Lifetime Maximization With Multiple Battery Levels in Irregularly Distributed Wireless Sensor Networks

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Abstract—**The recent advances in Wireless Sensor Networks technologies have shown that while computational limitations are transient issues, energy limitations are much more complicated problems. Due to the very nature of Wireless Sensor Networks, motes are generally powered from small batteries. Consequently, the amount of available energy is often scarce and the replacement of worn-out batteries in such systems is unthinkable. The problem is aggravated by the fact that the energy consumption rate varies from mote to mote thus leading to situations of premature death of network albeit most batteries in the network still hold a significant amount of energy. In this work, a strategy aiming to increment the lifetime of Wireless Sensor Networks is proposed. In the proposed strategy, batteries with different capacities are assigned to motes in inverse proportion to their consumptions. The energy consumption of a mote results from an estimate that is made of the signal routing, assuming that the network is time driven while the topology of the network is irrelevant. The proposed strategy was validated by means of simulations using mote models with realistic parameter values. Several different network topologies were evaluated and the results have proved that the proposed strategy is an effective means of extending the lifetime of WSN. Increases in lifetime exceeding 200% were obtained in several simulated cases.**

Keywords – Wireless Sensor Networks; battery; reallocation; mote; lifetime.

I. Introduction

Wireless Sensor Networks [1, 2] are important and valuable systems that emerged recently and, more and more, are reaching a substantial role on many types of applications.

The prediction made by Moore on 1965 [3] still working for any equipment that uses electrical circuits, turning computational limitations (*hardware* and *software*) just transient issues. Unfortunately, all electronic devices need electrical energy to work, turning any issue related with it a serious problem.

The operation of Wireless Sensor Networks is based on the cooperative behavior of many motes spread over a determined area, generally relying only on their own batteries. How the motes have no other energy source and changing the batteries of each mote spread over a wide area is such a difficult task, energy problems related to Wireless Sensor Networks are really serious.

It would be reasonable to imagine that the best solution to increase network lifetime would be just give the largest amount of energy possible to each mote. Nevertheless, as pointed out in [4], in some cases, 90% of the energy of a network is not used even when the network is inoperative.

Recent works show [5-13] that energy consumption of each mote is not uniform and varies depending on the mote's location. This effect was more in-depth studied on circular networks and the consequence of the unbalanced consumption, which leads to a fatal interruption of message flow toward the base station, has been called *Energy Hole* or *Doughnut Effect* [10-13]. Two known strategies have proven to be effective mechanisms to increase the lifetime of circular networks: one is based on increasing the number of motes (density) near the *base station* [10, 11] while the other suggests to allocate more batteries on the motes near the base station [12, 13]. Both strategies address the problem of a wireless sensor network lifetime by allocating more energy on a specific area of the network.

The strategies of energy reallocation proposed in [10-13] are very effective, but restricted to circular networks. In this work a similar strategy of energy reallocation is proposed, which however is not bound to any specific physical topologies, allowing its use on WSN implemented without rules of mote positioning.

II. Energy Consumption in Wireless Sensor Networks

Some works [10-13] presented very valuable observations and strategies for **circular** Wireless Sensor Networks, achieving interesting results related to energy wasting and lifetime increment. They achieved those successful results by allocating more energy on some specific areas of well-distributed **circular** networks. But there are some differences between their scenarios and a real implemented network.

In real-world scenarios, there are many obstacles that can forbid a perfect *physical* or *logical* organization of a network,

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which are required by those known strategies. Natural or artificial obstacles like trees, lakes, rocks, buildings, walls etc. or even the shape of the field where the network will be installed can forbid the construction of a network with a circular pattern or even any other type of perfect-organized physical topology.

Due the requirement of a perfect organization of a circular network and the difficulties related to their construction, required by [10-13], there is a need of a more embracing strategy aiming the lifetime increment of Wireless Sensor Networks.

A. Main Assumptions

In order to make a feasible and correct approach, some wide known assumptions were considered on this work. Like on [10-14], this work was made assuming a *time-driven* network. The choice of *time-driven* networks was made because of its well-known and repetitious behavior, which are very important points for estimations and predictions of their energy consumption.

In order to generate new messages, it was considered that a mote had to read its sensors just once. It was also assumed that there was no influence of the weather on energy consumption of the motes.

B. Notation

In order to organize all the formulation used on this work and for ease of reference, all notations are defined here.

B_{abs}	Absolute burden of a mote.
Ec	Energy consumption of a mote.
E_{sens}	Energy required to a mote read all its sensors.
E_{Tx}	Energy required to transmit a message.
E_{Rx}	Energy required to receive a message.
F_{Rx}	Quantity of received message flows.
f	Generation frequency of new messages.
T	Network Cycle.
M_{Rr}	Number of messages **rerouted** by a mote.
M_{Rx}	Number of messages **received** by a mote.
N_m	Set containing all neighbors of mote *m*
$P_{or}l$	Portion of message flows that will be routed through a link.
Ql_{msg}	Quantity of generated-message flows sent through a link.
Ql_{Rrmsg}	Quantity of rerouted-message flows forwarded through a link.
w	Number of motes of the network.

C. Energy Consumption Estimation

Due to their large number of motes, need of having cooperative behavior and the intrinsic mutual interference between them, energy consumption is a complex problem on WSN. Consequently, all the analysis about this subject has to consider not only a single mote, but also all the actions that it and all other motes of the WSN do.

Since in *time-driven* networks actions occur at the pace of clock, within a constant time period, T, the frequency with which a mote *n* generates new messages (or new *traffic*) can be defined as:

$$f_m = \frac{\text{generated messages}}{\text{T}} \tag{1}$$

By knowing the links between a mote and its neighbors and the way those links are used by them to exchange their messages, it is possible to estimate how many messages are forwarded through each link. Using the generation frequency of a mote *n* and how it uses each link between it and its neighbors, the quantity of generated-message flows forwarded through a link *x* can be defined as:

$$Ql_{msg_x} = P_{or}l_x \times f_m \tag{2}$$

The way that a link between motes is used varies with the protocol used. Each protocol has its own routing policies like, for example, the use of virtual neighborhood notions (used by VCP [15]) or asking each neighbor and choose the one with more energy left [10, 11].

Upon finding the quantity of generated-message flows sent through each link of a network, it is possible to estimate how many messages a mote will receive and, consequently, how many messages a mote will reroute by network cycle. Using the quantity of received messages of a mote *m* and how it uses each link between it and its neighbors to forward its received messages, the quantity of rerouted-message flows forwarded through a link *x* can be defined as:

$$Ql_{Rrmsg_x} = P_{or}l_x \times F_{Rx_m} \tag{3}$$

As properly stated in [16, 17], a mote does not receive only messages addressed to it, it also receives messages sent by its neighbors addressed to other motes. Although it sounds strange, but a mote will only know who is the target receiver of a message after processing the message. Consequently, when analyzing an entire network, each mote will have a specific burden that will affect. This burden, in terms of energy consumption, is the number of **generated** and **rerouted** messages sent by a mote for by a network cycle. In this work, this burden is called "*absolute burden*", and its definition is:

$$B_{abs_m} = M_{Rr_m} + f_m \tag{4}$$

Knowing the absolute burden of all motes of a networks, the quantity of messages that a mote will receive by network cycle can be find by simply analyzing its neighbors:

$$M_{Rx_m} = \sum_{i=1}^{w} B_{abs_i} \quad \text{,where } B_{abs_m} = 0 \ \forall\, i \notin N_m \tag{5}$$

After having all values by using (1-5), it is possible to estimate the energy consumption, by network cycle, of each mote of a network by using the following equation:

$$Ec_m = f_m(E_{sens_m}) + B_{abs_m}(E_{Tx_m}) + M_{Rx_m}(E_{Rx_m}) \qquad (6)$$

It is important to observe that (6) does not have any consumption related to *idle* state of motes. In cases that have long network cycles (and consequent larger idle state consumption), the absence of idle state consumption may generate some error. Consequently, for long network cycles, (6) must take to account idle state consumption by simply adding it in the equation.

III. Scenarios, Simulations and Results

The validation of the strategy proposed on this work was made by mean of simulations. Some scenarios were planned to test the strategy efficiency and its deficiencies.

A. Simulator

In order to accomplish an adequate evaluation of the dynamics of energy consumption in WSN, an open-source simulator called *Barrier Synchronization Simulator* [18] was chosen due to allowing unrestricted access to its main functions and its easiness to modify and create new classes and methods.

B. Mote

The mote used on the simulations was built using models of common and well-accepted commercial devices and parts.

- Battery: Panasonic Coin Batteries [19-21].
- Sensor: SHT11 [22].
- Radio Transceiver: CC2500 [23].
- Antenna: W1030 [24].
- Processing Unit: ATMEGA8 [25].

C. Protocols and Network Behavior

To send and reroute generated and received messages, all motes obeyed the policy of dividing equally all messages among its neighbors nearer base station (*successors*), shown on **Fig. 1**. For medium access control (MAC), it was used IEEE 802.11 RTS/CTS [26] and pure CSMA protocol [27].

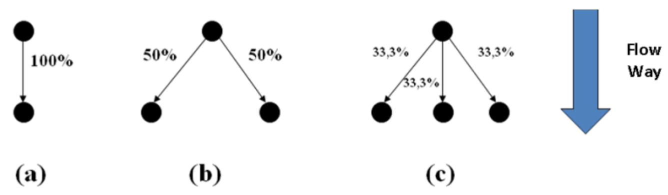

Figure 1 – Sending and routing policy.

D. Networks

In order to test the strategy efficiency, three different networks were made. The first network, showed on **Fig. 2**, was made to study impacts of the strategy on circular networks (like in [10-13]). The second network and third network, showed on **Fig. 3** and **Fig. 4**, were made to study impacts of the strategy on irregularly distributed networks, which is most common on real scenarios. It is important to elucidate that the base station displacement of **second** and **third**, in comparison to first network, network has a high impact on their regularity because all motes have to send their messages towards base station.

All networks had 34 motes.

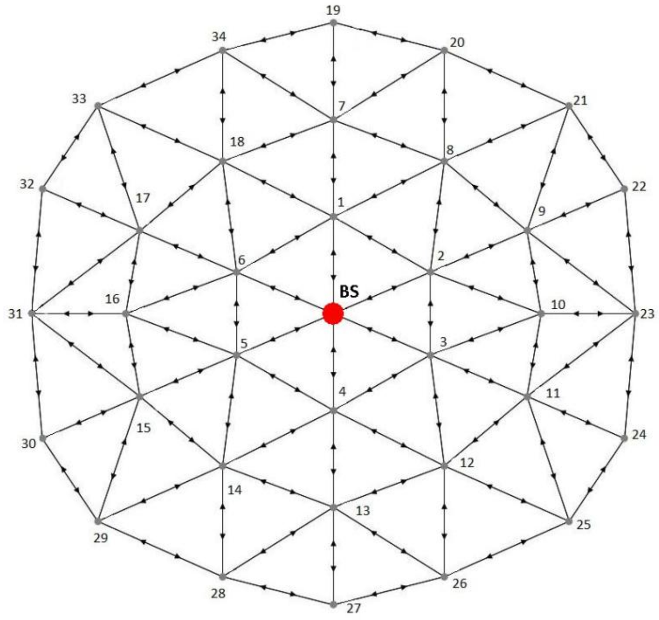

Figure 2 – Network I.

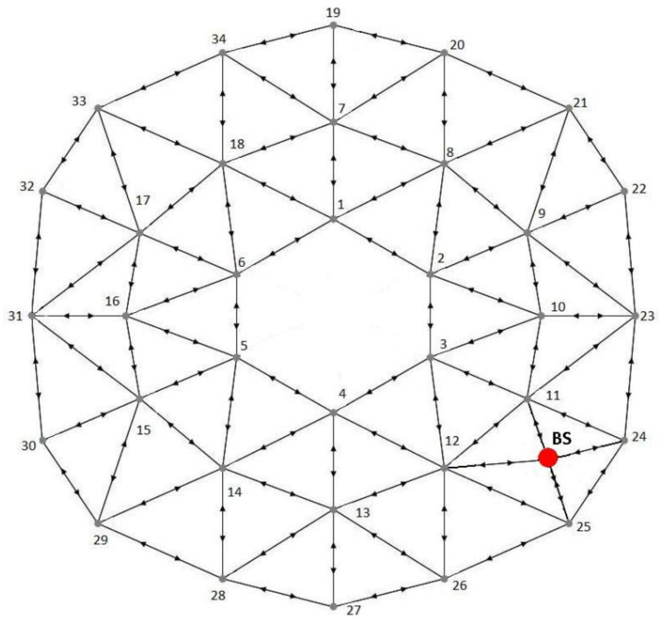

Figure 3 – Network II.

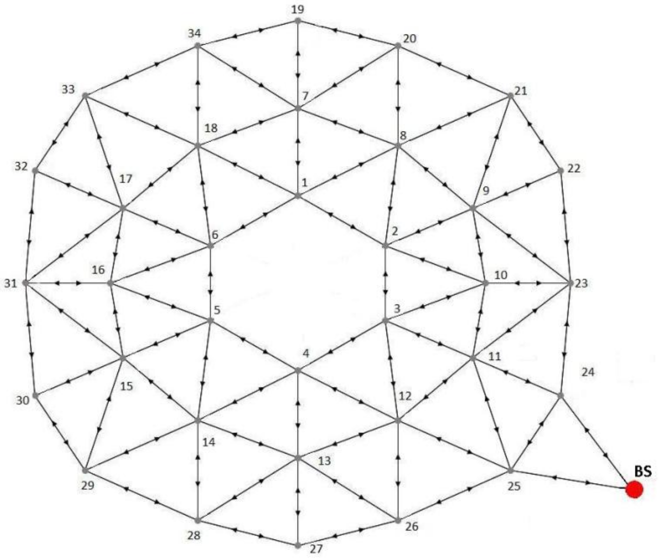

Figure 4 – Network III.

E. Simulations

All simulations were made keeping almost the same energy budget used on normal network (all motes with the same battery). In this work, normal networks had all motes equipped with 225 mAh batteries. After estimating the energy consumption of all motes, each mote was assigned a set of batteries (or a single battery), with capacity proportional to its energy consumption. The use of battery sets was made in order to reach values as close as possible to estimated values.

Battery with remaining charge of less than 1 mAh on a mote was used as stopping condition.

1) Simulations Using pure CSMA/CA

a) Network I

Simulation results of this scenario were:

- Increment of 62.5% on its lifetime, shown on **Fig. 5**.
- Reduction of energy waste from 40% (**Fig. 6**) to less than 3% (**Fig. 7**.)
- Error of less than 0.7% on energy consumption estimation (**Fig. 8**.)

Energy reallocation of this scenario is shown on **Fig. 9**.

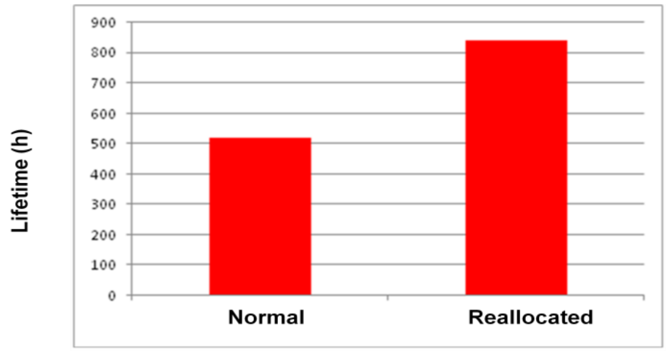

Figure 5 – Network I: Lifetime comparison (pure CSMA).

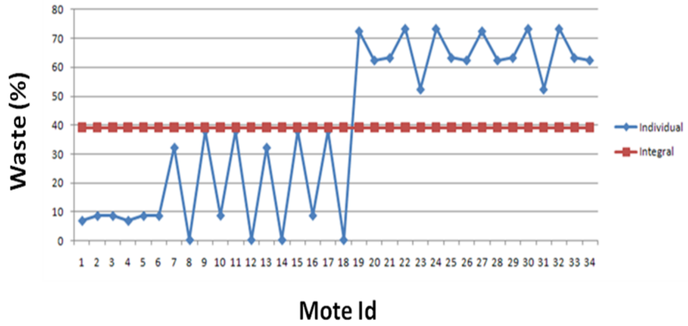

Figure 6 – Network I: Energy waste of normal energy distribution (pure CSMA).

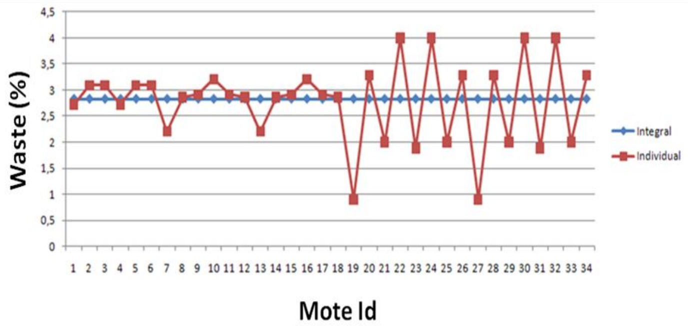

Figure 7 – Network I: Energy waste of reallocated energy distribution (pure CSMA).

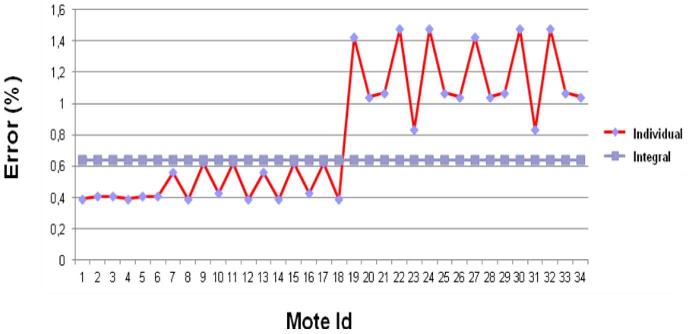

Figure 8 – Network I: Estimation error (pure CSMA).

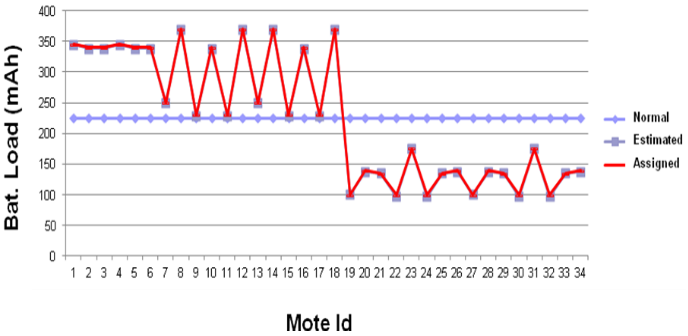

Figure 9 – Network I: Energy assignment (pure CSMA).

b) Network II

Simulation results of this scenario were:

- Increment of 165.44% on its lifetime, shown on **Fig. 10**.
- Reduction of energy waste from near 63% (**Fig. 11**) to less than 3% (**Fig. 12**.)
- Error of less than 0.5% on energy consumption estimation (**Fig. 13**.)

Energy reallocation of this scenario is shown on **Fig. 14**.

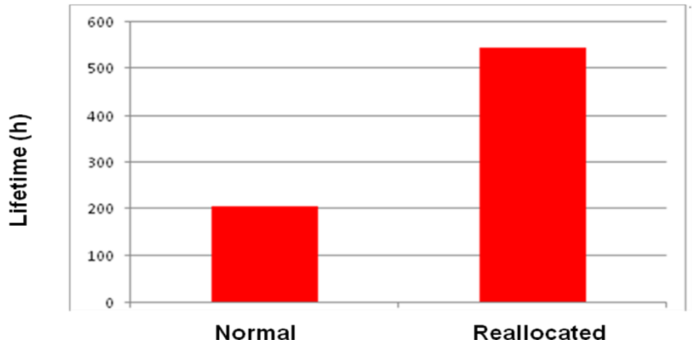

Figure 10 – Network II: Lifetime comparison (pure CSMA).

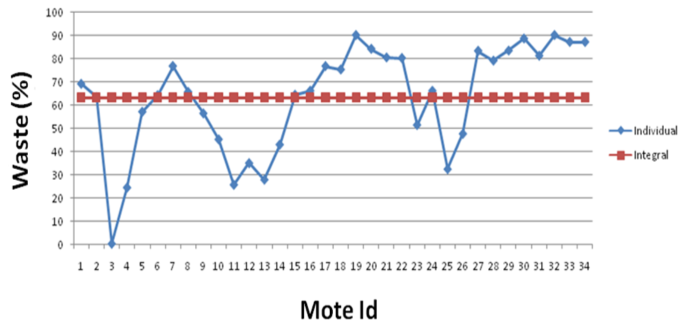

Figure 11 – Network II: Energy waste of normal energy distribution (pure CSMA).

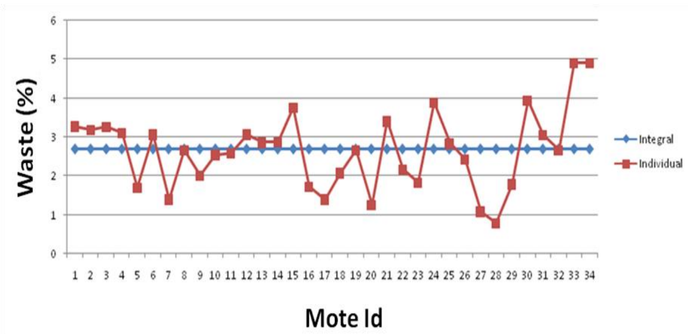

Figure 12 – Network II: Energy waste of reallocated energy distribution (pure CSMA).

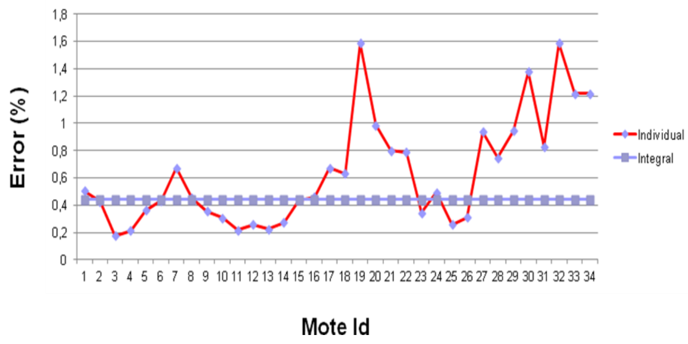

Figure 13 – Network II: Estimation error (pure CSMA).

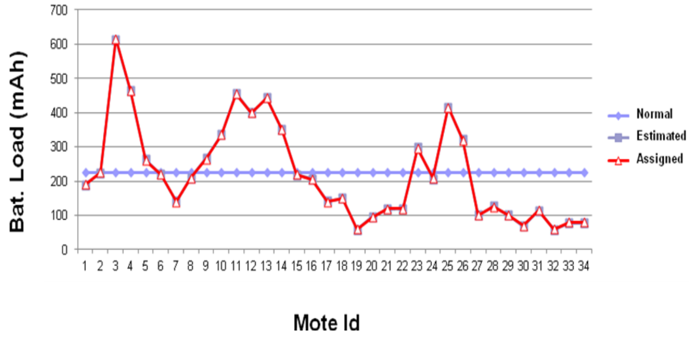

Figure 14 – Network II: Energy assignment (pure CSMA).

c) Network III

Simulation results of this scenario were:

- Increase of 222.27% on its lifetime, shown on **Fig. 15**.
- Reduction of energy waste from almost 70% (**Fig. 16**) to less than 6% (**Fig. 17**.)
- Error of less than 0.4% on energy consumption estimation (**Fig. 18**.)

Energy reallocation of this scenario is shown on **Fig. 19**.

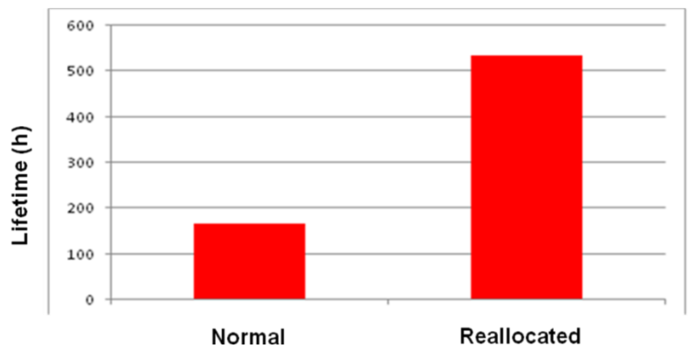

Figure 15 – Network III: Lifetime comparison (pure CSMA).

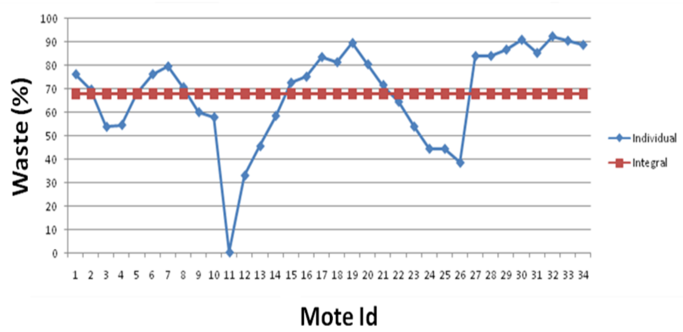

Figure 16 – Network III: Energy waste of normal energy distribution (pure CSMA).

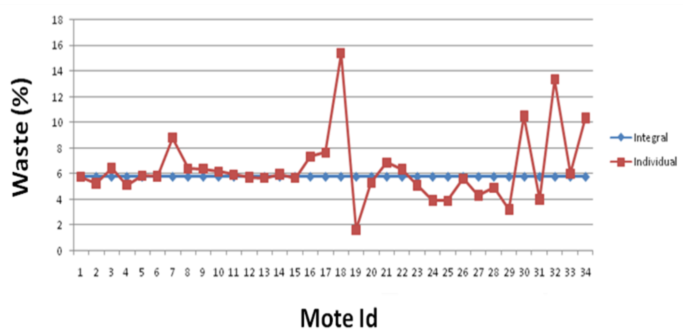

Figure 17 – Network III: Energy waste of reallocated energy distribution (pure CSMA).

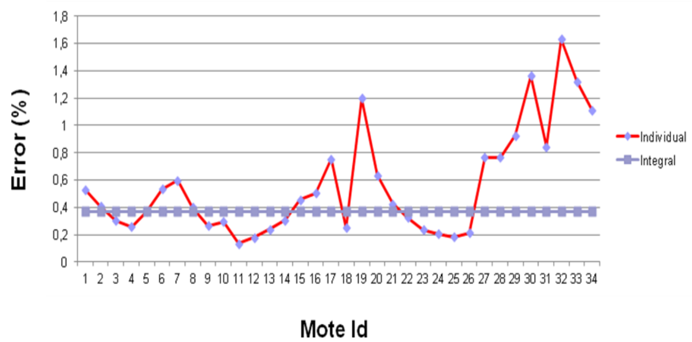

Figure 18 – Network III: Estimation error (pure CSMA).

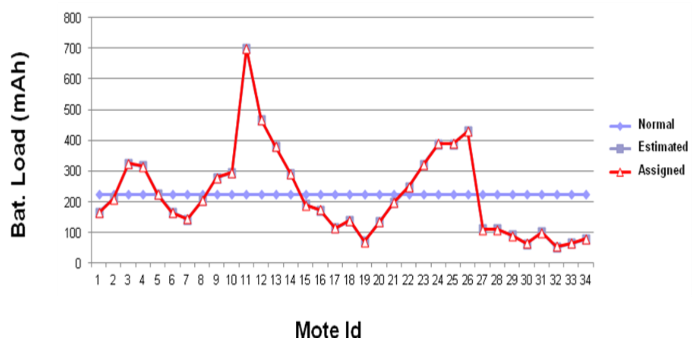

Figure 19 – Network III: Energy assignment (pure CSMA).

2) *Simulations Using IEE 802.11 RTS/CTS*

a) *Network I*

Simulation results of this scenario were:

- Increase of 149.43% on its lifetime, shown on **Fig. 20**.
- Reduction of energy waste from near 60% (**Fig. 21**) to less than 6% (**Fig. 22**.)
- Error of less than 0.2% on energy consumption estimation (**Fig. 23**.)

Energy reallocation of this scenario is shown on **Fig. 24**.

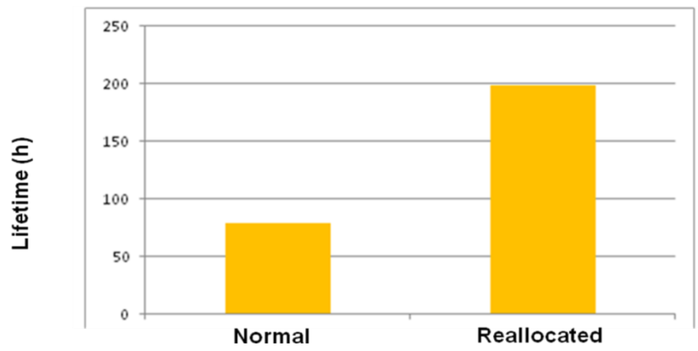

Figure 20 – Network I: Lifetime comparison (IEEE 802.11).

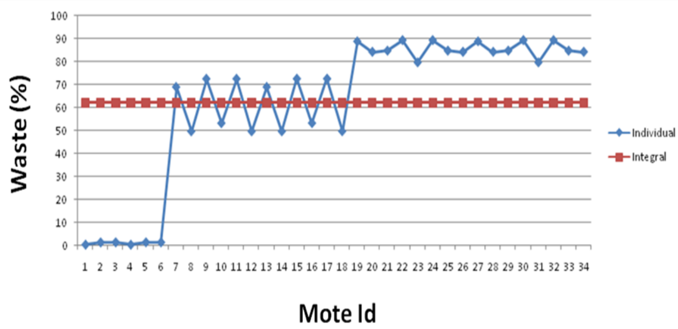

Figure 21 – Network I: Energy waste of normal energy distribution (IEEE 802.11).

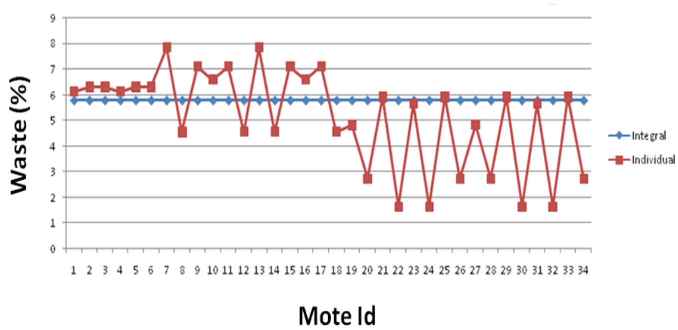

Figure 22 – Network I: Energy waste of reallocated energy distribution (IEEE 802.11).

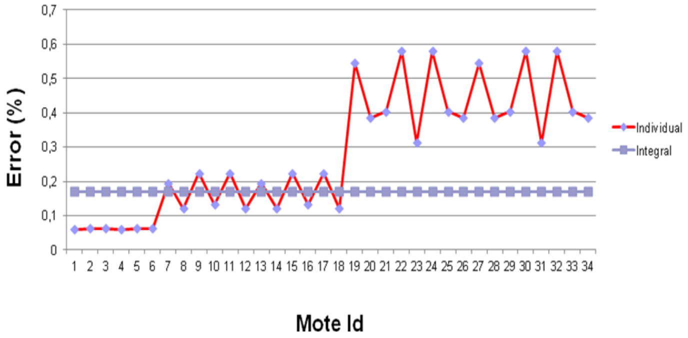

Figure 23 – Network I: Estimation error (IEEE 802.11).

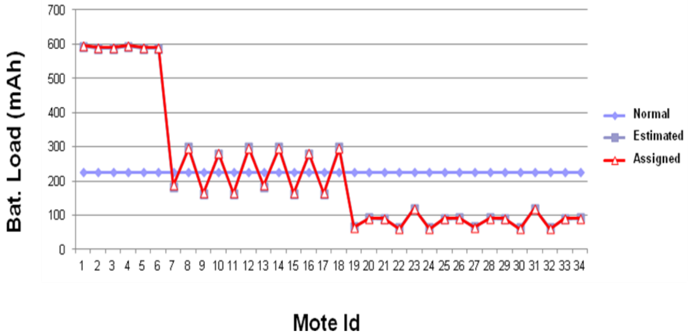

Figure 24 – Network I: Energy assignment (IEEE 802.11).

b) Network II

Simulation results of this scenario were:

- Increase of 172.39% on its lifetime, shown on **Fig. 25**.
- Reduction of energy waste from near 65% (**Fig. 26**) to near 5% (**Fig. 27**.)
- Error of near 0.1% on energy consumption estimation (**Fig. 28**.)

Energy reallocation of this scenario is shown on **Fig. 29**.

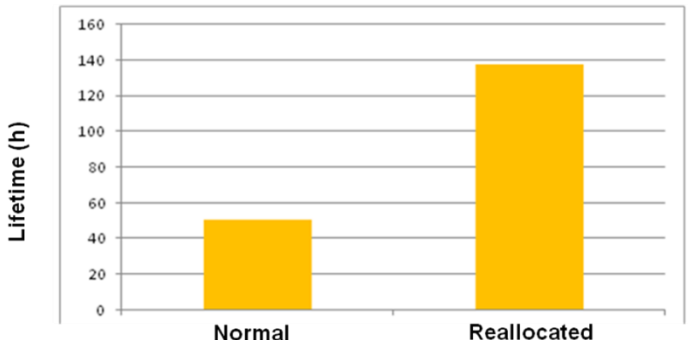

Figure 25 – Network II: Lifetime comparison (IEEE 802.11).

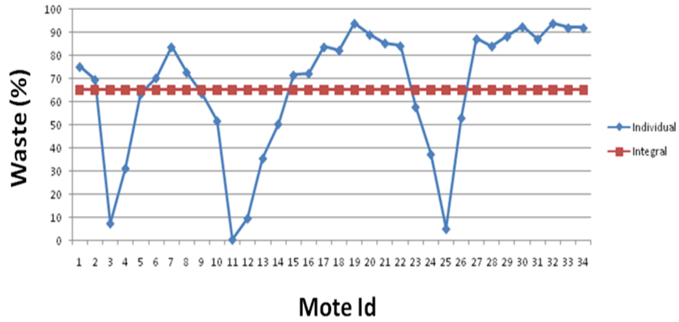

Figure 26 – Network II: Energy waste of normal energy distribution (IEEE 802.11).

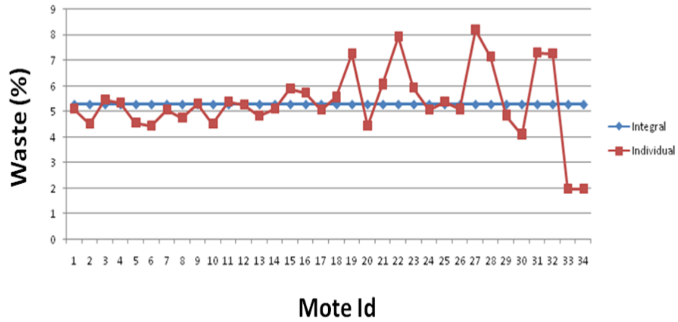

Figure 27 – Network II: Energy waste of reallocated energy distribution (IEEE 802.11).

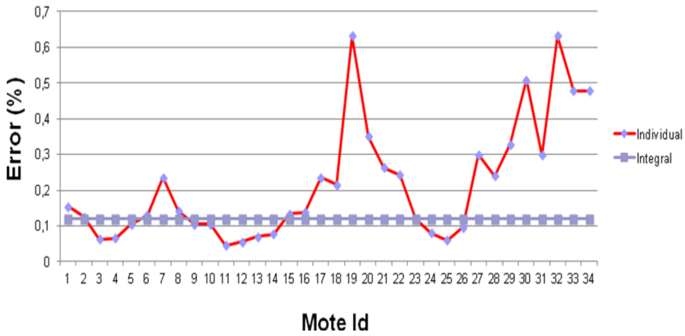

Figure 28 – Network II: Estimation error (IEEE 802.11).

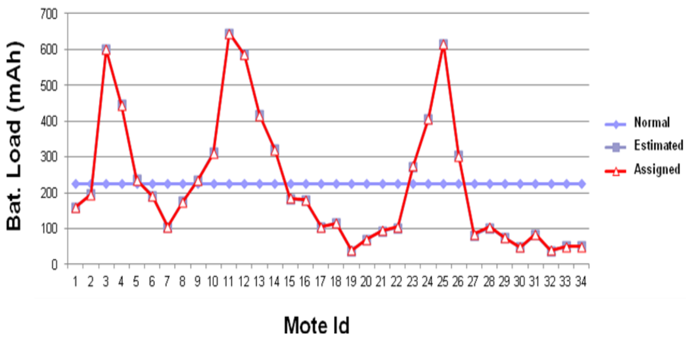

Figure 29 – Network II: Energy assignment (IEEE 802.11).

c) Network III

Simulation results of this scenario were:

- Increase of 201.59% on its lifetime, shown on **Fig. 30**.
- Reduction of energy waste from almost 70% (**Fig. 31**) to near 6% (**Fig. 32**.)
- Error of near 0.1% on energy consumption estimation (**Fig. 33**.)

Energy reallocation of this scenario is shown on **Fig. 34**.

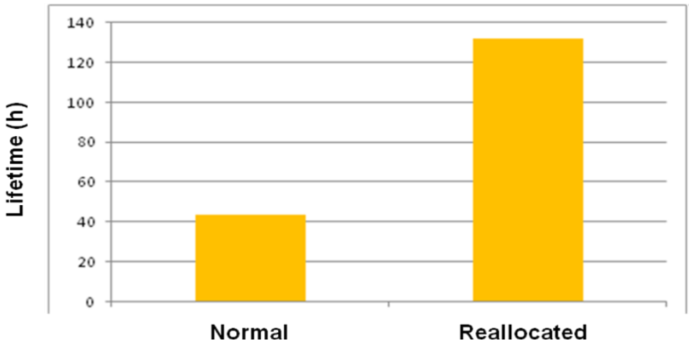

Figure 30 – Network III: Lifetime comparison (IEEE 802.11).

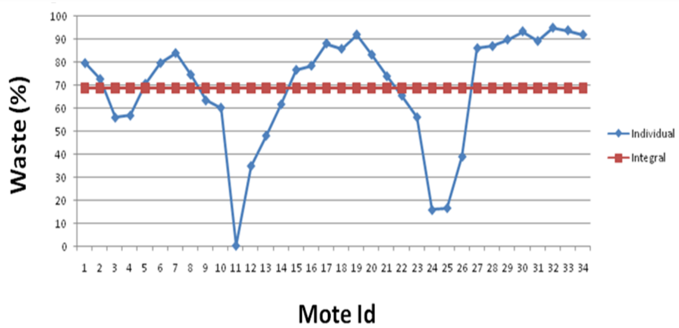

Figure 31 – Network III: Energy waste of normal energy distribution (IEEE 802.11).

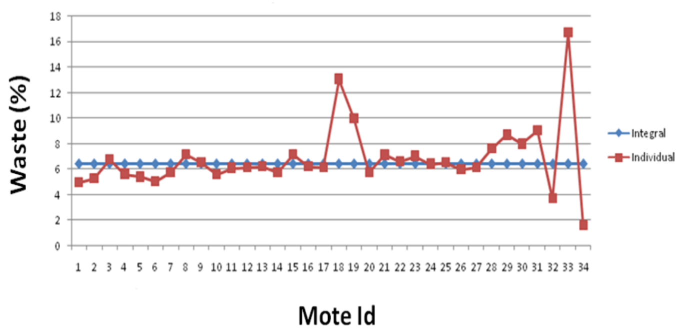

Figure 32 – Network III: Energy waste of reallocated energy distribution (IEEE 802.11).

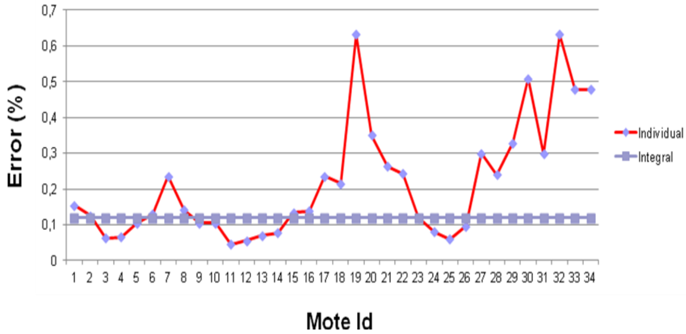

Figure 33 – Network III: Estimation error (IEEE 802.11).

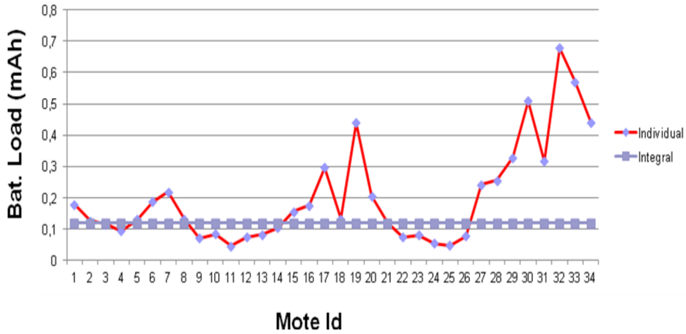

Figure 34 – Network III: Energy assignment (IEEE 802.11).

IV. Conclusions

The strategy devised to increase the lifetime of time-driven WSN proposed in this work was validated through exhaustive simulations, which showed that it is effective and unbound to particular network topologies. In all simulated scenarios the lifetime was increased, in many cases exceeding 200%, suggesting that its use is an important solution to reduce the waste of energy in systems of this nature, particularly in networks with irregular mote-distribution, to which previous similar solutions are not applicable.

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