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RESEARCH ARTICLE

Heterogeneous MAC duty-cycling for energy-efficient Internet of Things deployments

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Abstract The Internet of Things (IoT) paradigm aims at connecting any object to the Internet (i.e. to the IP world). Due to the physical constraints (limited energy capacities) and deployment conditions (numerous autonomous devices scattered into an area) of such *Things*, power management and scalability are key issues in IoT deployments. While the problematics of the IP addressing have been successfully transposed to IoT networks, the dedicated IEEE 802.15.4 Medium Access Control standard lacks of scalability, provides insufficient energy-efficiency and thus fails to fulfill their needs. In this paper, we consider alternative MAC protocols, compatible with IoT specificities. These protocols realize energy gains by asynchronously alternating active and passive periods at the radio scale, thus allowing both energy-efficiency and scalability. For the time being, most real IoT deployments implement static and homogeneous duty-cycling (i.e. invariant and identical for each node in the network). Although preventing any node isolation, such method fails to address the dynamics of the network efficiently. We propose a strategy to enable heterogeneous MAC duty-cycle configurations among nodes in the network. We aim at granting each node a specific sleep-depth, according to criteria specific to the deployment (e.g. applicative criteria, location in the routing structure). To implement this idea, the nodes are divided into disjoint subsets, each of them standing for a given duty-cycle configuration and leading to a network performance managed at its best (e.g. energy consumption, loss-rate, delays). We detail to what extent our approach preserves network connectivity with coherent heterogeneous duty-cycling, thus reaching a compromise between energy consumption and reactivity. The presented experimental campaign was led over the IoT SensLAB testbed. It demonstrates that our solutions provide up to 61% energy saving, preserve the loss-rate below 10% and guarantee the connectivity of the network. They thus offer a better compromise between energy-efficiency and network performances than any homogeneous MAC configuration.

Keywords Internet of Things, medium access control, low-power-listening, auto-adaptation

1 Introduction

The reduction in terms of size, weight, energy consumption, and cost of the radio enabled a new era of ubiquity, where a wide range of actuators and sensors can be connected altogether. In reaction, the last decade saw the emergence of a new paradigm called Internet of Things (IoT), where such smart objects cooperate to form a network. These *things*, ranging from everyday life objects [7] (e.g. water flow meters, motion sensors, power regulators) to entities dedicated to a specific deployment [16,10] (e.g. cardiometer for patient monitoring), interact with and provide information about their environment [3] through a specific entity (sink) connected to the Internet. Due to their physical constraints (battery powered or limited energy-harvesting systems), such smart objects cannot work continuously, without undermining their lifetime.

As the radio component is the main source of energy

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wastage in IoT, a common approach to deal with this problematic is to alternate active and passive periods of the radio [2]. This phase is managed by the Medium Access Control (MAC) layer. Yet, the dedicated standard for the MAC layer, IEEE 802.15.4 [8], fails to address the specific needs of IoT networks (energy preservation, scalability, low computation).

In consequence, we here focus on preamble-sampling protocols [4], for they require no prior knowledge nor negotiation (and are thus scalable). In such protocols, each node cyclicly wakes its radio up to sample the channel for incoming messages. This process is referred to as Low-Power-Listening or LPL. At the same time, each node willing to send information will have to emit a preamble beforehand, to ensure that the destination node will be awake. However, when sharing different sampling period and preamble length, two nodes may be unable to communicate with each other [13]. Indeed, a node with a preamble shorter than the sampling period of its destination may send its preamble solely during a sleeping period of the target, leading to a loss of the data packet.

To avoid this problem, the LPL configuration (sampling period and preamble length) is considered homogeneous (i.e. static and identical for each node) in most existing solutions, thus preventing any compromise between energy efficiency and reactivity. Substantial energy gains should be performed by providing to each node a specific configuration corresponding to its role in the network (e.g. location in the routing structure, applicative criteria). Still, the partitioning of the network must be avoided.

In this paper, we present a novel strategy, where different LPL configurations cohabit in a single network of *Things*. By using only local information (i.e. 1-hop neighborhood), each node selects a specific sleep-depth, according to criteria specific to the deployment (e.g. applicative criteria, location in the routing structure). Consequently, the nodes self-organize into disjoint subsets. Then, each node tunes its LPL configuration corresponding to its chosen subset. This step is performed so that the data of any node can cross adjoining subsets and eventually reach the sink. Such method therefore allows nodes with different configurations to coexist in the same IoT network, without endangering its connectivity.

The mechanisms proposed in this paper were developed and evaluated both by simulation and over the IoT testbed SensLAB [18], part of the Future Internet of Things (FIT) project[1]. In this paper, we focus on experimental results. We monitor the energy consumption, loss-rate and end-to-end delay of both homogeneous solutions and our propositions. We observe a diminution of up to 61% of the energy consumption as well as a loss-rate inferior to 10%, with no connectivity loss in the networks. Through a comparative study, we also demonstrate that both our contributions offer a better compromise between energy-efficiency and network performances than any homogeneous MAC configuration.

The remainder of this article is organized as follows. Section 2 lays the foundations of the problem we intend to address. We review some of the most pertinent related works in Section 3. In Section 4, we detail our contribution to perform smart heterogeneous configuration of the IoT network. In Section 5, we present a performance evaluation of these protocols, led on two testbeds of the IoT platform SensLAB, and provide some concluding remarks and future investigations in Section 6.

2 Problem statement

In typical IoT networks, radio communication stands for the main source of energy wastage [1]. In order to reduce their energy consumption, some or all of the nodes composing the network periodically alternate active and passive periods of the radio. This step, called duty-cycling, is managed by the Medium Access Control layer so that each node cyclicly wakes up its radio to check for incoming packets.

2.1 The IEEE 802.15.4 standard

The dedicated standard, IEEE 802.15.4 [8], proposes two communication modes, contention-based and synchronized. In the contention-based mode, all nodes keep their radio on and sample the channel continuously. To transmit a packet, a node ensures that the channel is clear by using the CSMA/CA mechanism.

In the synchronized mode, the nodes are divided into Full Function Devices (FFD) and Reduced Function Devices (RFD). RFDs are associated to a FFD in their neighborhood, forming a cluster for each FFD. All RFDs associated to a single FFD alternate active and passive periods of the radio at the same rhythm. The active period is then divided into slots dedicated to the communication between a single RFD and its FFD. FFDs are also synchronized with each other and communicate during the passive period of RFDs, in order to transmit information in a multi-hop fashion. An instance of an IEEE 802.15.4 network in synchronized mode is depicted in Fig. 1.

On one hand, the contention-based mode does not provide any energy saving, and is thus too energy-hungry for typical IoT deployments. On the other hand, the synchronized mode relies on time-synchronization [20] in the network and requires a complex FFD node selection mechanism to be developed. This mode is thus complex and hardly scalable.

[1] http://fit-equipex.fr/

In consequence, the IEEE 802.15.4 standard does not fulfill the requirements of typical IoT networks.

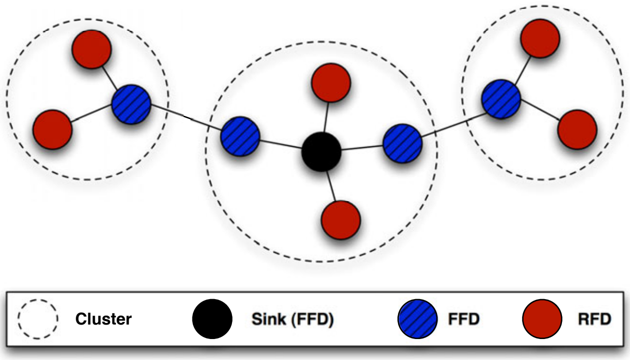


Fig. 1 An IEEE 802.15.4 network in synchronized mode

2.2 Preamble-sampling MAC protocols

In consequence, many IoT networks rely on preamble-sampling MAC protocols [4], where the nodes control their energy consumption by alternating active and passive periods of the radio. These protocols asynchronously sample the radio channel for incoming messages. The interval between two samples is called Low-Power Listening (LPL). When a node wants to send a packet, it has to send a preamble beforehand, in order to ensure that its destination is ready to receive. These principles govern the general functions of the B-MAC protocol [17]. X-MAC [15] improved this mechanism by splitting the preamble into multiple strobes that can be independently acknowledged. The general principles of B-MAC and X-MAC are depicted in Fig. 2.

Prior studies [14] demonstrated that the MAC parameters (preamble length and sampling period) have a strong influence on the network performances (e.g. energy consumption, loss-rate, delay). Indeed, when configured with a short sampling period, a node will have to wake up its radio more often, and thus consume more energy. However, it will also be able to manage more traffic load. Conversely,

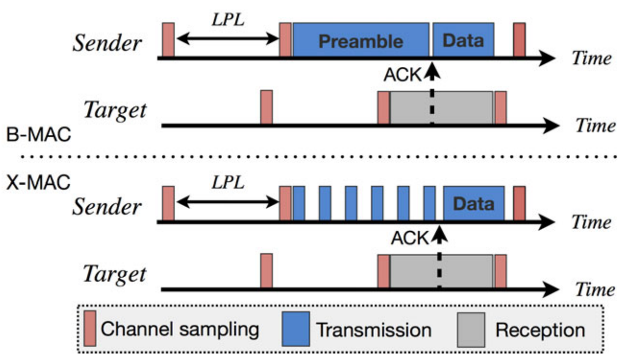


Fig. 2 B-MAC and X-MAC preamble-sampling MAC protocols

with a longer preamble length and a corresponding sampling period, a node will save more energy, but will not be able to deal with as much traffic [13].

2.3 Introducing heterogeneity in the network

In existing solutions, the LPL configuration is affected once and for all, homogeneously to each sensor node. Although preventing any node isolation (any preamble length is greater than any sampling period in the network), this situation is far from ideal, since the traffic load may vary greatly from one node to another [14]. Indeed, some nodes may have to relay more information from their neighbors than others, depending on the deployment conditions (e.g. data traffic model, routing protocol) and the occurring events on the monitored area.

While several contributions tackle this issue at the applicative layer [19,21] (i.e. activity scheduling), very few address it at the MAC layer. In order to fit with deployment conditions, a heterogeneous MAC configuration would be much appreciated. Indeed, the radio interface management is mainly responsible for the sensor nodes energy depletion [1]. Thus, network lifetime would greatly benefit from heterogeneous MAC configurations among the nodes.

The coexistence of several LPL, however, raises new problems. Any modification of the MAC configuration may lead to losses of connectivity (resulting to nodes isolation of the network) and a reduction of network performances (e.g. loss-rate, delays). Thus, this parameter must be specifically taken into consideration in the design of MAC adaptation algorithms.

3 Related work

Several former studies have proposed solutions for power management in IoT networks by introducing heterogeneity in MAC parameters. Here are some particularly interesting works in this field. Each solution aims at finding the best compromise between energy-efficiency and network performances (e.g. losses, delays).

A framework for runtime adaptation of MAC parameters is investigated in [24], using a collection of layer-dependent and independent metrics. This contribution demonstrates that MAC parameters adaptation is both realistic and advantageous for IoT networks. Yet, on the contrary to our approach, a dissemination of all MAC parameters throughout the network is required hereafter. This dissemination relies on a flooding algorithm that requires full node synchronization in the network to operate. Moreover, MAC parameters appear to be identical for all nodes since network connectivity under LPL auto-adaptation remains unaddressed.

Kansal et al. [11] present a duty-cycling approach based on the learning of field condition for solar-powered sensor nodes. Their algorithm tries to predict energy model (energy consumed and gained) using environmental information, and via extrapolation by discretizing the deployment time into small periods. Then, each node determines its optimal node duty-cycle according to this information. No MAC layer duty-cycling is, however, considered. They deployed this approach for experimentation, over their own Heliomote platform, and display promising results. Yet, this solution requires prior energy-consumption model, and a preliminary learning phase before full stabilization. It induces a lack of reactivity, as an abrupt change in the energy consumption model may endanger the good behavior of the deployment. It also concerns nodes with energy-harvesting capacities only (e.g. solar panel).

In [14], a study of the impact of LPL values of the B-MAC [17] and X-MAC [15] protocols on energy consumption, end-to-end delay and loss-rate is provided, with the goal of reaching a dynamic auto-configuration of MAC parameters over the network. All nodes composing the network start with a long duty-cycle, referred to as $T_{\max}$. When a message is transmitted toward the sink, an Energy Efficient (EE) path is activated, corresponding to the path followed by the message. Each node being part of this EE path then shortens its duty-cycle to a value called $T_{\min}$. Then, after a certain timeout, all nodes of the EE path return to their normal state, with $T_{\max}$ duty-cycle. This method displays promising results in case of traffic burst (i.e. several packets emitted by a single node for a short period). Yet this approach only allows two LPL configurations, and requires prior negotiation between nodes.

In [23], interesting algorithms for dynamic heterogeneous radio duty-cycling in energy harvesting networks are provided. While the first mechanism considers residual energy (i.e. remaining energy in the battery), the second one also takes in consideration prospective increase of energy (i.e. expected energy gain from harvesting). Depending on these parameters, a duty-cycle configuration is then calculated and assigned to each node of the network. However, this contribution only takes energy criterion into account, and may worsen networks performances. Finally, it does not consider necessary communication adjustments in case of upstream traffic. Thus, it may endanger network connectivity.

4 Proposed solution

In a nutshell, we aim at dividing the set of nodes into disjointed subsets. To do so, each node must identify the subset it will belong to, according to a criterion dependent of the deployment requirements. Afterward, to each subset is affected a specific LPL configuration. Among all eligible criteria for the profiling step, two appeared particularly suited:

- **ROUTING ROLE.** The routing layer is in charge of handling data traffic to the sink. In some traffic models (e.g. time-driven), the data traffic crossing a node is directly linked to the number of upper nodes in the routing tree (i.e. farther to the sink). This criterion allows for each node to perform an estimation of intended traffic load. The greater the number of upper nodes in the routing structure, the greater the potential data to forward, thus the shorter the duty-cycle.
- **SLEEP DEPTH.** Depending of the deployment requirements, applicative criteria can also be considered. Precisely, these criteria are used to divide the nodes into different sleep depths, represented as disjointed virtual layers. Among all possible criteria, the radio density (i.e. the number of nodes within communication range) appears particularly interesting, because of its genericity. Each node estimates the number of its neighbors, that may occupy the radio channel. The lower the density, the higher the probability of having to forward data, thus the shorter the duty-cycle.

4.1 Routing role

Most routing protocols for IoT networks consist in a Destination Oriented Directed Acyclic Graph (DODAG), centered at the sink (e.g. [12,9]). The IETF standard RPL [22] belongs to this category and relies on two gradient structures to decide the routes to the sink in the network. These approaches have many advantages, such as a distributed construction and low overhead. They can also be adapted to deduce an estimation of the expected traffic for each node.

In a DODAG, the next hop of a node toward the sink is called *father*, and a node having for father the node N is said to be the *son of N*. Any node having no son is referred to as a *leaf*. To obtain an estimation of the expected traffic, each leaf must send a message up to the sink, containing the number of its sons (thus initially 0). Each forwarding node will then maintain a value corresponding to the number of nodes above in the DODAG construction (i.e. its sons, the sons of its sons, etc.), and forward this value to their father in the DODAG. This way, through cooperation between routing and MAC layers, any node is able to know how many nodes it will have to forward information from. This traffic estimation process is detailed in Fig. 3, and pseudo-code is provided in Algorithm 1.

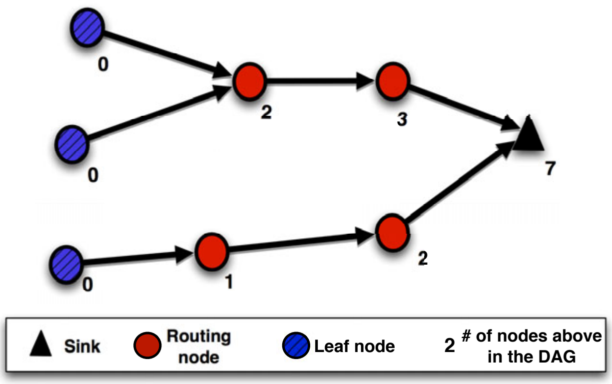


Fig. 3 Traffic estimation in a DODAG topology

Algorithm 1: Routing role algorithm

```
begin
    nbSons = Number of sons in the routing structure;
    nbUpper = ø; //Nodes above in the DODAG
    nbDone = ø;
    if nbSons == 0 then
        send_FatherID(ID, nbUpper);
    end
    while Reception of packet P do
        nbUpper += P.nbSons;
        nbDone += 1;
        if nbDone == nbSons then
            send_FatherID(ID, nbUpper);
        end
    end
end
```

This information can then be exploited to deduce a LPL configuration accordingly. Each node starts with the shortest LPL length, in order to be able to handle as much traffic as possible during the traffic estimation phase (i.e. when it is yet unsure of the number of nodes above him in the DODAG). Then, when a node receives the information from all its sons, it can select a configuration accordingly. The more nodes above in the DODAG topology it will have, the shorter its LPL value. This way, each node selects a configuration that fits its needs (i.e. handling incoming traffic and save as much energy as possible).

4.2 Sleep depth

We also designed an algorithm to separate the nodes into different sleep depths, represented as virtual layers. A threshold D_{max}, either provided by the user as a parameter of the targeted deployment or deduced from the deployment requirements, allows each node to estimate its potential sleep depth.

Let us consider for instance the radio density as the selected criterion, for it requires no deployment specific nor inter-layers knowledge. Each node determines which layer it belongs to after a random delay. During this period, it will process messages from its neighbors, indicating which layer they belong to. Thus, each node maintains a list of its neighbors and their respective layers. Upon timeout expiration, the deciding node considers its layer as the highest one for which the number of its neighbors belonging to it is below D_{max}, or the layer 0 if no neighbors have already signaled themselves. It then transmits a message to inform its neighborhood of its decision.

Pseudo-code describing the functioning of the sleep-depth based mechanism is provided in Algorithm 2.

Algorithm 2: Sleep-depth algorithm

```
begin
    layer= ø;
    neighbors=[];
    wait(RANDOM_TIMEOUT);
    i=0;
    while neighbors[i] > D_max do
        i+=1;
    end
    layer=i;
    send_broadcast(ID, layer);
end
```

Each node starts with the shortest LPL value, and select a new one when being affected to a specific layer. The newly chosen LPL value will depend on the layer the node belongs to. Nodes belonging to the first layer do not change their configuration. Otherwise, the LPL value is doubled for each layer below the selected one.

The lowest layer, which will have the shortest duty-cycle (and thus be able to handle more traffic) will be dedicated to the routing backbone. Each node belonging to upper layers will transmit its data to one of its neighbor of the lowest layer, that will forward it up to the sink.

5 Experimental evaluation

In this section, we present the performances of the mechanisms detailed below. All the provided results were obtained via experimentation carried out over the Strasbourg platform of the SensLAB testbed [18], part of the Future Internet of Things (FIT) project. This platform is a 10 m × 8 m × 3 m 3D grid composed of 240 indoor nodes. We implemented our contribution using the Contiki operating system [5], in conjunction to the preamble-sampling protocol X-MAC [15]. The profiling step of our contributions selects a LPL ranging from 125 ms to 500 ms. Experimental parameters are exposed in Table 1.

Table 1 Specifications of the SensLAB testbed

Experimental parameters	Value
Deployed nodes	240 indoor static nodes
Experimental testbed	10 m × 8 m × 3 m 3D regular grid
MAC layer model	X-MAC [15]
Hardware parameters	**Value**
Microprocessor	Texas Instruments MSP430
Antenna model	Omnidirectional CC1101 interface
Frequency	868 MHz
Modulation	GFSK 76.8 kBaud
Emission power	−20 dBm
Battery capacity	880 mAh, 3.7 V

Energy efficiency being the most important criterion in IoT deployments and the main subject of this paper, we started our investigations with this point. We used Contiki's Energest module [6] to quantify the amount of energy consumed each second by each node. This module provides every second estimates of the total amount of energy consumed by a node during one second, according to the consumption model of our sensor nodes components. Figure 4 depicts the energy consumption of our IoT network, free from traffic, with different LPL values. This LPL is initialized at 125 ms, and is doubled every 100s. Consumption of automation and sensor components varying greatly from one to another, we did not take it into consideration in this study. We can observe that the microprocessor is responsible for less than 5 mW of the average nodes energy wastage, while the radio component represent between 5 mW and 20 mW. We can also observe, that the LPL duration strongly impacts radio consumption. Indeed, changing the LPL from 125 ms to 250 ms reduces by 40% the energy consumed, and by 65% when changing from 125ms to 500 ms. Thus, allowing heterogeneous LPL configurations over the network makes sense, since it is of prime importance to control this source of energy wastage.

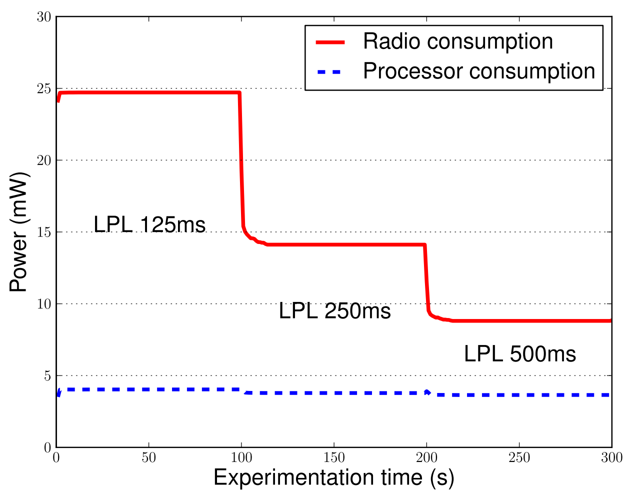


Fig. 4 Energy consumption versus LPL value

Figures 5 and 6 respectively depict the total energy consumption of our sleep depth-based and routing information-based solutions for MAC duty-cycle adaptation in the network. The first period, before the first vertical line (respectively 0 ms–334 ms and 0 ms–294 ms), corresponds to the initialization of both the routing structure and our mechanisms. The off-peak observed around 100 s is due to the transition step, between the routing structure construction and the profiling stage. Afterward, each node has received a specific configuration, and the network is stabilized. In between the two vertical lines (respectively 334 ms–493 ms and 294 ms–486 ms), the network is traffic-free. In this particular case, the regular sampling of the radio channel (i.e. the LPL) is responsible for most of the nodes energy consumption. Since the MAC configuration of each node depends on its mode and the proportion of nodes in each

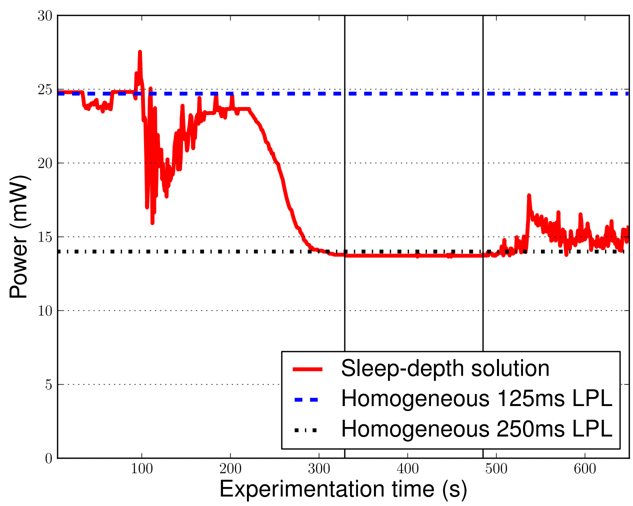


Fig. 5 Energy consumption with our sleep-depth solution

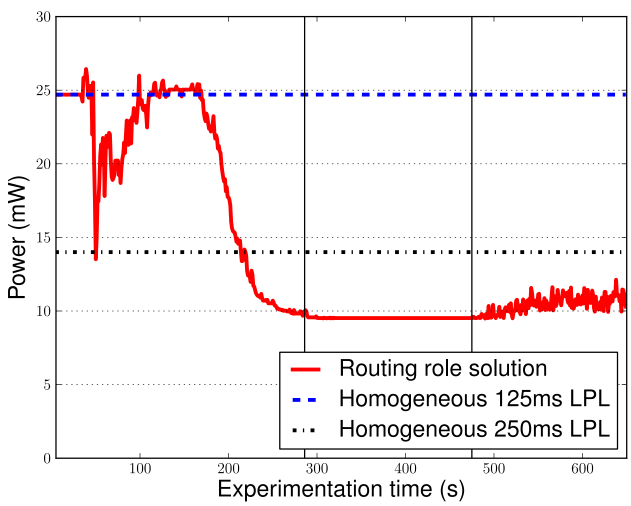


Fig. 6 Energy consumption with our routing role-based solution

mode depends on the considered scheme (i.e. sleep-depth solution or routing role-based solution), the average energy consumption with no traffic is different depending on the considered scheme. After the second line, a homogeneous traffic is introduced. As we can observe, our mechanisms respectively reduce by 44% and 61% the average energy consumption of the nodes, in comparison with a homogeneous LPL configuration of 125 ms. Even though the sleep depth-based and routing information-based solutions could used in combination, we here provide results of these mechanisms separately in order to precisely measure their impact.

In Fig. 7, we evaluated one of the main parameters for network communication performance evaluation: end-to-end loss-rate. To do so, we implemented a data traffic model, where each node sends its data up to the sink every minute, ten times. We evaluated our contributions, in addition to networks with homogeneous radio duty-cycles. With respective loss-rates of 7.25% and 9.31%, our solutions offer a compromise between homogeneous duty-cycles of 125 ms and 250 ms. Note that our solutions never lead to node disconnections.

Finally, Table 2 details the impact of our contributions on end-to-end delays. As for loss-rate, both our routing information-based and our sleep depth-based solutions outperform homogeneous networks configured with a LPL value of 250 ms (respectively by 88% and 74%). The delay increases exponentially as the LPL decreases, 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.

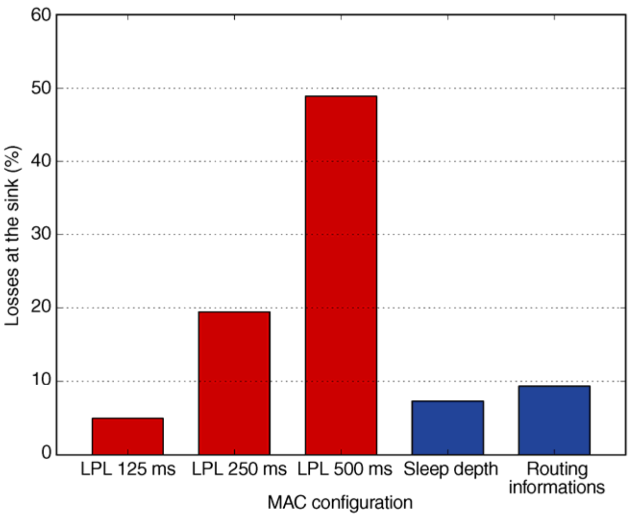


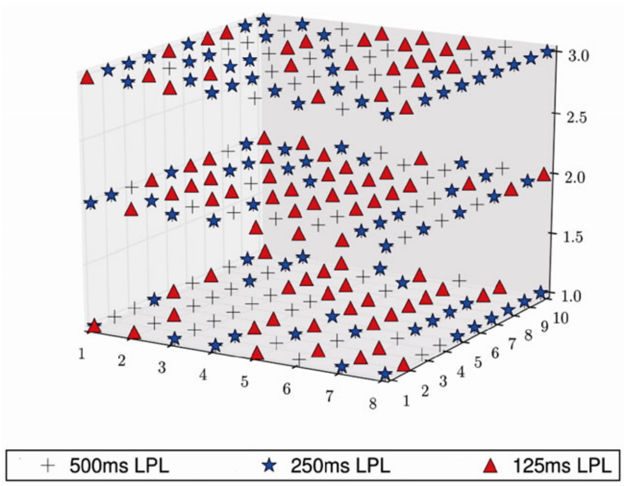
Fig. 7 Applicative loss-rate

Table 2 End-to-end delay

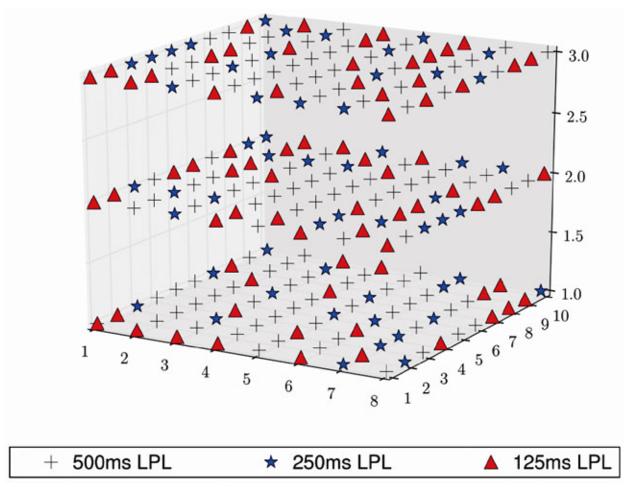
Solution deployed	End-to-end delay
Routing information	1748.6 ms (±133.5)
Sleep depth	3727.1 ms (±270.8)
Homogeneous LPL 125 ms	1234.6 ms (±142.4)
Homogeneous LPL 250 ms	10 243.6 ms (±692.1)
Homogeneous LPL 500 ms	60 869.1 ms (±4750.1)

Figure 8 provides example distributions of LPL assignment with our solutions.

The results exposed below demonstrate that a homogeneous MAC duty-cycle configuration with a LPL of 125 ms provides a very low loss-rate (4.9%) and delay (1234 ms), at the price of an increased energy consumption (24.6 mW). Similarly, a LPL value of 500 ms leads to a low energy consumption (8.6 mW), at the price of a higher loss-rate (48.9%) and delay (60 869 ms). A LPL value of 250 ms offers a compromise between those two, with an energy



(a) Sleep-depth solution



(b) Routing role-based solution

Fig. 8 Example distributions of LPL assignment with our solutions consumption of 14.7 mW, a loss-rate of 19.4% and a delay of 10 243ms. Our contributions always outperform this last solution, both in terms of energy consumption, loss-rate and delays. Thus, they offer a better compromise between energy-efficiency and loss-rate than with any homogeneous configuration.

6 Conclusions and future work

In this paper, we presented two distinct solutions for heterogeneous MAC duty-cycling in Internet of Things networks. The first mechanism makes MAC and routing layers cooperate, so that each node is able to know the number of nodes above in the routing tree (i.e. farther to the sink). This value is then used to divide the nodes into disjoint subsets, each being attributed a MAC duty-cycle configuration. Another mechanism was proposed, that relies on applicative criteria to separate the nodes into different sleep-depth, represented as disjoint virtual layers (each having a specific LPL configuration). Both mechanisms require no prior knowledge and induce at most one control message per node in the network.

We also led a thorough experimental campaign over the SensLAB testbed, part of the Future Internet of Things project. The evaluation of our contributions displays a reduction by 61% of the overall energy consumption. This saving comes along with a division by 2 of the loss-rate and by 3 of the delay, compared to homogeneous solution with a LPL of 250 ms. Thus, our contributions provide a better compromise between energy-efficiency and networking performances than any homogeneous LPL configuration.

In close future, we plan to extend the evaluation of our contributions by considering different scenarios and parameters. We also intend to perform a more detailed analysis by adding results on the throughput and energy-consumption repartition. IoT networks being prone to failure and often partly constituted of mobile devices, auto-adaptation and reactivity are also an important parameter to be taken into consideration. We thus aim at extending our contributions, in order to provide mechanisms to compensate network dynamics. This step could be performed by dynamically adapting decision criteria, depending on networks characteristics. Several network metrics (e.g. traffic, RSSI, PRR) could be passively monitored, triggering duty-cycle changes when exceeding a certain threshold. For instance, the LPL could be temporarily adapted, to handle traffic changes. We also intend to adapt our contributions to fit with synchronized MAC protocols, by adapting timeslots attributions. Our decision criteria could be used to deduce the length of the slot dedicated to each node.

Acknowledgements

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