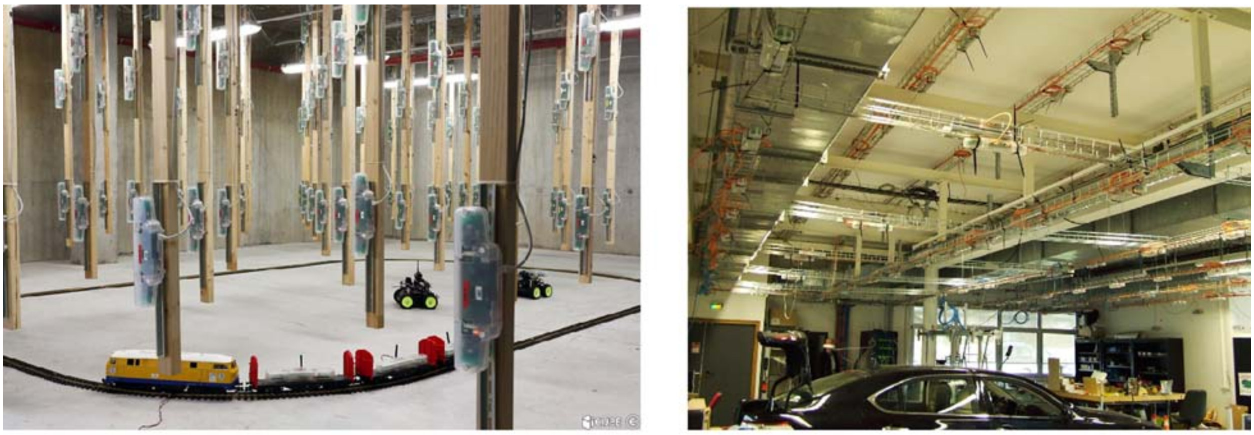
6 Experimental results

In addition to simulations, we performed a campaign of experiments in order to both evaluate the mechanisms we rely on and validate our contribution in real conditions. This campaign allowed us to apprehend their behaviour over large-scale testbeds, for long periods, and in real deployment conditions. Both simulations and experimentations are complementary, and together provide us a vast range of results, covering each aspect needed for ulterior deployment.

Several other experimental studies have been led recently to evaluate activity scheduling schemes (Yuan et al., 2011; Lambrou and Panayiotou, 2012). Yet, these campaigns were always performed at a limited scale only, without any strategy for identifying the subset of *Active* nodes (all of them being selected *a priori*).

In comparison, our analysis was performed on topologies consisting of up to 240 nodes, and the activity states of the

Figure 10 A view of two SensLAB platforms: (a) the Strasbourg grid platform and (b) the Grenoble heterogeneous platform (see online version for colours)



(a) (b)

nodes were determined at the beginning of our experiment by the considered activity scheduling mechanisms.

6.1 *Experimental setup*

This campaign was performed over the large-scale SensLAB open testbed (des Roziers et al., 2011). This testbed is composed of 1024 sensor nodes divided into four platforms, each consisting of 240 static nodes. We restricted our experiments to two of these platforms, one being homogeneous (a $10 \times 8 \times 3$ m 3D grid), and the other one heterogeneous (sensors being placed at random positions over a $16 \times 14 \times 3$ m area). Photos of each platform are provided in Figure 10. The homogeneous platform is located in Strasbourg, France. It is isolated from any radio disturbance other than the one induced by the testbed itself. The heterogeneous one is located in Grenoble, France. It is deployed within a robotics warehouse, whose daily activity induces additional disturbance thus making the radio environment even more realistic.

Sensor nodes are equipped with highly configurable Texas Instruments CC1101 omnidirectional radio interfaces[1] and a MSP430 microcontroller.[2] Both components are specifically designed for very low-power wireless applications such as the ones targeted by WSNs. We set the transmission power at -20 dBm to guaranty multiple communication hops and practicable density yet preserving connectivity of the initial topology. Each experiment was performed at least 20 times for each parameter. The following results are only based on topologies where the connectivity could be guaranteed. Thus, results from topologies with too low initial density are not provided.

The nodes composing the SensLAB platform are not equipped with localisation system. Exact or relative localisation mechanism not being the scope of this paper, we had to adapt the area coverage criterion to fit these constraints. To do so, in spite of considering area coverage as a criterion, we used the number of already identified neighbours. This criterion is set to 10, in order to fit with the densities observed while performing area coverage by simulation. Note that, this way, we consider the problem of density-control instead of area coverage. However, those two problems having a common goal (finding minimum subsets of nodes), both can be addressed in a similar way.

The gradient-based solution for *Sensing-Only* subset determination, having shown the best performances in simulation and proven to be very realistic several prior deployments (Ingelrest et al., 2010), was chosen for our real large-scale experimentation. The LMST-based solution will however be the subject of future experiments.

Experimental parameters are exposed in Table 2.

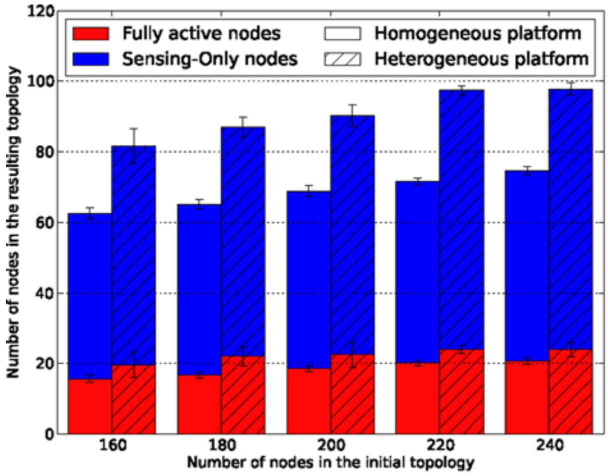
Table 2 Specifications of the SensLAB testbed.

Experimental parameters	*Value*
Deployed nodes	240 indoor static nodes
Homogeneous platform	$10 \times 8 \times 3$ m
(Strasbourg, France)	3D regular grid
Heterogeneous platform	Randomly deployed nodes
(Grenoble, France)	over a $16 \times 14 \times 3$ m area
MAC layer model	X-MAC (Buettner et al., 2006)
Hardware parameters	*Value*
Antenna model	Omnidirectional CC1101 interface
Frequency	868 MHz
Modulation	GFSK 76.8 kBaud
Emission power	-20 dBm
Battery capacity	880 mAh, 3.7 V
CC1101 radio	90 μs from IDLE to active
state switching time	240 μ s from SLEEP to active
MSP430 microcontroller	3.28 mA in active mode
consumption	2.72 mA in Low Power Mode

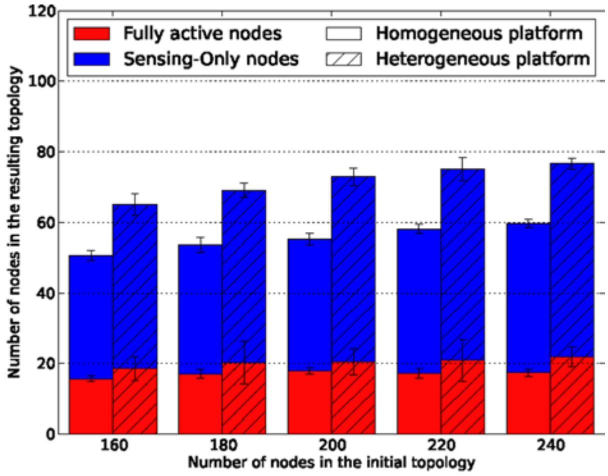
6.2 *Performances of activity scheduling and Sensing-Only characterisation mechanism*

In Figure 11, we studied the proportion of *Active* nodes in the resulting topology, after application of our protocols PO and PR. These results confirm the tendency observed by simulation. A large subset of nodes is set to *Passive* state in the activity scheduling phase, denoting the performances of these mechanisms.

Figure 11 Activity scheduling and *Sensing-Only* determination: (a) with Positive-Only and a gradient construction and (b) with Positive-Retreat and a gradient construction (see online version for colours)



(a)



(b)

Among the remaining sensor nodes, our gradient construction allows between two thirds and three quarts of *Active* nodes to enter *Sensing-Only* state. As expected, this depends on the activity scheduling mechanism we rely on and on the initial topology.

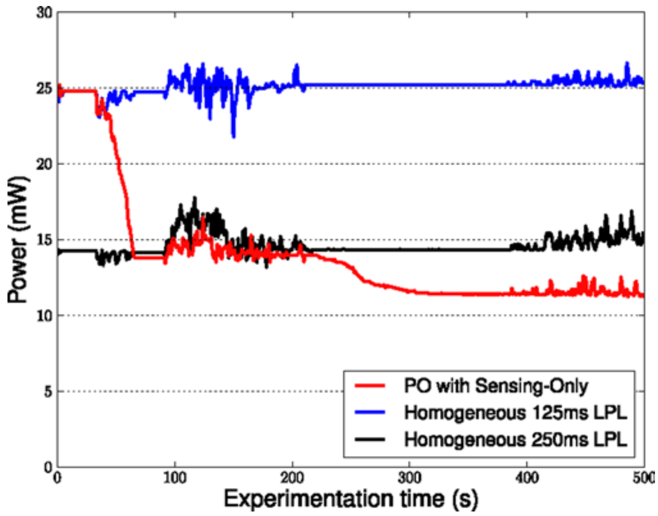
The results are of the same order in simulation and experimentation, albeit differences due to topologies and radio propagation conditions differences. Similar remarks stands for the differences observed between homogeneous and heterogeneous platforms. Indeed, the heterogeneous platform topology is much sparser, and more prone to radio disturbance than homogeneous one. We also observe, as in simulations, that the subset of selected fully active and *Sensing-Only* nodes, both with PO and PR, remain quite stable, only increasing by 20% when increasing by a third the topology density. Such results demonstrate the stability and good behaviour, as well as the validity of our simulation campaign.

6.3 Activity states going real

In order to give life to the concept of passivity of a sensor node, we also implemented our contribution detailed in Section 4.2. Considering that the radio is one of the main source of energy depletion, we can predict the potential energy gain induced by both activity scheduling schemes and the introduction of our *Sensing-Only* state while using our activity state translation based.

The average energy consumption of the network is displayed in Figure 12. In this case, the first $30s$ are dedicated to nodes initialisation (i.e., ensuring that all nodes booted correctly). The PO mechanism is performed until $90s$, each node deciding whether he remains *Active* or enter *Passive* mode. Then, the gradient construction starts at $100s$. The construction messages sent can be observed through the peaks during this period. Each node calculates the number of its sons $90s$ having selected its rank and father, in order to ensure that all sons have been registered. Finally, a time-driven data traffic is introduced at $400s$, initiated by each *Active* and *Sensing-Only* node.

Figure 12 Energy consumption of the network (see online version for colours)



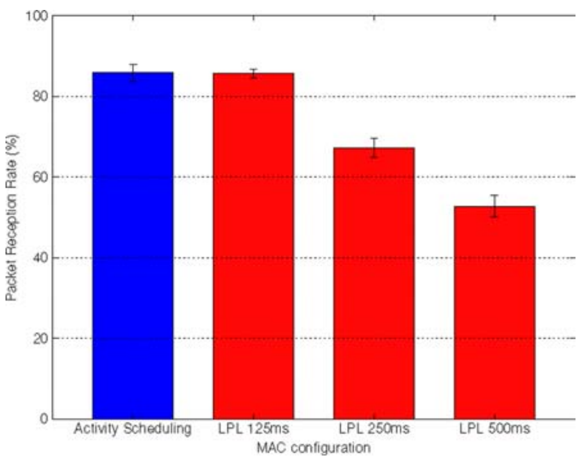
Our contribution changes the nodes MAC configuration on-the-fly upon each activity decision. Initially, all nodes start with a 125 ms LPL. This LPL is then doubled for *Sensing-Only* nodes and quadrupled for *Passive* nodes. We compared our contribution with networks where the MAC configuration remains homogeneous. We can observe that our contribution allows a reduction of energy consumption by up to 48% when compared to an homogeneous 125 ms LPL network, and by up to 15% when compared to an homogeneous 250 ms LPL network.

We also conducted evaluations of end-to-end packet reception rate (PRR) and end-to-end delay in order to ensure that our mechanisms did not undermine networks performances. As displayed in Figure 13, the end-to-end delay is not impacted by the MAC configuration changes performed by our contribution. Indeed, it remains identical either if the MAC adaptation mechanism is activated or not. This is due to the fact that only nodes with no forwarding role in the routing tree are impacted by MAC configuration changes. We can make the same statement for end-to-end delay based on the results provided in Table 3, where no significative impact can be observed. In this case, the delay increases exponentially due to channel occupation. When a node is willing to send a message, it first checks if the channel is occupied. If yes, it then has to put its message in queue and try to send it later, waiting for the channel to be free. The LPL reduction strongly impacts this phenomenon, as it both increases messages preambles (and thus channel occupation) and reduces the traffic a node can handle.

Table 3 End-to-end delay

Solution deployed	*End-to-end delay*
Positive-Only with gradient	351.2 ms (± 18.8)
Homogeneous LPL 125 ms	346.6 ms (± 17.3)
Homogeneous LPL 250 ms	4232.3 ms (± 1124.2)
Homogeneous LPL 500 ms	37118.5 ms (± 6500.3)

Figure 13 End-to-end packet reception rate (see online version for colours)



Our approach presents several advantages when compared with the related work in the field (c.f. Section 2.2). Indeed, while shutting down the nodes as suggested in Gupta et al. (2006a) and Gallais et al. (2008) may reduce their consumption to up to 2.4 mW (i.e., the energy consumed when all the components are idle, except one clock of the CPU to wake-up later), it requires a synchronised wake-up mechanism to ensure that all nodes will be *Active* for the next activity decision round. Yet, as stated in Sivrikaya and Yener (2004), such a mechanism is hardly scalable and implies the emission of several control messages per node, which increases the channel occupancy and may undermine the overall network performance.

Similarly, reducing the applicative traffic rate for *Passive* nodes as suggested in Choi et al. (2012) induces a greater energy consumption (i.e., -12% against -48% for our approach) and has limited impact on network performance (-10% in terms of delay against $+2\%$ for our scheme) when compared to our approach.

Finally, the inter-layer scheme presented in Yang and Heinzelman (2009) improves the overall network performance, but has no impact on energy consumption. This parameter being utterly important in WSNs, we believe that our approach is more suitable for such deployments.

6.4 Experiment conclusion and discussion

The results of this experimental campaign enlighten the good performances and realism of our proposition. Indeed, using the SensLAB testbed allowed us to investigate each aspect of our integration of a new *Sensing-Only* state within Positive-Only and Positive-Retreat protocols. Specifically, we investigated the proportion of nodes depending on their activity state. Activity scheduling mechanisms considered in this paper enable a large subset of nodes in the WSN to enter *Passive* state. Among the remaining *Active* sensors, the introduction of a *Sensing-Only* state, here evaluated in coordination with a gradient construction, allows up to three quarts of nodes to enter *Sensing-Only* state.

In addition, we performed an evaluation of our MAC configuration based translation for activity states. We demonstrated that our contributions enable substantial energy gains, by reducing by up to 48% the average energy consumption. In particular, the introduction of a *Sensing-Only* state for *Active* nodes counted for 20% of this energy gain. In addition, we showed that our contributions had no impact on network performances, by preserving both end-to-end PRR and delay. Then, through a comparison with several state-of-the-art activity states translation schemes, we demonstrated that our approach offers a better compromise between energy consumption, network performance and messages overhead.

Finally, Figure 14 shows an example of a resulting topology on the homogenous platform, using PO and PR in coordination with our Sensing-Only introduction via a gradient structure. It also shows how much energy savings our schemes provide as the obtained topology is much sparser than the original (i.e., physical) one. The difference, in term of proportion of fully active and Sensing-Only nodes, between PO and PR can also be observed.

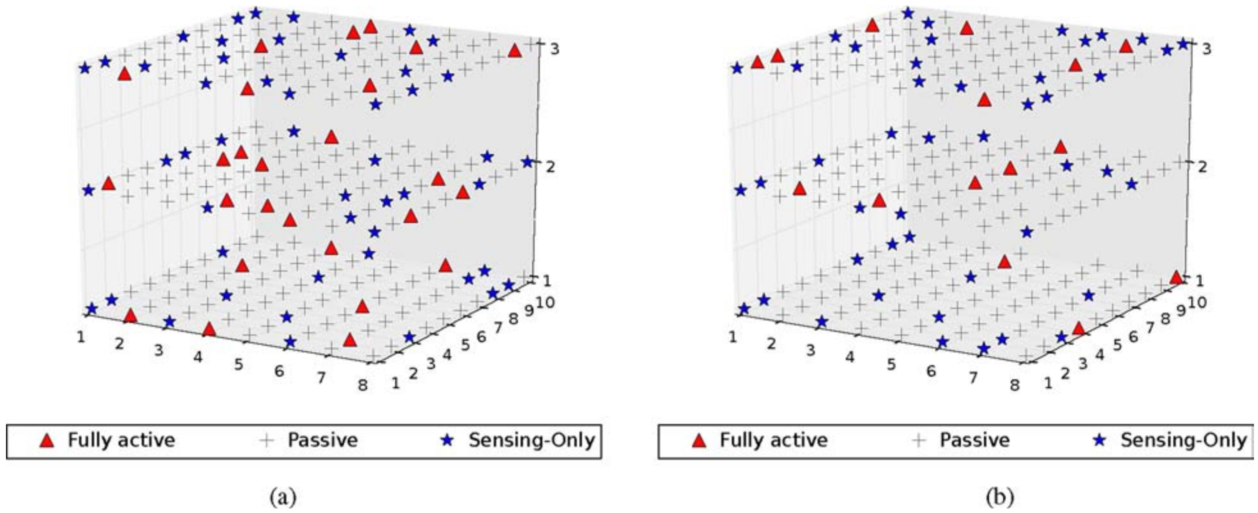
To the best of our knowledge, our campaign represents the first experimentation of activity scheduling mechanisms at large-scale. Indeed, recent studied led on this topics (Yuan et al., 2011; Lambrou and Panayiotou, 2012) were performed at limited scale only (46 and 14 nodes, respectively), with a fixed topology (all the *Active* nodes being selected *a priori*). The energy consumption and delays of these solutions also remained unevaluated. In comparison, our analysis was performed on topologies consisting of up to 240 nodes, and the activity states of the nodes were determined at the beginning of our experiment by the considered activity scheduling mechanisms. We also thoroughly evaluated the impact of our contributions on the energy consumption of the nodes and on the network performance (i.e., delays, loss-rate).

7 Conclusion and future works

7.1 Conclusion

In this paper, we extended two activity scheduling mechanisms (namely PO and PR), that both outperformed state-of-the-

Figure 14 Activity scheduling and *Sensing-Only* subsets on homogeneous testbed: (a) with positive-only and gradient mechanisms and (b) with positive-retreat and gradient mechanisms (see online version for colours)



art contributions (Gupta et al., 2006a; Zhou et al., 2009). Then, we introduced a new activity state, called *Sensing-Only*. This new sensor node state concerns formerly *Active* nodes, all the more reducing the size of this subset. We provided techniques to determine which nodes can be switched *Sensing-Only*, based on routing layer information. We showed that the introduction of our new *Sensing-Only* mechanism reduces by a third to a half the number of *Active* nodes in the network. We also proposed a realistic translation of activity states. Most prior activity scheduling studies suggested either to turn of *Passive* node until the next activity decision round (Gupta et al., 2006a; Gallais et al., 2008), which may require costly and hardly scalable time-synchronisation of sensor nodes (Sivrikaya and Yener, 2004), or to reduce their data transmission frequency (Choi et al., 2012), which have only little impact on energy consumption. Noting that the radio component is the main source of energy usage (Akyildiz et al., 2002), we proposed to adjoin to each activity state a specific configuration of the MAC layer. We established that our solutions allow to reduce nodes energy consumption by 48%, with no significative impact on network performances (i.e., loss-rate, delays).

We provided a complete evaluation, which underlined the realism and the performances of our propositions, both by simulation and over the open large-scale WSN testbed, SensLAB (des Roziers et al., 2011). Another contribution of this paper is to emphasise the difficulty to mind the gap between theoretical contributions and real communication stacks that are meant to be embedded in the sensor devices. even when facing real-life conditions (i.e., realistic MAC layer, real radio environment, several deployment topologies).

7.2 Future works

In close future, we intend to investigate other methods to characterise this *Sensing-Only* subset of nodes. Specifically, we are focusing on local constructions of a MLST. The MLST local construction being a NP-complete problem (Galbiati et al., 1994), similarly to connected area coverage problem, we are providing solutions that approximate this tree in a localised manner.

Wireless sensor networks often being deployed on remote or hardly accessible environments, both lifetime and auto-configuration of the network should be considered. Although the former has been addressed in the present paper, the latter remains an open subject. For instance, the network could adapt itself to the topology and adapt its coverage criterion (e.g., multiple coverage, where at least k sensor nodes monitor each point of a certain area) to compensate loss rate, failures, nodes mobility or imprecisions in the network. Such criterion could also be made heterogeneous at each node and adapted to some key characteristics (e.g., local density, average RSSI obtained).

Acknowledgements

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