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Abstract

Wireless sensor networks (WSNs) consist of a large number of entities that collaborate in order to provide given services. Unfortunately, due to their tiny size, these entities cannot be equipped with a long-life battery. In order to minimize overall energy consumption and maximize the lifetime of the network, a widely accepted approach is to implement a *duty cycle*. Specifically, in order to save energy, sensors are not active all the time, and switch off their capabilities according to a specific schedule. In this paper, we propose a generic method to schedule these duty-cycles, taking into account two important challenges in WSNs: *strong reliability* of the network and *fairness* between sensors. To achieve these aims, we ensure reliability by deploying several k-connected overlays, which became active one after the other. The fairness rule is ensured by spreading the sensors into overlay according to specific characteristics as energy consumption, network density, *etc.* We then propose different heuristics and probability models to achieve our outcome, and finally validate them through numerical evaluation.

1 Introduction

Recently, wireless sensor networks (WSNs) have received an increasing attention from academia and industry. Attempts are being made to deploy such networks for a variety of applications. In most of these application scenarios, there is a desire for an extended duration of unattended operation. However, one of the biggest impediment to unattended operation is the limited life of a sensor node's battery and the low rate progress in battery technology [10]. Limited battery is actually an issue when the sensors need to transmit continuously data due to the high energy consumption of the radio. Indeed, energy consumption is a first class concern in WSN deployment.

Shutting down sensors periodically for extended periods is one of the common method to save energy, usually denoted as *duty cycle*.

An important aim of WSN deployment is guaranteeing *strong reliability* [2]. Some specific graph topologies appear to be promising choices for achieving network reliability. An example is the case of k-connected graphs [7]. Such graphs remain connected as long as less than k nodes fail. All the information located at correct nodes can be communicated as long as the number of failures is below a given threshold. In this paper, our objective is to merge reliability and energy efficiency, while achieving balanced load among the network nodes, to ensure a longer period of unattended operation for the network. To reach this goal, we propose FAROES, a multi-overlay structure. The duty cycle is organized as a sequence of network overlay swapping. A set of overlay is defined and each overlay becomes active one after the other. Each sensor remains in the *idle* state as long as it does not belong to the current active overlay. All these overlays are influenced by a k-connected topology. Indeed, one of our main objective is that the information sensed by the sensors are reliably communicated to the central unit that will process them. In a nutshell, we want that:

- the central unit receives the information related to the entire sensor field, and
- each sensor have the same load and the same responsibility with respect to communication of the sensed information.

In the following, we first introduce our system model in Section 2. Section 3 provides a method to iteratively construct the overlays using some heuristics and probability distributions, directly in the construction of overlays, which take into account different characteristics of the network as density, energy consumption, selection balancing, *etc.* Finally, we evaluate the outcomes by numerical simulation and present the results in Section 4. Then, Section 5 provides a context for our work among a subset of related works, before concluding in Section 6.

2 System model

The sensor network is deployed over a region S of dimensions $W \times H$[1]. S is subdivided into squared sub-regions of dimension $d \times d$. So, S can be seen as a matrix $p \times q$ (where $p = \lceil \frac{W}{d} \rceil$ and $q = \lceil \frac{H}{d} \rceil$). Every sub-region of S can be identified by its position in the matrix and we call $S_{i,j}$ the sub-region located at the i-th row and the j-th column.

An arbitrary[2] number n of sensors are spread among S and we call Π such set of sensors. Inside a specific sub-region $S_{i,j}$ there is a sub-set $\Pi_{i,j} \subset \Pi$ of sensors, and each sensor in $\Pi_{i,j}$ has the same capability to sense, meaning that they can be considered as replicas of the same sensor. We assume that inside each sub-region $S_{i,j}$ there is at least one sensor (*i.e.* $|\Pi_{i,j}| \geq 1$).

Each sensor has a limited computational power and is equipped with *(i)* a battery having a finite power, *(ii)* a sensing module able to make the measurements required, and *(iii)* a transceiver unit (transmitter-receiver unit) needed to communicate with other sensors. We represent the energy remaining on a given sensor s at time t as $\xi_s(t)$. The transceiver of each sensor has a limited communication range ρ. We assume that *(i)* the communication range is very small with respect to the region dimension (i.e. $\rho << W$ and $\rho << H$) and *(ii)* any sensor node can communicate with any other in the surrounding sub-regions (*i.e.* $\sqrt{5} \cdot d \leq \rho$).

Each sensor could be in *idle* or *up* state. If the state is idle, the transceiver unit is switched off and the sensor does not participate in any communication even if it is still sensing. If the state is up, the sensor is transmitting the sensed information and listening from other sensors. We assume to have a wake-up service [4] implemented that report to the sensors when they are allowed to broadcast information to avoid collision.

We assume that there exists an high computational power central server C that is stable (*i.e.* always up). C elaborates the information reported by the sensors and is responsible for determining which sensors have to be up in each time unit.

Both server C and the sensors can be seen as an undirected graph $G = (V, E)$ where each vertex represents a sensor or the server ($V = \Pi \cup C$) and, given a pair of vertices s_i and s_j such that $s_i, s_j \in V$, there exists an edge $< i, j > \in E$ iff s_i and s_j are able to communicate. Each sensor can crash due to several causes (lack of energy, physical disaster, hardware failure, *etc.*). When a sensor crashes, it cannot perform any further action. A correct sensor is a sensor that never crashes. A correct sensor executes the schedule assigned by C.

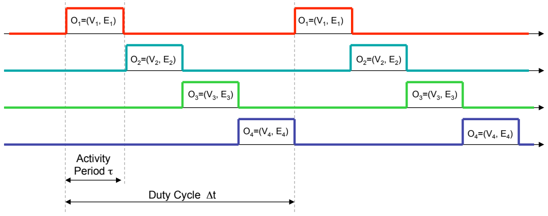

Figure 1: Overlay swapping used for duty cycle.

3 Faroes approach

Our aim is to build a k-connected overlay network on top of the physical graph G assigning to each sensor s_i a schedule defining when it has to switch on the radio and the periods in which it has to transmit and receive. Switching on and off the radio of all the sensors, it is possible to implement a duty cycle that reduces energy consumption and satisfies the following requirements:

- *Reliability:* At any time at least $p \times q - (k - 1)$ sub-regions $S_{i,j}$ have to be available[3].
- *Fairness:* Let x be a constant. For any pair of sensors s_i and s_j, the ratio between the energy spent by s_i and s_j should be less than the threshold x.

Figure 1 represents the temporal evolution of the system with 4 overlays. In the beginning, an overlay – represented by the k-connected graph $O_1 = (V_1, E_1)$ – is activated (where $V_1 \subseteq V$). In the beginning of the duty cycle, each sensor $s_i \in V_1$ exits from the idle state and becomes active for τ times. After this period, every sensor $s_i \in V_1$ return to idle state, and all $s_i \in V_2$ become active. Therefore, every τ time units, we have an overlay swapping. The total number of distinct overlays defines the lenght Δt of the duty cycle.

3.1 Overlay Construction

Since the region S is represented by a $p \times q$ matrix, a simple topology that can be used to build a k-connected graph is a grid. Note that we choose to use a grid only for sake of simplicity and actually this is not a limitation to the proposed solution.

A grid is a 2-connected graph due to nodes on the corners having degree 2. However, most of the nodes have degree 4. So, with a small extension, we can build a 4-connected grid-based topology for those overlays.

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[1] For sake of simplicity, we consider a regular region (i.e. rectangular or squared) but the approach proposed here is general and can be applied to any space.

[2] In every execution of the system the value of n can be different but is always finite.

[3] A sub-region $S_{i,j}$ is said to be available at a certain time t if there is one sensor $s \in S_{i,j}$, whose state is *up*, that is designed by the central server to sense at time t.

```
Function selectRepresentative ()

$R_\ell \leftarrow \emptyset$;
for i=1 to p
    for j=1 to q
        Select $s \in \Pi_{i,j}$ with probability $p_{repr}(s)$;
        $R_\ell \leftarrow R_\ell \cup \{s\}$;
return $R_\ell$.
```

Figure 2: Representative selection for overlay ℓ.

To construct a single overlay, the base idea is to build a grid by associating to each sub-region a sensor node (a *representative*) and connecting each of this node with its neighbors (along the north, south, east and west directions). In this way, we obtain a simple grid. Once we have such a grid, we link each node having less than 4 links to other nodes using intermediate sensors in other sub-regions as *bridges*.

The sensors activated in each overlay can be then divided into two sets *(i)* the *representatives* and *(ii)* the *bridges*.

Definition 1 (Representatives Set)
We define as R_ℓ the sub-set of sensors Π such that $\forall(i,j) \in [1,p] \times [1,q], \exists s \in R_\ell$, such that $s \in S_{i,j}$ and s is the representative *of $S_{i,j}$ for the overlay ℓ.*

Definition 2 (Bridges Set)
We define as B_ℓ the sub-set of sensors Π such that $\forall s \in B_\ell, \exists(i,j) \in [1,p] \times [1,q]$, such that $s \in S_{i,j}$ and s is selected as bridge between two non-adjacent sub-regions $S_{i',j'}$ and $S_{i'',j''}$ for the overlay ℓ.

The above two sets should satisfy the following constraints:

- **unique representative**: each sub-region is represented by one sensor in each overlay and each sensor can represent only the sub-region it is part of ($\forall(i,j) \in [1,p] \times [1,q]$, $\exists! s \in R_\ell$ such that $s \in S_{i,j}$ and $\forall\ell, |R_\ell| = p \times q$).
- **no duplication**: if a sensor is used as representative, it cannot be used as bridge in the same overlay and *vice versa* ($\forall\ell, R_\ell \cap B_\ell = \emptyset$).

Representative Selection. In each overlay ℓ, any sub-region $S_{i,j}$ has to be represented by a sensor that pertains to this overlay. To select a representative for each sub-region, we propose the heuristic, presented in Figure 2. Basically, a representative sensor s is selected from the set of sensors $\Pi_{i,j}$ in a sub-region $S_{i,j}$ according to a certain probability $p_{repr}(s)$. Such probability can be calculated for each sensor following several policies.

The simplest way to select the representative for every sub-region $S_{i,j}$ is selecting randomly a sensor by the set $\Pi_{i,j}$. In this way, no matter how many times a sensor s is selected to be part of an overlay, its probability $p_{repr}(s)$ is simply calculated as $p_{repr}(s) = \frac{1}{|\Pi_{i,j}|}$. More sophisticated policies are discuss later in this paper (*cf.* Section 3.2).

Bridge Selection. In order to link two non-adjacent sub-regions $S_{i,j}$ and $S_{i',j'}$, in an overlay, a *path* between $S_{i,j}$ and $S_{i',j'}$ has to be identified in the underlying network. Such a path is obtained by appropriately selecting some bridge sensors. Hence, to connect the representative node of sub-region $S_{i,j}$ having degree less than 4 in the grid overlay, we select more sensors to wake up in the adjacent sub-regions. We define as $N_{i,j}$ the set of surrounded sub-regions of $S_{i,j}$, *i.e.* $N_{i,j} = \{S_{h,k} | \ (h = i, \ k = j \pm 1) \vee (h = i \pm 1, k = j)\}$.

The selection phase works as follows. Consider the set of sub-regions whose representative has a degree less than 4 in the overlay. Let $S_{i,j}$ one of these sub-regions. One of the adjacent sub-regions of $S_{i,j}$, is selected according to a specific probability $p_{srb}(S_{i',j'})$. If this sub-region $S_{i',j'}$ is connected to another sub-region whose representative has degree less than 4 in the overlay, then two sub-regions with degree smaller than 4 have been connected, and the selection phase is restarted with another remaining sub-regions with a degree less than 4. In all other cases (the bridge region is not directly connected to a sub-region whose representative has a degree smaller than 4), the path is extended with another bridge sub-region, selected in the same way as above. This process continues until all sub-regions have a degree at least equal to 4.

The selection of bridging sub-regions can be considered as a weighted walk through the grid; note that if the weights associated with all the sub-regions are identical then this selection process is a random walk. and there is always a possibility that the selection process may pass through several sub-regions before hitting a sub-region with degree less than 4, resulting in extremely long bridging paths. This problem may be especially pronounced when very few sub-regions with degree less than 4 are present. To limit the run-time of the selection phase and to limit the length of the resulting bridging path, an invocation of the selection phase can be terminated with a certain probability p_{repeat} or another adjacent sub-region may be selected with probability $1 - p_{repeat}$.

Once a bridge path has been selected, from each of the selected sub-regions on this path, a non-representative sensor is selected (with a probability $p_{bridge}(s)$) to became a bridge node, and to wake up during the corresponding overlay's active period.

Figure 3 presents the heuristic for the selection of the bridging sensors. In this figure, *to_connect* corresponds to the multiset in which any sub-region S appears exactly $k - k_S$ times (where k represents the required k-connectivity of the graph and k_s is the cur-

```
Function selectBridge ($R_\ell$)

(01) $B_\ell \leftarrow \emptyset$;
(02) $to\_connect \leftarrow$
       $\{S_{i,j} | (i = \{1,p\}, j \in [1,q]) \vee (j = \{1,q\}, i \in [1,p])\}$;
(03) for each $S_{i,j} \in to\_connect$
(04)     $to\_connect \leftarrow to\_connect - \{S_{i,j}\}$;
(05)     Select a sub-region $S_{h,k}$
         from $N_{i,j}$ with probability $p_{srb}(S_{h,k})$;
(06)     Select a sensor $s \in \Pi_{h,k} - (R_\ell \cup B_\ell)$
         with probability $p_{bridge}(s)$;
(07)     $B_\ell \leftarrow B_\ell \cup \{s\}$;
(08)     if $(N_{h,k} \cap to\_connect \neq \emptyset)$
(09)         Select a sub-region $S_{h',k'}$
             from $N_{h,k} \cap to\_connect$;
(10)         $to\_connect \leftarrow to\_connect - \{S_{h',k'}\}$;
(11)     else go back to Line 05 with probability $p_{repeat}$
         to select a neighbour of $S_{h,k}$;
(12) return $B_\ell$.
```

Figure 3: Bridging sensor selection for overlay ℓ

rent degree of the sub-region).

3.2 Probabilistic Selection of Sensors

The heuristics described so far are based on four different probability functions: p_{repr}, p_{srb}, p_{bridge} and p_{repeat}. In this section, we provide some probability policies that can be applied to these heuristics.

First, we consider that a sensor selected as a bridge has the same load as a representative sensor. Then we assume that for a given sensor node s, $p_{repr}(s) = p_{bridge}(s)$ (*i.e.* the selection of sensor to act as a bridge is done in the same way as the selection of a representative). The probability p_{repeat} influences how long the bridging heuristic can execute. This can be viewed as a threshold initially set by users.

Next, let us discuss how p_{srb} and p_{bridge} are determined. Let us consider a sub-region $S_{i,j}$ to bridge with another sub-region. The probability to select a sub-region $S_{i',j'} \in N_{i,j}$ as bridge ($p_{srb}(S_{i',j'})$) can be calculated with respect to different parameters:

- density of the sub-region:

  $$p^{\mathcal{D}}_{srb}(S_{i',j'}) = \frac{n_{i',j'}}{\sum_{S_{h,k} \in N_{i,j}} n_{h,k}}$$

- energy consumption of the sub-region[4]:

  $$p^{\mathcal{E}}_{srb}(S_{i',j'}) = \frac{\mathbb{E}[\xi_s(t)]_{s \in \Pi_{i',j'}}}{\sum_{S_{h,k} \in N_{i,j}} \mathbb{E}[\xi_s(t)]_{s \in \Pi_{h,k}}}$$

  where $\mathbb{E}[\xi_s(t)]_{s \in \Pi_{i,j}}$ represents the average amount of energy remaining among the sensors that belong to $\Pi_{i,j}$.

- combination of density and energy consumption (in this complete equation, α_{srb} is a parameter set by the user in order to balance the weight of the aforementioned policies):

$$p_{srb}(S_{i',j'}) = \alpha_{srb} \cdot p^{\mathcal{D}}_{srb}(S_{i',j'}) + (1 - \alpha_{srb}) \cdot p^{\mathcal{E}}_{srb}(S_{i',j'}).$$

Last but not least, the probability of selecting a sensor inside a sub-region (p_{bridge}) to act as bridge, or a representative, can be calculated in the same way as above. Let c_s be the number of times sensor s has been chosen, thus far, to act as a bridge or a representative in all overlays. The selection probability can be calculated as follows, for a sensor $s \in \Pi_{i,j}$:

$$p_{bridge}(s) = \alpha_{bridge} \cdot w^{\mathcal{C}}_{bridge}(s) + (1 - \alpha_{bridge}) \cdot w^{\mathcal{E}}_{bridge}(s)$$

according to the number of times this sensor has been selected:

$$w^{\mathcal{C}}_{bridge}(s) = \frac{2^{-c_s}}{\sum_{s' \in \Pi_{i,j}} 2^{-c_{s'}}}$$

and the energy consumption of the sensor:

$$w^{\mathcal{E}}_{bridge}(s) = \frac{\xi_s(t)}{\sum_{s' \in \Pi_{i,j}} \xi_{s'}(t)}.$$

As previously, α_{bridge} is a parameter set by the user in order to determine how a node's past activity and energy consumption influence its selection as a bridge.

Once we have built one overlay, we can repeat the heuristics to construct the next overlay after updating the sensors' state (number of times chosen, presumed energy remaining, *etc.*). In case a representative or a bridge becomes unavailable (due to failure or depletion of battery energy), these heuristics can be launched another time for any single overlay to which more than k failed sensor belongs.

Obviously, more probability can be design, but due to space constraint, we cannot present an extended list of these functions. Moreover, the same argument conducts that a theoretical analysis could not be included in this paper.

4 Numerical Evaluation of Faroes

We evaluate the proposed heuristics in terms of reliability and fairness. Since the evaluation is focused on the measurement of the proposed heuristics' goodness, we simulated only the procedure related to the formation of the overlays used to realize the duty-cycle, without considering *(i)* the preliminary information gathering needed for the central server to know how many sensors are in the considered region, their physical locations and how much energy remains on each sensor, and *(ii)* the dissemination phase in which the central sever assigns to each sensor the schedule according to

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[4] The energy consumption of a sub-region $S_{i,j}$ can be calculated by considering the average value of the energy consumed by each sensor. Note that in the beginning, in a homogenous network, all the sub-regions have the same probability to be selected as bridge but this may not be so later.

which the sensor has to wake up and sleep. All the results are obtained by simulating the behavior of the central server using a numerical Java simulator implementing both heuristics presented in Section 3.1.

General Parameters. In all the simulations, space is subdivided into a sub-regions matrix of dimension 10×5 and the sensors are distributed in space as follows: each sub-region has at least 1% of the total number of sensors[5] and the remaining sensor nodes are distributed uniformly at random all over the space. In the beginning of the simulation all sensor have the same amount of energy, and we assume that an activated sensor spends 1% of its energy per τ times.

Due to the space constraint, we can only present in this paper only the fundamental subset of results.

4.1 Evaluation of Reliability

The reliability property can be viewed as a boolean condition that has to be satisfied, ideally, for the entire computation. In order to evaluate the goodness of our heuristics with respect to this property, we are going to consider the first time at which one of the overlays that is part of the duty cycle suffers k faults (either node faults or link faults). We compare the different representative/bridge selection policies with respect to the k-fault time.

More formally, we call *lifetime* of the system the earliest instant at which one of the overlays realizing the duty-cycle suffers k or more faults and evaluate reliability considering the maximum *lifetime*: higher the *lifetime*, better the selection policy.

System lifetime is expressed in terms of τ, *i.e.*, the time that each overlay is active (*cf.* Section 3). In fact, the system lifetime is the total amount of time that passes before one of the overlays composing the duty cycle suffers k faults and it can be practically determined by multiplying Δt, the duty cycle duration, with the number of duty cycles before k faults occur. For example, if the duty cycle length is 3 overlays and the number of iterations before the first occurrence of k faults in one overlay is 33, then the system lifetime will be $99 \cdot \tau$.

In our experiments we have considered duty cycles of different length and in particular we start from a duty cycle composed of only one overlay (*i.e.* practically there is no duty cycle and the resulting lifetime corresponds to the lower bound on the system lifetime) until the longest duty cycle that can be obtained using all the sensors at least once (we call such a value *longest duty cycle*).

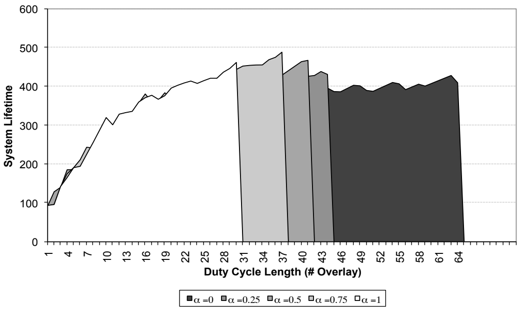

Figure 4: System lifetime for a WSN of size n=1000.

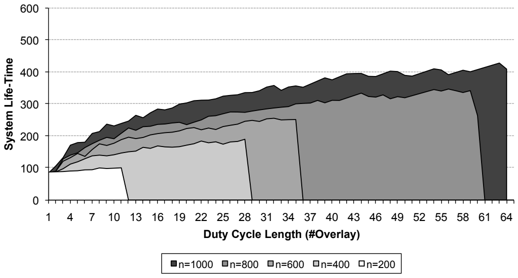

Figure 5: System lifetime for $\alpha_{srb} = \alpha_{bridge} = 0$.

Figure 4 shows the average system lifetime for a network of $1,000$ sensors, for different value of α^6. The lifetime of the system is almost the same for every value of α, if the largest number of overlays is used.

Figure 5 shows the average system lifetime for different network size and $\alpha_{srb} = \alpha_{bridge} = 0$. Even in this case, the ratio between lifetime and size of the system is almost the same if the largest number of overlays is used (more trends for different pairs $\alpha_{srb}, \alpha_{bridge}$ can be found in the extended version [3]).

4.2 Evaluation of Fairness

In order to evaluate the fairness of the system, we have calculated the energy distribution (Figure 6) of the nodes at the end of the first duty-cycle defined from the longest duty-cycle for a network of $1,000$ sensors, according to different values of α^6.

From Figure 6, we can observe that the load in terms of energy consumption at the end of the duty cycle is well balanced. Note that the energy distribution is strictly related with the usage distribution and in particular, they are directly proportional; due to space constraints we voluntarily omit here the usage distribution. From the distribution, we can also deduce the fairness threshold x that can be smaller for an higher value of α.

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[5] Having a minimum number of sensors in each sub-region is actually required only to simplify the presentation by ensuring that it is always possible to build at least one overlay to be used as bound in the calculation of the system lifetime.

[6] In this figure, plots are obtained by using the same weight for both sub-region selection and representative/bridge sensors selection (*i.e.* $\alpha_{srb} = \alpha_{bridge}$).

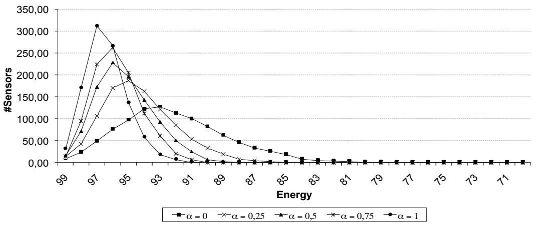

Figure 6: Energy Distribution after the first duty-cycle (n=1000).

4.3 Discussion

From Figure 4 and Figure 5, it is possible to observe that duty cycle length and system lifetime are strictly related. In particular, longer the length of the duty cycle, higher the system lifetime [7]. Those plots speak about a common behavior independently of network size or the value of the parameters α_{srb} and α_{bridge}. We can then conclude that reliability is not dependent on the parameters used in the selection of the neighbors.

On the contrary, it is possible to say that fairness is strongly affected by the selection strategy and in particular, selecting the sub-region according to its density and selecting a sensors considering its usage ($\alpha_{srb} = \alpha_{bridge} = 1$) seems to be the best strategy. Most of the sensors have comparable amount of remaining energy (this is mostly due to the fact that usage and energy consumption are directly related).

Moreover, looking at lifetime distribution, we can say that our heuristics are effective in dense networks. In fact, looking at the plots of Figure 5 for networks with a small number of nodes (which are obviously sparser), the system lifetime remains constant while moving towards dense networks we have an increment of the lifetime of almost 400%[7].

On the distributed possibilities. In order to release the presence of an omniscient central server C and the problem of duty-cycle scheduling dissemination (initial one or update in case of to much failures), the centralized approach can be simply distributed. As C follows a sequential algorithm, this last can be replace by a decentralized token-based cycle algorithm among each sub-region. Inside each sub-region, a leader election is launched to decide which sensor will be the representative for the corresponding overlay. In other hand, for each edges to be added in the overlay, a sub-token-based mechanism is launched, and for each selected bridge sub-region, another leader election is run to determine the bridge sensor.

5 Related Work

Duty-cycling is a well-studied topic in sensor networks. Unfortunately, in most of those works, energy consumption is the first-class concern, without ensuring a strong reliability as we propose. In fact, large majority of contributions consider duty-cycle scheduling for routing or broadcast mechanisms, with a probabilistic approach. For instance, in [12], authors investigate a randomized algorithm to provide robustness to the variations in network connectivity.

Nevertheless, following a generic approach, Hsin and Liu studied both random and coordinated sleep algorithms and discussed their design tradeoffs [8]. They shown notably that using coordinated sleep algorithms, a greater reduction in duty cycle can be obtained at the expense of extra control overhead. This paper motivate our structured approach.

In [9], authors take into account the problem of dynamic duty cycling with energy harvesting, maximizing both lifetime and performance. From this study, the extension [13] presents an adaptive duty-cycling of energy harvesting sensor nodes. These specific nodes are not the core of our system model. Moreover, as we shown above, our approach permits to ensure a very large lifetime, without adapting the overlay and their schedule. Thus, this dynamic scheduling can be viewed as an alternative of our static one.

Not exactly located in the field of our contribution, but sufficiently interesting, several approaches leverage the use of duty cycle. For instance, [14] looks into the problem of broadcast in presence of duty-cycle. Indeed, most of broadcast for wireless network assume that the sensors are awake all the time, which is inconsistent with this kind of networks. In the context of connectivity, some distributed scheduling algorithm are proposed as [11]. The latter leverages the cross-layer approach to ensure a greater network lifetime. More recently, in [6], Shu Du *et al.* proposed an enhanced duty-cyle MAC protocol that reduces the end-to-end latency and contention traffic, while remains lightweight, also based on cross-layer routing.

Therefore, in [15], authors do not consider classical duty-cycle, but argue to save energy by turning off sensors identified as *equivalent*, from a routing perspective. Their *geographical adaptive fidelity* effectively permits to consume almost half less energy in routing scheme than classical protocols, but it does not ensure a strong connectivity as FAROES, assuming only a high probabilistic delivery ratio.

Also, Abawajy *et al.* [1] proposes an asynchronous scheme for duty-cycle scheduling, but in the context of grid-based sensor network. Starting from the assumption of a mobile base station, this work can be viewed as an extension of our contribution, considering each of our overlays independently (*i.e.* after the representative and bridge selection).

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[7] This consideration is confirmed also from the other plots reported in [3].

In other hand, building reliable overlay networks on top of a wireless sensor network is actually an open problem [17]. The main approach followed to achieve reliability to failure is the use of a richly connected topology (usually a k-connected graph) built by means of clustering techniques.

Finally, the most related work has been proposed in [16]. In this paper, a protocol to construct a k-fault tolerant (*i.e.*, k-connected) clustered network is presented, where k is a constant determined by the application. Fault tolerance is achieved by selecting k independent sets of cluster heads between the sets of sensors, so that each node can quickly switch to other cluster heads in case of failures. Each of these sets forms an overlay called *cluster head overlay* and each such overlay is independent of the other. Network lifetime is prolonged by selecting cluster heads with high residual energy and low communication cost, and periodically re-clustering the network. A similar approach is followed in [5] where the k-connected overlay is built by selecting a set of sensors representing a k-dominating set.

6 Conclusion

In this paper, we have proposed a new method to schedule the duty-cycle mechanism, in order to save energy and ensure high reliability. To achieve this goal, we proposed several heuristics in order to construct a set of k-connected overlays. These heuristics employ several probability functions which take into account some specific characteristics of the sensor nodes such as residual energy or network density. These characteristics can be weighted according to the application's needs.

We then evaluated our outcomes by simulation. We observed that these heuristics enable us to balance the load of the network, thus satisfying the fairness condition. Moreover, we leverage the reliability of k-connected graphs to significantly increase the life of the network. So, it is possible to increase both objectives (reliability and fairness) in an efficient way.

References

[1] J. Abawajy, S. Nahavandi, and F. Al-Neyadi. Sensor node activity scheduling approach. In *Intl. Conf. on Multimedia and Ubiquitous Engineering (MUE '07)*, pages 72–77, April 2007.

[2] H. Abo-El-Fotoh, E. El-Mallah, and H. Hassanein. On the reliability of WSN. In *IEEE Intl Conf. on Communications (ICC '06)*, pages 3455–3460, June 2006.

[3] R. Baldoni, S. Bonomi, Y. Busnel, and R. Prakash. FAROES: Fairness And Reliability using Overlay Expenseless Set-out for duty-cycle optimization in WSN. Technical Report 1/09, MIDLAB, January 2009.

[4] G. Chockler, M. Demirbas, S. Gilbert, N. Lynch, C. Newport, and T. Nolte. Consensus and collision detectors in radio networks. *Distributed Computing*, 21(1):55–84, 2008.

[5] F. Dai and J. Wu. On constructing k-connected k-dominating set in wireless networks. In *the 19th IEEE Intl Parallel and Distributed Processing Symposium (IPDPS '05)*, page 81.1, April 2005.

[6] S. Du, A. Saha, and D. Johnson. RMAC: A routing-enhanced duty-cycle mac protocol for WSN. In *the 26th IEEE Intl Conf. on Computer Communications (INFOCOM '07)*, pages 1478–1486, May 2007.

[7] F. Harary. *Graph Theory*. Addison-Wesley: Reading, Masachusetts, 1969.

[8] C. Hsin and M. Liu. Network coverage using low duty-cycled sensors: random & coordinated sleep algorithms. In *the 3rd Intl Symposium on Information Processing in Sensor Networks (IPSN '04)*, pages 433–442, April 2004.

[9] A. Kansal, J. Hsu, S. Zahedi, and M. B. Srivastava. Power management in energy harvesting sensor networks. *ACM Transaction on Embedded Computing System*, 6(4):32, 2007.

[10] H. A. Kiehne. *Battery Technology Handbook*. CRC Press, 2003.

[11] M. Sichitiu. Cross-layer scheduling for power efficiency in WSN. In *the 23th IEEE Intl Conf. on Computer Communications (INFOCOM '04)*, pages 1740–1750, March 2004.

[12] J. van Greunen, D. Petrovic, A. Bonivento, J. Rabaey, K. Ramchandran, and A. Vincentelli. Adaptive sleep discipline for energy conservation and robustness in dense sensor networks. In *IEEE Intl Conf. on Communications (ICC '04)*, pages 3657–3662, June 2004.

[13] C. Vigorito, D. Ganesan, and A. Barto. Adaptive control of duty cycling in energy-harvesting WSN. In *the 4th IEEE Conf. on Sensor, Mesh and Ad Hoc Communications and Networks (SECON '07)*, pages 21–30, June 2007.

[14] F. Wang and J. Liu. Duty-cycle-aware broadcast in WSN. In *the 28th IEEE Intl Conf. on Computer Communications (INFOCOM '09)*, April 2009.

[15] Y. Xu, J. Heidemann, and D. Estrin. Geography-informed energy conservation for ad hoc routing. In *the 7th Intl. Conf. on Mobile Computing and networking (MobiCom '01)*, pages 70–84, July 2001.

[16] O. Younis, S. Fahmy, and P. Santi. An architecture for robust sensor network communications. *Intl Journal of Distributed Sensor Networks*, pages 305–327, 2005.

[17] O. Younis, M. Krunz, and S. Ramasubramanian. Node clustering in WSN: recent developments and deployment challenges. *IEEE Network*, 20(3):20–25, 2006.