Energy-efficient Geographic Multicast Routing for Error-prone Wireless Sensor Networks

Juan A. Sanchez, Pedro M. Ruiz,
Dept. Information and Comms. Eng.
University of Murcia,
{jlaguna,pedrom}@dif.um.es

Abstract— **Most usage scenarios for ad hoc and wireless sensor networks (WSN) require some degree of one-to-many or many-to-many interactions. In particular, for the case of WSN there is a number of scenarios in which a node has to send the same data to multiple destinations. Given that sensor networks have very limited resources, multicasting is a very interesting approach to deliver the same data packet to multiple destinations while reducing the amount of bandwidth and power consumption. Furthermore, recent studies have shown that it is of paramount importance to take into account the error prune nature of the wireless links when designing energy-efficient routing protocols. In this paper, we extend our previously proposed protocol LEMA (Localized Energy-Efficient Multicast Algorithm), to deal with the problems of the error prone WSN. Our simulation results show that for networks with enough density the protocol is able to outperform even well-known centralized heuristics such as Minimum Incremental Power (MIP) and Shortest Path Tree (SPT) based on energy.**

I. Introduction and Related Work

There is a growing number of applications being developed to take advantage of the properties of Wireless Sensor Networks (WSN). They are considered as one of the most promising network technologies, both in academia and industry. One of the typical usage scenarios is monitoring of environmental parameters in physically complex or dangerous areas. The new applications designed to work over WSN usually require group-based communications. Changing the behavior of some sensor of the network or sending commands to a group of nodes are examples of one-to-many communications. Multicast is a network primitive specifically designed to provide that kind of communications to multiple destinations.

On the other hand, WSN are made upon hundreds (probably thousands) of sensor nodes. Sensors are tiny devices that sense their environment and communicate among them using an on-chip integrated radio interface. They are usually operated by batteries. Thus, their energy and computational power is limited. For that reason, protocols for WSN must take care of saving as much energy as possible.

Moreover, recent studies such as the ones by Zhao and Govindan [1] or the work of Woo [2] show that there is an enormous difference between the wide used UDG model and the behavior of real links. Thus, considering the probability of error in transmissions between nodes is very important to design routing protocols for WSN, specially when energy-efficiency is a goal.

There has been a big amount of work in the field of energy-efficient multicast routing algorithms for wireless networks. Two famous examples of centralized algorithms are the Minimum Incremental Power (MIP) [3] and the use of Dijkstra algorithm to build Shortest Path Tree (SPT). Those algorithms cannot be applied to WSN due to their centralized architecture.

Geographic routing (GR) was first introduced by Finn in [4]. It is a decentralized routing technique in which nodes select their next hops solely based on the positions of destinations and their own. The main goal is to make progress, i.e., forwarding the message to a neighbor which is closer to the destination than the current one. GR is state-free because nodes do not need to maintain complex routing tables and is flexible enough to adapt to the non-static topology of WSN. Thus, it is a well-suited technique for WSN and it is a basic building block for the different solutions proposed in the literature to provide multicast for WSN.

Position Based Multicast [5] and Scalable Position-Based Multicast [6] algorithms are two examples of multicast geographic routing protocols. The first one is an adaptation to multicast of the Greedy Perimeter Stateless Routing (GPSR) protocol which tries to find a trade-off between path length and total number of messages by configuring a parameter. The problem of this algorithm is that in each step (each node routing a message), all possible subsets of neighbors are computed to select the best one. These neighbors are called forwarding nodes. For each destination, one of them takes responsibility for forwarding. Given n neighbors, the number of possible subsets is $\sum_{k=0}^{n} \binom{n}{k} = 2^n$. This leads to an exponential time complexity, too high to be feasible in a sensor node.

Sanchez, Ruiz and Stojmenovic describe in [7] a free-of-parameters algorithm called GMR, which is based on the cost over progress framework. Results show that GMR outperforms PBM regardless of the λ value selected over a variety of network scenarios. The reason is that the neighbor selection function manages to achieve a very good approximation of the minimum bandwidth consumption multicast tree. In addition, GMR is more efficient in computation time, thanks to a greedy set merging scheme.

Scalable Position Based Multicast for Mobile Ad-Hoc Networks (SPBM [6]) is another multicast protocol designed to improve scalability. It uses the geographic position of nodes to provide a scalable group membership scheme and to forward data packets. SPBM is mainly focused on the task of managing multicast groups in an scalable way. However, they fail to provide efficient multicast forwarding, because it uses one separate unicast geographic routing for each destination, which turns out to be inefficient for most network scenarios. Unfortunately these geographic routing protocols are not designed to take into account the energy spent by the network while routing the messages.

In this paper we have developed and tested an extension to LEMA to deal with the inherent errors of wireless transmissions. Unlike in the previously mentioned algorithms, LEMA [8] is a geographic multicast routing protocol designed to build energy efficient trees. Our goal is to achieve a trade-off between the delivery ratio and the energy consumption for building energy efficient multicast tree in WSN. The basic idea is to modify the function used by LEMA for labeling edges between neighbors. Our new function takes into account errors and possible retransmissions in each node taking part in the routing process. Several simulations have been made showing that our protocol is as good as centralized approaches such as MIP and even better as density increases.

The rest of the paper is organized as follows: we show the model used to propose the modification of LEMA in section II. Next, we describe the modification of the protocol in section III. In section IV we show an analysis of the performance of the modified LEMA. Finally, section V provides some conclusions.

II. Energy and Network Model

We represent a WSN as an undirected graph $G = (V, E, \omega)$ where V is the set of vertices, E is the set of edges and $\omega : E \rightarrow \mathbb{R}^+$ is a non-negative cost function associated to edges.

We define the packet reception rate between two nodes $u, v \in V$ as $prr(u, v)$. That is, $prr(u, v)$ is the probability for v to receive a packet from u. An edge $(u, v) \in E \iff prr(u, v) > 1\%$. In real scenarios, $prr(\cdot, \cdot)$ depends on the distance between nodes. In our case, to model the attenuation problems of wireless links, instead of using the complex Log-Normal Shadowing Model [9], we had rather used data derived from previous measurements by Zhao and Govindan [1]. The reason for this election is that we prefer to use data from real experiments rather than a mathematical model for approximating the propagation effects of the signal.

We take into account not only the probability of transmission but also the need of an ARQ system that guarantees the delivery of the message. Therefore we need to account for the energy needed to send messages and ACK responses. We take advantage of the possibility of adjusting the transmission power so that each message is sent using only the minimum required power to reach the desired destination.

Most of the papers related to energy-efficient geographic routing use the energy model proposed by Rodoplu and Meng in [10] to associate costs to edges of the graph representing a network. In their model, they assume that the energy consumption associated to the transmission of a fixed size message at distance d is proportional to:

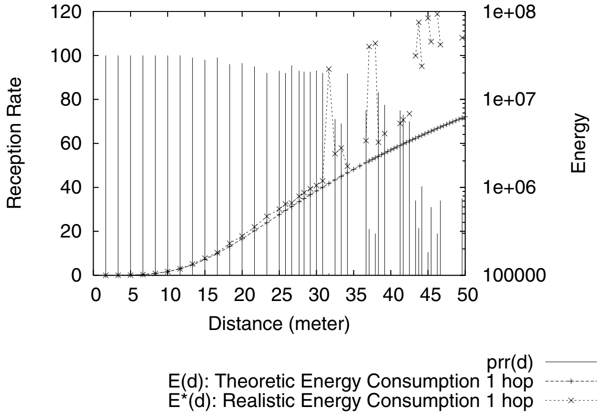

Fig. 1. Packet reception rate and energy Consumption.

$$E(d) = d^{\alpha} + C \tag{1}$$

being α the media attenuation factor satisfying $2 \leq \alpha \leq 6$ and C a constant representing the power used to process the radio signal. In our work we have decided to use the same values for α and C than in the original work of Rodoplu and Meng, that is $\alpha = 4$ and $C = 10^8$. As some recent empirical studies confirm [11], obstacles, walls, and other typical elements of real scenarios can degrade radio transmissions severely. Therefore, that attenuation factor is more representative of these scenarios than a lower one.

ACK messages are sent by receivers to confirm the reception of messages. When the sender node does not receive the ACK it retransmits the message. We define T as the maximum number of retransmissions allowed. Using the function $prr(\cdot, \cdot)$ we can determine the mean number of retransmissions needed to achieve a successful transmission of a message between two nodes. Thus, mixing all those facts, we end up with the function E^* to estimate the energy to send a message between two nodes.

$$E^*(d_{uv}) = E(d_{uv}) min \left(\frac{1}{prr(u, v)^2}, T \right) \tag{2}$$

being $u, v \in V$ two nodes at distance d_{uv}, $E(d_{uv})$ the energy of issuing a transmission from u to v, $prr(u, v)$ the probability of v receiving a packet from u and T the maximum number of retransmissions allowed.

Using E^* to label the edges of the graph G and applying the Dijkstra algorithm we could compute the energy efficient path between two nodes in presence of errors.

In Fig. 1 we can see the difference between the energy needed to send a single message and the one needed to send the same message at the same distance but guaranteeing its correct reception through the use of ACK messages, i.e. $E(d)$ vs $E^*(d)$, at increasing distances. In the same figure we show the value of the empirically built *prr* table that is being used to compute the value of $E^*(d)$.

III. Adapting LEMA

One to many communications in WSN are usually employed to send messages to a reduced group of nodes. Moreover, the list of destinations might be included in the message itself. The authors of LEMA [8] define the Euclidean Enclosure as a graph whose nodes are the ones in the destination list and where there are edges between each two nodes. Those edges are labeled with the Euclidean distance between the linked nodes. When a node running LEMA receives a message, it uses that list to compute the Minimum Spanning Tree of the Euclidean Enclosure. The resulting tree is used to take the routing decision. If the current node only has one descendant in the resulting tree, no splitting is made. If the number of descendants is two or greater, the current node generates a new path towards each direct descendant. Each new path delivers a message for a subset of the original destination list. This partition is made using the same resulting tree. Calling first descendants to the nodes directly connected to the root in the resulting tree, all the nodes being descendant of the same first descendant share the same path.

The last part of the algorithm is the delivery of the message to the selected neighbors. When only one neighbor is selected to be the next forwarder, the current node computes the energy-efficient path to reach it. To do that, it applies the Dijkstra algorithm over the local graph, i.e. the graph made only with current node's neighbors. The message is sent following that path until a node providing advance towards the destination is found. The Source Routing technique is used to force the message to follow the path [12]. The links of the local graph are labeled using the Eq. 1 to reflect the energy consumption associated to use that link. To addapt LEMA for dealing with error prone networks we propose to label the links using the function E^* defined in Eq. 2.

On the other hand, when a node currently routing a message decides that its next forwarder must be a set of more than one neighbor, the SPT algorithm is used to determine the best way to reach those neighbors. We apply the same modification to that part of the algorithm. The SPT algorithm is applied over the local graph whose edges are labeled using the function E^*. In that way, the paths and the resulting tree take into account that some links are worse than others in terms of energy consumption due to their probability of error and, consequently, to the expected number of retransmissions required.

Finally, when a node does not have any neighbor providing advance towards any of the destinations included in the header of the message, a recovery mechanism is applied. It is based on the GPSR [13] algorithm. In fact, that algorithm is applied separately for every destination. Once the next forwarder is selected, it is also computed the best energy-efficient path to reach it. Therefore, we also modified the way in which the edges of the locally-planarized graph are labeled. In this case we also use the function E^* to label the links.

To sum it up, the proposed extension is simple and, as we will see in the next section, it is effective enough to achieve a low energy consumption while achieving a good delivery ratio in presence of errors.

IV. Experimental Results

In this section we evaluate the performance of our protocol by means of simulations. The basic scenario is a square of 250x250 meters with the source and destination nodes randomly placed and with guarantee that all destinations are reachable from the source. All the nodes have the same maximin radio range set to 50m. The two metrics evaluated in our simulations are the mean energy consumption and the packet delivery ratio. We wanted to know the impact of the mean density in the performance of the protocol, therefore the tests have been made on sets of graphs with different mean number of neighbors per node. Due to space restrictions only the results for scenarios with 10 destinations are shown. To obtain accurate results, each algorithm has been simulated 50 times in each of the 50 different graphs for each combination of mean density and number of destinations. The results are processed and the mean of every parameter is used in the figures.

The simulated algorithms are two centralized (SPT and MIP) and a distributed multi-unicast routing algorithm that we call Energy Efficient Multi Unicast (EEMU). While MIP is the well known centralized heuristic Minimum Incremental Power [3], the SPT algorithm applies the Dijkstra algorithm over the complete topology. Both algorithms consider as edge weights the value of $E(d)$ being d the distance between nodes.

On the other hand, EEMU is based on IPOW [14] and it is probably the easiest alternative to simulate multicast without using an specifically designed multicast routing protocol. By EEMU we understand the use of the IPOW algorithm for each destination independently. IPOW is a geographic routing protocol designed to find energy-efficient paths. It selects a neighbor and try to optimize such selection by looking for another one through which reach the previously selected.

A. Effect of the density

Figure 2 shows the total energy consumption of each protocol at increasing densities for the multicast scenario with 10 destinations. As expected multicast oriented protocols perform better than EEMU. LEMA is a 65% better than EEMU even at low densities. Furthermore, MIP and SPT, the centralized algorithms, do not improve significantly their performance at increasing the density. This is due to the high probability of finding void zones (local optimum) during the routing in greedy mode when density is very low. Thus, the performance of the greedy part of our algorithm improves as density increases. Only when density is higher than 12 the energy consumption is mostly due to the work of the greedy part of the algorithm. For that reason, MIP and SPT obtain better results than our protocol for densities lower than 12. On the other hand, when density is higher than 12, the results are almost the same and even better than the centralized algorithms.

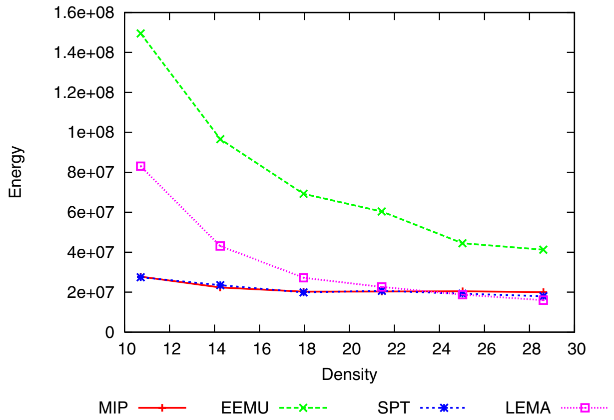

Fig. 2. Total energy for 10 destinations

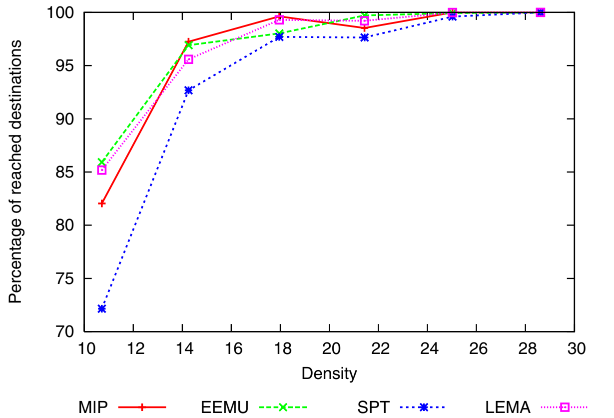

Fig. 3. Delivery ratio for 10 destinations

B. Delivery Ratio

The delivery ratio is an important metric for multicast routing protocols because they do not offer any end to end recovery mechanism. As WSN are error prone networks, building multicast trees with a high percentage of successful transmissions is crucial. Our energy estimation function must fullfill these two objectives allowing the protocol to determine reliable and at the same time, energy efficient paths.

In fig. 3 we can see the delivery ratio achieved by each protocol in the scenarios with 10 destinations at increasing the mean density. As it can be seen, the higher the density the higher the delivery ratio obtained by all the protocols, even the centralized ones. Moreover, the delivery ratio achieved by LEMA is greater than 82% in all the scenarios tested and it increases with the mean density further than the rest of the algorithms. EEMU has better results because being a multi-unicast algorithm, when a link is broken, only a destination fail to receive the message while in the multicast algorithms all the descendants of that subtree would fail.

V. Conclusions

Providing an energy-efficient multicast routing protocol is of paramount importance for many new applications being developed for the resource scarce WSN. It has been also shown recently the importance of taking into account the errors produced in the transmissions between nodes. In this paper we have extended the Localized Energy-Efficient Multicast Algorithm (LEMA) to adapt its behavior for error prone WSN. Our simulation results show that for networks with enough density the adapted version of the protocol is able to outperform even well-known centralized heuristics such as Minimum Incremental Power (MIP) as well as Shortest Path Tree (SPT) based on energy.

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