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***Abstract* — The evolution of wireless communications and embedded system had lead to a big acceptance of Wireless Sensor Networks (WSNs): network of few to hundreds of thousands of sensor nodes, often with low processing and energy capacities that are capable of physical measurements and ambient monitoring, like temperature, humidity and light.**

Considering their limited resources it becomes necessary to support mechanisms that ensure rational use of their resources. It is in this context that we examine routing protocols, and show how these can be energy conscious by avoiding nodes with less spare energy.

Was evaluated six energy based metrics with the objective to make capable the study of some metrics that they can be used for the routes selection in wireless sensor networks and then verify which of them adjust better to the new context introduced in the routing problem by these networks.

***Index Terms* —Routing protocols, Energy conservation, Sensor networks, Resource management**

I. INTRODUCTION

The continuous miniaturization of the hardware components joined to the evolution of wireless communications technologies had stimulated the use of Wireless Sensor Networks (WSN) in many applications as environments monitoring, objects tracking and military systems.

This networks were very used as environments monitoring and are often composed by a large number of sensor nodes (hundreds to thousands) with low processing power and energy capacities capable of physical measurements such temperature, light, movement and humidity and convert the collected data in a phenomenon description that can be used to analyze the monitored area.

Different of traditional ad hoc networks, sensor networks equipments have little resources and in the majority of the proposed applications are located in remote areas making difficult the access to maintaining these equipments. In this scenario the network lifetime and the accuracy of the collected data is extremely dependent of the nodes available energy what demands the balancing of that limited resources to allow the functioning of the network for a bigger period and answer to the application specific requirements(i.e. throughput or delay).

To optimize the implementations to this requirement energy conservation techniques must be applied in all stack protocol layers by specific control mechanisms. In the routing layer particularly the main challenge is how to establish energy efficient routes between the nodes and guarantee the delivery of collected data by sensor node to the sink node in order to maximize the functioning time of the network.

Over this scenario is possible see that in sensor networks the routing task is very challenger because of their specifics characteristics and the dependency of the proposed activity for the network. These differences motivate the development of new algorithms that appreciate the new requirements and characteristics of each application to influence in the routes selection process.

The process of search and maintain routes is not minor considering the equipments energy restrictions and the frequents and unexpected network topology changes. To minimize the energy consumption usually techniques as data fusion, data aggregation and nodes clustering are applied by recent researches.

This work presents a sensor network routing protocol family called OPER (On-Demand Power-Efficient Routing Protocol) designed for applications that use a reactive monitoring scheme. OPER was based on AODV (Ad hoc On-Demand Distance Vector) [1] [2] mechanisms for establishing on-demand routes, searching and allocating these as well as DSDV (Destination-Sequenced Distance-Vector) [3] for the control of in order to maintain route table entries.

OPER implements new mechanisms to control route selection using nodes energy information to increase the lifetime of the network. The proposed OPER family can be divided into two algorithm classes considering the mechanisms each one uses to control the residual energy and the routing selection. These two classes are OPER-NE (Node Energy-Aware) and OPER-PE (Path Energy-Aware).

In OPER-NE, a mechanism for route requests acceptance based on the residual energy of each node is applied and evaluated. The algorithm also uses hop count as metric for route selection.

The main purpose of OPER-NE is allow the control of energy resources in the network nodes in order to avoid they accepting new routing requests when their residual energy cannot attend the lifetime of the solicited new route.

OPER-PE uses the same mechanisms of OPER-NE for route discovery and maintaining as well as the mechanism of selective acceptation of route requests. However, OPER-PE route selection is performed according to the evaluation of heuristics based on the energy state of the nodes in the verified routes as: battery cost and average energy consumption.

Simulation results show that the OPER protocol family offers better results than other routing algorithms evaluated in this work in all the analyzed scenarios. An evaluation score (behavior score) is another contribution of this study and offers a normalized value to simplify the set of metrics evaluated and analyzed.

The rest of this paper is structured as follows: the section 2 discusses some related works in wireless sensor networks routing protocols. Section 3 presents the functioning overview (messages, phases and routing table) of the proposed protocol. The section 5 presents the simulation setup and sixth section shows the simulation results. Finally the 7th section shows the conclusions and future works to be developed.

II. Related Work

Sensor networks introduce new challenges that need to be dealt with as a result of their special characteristics. Their new requirements need optimized solutions at all layers of the protocol stack in an attempt to optimize the use of their scarce resources [4] [5].

In particular, the routing problem, has received a great deal of interest from the research community with a great number of proposals being made. The proposed protocols often resort to the use of artifacts such as data aggregation, nodes clustering and location information.

The majority of these routing protocols can be classified in basically four main classes based in [6]: Data centric, hierarchical, location-based and Network Flow and QoS awareness.

Data centric algorithms are based on the use of network queries where the collected data is named to allow the nodes to search and get only the desired information. This technique is used to avoid the transmission of redundant data in the network and hence saves the network unnecessary work and energy. Two of the main algorithms are Direct Diffusion [7] (that each node disseminate the data interested in receive) and SPIN [8] (meta-data information are transmitted between the nodes to identify the nodes to who send the collected data).

Hierarchical algorithms separate the nodes in subregions called clusters in order to segregate the areas of the monitoring environment as LEACH [9], PEGASIS [10] and TEEN [11]. To allow communication between the clusters a leader is selected from each cluster (cluster-heads). Leaders are then responsible for the management (data aggregation, queries dispatch) and transmission of the collected data in the region they control.

Location-based algorithms (i.e. GAF [12] and GEAR [13]) rely on the use of nodes position information to find and forward data towards a destination in a specific network region. Position information is usually obtained from a GPS (Global Positioning System) equipment.

Finally, network flow and QoS awareness algorithms uses network traffic models and apply QoS based mechanisms to support their routing requirements as SAR [14] or SPEED [15].

In energy routes allocation is founded few works and in the majority it's not evaluate the sensor networks context, analyzing scenarios where these kind of mechanisms are applied in Ad-hoc networks, what does not reflect the same conditions because of the great differences between the resources restrictions of the equipments of each type of network.

Two of the main works in this evaluation of energy based routes selection are [16] and [17] where are presented some metrics to choose path between the network nodes but as said previously are not contemplated sensor networks restrictions making an evaluation that does not demonstrate the efficiency of such mechanisms for networks with scarce resources and without processing capacity to the evaluation of very complex metrics.

III. Evaluated Algorithm

The evaluated algorithm (OPER – On-Demand Power-Efficient Routing Protocol) is a propose presented in [18]. Its consider the sensor networks restrictions, a problem that can be pointed and many of the existing routing algorithms do not answer completely because not evaluate nodes energy parameters in routes selection leaving of appreciate important information about network energy status that allow a better adequacy to the applications requirements.

To allow an increase in the network lifetime the addition of mechanisms in routing protocols to verify another parameters set beyond the hop count that accept a more intelligent routes establishment for the nodes residual energy conditions. This task is done by the applied routes selection process that uses energy based heuristics to adopt it self better to network power consumption than the most of sensor networks routing algorithms.

The algorithm was developed to answer to this objective over the implementation of a power-efficient routing protocol that disseminates the collected data considering nodes energy state.

Next will be presented the main information about the algorithm like messages main phases and routing table one time that are responsible for data forwarding through the network and will be used to exchange information and maintain the created routes.

A. *Messages*

OPER protocol uses four messages to allow the communication between the nodes: hello, route request, route reply and route error.

1) Hello Message: The hello message is transmitted always that a node enters in the network to help the neighbors discovery process executed during the network startup. These messages are also transmitted periodically to check topology changes.

2) Route Request Message: This message is used in route establishment process. This process is started when a local entry table is not found for the required route. The network nodes disseminates the request in order to discover a given route.

3) Route Replay Message: Is generated when a node (required destination or an intermediary node) knows of a route that reaches a given destination. The route reply message data is used to create a new entry into the local routing table of origin node.

4) Route Error Message: Is used to signal that no route to the requested destination can be allocated. Another nodes in the network may take advantage of this message to remove any routing reference to this destination previously stored in the routing table.

B. Algorithm Phases

Three phases are responsible for data forwarding through the network. These are based on the previously introduced messages to exchange information between the nodes and the management and maintenance of existing routes.

1) Neighbor Discovery: Before sending data to the sink node, a node must start the neighbors discover process to create a neighbors list that is the address of all nodes that it is able to communicate directly. This information is used to forward packets to a destination and to check for network topology changes.

During this process, hello messages are asynchronously exchanged by the network nodes. Periodically these messages are broadcast to verify nodes reachability and then maintaining the neighbor list up to date. On the receiver of the hello message the sender address is added in its neighbors list and the message is removed from the network. If some neighbors still not transmitting after a period its address is removed from the neighbors list.

2) Routes Discovery: Once the neighbor discovery is terminated the node can initiate the routes discovery when it need establish a route to communicate with the sink node. The presented algorithm adopt an on-demand avoiding the large cost of establish a complete routing infrastructure ready for use at any moment although it is not necessary.

Route Discovery starts with the broadcast of a route request message (RREQ) by the originating node. This message therefore reaches all the neighbors. Upon the receipt of a RREQ, a node performs one of the following actions:

- Send a route replay message (RREP) if it has a path leading to the target destination in its routing table.
- Retransmit by broadcast the RREQ to further nodes (its neighbors).
- Discard the message if the node has already received this request with a better value to the metric, or that its energy is below a threshold stipulated by an application.

3) Route Maintenance: Route maintenance takes two steps: the maintenance of local connectivity achieved through periodic update of neighboring nodes list as well as the maintenance of routes established between nodes.

Hello messages are used to maintain a node's list of neighbors updated. The second step consists of checking whether next hop neighbors maintained their connectivity.

This process also supports route failure notification to all the nodes that use a given route until all the sources using this route are informed of the problem.

C. Routing Table

After established the routes between the network nodes their will be store in a routing table (Table 1) to allow future queries for the allocated paths. The routing table store information about the paths that can be used to direct data messages and verify the validity of each table record.

Table 1. Routing Table

Fields	Description
Destination	Destination Address
Destination Sequence Number	Control Validity Sequence
Next Hop	Next node Address
Hop Count	Hop Count to Destination
Lifetime	Route Validity

These route table also will be updated periodically to reflect the time to invalidate the route entry if it isn't in use and to adapt to the occurred changes in the network.

D. Path energy heuristics

Are used heuristics that evaluate metrics related to the energy state of the nodes that make up a given path the verify the functioning of each one and then analyze the benefits bring by the evaluation of energy based paths and the better set of heuristics for sensor networks.

Six energy based heuristics was implemented: MAER (Maximum Average Energy Routing), MBCR (Minimum Battery Cost Routing), MERVR (Major Energy per Route Validity Routing), MMAER (MMAER - Min-Max Average Energy Routing), MMBCR (Min-Max Battery Cost Routing) and MMERVR (Min-Max Energy per Route Validity Routing).

1) MAER: Hop count based route selection does not offer the best approach when it comes to energy saving within a sensor network. It does not consider the residual energy left within a node when choosing a path and lacks adapting its decisions to changes in the energy map of a sensor network.

In order to recover from these limitations, this work implements the heuristic MAER as route selection metric. That takes into account residual energy of all the nodes that make up a path to compute the average residual energy for each node n_i, $Energy(i)$, over a route R with D hops between origin and a destination, as shown by equation 1.

$$AVG = \frac{\sum_{i=1}^{D-1} Energy(i)}{D-1} \quad (1)$$

This energy average value is obtained for all possible routes between the origin and destination and the one with maximum energy average is selected as shown in equation 2. In other words, the algorithm opts for using the route that has more overall energy.

$$R_i = \max_{i \in Routes} (AVG) \quad (2)$$

So far this solution may present a serious drawback as it is. The fact that the average energy value over a path is the highest does not imply necessarily that all its nodes have a satisfactory level of residual energy. Actually, one may have a mix nodes with very low and nodes with very high levels of energy. In such extreme cases, the average path energy may also consequently be higher than all the others. One way for dealing with this problem, would be to adopt a second constraint where a path with nodes below a given energy threshold will not be selected.

2) MBCR: Minimum Battery Cost Routing. The second heuristic implemented is the MBCR. That is a proposed routing algorithm based in the functions proposed in [16] and [17] that considers residual energy as a metric for selecting its routes. It associates a cost to each route to a given sink.

Since the inclusion of a node into the path is determined by its residual energy level, the lower this one is the bigger its cost is hence turning it less likely to be selected. The adopted cost function is given by equation 3.

$$C_i = \frac{Total\_Energy}{Residual\_Energy} \quad (3)$$

Where *Total_Energy* is the total node battery capacity and *Residual_Energy* represents its current residual energy of each node. The decrease of *Residual_Energy* results in cost increase. The cost of a route from node *j*, Rj, with Dj is established according to equation 4.

$$R_j = \sum_{i=0}^{D_j-1} C_i \quad (4)$$

Hence in order to obtain a route with the highest residual energy or lowest cost, equation 5 is used to select a route among all the possible ones with minimum cost.

$$R_i = \min (R_j) \quad (5)$$

3) MERVR: The third heuristic implemented in this work is the MERVR. That evaluate the energy that each node can offers during the route validity for a received request. To that the residual energy of all the nodes that make up a path is divided by the route validity established (equation 6).

$$Time\_Energy = \frac{Energy}{Route\_Validity} \quad (6)$$

Once verified this value the obtained result of all nodes are added to calculate the validity energy of the route *D* nodes, as shown by equation 7.

$$Route\_Energy = \sum_{i=1}^{D-1} Time\_Energy \quad (7)$$

This value is obtained for all the path between the origin and destination and the one with maximum score must be selected using the equation 8.

$$R_i = \max_{i \in Routes} (AVG) \quad (8)$$

4) Min-Max: The last OPER-PE implemented heuristic was the Min-Max Battery Routing (MMBR), proposal initially as a refinement of the minimum battery cost heuristic (MMBCR [16] - Min-Max Battery Cost Routing). The initial proposal was extended to allow the use of the maximum average energy (MMAER - Min-Max Average Energy Routing) and major energy per route validity (MMERVR), enabling the adequacy evaluation of both heuristics with the establishment of a minimum threshold of nodes energy in the selected routes.

This algorithm chooses the route that have the greater energy average greater or the lesser battery cost, calculated through Equations 2, 5 and 7, respectively. With this the best routes will be selected since that all nodes who compose it possess a residual energy value above one determined threshold.

Therefore, this metric always tries to prevent routes that possess a lower residual energy of all the possible found routes and expects that the energy of each node will be used more correctly than in the other presented heuristics, preventing the overload of the nodes.

IV. Simulation Setup

The TinyOS [19] platform was used to carry out the simulations. This is a sensor networks development environment that can be used to build and test applications for sensors of the MICAMOTES [20] platform. It also can perform experiments using the TOSSIM simulator also available under this platform.

The values used to build the energy model for the simulations correspond to those for Mica2 sensors and were obtained from [21] and was evaluated the six routing selection energy heuristics presented.

A. *Evaluated Metrics*

Four metrics were established for the purpose of comparing the algorithms presented in this work.

1) Packet Delivery: The first metric that was analyzed in this work is the packet delivery. This is seen as the fraction of the sink node received messages by the total of messages actually sent by the sensor nodes. Packet delivery provides us with an idea of how efficient a routing algorithm has been in its use of network available bandwidth.

2) Lifetime Duration of Failing Nodes: A second important metric is that of life duration of a node. Power limitations as well the difficulty in reloading nodes with new energy remain considerable obstacles. As a result, a routing algorithm should use as little as possible network resources. As far as the experiments conducted in this work, only average nodes lifetimes were considered for those that were switched off.

3) Number of Failed Nodes: The third evaluated metric is the number of nodes that do not make it to the end of the simulations under each routing algorithm. This information is presented in the form of a fraction.

4) Behavior Index: Finally a composite metric (behavior index) combining the previous three metrics is also used. The idea is to give an overall view of the benefits of each of the examined routing algorithms. This last metric allows for a comparison that takes into consideration the average node lifetime, packet delivery rates and the number of nodes that switch off. The idea is to find a balance between these metrics.

Equation 9 shows the used approach to establishing the composite metric. The smaller its value the better the behavior of the algorithm being analyzed.

$$BI = \frac{\left[\left(\frac{Initial\_Energy}{Life\_Duration}\right) * Failed\_Nodes\right]}{Packet\_Delivery} \quad (9)$$

V. Simulation Results

Next, the simulation results are presented showing the performance of each of the routing algorithms using the metrics described earlier. To claim good accuracy for our study, 100 replications were conducted giving our results a 95% confidence level.

A. Packet Delivery

Fig. 1 shows that depending of the based heuristic of each implementation we can find different functioning related to the packet delivery rate.

Implementations based on the routes cost evaluation (MBCR and MMBCR) present intermediate values and practically didn't suffer to the influence of the network increase maintained an almost constant delivery rates throughout the simulated scenario.

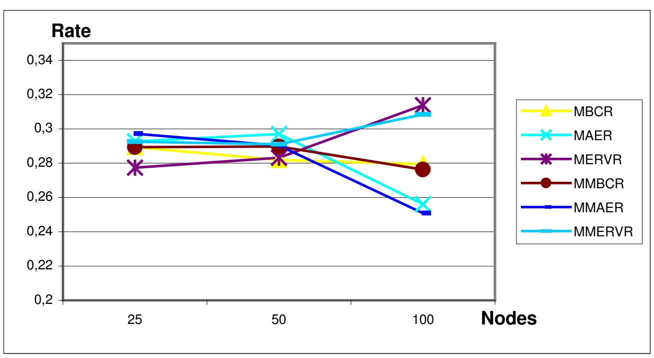

Fig. 1. Packet Delivery Rates.

The MAER based implementations suffers had been the most affected by the network nodes increase. Initially this implementations has presented the better results in the 25 nodes networks but with the increase in the amount of nodes their delivery rate reduce significantly decreasing almost five percentile points (equivalent more than 10% of reduction).

Finally MERVR based implementations presented the better functioning of the heuristics: even don't presenting the best values in small networks these heuristics has adapted better to the network growth and present an increase in the packet delivery rate in the largest networks.

B. Lifetime Duration of Failing Nodes

In Fig. 2 is possible see the obtained results by the algorithms in terms of nodes lifetime duration.

Every algorithms present a tendency of decrease in the nodes lifetime with the increase in the amount of nodes deployed in the network. This decrease depicted in Fig. 2 is a result of their use of message broadcast during route discovery computation process.

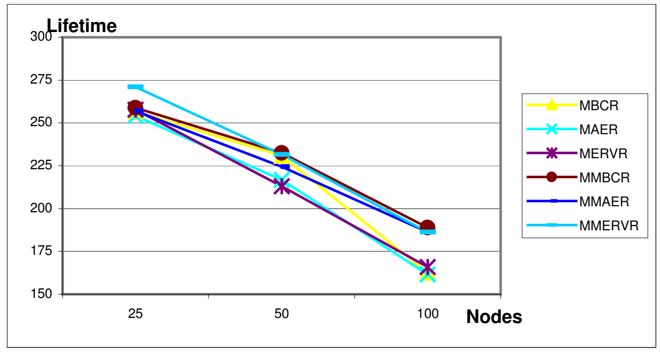

Fig. 2. Average lifetime of failing nodes.

Is possible see that the implementations that uses Min-Max heuristic had obtained higher values for node lifetime than the others implementations even presenting the same decrease trend. The average gain presented by these implementations was bigger than 5% in all the topologies.

C. Number of Failed Nodes

The number of failed nodes in the simulations (Fig 3) present the same trend founded in the nodes lifetime: the implementations that evaluate Min-Max heuristic has obtained better results (with gains greater than 10%) and consequently deactivated less nodes than the implementations of the "pure" heuristics.

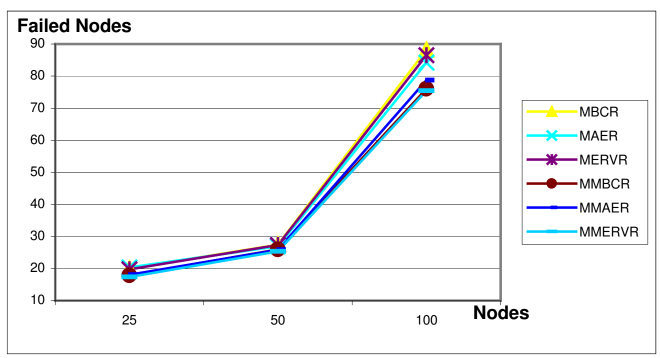

Fig. 3. Number of failed nodes.

Despite it is possible to verify one better adequacy of the heuristics based in the available energy per validity of the routes: implementation MMERVR was the best one between that uses the Min-Max heuristic and the MERVR the best one considering the ones that do not evaluate it.

D. Behavior Index

As expected the values of the BI (Fig. 4) are better to the implementations that evaluate the Min-Max heuristic showing that the addition of more mechanisms to control the energy of the allocated routes enable a better functioning of the algorithms in view to answer the sensor networks requirements.

This implementations obtained an average gain of 15% when compared to the implementations that do not uses the Min-Max heuristic in the routes selection evaluated metric.

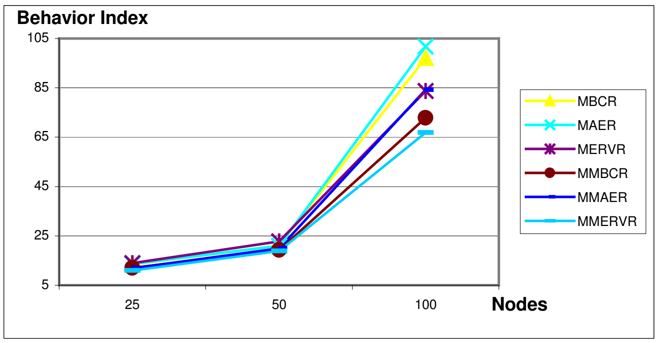

Fig. 4. Behavior Index.

However an unexpected result was the excellent behavior index obtained by the MERVR heuristic that presented similar results to MMAER heuristic on the network increase, allowing therefore a similar network functioning demanding a lesser nodes processing charge.

VI. CONCLUSION

We can verify that the selected set of information to be used in the route discovery process to evaluate the possible path between the nodes cause a significant difference in the functioning of the network.

This set of information (that base the heuristics to route selection) must be selected considering the nodes restrictions to analyze if the processing charge to be submitted is acceptable. Another point to be considerate is the applications requirements what can be adapted better to the particular characteristics of some heuristic.

As future work we can point to the evaluation of another energy heuristics to routes selection to refine the presented evaluated mechanisms.

Another evaluation to be carried consists of the creation of algorithms for multiple routes allocation. This technique could also be considered in order to improve overall delay, mainly in situations with highly fail of the used routes and to avoid route discovery allowing considerable energy savings in such scenarios.

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