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An Innovation-Based Algorithm for Energy Conservation in Multihop Wireless Sensor Networks

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***Abstract*—We propose an energy-efficient algorithm for sensing a process *f(x,y,t)* using a multihop Wireless Sensor Network (WSN). The innovation-based algorithm aims at saving node energy by managing the transmission necessity. The nodes can also switch to an inactivity state, between innovative transmissions. When a node needs to send data, it transmits its inactivity period attached within the packet. Then, forwarding nodes (in the route path) can sleep without affecting the communication process. Results show that a gain up to twenty times was obtained in the network lifetime, with a significant decrease in the amount of transmission by sensors, as compared to a network without any kind of node energy management strategy.**

***Index Terms*—Wireless Sensor Networks, Innovation, Energy, Multihop, Reconstruction.**

I. INTRODUCTION

A Wireless Sensor Network (WSN) is a special kind of ad hoc network, in which nodes are used to sense, process, and communicate data. These data, measured in a certain interest region, are collected and transmitted to a sink node [1].

Some of the major applications of WSNs are military (enemy forces monitoring), medical (telemonitoring of human physiological data), and home and industrial automation [1]. Another important application of WSNs is the monitoring of an interest region, sensing some environmental variables, like temperature, humidity or pressure [2] [3]. We focus on these applications. We use a WSN to monitor a process, modeled as a bidimensional surface that varies with time. The objective is to reconstruct the process in the sink, using data from the sensor nodes and guaranteeing an acceptable reconstruction error, with a low energy consumption for increasing the monitoring period.

Sensor nodes have four main units: a processing unit, a communication unit, a sensing unit, and an energy unit, composed by a battery [1]. Important issues in WSNs are the energy spent by sensor nodes and how to save energy to extend the network autonomy, by increasing it's lifetime. We define the network lifetime as the time until the first node dies, i.e; when its energy ends [4]. Then, energy saving methods must be used to increase the network autonomy [5]. If we consider the process sensing application, using energy saving methods may lead to an increase of the monitoring period.

In general, the communication process (transmission and reception) is the task that spends more energy in a WSN [1]. Then, it is better to process data, instead of transmitting raw data. In [6], a transport protocol for field estimation (application that uses a WSN to sense space-temporally variable processes) is proposed, and it is used to reduce the amount of data sent by sensor nodes. In [7], in order to reduce the energy consumption, the spatial and temporal correlations of the samples measured by nodes are used to decrease the amount of transmissions.

This work proposes an innovation-based algorithm for multihop WSNs. The algorithm aims at saving nodes energy, by managing the transmission necessity, and by using a sleeping mode. Furthermore, it uses a mechanism in which nodes can act as information sources, and also as routers.

The remaining of this paper is organized as follows: in Section II, a concept used to manage the transmission necessity is described; in Section III, the algorithm proposed in this work is presented; in Section IV, energy and simulation models are shown; in Section V, simulation results are presented and discussed; Section VI presents an evaluation of the reconstruction error; and finally, concluding remarks are presented in Section VII.

II. INNOVATION THRESHOLD

In the algorithm proposed in [8], there are two ways to save energy: by using data processing to reduce the amount of communication [1] and by exploiting the inactivity state [9]. In [8], it is considered that the sensed process is smooth, and an Innovation concept is defined. This concept is used to reduce the amount of transmission by sensor nodes, in which the nodes only transmit measured samples having a certain amount of innovation. Nodes transmit the first sample (measured in the interest region); then, each node compares the sensed sample with the last transmitted one. If the percentual variation between these samples is higher than an Innovation Threshold (IT), the node transmits the sample; otherwise not. Considering $x_i(j)$ a measured sample, in which i represents the sensor node and j is the sequential order of samples, a node i will transmit a new measure $j+n$ only if:

$$\frac{|x_i(j+n)-x_i(j)|}{x_i(j+n)} > IT. \tag{1}$$

The algorithm makes sensor nodes switch into an energy saving operation mode (sleep mode) [9] between transmissions. If Δt is the period of time between two innovative transmissions, the respective node will sleep for $t_{in} = \Delta t/2$ seconds.

Therefore, the algorithm increases network autonomy, by extending its lifetime, while its sensor nodes are monitoring some process. An important issue is the impact of reducing the amount of transmissions on the reconstruction of the sensed process (in the sink). When a node is sleeping, the process can vary and this may lead to a reconstruction error. Then, the algorithm has to guarantee that the reconstruction maximum error is lower than an acceptable predetermined value.

The work in [8] uses the this method to save energy in single hop WSNs, in which all sensors nodes can reach the sink within one hop. This work extends this idea, proposing an improved algorithm with the same energy saving principles, but that can be used for multihop WSNs.

III. THE PROPOSED ALGORITHM FOR A MULTIHOP WSN

This work uses a WSN to monitor a process $f(x,y,t)$, function of sensor nodes coordinates x and y, and time t. The algorithm is used to extend the network autonomy, by saving node energy.

In multihop networks, nodes forward data by using a routing protocol, like AODV (*Ad Hoc On-Demand Distance Vector*) [10] [11]. Then, the multihop communication allows the network to cover a larger area and to save more energy than using a single hop communication [1]. Furthermore, in multihop WSNs, several routes are established between the information sources (sensor nodes) and the sink node. Once a route is established, data can flow through forwarding nodes until they reach the sink. Then, it would be reasonable to expect that routing nodes would be awake all the time. In this case, for example, some nodes can be positioned near the interest region (collecting data) and others can simply forward messages (router nodes) until they reache the sink.

In this work, a more general situation is considered. In real scenarios, sensor nodes are randomly spread in some interest region, to sense a process. The main idea is that any node can be an information source (collecting measurements from the process) and also a router, when it is forwarding a data packet. Furthermore, if occurs a phenomenon, like a fire in a forest, any node must be able to collect and transmit this information (acting as a source) and forward it through the network (acting as a router).

In the algorithm proposed, each node can switch to a sleep mode between transmissions. But now, every node must guarantee that the path, once established by the routing protocol, will not be affected when a node sleeps. In the proposed innovation-based algorithm, when a node S_i has to transmit a sample, it attaches its inactivity period (I_{pi}), the period that this node will be asleep, within the message. Then, every node knows the Inactivity periods of its neighbors. Nodes calculate their own Inactivity periods based on the periods of their one-hop neighbors, since they must be awake to forward their messages.

In Fig. 1, we present an example that illustrates this idea. Nodes S_1, S_2 and S_3 are information sources (sensing some process) and the sink is the node S_4. Suppose that, within their transmitted messages, S_1 and S_2 attach their Inactivity periods I_{p1} and I_{p2}, respectively. The node S_3 keeps an Inactivity period vector (I_{pv3}), composed by the Inactivity periods of nodes S_1 and S_2 ([I_{p1},I_{p2}]). When S_3 has to sleep, it calculates its own Inactivity period (I_{p3}), but it can sleep just for a period equal to the half of the minimum value between I_{p1}, I_{p2} and I_{p3}, so that the node does not lose any information. Then, the node S_3 will sleep for t_{in3} seconds, as shown in Eq. (2):

$$t_{in3} = \frac{1}{2} \times min(I_{p1}, I_{p2}, I_{p3}). \qquad (2)$$

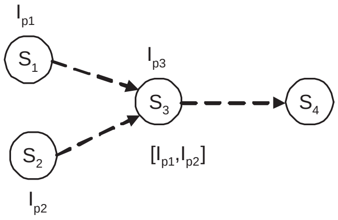

Fig. 1. Example that illustrates nodes and their Innovation periods.

When S_3 wakes up, it calculates its Inactive period (I_{p3}) again, and forwards its neighbors messages.

Doing this, the algorithm makes node S_3 to save energy, as it will sleep for t_{in3} seconds, and enforce it to be awake to forward messages transmitted by its one hop neighbors. This process is done by all sensor nodes, imposing small effects on the network connectivity by the sleeping nodes.

Another important issue is that the algorithm operates directly in the application layer. From the above example, when the node S_3 receives a message that comes from its neighbors, it passes the message to the application layer to update the Inactivity periods in I_{pv3}. Then, when it measures a sample from the environment, the innovation test occurs, using Eq. (1), and all data processing is done in this layer. The idea is that the algorithm is as generic as possible, regardless of the routing protocol.

The innovation-based algorithm steps (for each node S_i) is presented bellow:

```
$j \leftarrow 1$
$I_{pi} \leftarrow 0$
while ($energy_i > 0$) do
  $s_i$ measures $x_i(j)$
  if ($j = 1$) then
    $s_i$ transmits $x_i(j)$
    $Tx_i \leftarrow x_i(j)$
    $t_i(j) \leftarrow$ transmission time
    $tr \leftarrow t_i(j)$
  else
    if ($\frac{|x_i(j) - Tx_i|}{Tx_i} > IT$) then
      $s_i$ transmits $x_i(j)$
      $Tx_i \leftarrow x_i(j)$
      $t_i(j) \leftarrow$ transmission time
      $I_{pi} \leftarrow \frac{t_i(j) - tr}{2}$
      $tr \leftarrow t_i(j)$
      if $I_{pvi}$ (is empty) then
        $S_i$ sleeps for $I_{pi}$
      else
        $S_i$ forwards the packets
        $I_{pvi} \leftarrow I_{pi}$
        $I_{pi} \leftarrow \frac{1}{2} \times \min(I_{pvi})$
        $S_i$ sleeps for $I_{pi}$
      end if
      $s_i$ wakes up after $I_{pi}$
    end if
  end if
  $j \leftarrow j+1$
end while
```

IV. ENERGY MODEL AND SIMULATION ASPECTS

The energy model used in this work is a state-based model, in which the nodes may operate in two states: inactive or active. The inactive state (sleep mode) is an energy saving mode [9]. The active state is composed by four operation modes: measuring, processing, transmission, and receiving. The proposed energy model takes into account the packet payload size, and it is based on [12], an empirical energy model, obtained using the TELOS commercial hardware [13], in which it is observed that the energy consumption and the packet payload size are linearly related (in the transmission mode).

We can estimate a node energy consumption E_C, as a function of the time period in which the node stays in a given operation mode, by Eq. (3).

$$E_C = t_I \times C_I + t_A \times C_A + t_M \times (C_A + C_M) + t_P \times (C_A + C_P) + t_R \times (C_A + C_R) + t_T \times (C_A + C_T). \tag{3}$$

From the Eq. (3), t_I, t_A, t_M, t_P, t_R and t_T are, respectively, the time periods of inactive, active, measuring, processing, receiving and transmitting states, and their associated consumptions C_s are presented in Table I.

The simulations were performed in TrueTime 1.5 [14] [15], a simulation environment based in MatLab/Simulink and the network standard was the IEEE 802.15.4 [16]. Table I shows main static parameters used in the simulations.

TABLE I
STATIC PARAMETERS OF THE SIMULATIONS.

`Node initial energy (J)`	`2`
`Transmission power (dBm)`	`-5`
`Reception sensibility (dBm)`	`-66`
`Radio range (m)`	`40`
C_I`:Consumption in inactive state (mJ/s)`	`1,8`
C_A`:Consumption in active state (mJ/s)`	`10`
C_M`:Consumption in measuring mode (mJ/s)`	`18`
C_P`:Consumption in processing mode (mJ/s)`	`18`
C_R`:Consumption in receiving mode (mJ/s)`	`62,4`
C_T`:Consumption in transmitting mode (mJ/s)`	`58,62`
`Payload size (Byte)`	`1`

In the simulations presented in this work, a smooth process, function of the sensor nodes coordinates x and y, and the time t is considered. The process is described by:

$$f(x,y,t) = [e^{\frac{-(x-m_x)^2}{2 \cdot dp_x^2}} + e^{\frac{-(y-m_y)^2}{2 \cdot dp_y^2}}] \times [e^{\frac{-(t-m_t)^2}{2 \cdot dp_t^2}}] + C. \tag{4}$$

For the sensed process, $m_x = m_y = m_t = 40$ are means of x, y and t; $dp_x = dp_y = dp_t = 20$ are standard deviations of x, y e t, and $C = 5$ is a constant value. This function was used to evaluate the algorithm in a generic way. Fig. 2 illustrates the surface for $t = 0$, in a $80m \times 80m$ cover area.

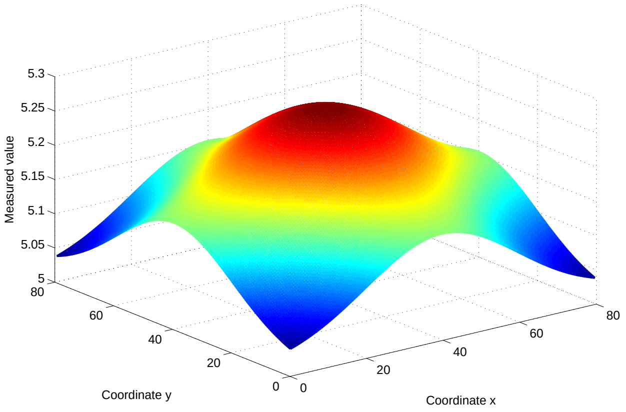

Fig. 2. Sensed surface for $t = 0$ (in a $80m \times 80m$ cover area).

The routing protocol used in the simulations is AODV [10]. We have evaluated the algorithm using static routes. Therefore, two parameters of this routing protocol were modified, the *hello interval* and the *active route timeout* [10]. The first one is a parameter used to check the local connectivity of a given path. Periodically, nodes broadcast a *hello* message. When one of its one-hop neighbors receives this message, it sends an acknowledgment to confirm that it is active. If the sender node does not receive the *ACK* in a few tries, it assumes that the route is broken and, then, a new route is created by the protocol. The *active route timeout* is a parameter that defines if a route is active. If no data packets are sent during this timeout interval, the route is disabled. So, to make static routes, this two parameters were defined with high values.

Table II shows two other simulation parameters: the amount of nodes in the network and the area covered by the multihop WSN. For each scenario, the sink node was placed in the right most and vertically centered position of the monitored region and the sensor nodes were scattered randomly.

TABLE II
SIMULATION SCENARIOS (SCALABILITY X AREA).

`7 nodes`	`80`m `x 80`m
`15 nodes`	`140`m `x 140`m
`30 nodes`	`200`m `x 200`m
`50 nodes`	`250`m `x 250`m

V. SIMULATION RESULTS

This Section presents the results obtained. Each simulation was run ten times, and a 90% confidence interval for the mean is used in the presented graphs.

Fig. 3 shows the percentual increase of the network lifetime (with respect to the simulations without any energy management) in contrast with the Innovation Threshold (IT). In simulations without energy saving methods, transmissions occurs each 0.1 seconds. It can be observed that the increase of the threshold leads to a gain in the network lifetime. For greater thresholds, nodes only transmit samples having a greater percentual variation. Then, the overall amount of transmission is reduced. Furthermore, nodes stay longer in sleep mode. It is also observed that, as we increase the number of nodes in the network, the lifetime increases as well.

The same behavior is observed with respect to the decrease of the amount of transmissions as the Innovation Threshold is increased, as in Fig. 4. In fact, the percentual reduction of the amount of transmissions (with respect to the simulations without any energy management) in association with the transitions to the sleep mode, leads to gains in network lifetime, because sensor nodes can save more energy.

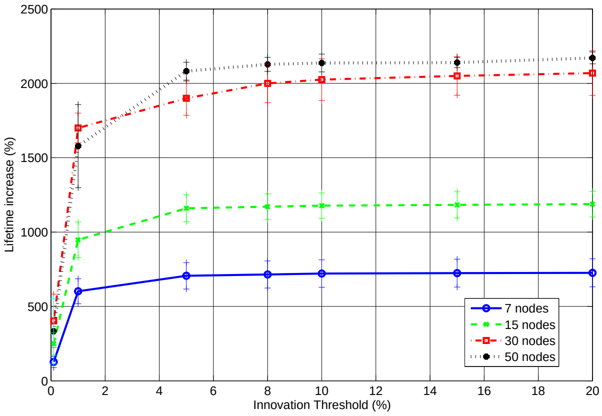

Fig. 3. Normalized network lifetime x Innovation Threshold.

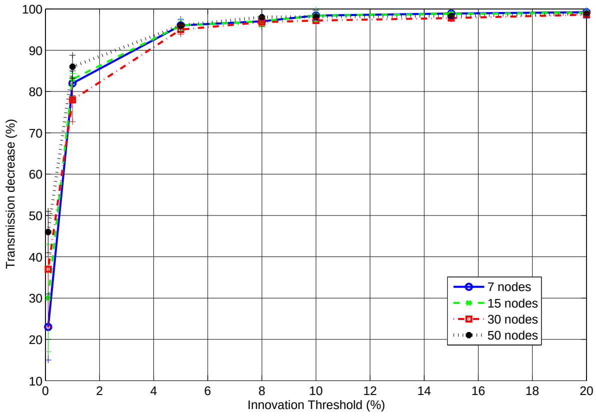

Fig. 4. Percentual transmission reduction x Innovation Threshold.

Fig. 5 shows the packet delivery ratio [16] in function of the Innovation Threshold. This metric evaluates the network connectivity, using the ratio between received and sent packets. It can be seen that the ratio decreases with the increment of the threshold. As the Innovation Threshold increases, the reduction in the amount of transmission also increases. For a small number of transmissions, any missing packet leads to a greater impact in the evaluated metric. When IT increases, each node sleeps for longer periods of time, and it also affects the packet delivery ratio. Furthermore, it can be observed that this ratio decreases with the network scalability, i.e., when the amount of nodes in the network becomes larger, there are more transmitted messages.

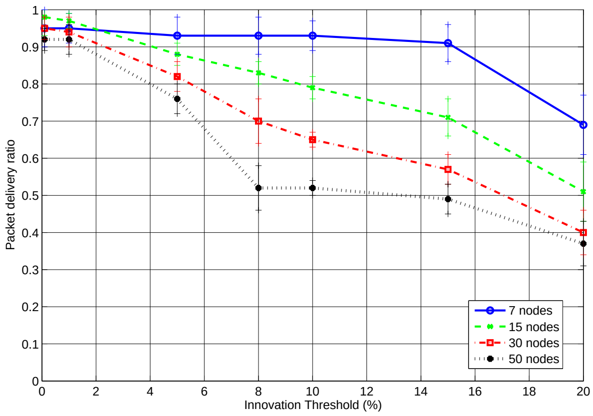

Fig. 5. Packet delivery ratio of the network.

VI. RECONSTRUCTION ERROR ANALYSIS

This Section presents a statistical analysis of the reconstruction error of the process. The application evaluated in this work aims at using a WSN to sense a given process and to reconstruct it, from samples sent by sensor nodes. Fig. 6 shows the Cumulative Distribution Function (CDF) of the reconstruction error, for each Innovation Threshold (for fifteen nodes). It evaluates the probability of the reconstruction error being smaller than a given threshold. Furthermore, Table III shows some statistical analysis of the reconstruction error, in which IT is the Innovation Threshold, AE is the average error (for each IT) and MRE is the maximum reconstruction error (for each IT). To calculate the CDF, we consider that the sensor nodes coordinates are fixed (x_i and y_i) and we also consider a continuous time t. Then, the reconstruction error is given by:

$$e(x_i,y_i,t) = f(x_i,y_i,t) - \hat{f}(x_i,y_i,t). \quad (5)$$

In Eq. (5), $f(x_i,y_i,t)$ is the monitored process and $\hat{f}(x_i,y_i,t)$ is the reconstructed one.

In Fig. 6, it can be observed an increase of the reconstruction error with the increment of the IT, as expected. It can be observed, in Table III, that larger percentual errors occur for lower ITs. For higher thresholds, the average error is closer to IT, as observed in the column AE/IT.

As this work uses a WSN to make an energy-efficient sensing of a given process $f(x,y,t)$, it is important to evaluate the trade-off between the increase of the network lifetime and the reconstruction error. It can be observed (in Fig. 3) that, for thresholds above 5%, network lifetime almost stops increasing. However, the average error increases, as far as the Innovation Threshold increases, as shown in Table III.

VII. CONCLUSION AND FUTURE WORKS

This work discusses the problem of using a multihop WSN to sense a given process. An energy-efficient and innovation-based algorithm is proposed for that purpose.

The algorithm considers that sensor nodes can act as a sources of information and also as a routers. Furthermore, a mechanism that tries to guarantee that the nodes sleep (for saving energy) but also awake to forward messages from its neighbors is employed.

The results show that a gain up to twenty times was obtained in the network lifetime, with respect of the simulations without energy management, with a significant decrease in the amount of transmissions by sensor nodes. It was seen that, for Innovation Thresholds longer than 5%, there is no significant increase in the lifetime, but the reconstruction error largely increases. It seems to be a trade-off between lifetime gain and reconstruction error.

For future works, it is intended to make an analytical analysis of the error behavior and the IT. The objective is to set an acceptable error and calibrate IT. It is also intended to test the proposed algorithm in a WSN that uses other routing protocols, like AODV-E (*Energy-Aware AODV*) [17], an improved variant of AODV that provides a better energy consumption balance.

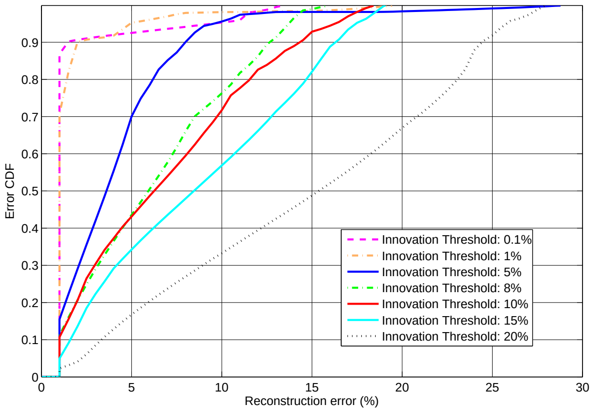

Fig. 6. Reconstruction error CDF.

TABLE III
RECONSTRUCTION ERROR STATISTICS.

IT	AE	MRE	AE/IT	MRE/IT
0,1%	0,9%	1,9%	9	19
1%	1,3%	3%	1,3	3
5%	4,2%	6%	0,84	1,2
8%	6,3%	9,4%	0,79	1,17
10%	7%	18%	0,7	1,8
15%	8,7%	19%	0,58	1,27
20%	14,6%	27%	0,73	1,35

VIII. ACKNOWLEDGMENT

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