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# Exploiting Redundancy for Energy-Efficiency in Wireless Sensor Networks

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**Abstract**—Wireless Sensor Networks (WSNs) are used today in many applications that differ in their objectives and specific constraints. The common challenge in designing WSN applications comes from the specific constraints of sensors because of their limited physical resources such as weak computational capability, small memory capacity, and especially limited battery. In this paper, we consider sensor redundancy in WSN and we conduct an experimental study to better highlight the importance of its exploitation. We also implement OER 'Optimization of Energy based on Redundancy', a protocol that exploits redundancy in order to save energy. Moreover, we extend OER by a fault tolerance mechanism. Through extensive simulations, we show how OER combined with FTMOer outperforms traditional routing protocols that do not exploit redundancy.

**Index Terms**—Wireless sensor networks, redundancy, fault tolerance, energy efficiency.

## I. INTRODUCTION

Wireless sensor networks (WSNs) are often characterized by a dense deployment in environments limited in terms of resources. Indeed, the limits are due to processing capability, storage, and especially energy because they are usually powered by batteries [11]. Recharging the batteries in a wireless sensor network is sometimes unfeasible mainly due to the location of the nodes. It is therefore recognized that the energetic limitation is an unavoidable issue in the design of wireless sensor networks. In fact, energy consumption plays an important role in the network lifetime, and it has become the major performance criterion for this type of networks. To increase the network lifetime, we should make compromise between different tasks at the node as well as in the network.

Several research studies have appeared with a goal of optimizing the energy consumption of nodes through the use of conservation techniques to improve network performance and maximize its lifespan. The random deployment of networks can induce high spatial redundancy between nodes. Such a redundancy is a feature that is both cost effective and penalizing. Indeed, it can be used to improve detection reliability or accuracy of the data collected. But it generates greater data transfer and involves an additional traffic load.

In this paper, we are interested in redundancy in wireless sensor networks. Consequently, we implemented OER [7] in NS2 to show the benefits of exploiting the redundancy

in terms of energy consumption. Besides, we extended it by a fault tolerance mechanism (FTMOer). Indeed, FTMOer finds a solution to notify the event even if it is not detected by the representative node.

The reminder of this paper is organized as follows: In the next section, we discuss previous related work. The principle of redundancy, its types and its usefulness are described in Section III. Experimental study is explained in Section IV. Section V gives an idea about the protocol that we studied and implemented and explains our fault-tolerant mechanism. Simulation results are presented in Section VI. Section VII summarizes the paper and concludes the paper.

## II. RELATED WORK

In [10], Heinzelman et. al proposed a distributed clustering algorithm called LEACH for routing in homogeneous sensor networks. In LEACH, nodes self-configure into groups. Each group is controlled by an elected cluster-head. The cluster-head selection is based on the energy level of each node. In fact, it is chosen randomly and its role is assigned to different nodes to ensure fair energy consumption because the cluster-head consumes a lot of energy. The cluster-heads aggregate the data captured by other nodes in the cluster and send an aggregated packet to the base station. LEACH has two phases set-up and steady state. During the set-up phase, the cluster-heads are elected and groups are formed. During the steady state phase, the data is sent to the base station. However, although LEACH allows energy saving, therefore increasing the lifetime of the network, it has certain limitations. It is not suitable for large networks and it selects randomly the cluster-head which causes a concentrated distribution point in one place that generates a lot of isolated nodes. In addition, data aggregation might increase delay.

MR-LEACH [6] uses a clustering technique based on the geographical proximity of nodes. This technique allows the grouping of nodes having the same measurement so that only representative nodes send their data. MR-LEACH is based on a LEACH-like architecture. Nodes are deployed randomly and densely. They observe the same physical phenomenon, generate a periodic monitoring traffic and send it to the base station via the cluster-head. MR-LEACH also has two phases. During the first phase of observation, groups are formed and every cluster-head

collects readings from nodes. After that, the cluster-head analyzes the collected measurements and according to the geographical proximity of the nodes, it determines the groups of redundant nodes. After grouping, a single node sends its reading and the other nodes stop their transmission.

In [4], Bahrami et. al proposed DACA, a clustering approach that uses the correlation of data to form groups led by queries. Indeed, DACA selects the cluster-head nodes forming a request with three parameters (residual energy, the data value and the number of neighbors of each node) which reduces the number of groups, the number of transmissions and energy. DACA also operates a fusion method groups to prevent the formation of a single node which prolongs the network lifetime.

DDFC [9] has been developed to create and maintain a logical grouping of nodes with similar spatial values. Each node of a group must keep its aggregated data in its group to know when that group should be split or merged with another group. For DDFC, a group may have more than one cluster-head. DDFC defines three agents that perform its functions. Firefly agent allows synchronization of aggregated data and maintenance of groups. Indexing agent that assigns scores to each of the network nodes and the node with a maximum score is selected as the cluster-head. And adaptive agent adapts dynamically the interval between each frame, which provides stability. High density may cause instability in the network and the use of adaptive agent solves this problem.

### III. REDUNDANCY IN WSNs

Most works offer improvements in terms of energy consumption without taking into account the redundancy measure that is also a source of unnecessary energy consumption. Redundancy is an inherent characteristic of WSNs that must be carefully considered to improve major aspects of their operation. Almost all sensor networks are deployed with a certain degree of redundancy. If it is not used in an intelligent way, redundancy will cause a waste of energy due to redundant transmissions and reception operations. There are several explanations in the literature that find that eliminating any redundancy helps to save a lot of energy and combining them is expected to save more. Sensor networks are characterized by a large number of nodes. So redundancy measure may result from densely deployed nodes. Several nodes can detect the same event and therefore the same measured value. It is hence necessary to consider mechanisms for the management of possible measurement redundancies. The challenge is the inclusion of redundant measurement in sensor networks for better improvement in energy consumption.

#### A. Types of redundancy

Redundancy is an inherent characteristic of WSNs. There are two types of redundancy: Spatial redundancy related to measurements detected by several sensors at the

same time and Temporal redundancy related to identical measurements detected over time.

1) *Spatial redundancy*: Spatial redundancy is the possibility to obtain information for a specific location from different sources [5]. It is based on the geographical location of the sensor nodes and involves the replication of resources in the network coverage area. Spatial redundancy is used to improve the reliability of the measured data and to increase the safety level. Physical redundancy [12] is the most used technique to ensure the reliability of a system. It can measure a variable in a specific location using more than a sensor. So it is based on the deployment of multiple nodes that cover a specific area. This type of redundancy uses the aggregation of sensor measurements with similar data. When nodes are close to each other and redundancy exists in the detected data, the source nodes generate a large amount of traffic on the wireless channel that causes not only a waste of bandwidth but also a loss of battery power.

2) *Temporal redundancy*: Temporal redundancy may be defined as the achievement of a specific action more than once in time followed by a checking result to increase reliability [5]. It is used to improve the accuracy of measurements by the sensor nodes to withstand transient faults during detection and communication. There are cases where the use of temporal redundancy is tricky to be applied [5]. One of these situations is the use of sensors in the detection dynamic environments where the parameters are changing rapidly in time. Temporal redundancy can be attached either to the detection or communication or both at the same time.

- Temporal sensing redundancy: In an ideal scenario where the sensing is perfect, a high level of confidence in data measurement can be obtained using a single sensor [5]. In the real world detection devices sometimes have inaccurate measurements thus reading from a single sensor would not give reliable measurements. To improve the reliability of the whole system, we should increase redundancy using multiple reports from the same sensors.
- Temporal communication redundancy: Temporal communication redundancy is defined as sending the same package of data more than once skewed in time [5].

#### B. Usefulness of redundancy

Redundancy usefulness is summarized hereafter:

- Energy saving is one of the most important concerns in wireless sensor networks where nodes have limited battery power. Energy saving strategies exploit the spatial redundancy by defining subsets of active nodes in different time periods to allow nodes to save energy when they are in the idle mode. Thus they put as many redundant nodes as possible in sleep mode and they only use a few of the energy spent in active mode.

- The topology control is a method to save energy based on spatial redundancy which reduces the number of nodes involved in routing and forwards packets created by the other nodes without reducing network connectivity and coverage.
- Redundancy provides robust and faulty tolerance information when sensor nodes are faults or even malicious. Since the sensors are often deployed in harsh environments, erroneous damaged sensor readings may impact the accuracy of the readings of the sensor network. Hence several observation nodes in the same place and at the same time might ensure better monitoring of quality.
- As sensors may be deployed in harsh environments WSNs can be seriously affected by any type of sensor failure or malicious attacks. The security objectives in sensor networks require the development of specific approaches, most of them exploit redundancy.

Almost all sensor networks are deployed with a certain degree of redundancy and the redundancy is used only for robustness purposes.

#### IV. EXPERIMENTAL STUDY

In order to highlight how important is the exploitation of spatio-temporal redundancy in WSNs, we carry out an experimental study. The amount of information collected by sensors is very important. Thus, exploiting redundancy to reduce the number of transmissions with the same sensor readings leads to save energy and to maximize the network lifetime.

##### A. Experimental Set-up

Experiments were performed using Tmote Sky [1] devices. The platform produced by moteiv, is an ultra low power IEEE 802.15.4. The mote uses a Texas instrument MSP430 micro-controller running at 8MHz and 48k of flash memory. We deployed a network with 4 nodes: a base station and 3 nodes integrating humidity, light and temperature sensors. Each device operates on 2 AA batteries. The experiments were performed on the campus of the university between 8 am and 9 am in a cloudy day. A picture of the site is shown in Fig.1. 3 sensors were placed on trees spaced with 35 feet. To collect the measurements, the base station was connected to a laptop. The network topology is a star one.

##### B. Experimental Results

As we mentioned before, the sensors measured temperature and humidity during more than one hour. The sensor readings are shown in Fig.2.

During one hour, we collected more than 9000 samples per node. As depicted in Fig.2., the sensors have almost the same readings. Consequently, they send redundant values. At the beginning, sensors present different measures

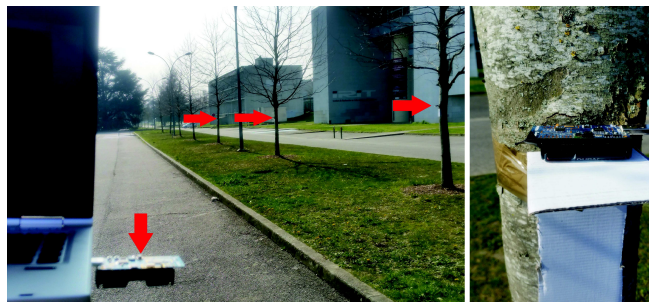
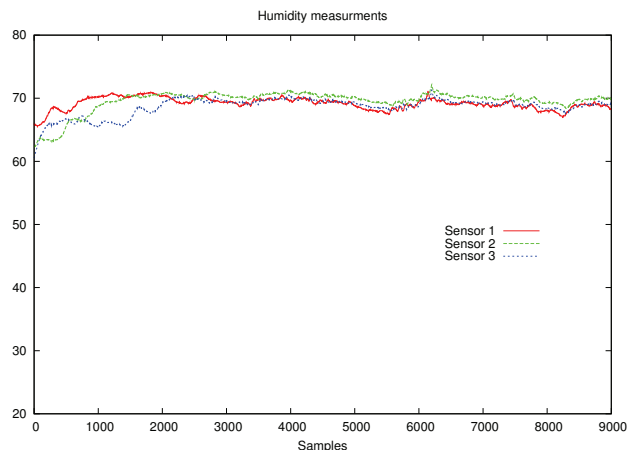
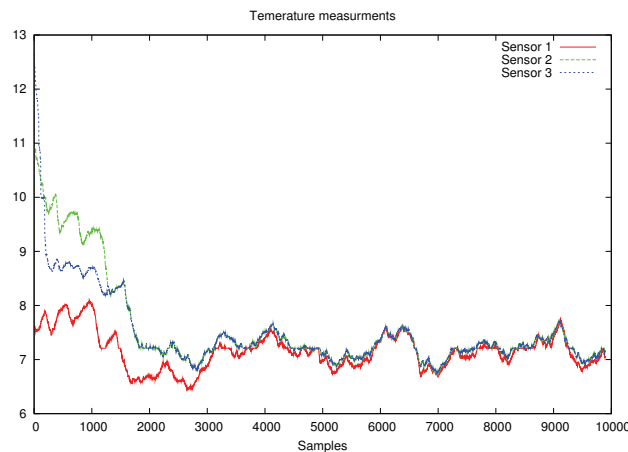


Fig. 1: Experimental setup



(a) Humidity %



(b) Temperature °C

Fig. 2: Different measures

due to the fact that they were in a box and that they take time (around 10 minutes) to measure the right temperature or humidity. In order to exploit this redundancy, we implement in the next section a protocol based on spatial redundancy.



## V. ENERGY OPTIMIZATION IN REDUNDANT WSNs

To exploit spatial redundancy in WSNs, we implement OER [7] an energy optimization protocol in redundant WSNs under deterministic and probabilistic sensing models to take benefit from measurement redundancy to optimize the energy consumption. We also improve it with FTMOer, a fault-tolerance mechanism.

### A. Principle of OER

OER 'Optimization of Energy based on Redundancy' exploits redundancy in order to improve the network lifetime. It uses a clustering technique that allows the grouping of nodes detecting the same events like LEACH. Based on the probabilistic model of Elfes [8], it combines its geographic position and its probability to detect the same event in order to reduce the number of transmissions. In the Elfes model, the probability that a sensor detects an event over a distance  $x$  is expressed as follows:

$$Pdet(x) = \begin{cases} 1 & \text{if } x \leq R \\ \exp^{-\lambda(x-R)^\beta} & \text{if } R < x \leq R_{max} \\ 0 & \text{otherwise} \end{cases} \quad (1)$$

The protocol has two main phases illustrated in Fig.3. In the first phase, it determines and groups redundant nodes. During the second phase, it checks whether the resulting partitioning is the best to minimize an objective function which optimizes the energy. The process is repeated until an optimal partitioning is found.

After the initialization phase, OER enters in the phase of detection and transmission. One representative node is active in the same redundant group. The representative nodes detect events and send their data to the sink. For the network partitioning, OER starts by choosing a random node that serves as the first event center area. Depending on the probability, it identifies redundant nodes in that region. After having formed the first group, the center moves to another node and other groups are formed. This process is repeated until each node becomes a group member. According to the Elfes detection model, a node detects an event held at a distance less than or equal to  $R$ .

OER uses a tabou search for partitioning, which minimizes the best overall energy consumption of the network. This research uses a partitioning algorithm to group the redundant nodes and evaluates the cost of partitioning. At the end of the search the optimal solution is obtained.

### B. Fault Tolerance

Sensor data are sometimes incomplete and sometimes redundant. Indeed, the sensors can either do not detect the information or do not detect the right information. The errors in data can arise at different levels of the system and they are directly related to the data acquisition and processing.

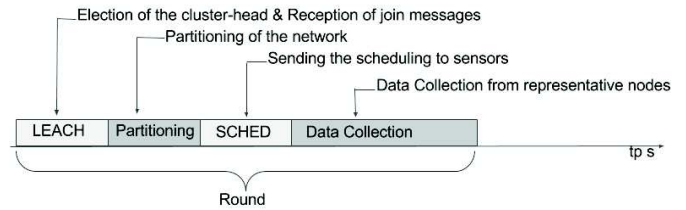


Fig. 3: Phases of OER

They represent specific failures due to the following four main factors: the sensor, the measurement methods, the environmental factors, and the sensors' communication.

- **Sensors:** Sensor lifetime, its calibration, the degradation of the device or the installation errors are aspects that may impact the quality of data during the measurement. The resources of the sensor also represent a source of errors. The limitations of computing and storage capacity reduce the amount of processing performed within the sensors. This may cause a loss of information, miscalculation, the unavailability of the sensor or the sending of data to the central server without direct request.
- **Environmental factors:** Sensor networks are often deployed in hostile areas, therefore the operating conditions of a sensor or a sensor network can be affected by the environmental conditions. These factors have a significant impact on the performance of the sensors and therefore on the measures they realize.
- **Measurement methods:** Usually sensors measure only one element at a time because of its size, its energy and its processing capacity are limited. These aspects encourage the use of methods of measurement that economize in term of energy despite the reliability of precision and accuracy of the data.
- **Communication:** Once the data is measured, the sensors often use wireless communications to communicate the acquired data to a central node or a server. However, this communication may be damaged due to bad environmental conditions, interference, or congestion. Moreover, bad communication can lead to erroneous or missing data.

Since OER present some failures in detecting data, we thought about improving it by implementing a fault tolerance mechanism.

#### a) FTMOer 'Fault Tolerance Mechanism for OER':

An event is detected by one or  $m$  nodes of the same group. We have two instances of detection, deterministic and probabilistic.

Deterministic detection where all nodes detect the event. And probabilistic detection where only  $k$  nodes ( $k < m$ ) detect. And it is in the second case that we implement a fault tolerance mechanism.

During a super frame, only one node sends its data.

This representative node operates on 3 modes:

- it detects and sends the data.
- it doesn't detect (eg. detection threshold not reached) and the other nodes won't react because it is not their turn. So the event is lost.
- it is faulty (eg. depleted battery) so it can not detect and the event is not notified.

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**Algorithm 1:** Association of listening nodes

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input :  $P_{det}$ : probability of detection
          $Gp$ : group of nodes
          $\alpha$ : number of nodes with  $P_{det} = 1$ 
          $\beta$ : group size
output :  $List\_Node$ : associated listening nodes
1 :  $Threshold \leftarrow \lceil \frac{\beta - \alpha}{\alpha} \rceil$ ;
2 : for each  $node \in Gp$  do
3 :    $node.count \leftarrow 0$ ;
4 : for each  $node \in Gp$  do
5 :   //If the node has a probability < 1, then associate
6 :   //a listening node with a probability = 1.
7 :   if ( $node.P_{det} \neq 1$ ) then
8 :     for each  $node' \in Gp$  do
9 :       if ( $node'.P_{det} = 1$ ) then
10 :        if ( $node'.count \leq Threshold$ ) then
11 :           $List\_Node \leftarrow node'$ ;
12 :           $node'.count++$ ;

```

---

The idea proposed here is to improve fault tolerance of the OER protocol for the formation of redundant groups under the assumption of probabilistic detection model. After the formation of the groups, we know which node is to transmit the event in the super frame. So, we propose to associate a listening node to the representative node. Suppose that we have a representative node that sends its data, we begin by checking its detection probability  $P_{det}$ .

If  $P_{det} = 1$ , we are sure that the node detects the event and it will send its measurements to the cluster-head. Otherwise, if there is a risk that the node has not detected (when we relax the probability), we associate another node from the same group having a probability of detection equal to 1. For example when  $P_{det} = 0.95$ , there is a risk of 5% that the node didn't detect. The associated node sends its data instead of the representative node. So at the beginning of each transmission, the associated nodes listen to see if they are working or not. This affects energy saving but we are sure that all the events occurred are notified to the sink. FTMOer listening node association is detailed in algorithm1.

## VI. EVALUATION

We evaluate the performance of OER and show the importance of the fault tolerance mechanism that we proposed to indicate that OER combined with FTMOer can save more energy. Our purpose is not to improve especially LEACH but is to highlight that our protocol is better than a protocol that does not exploit redundancy.

### A. Simulation Set-up

For the implementation of OER, we chose to start with the code of LEACH and to make changes to suit OER requirements.

For the clustering algorithm, we implement it in C++. The code is used to find a network partitioning and then propose a scheduling of transmissions that we inject in a NS2 simulation model.

We consider a wireless sensor network deployed on a surface of  $100 \times 100 m^2$ . The number of nodes varies from 50 to 200. The nodes have the same radius detection. For the parameters of detection range we set the values of analog PIR [2].

### B. Evaluation metrics

We compare our scheme to LEACH. For this we performed simulations with the same parameters and metrics for both approaches. We are interested primarily in energy consumption since it is a key criterion for determining the network lifetime.

The performance metrics that we chose are:

- Energy consumption: we measure the energy consumed by the whole network.
- Number of packets sent: to evaluate the fault tolerance mechanism, we measure the number of packets sent with and without FTMOer.

### C. Simulation Results

We compare the energy consumption of the network for OER and LEACH under different network sizes.

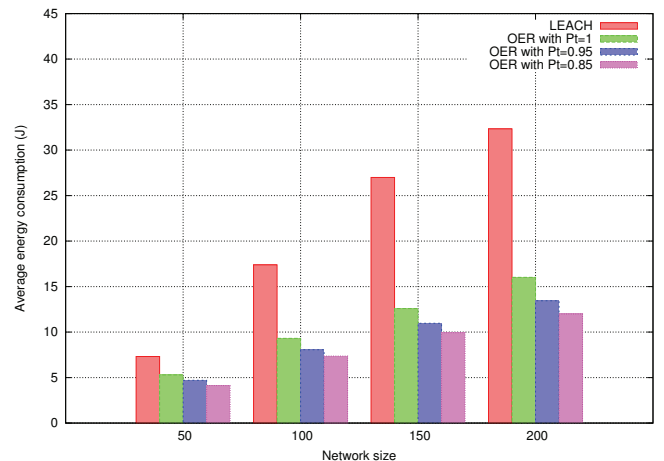


Fig. 4: Energy Consumption (J)

For LEACH, all nodes send their data periodically while for OER, only the representatives of the groups send their values to the cluster-head. As depicted in Fig. 4., OER consumes less energy than LEACH. We observe that during a super frame for 150 nodes, LEACH consumed 26.99J while OER consumed 12.59J. So it realized a gain of 14.4J. Thus, OER enables energy saving. Indeed, when

the network density increases, the measurement redundancy increases and less nodes transmit data. With a high density, the size of the groups increases. Therefore the number of transmissions per node decreases over time and the network lifetime increases.

Fig. 4. also illustrates a gap in terms of energy consumption between a deterministic detection model a the probabilistic detection model. Besides, we can note that energy consumption decreases when we relax probability because the size of each group increases.

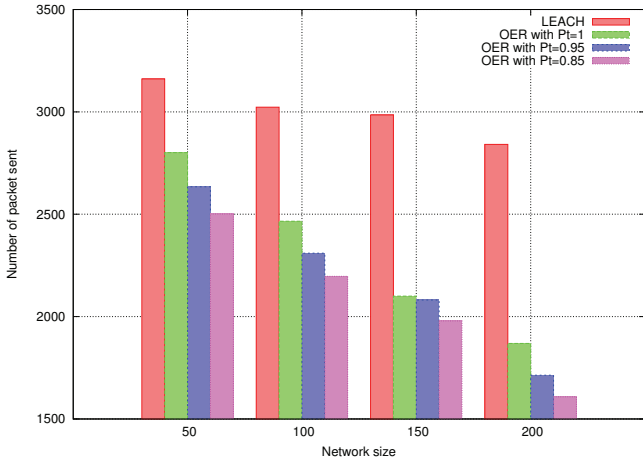


Fig. 5: Number of packets sent

As shown in Fig. 5, with OER, the nodes send less packets than with LEACH because in LEACH all nodes send their data in turn. While, in OER only representative nodes per group send their data. Thus when the number of nodes increases, the number of nodes per group increases and less nodes send packets. We note also that when we relax the probability, the number of packet decreases. Because for example for a probability equal to 0.95, we have a risk of 5% that a node didn't detect the event. So, due to the probability of the Elfes model, larger groups with more nodes are formed and the number of packets sent decreases.

*a) Impact of including the mechanism of fault tolerance:* Here we take the example of a node with a probability 0.95. We begin by checking if the node really detected the event or not. If there is a risk that it didn't detect, another node from the same group which detected the information will send instead of the representative node during this round.

Fig. 6. presents the energy consumption for OER with and without the fault tolerance mechanism when we relax the probability to 0.95. For the energy consumption, we note that after including the fault tolerance mechanism, the nodes consume slightly more energy. This is due to

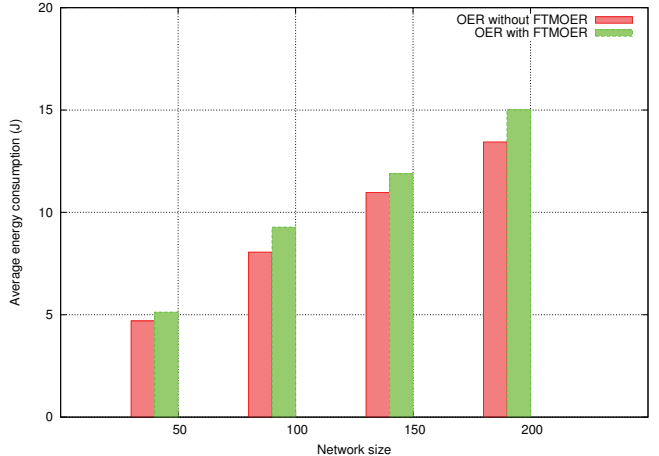


Fig. 6: Energy Consumption (J)

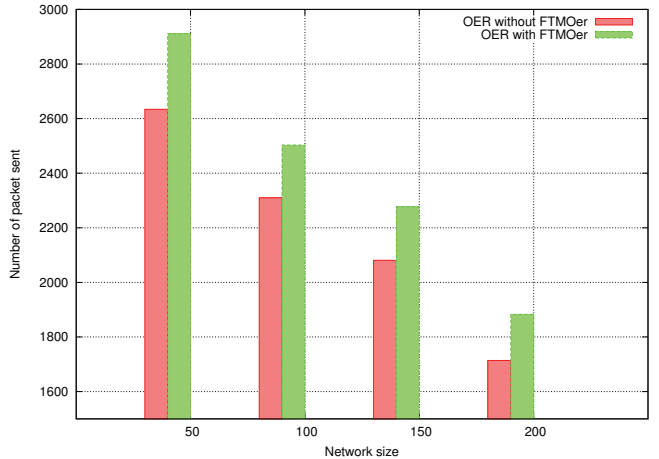


Fig. 7: Number of packets sent

the activity of listening nodes and to the sending of data not detected by representative nodes. Compared to LEACH, OER always consumes about 45% less energy even combined with FTMOer.

We notice that after including the fault tolerance mechanism, more data were sent. In consequence, we lost slightly 10% in terms of energy but we win in term of reliability. For example for 100 nodes, during 50s, more than 9% of data were sent for a detection probability of 0.95. So the mechanism has ensured the transmission of data even detected at 95%.

## VII. CONCLUSION

In this paper, we describe redundancy and its usefulness. By the experimental tests, we highlight the presence of redundancy in WSNs. We also present OER, a redundancy based routing protocol that minimizes global energy usage by exploiting redundancy and geographical localization. We demonstrate that OER with FTMOer outperforms LEACH in term of energy consumption.



As a future research work, we plan to implement OER and FTMOer on tmoteSky nodes for a biodiversity monitoring application at Toulouse university campus. Besides, we will address the problem of the temporal redundancy. Indeed, we believe that there is room for enhancement in terms of energy if the freshness of the sensor readings and their lifetime are considered.

#### ACKNOWLEDGMENT

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