Exploiting Local Knowledge to Enhance Energy-Efficient Geographic Routing*

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Abstract. Geographic routing is one of the most widely-accepted techniques to route information in large-scale wireless sensor networks. It is based on a greedy forwarding strategy by which a sensor node selects as next hop relay the most promising neighbor (according to some metric) among those being closer to the destination than itself. This decision is based solely on the position of its neighbors and the destination. Given that sensor nodes are usually operated by batteries, energy-efficiency is a very important metric to be considered by the routing protocol. In this paper we present Locally-Optimal Source Routing (LOSR), a new localized and energy-efficient geographic routing algorithm for wireless sensor networks. Unlike existing energy-efficient geographic routing algorithms, in which current node routing the packet only considers nodes closer to destination than itself, LOSR uses all nodes in the neighborhood to compute a local energy-optimal path formed only by neighbors of the current node towards the selected next hop. Then, *source routing* is used to force data packets to follow that locally optimal path until next hop is reached. Our simulation results show that the proposed algorithm outperforms the best existing solution, over a variety of network densities and scenarios.

Keywords: Unicast Geographic Routing; Energy efficient; WSN.

1 Introduction and Related Work

Wireless Sensor Networks (WSN) consist of a set of tiny components called sensors which are able to acquire data from its environment, process it and communicate with other sensors using low-range and low-power radio interfaces. WSNs are specially useful in scenarios in which data needs to be gathered and processed in a distributed way. In addition, their battery-operated nature and tiny size, allows them to be a good solution for those cases in which technologies need to be non-intrusive. Some of those scenarios for which sensors are considered include among others: disaster relief, habitat monitoring, wildfire detection, etc. Their wide applicability is one of the reasons for their increased popularity both in industry and academia.

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Devices participating in a WSN sense their environment using special hardware called sensors. We will call those devices sensor nodes along the paper. In addition, they are also equipped with radio interfaces which allow them to form a multihop network. That is, they are able to transmit messages using as relays their neighbors. Sensor nodes have very limited resources, in terms of computing power, memory and battery life. In particular, the limited energy can be really problematic. Radio communications are the main cause of energy consumption of a sensor node [3]. Thus, it is of vital importance to reduce the energy consumption due to communications in order to extend sensors lifetime as long as possible. For this reason designing energy efficient routing algorithms for WSN is of paramount importance.

Geographic routing algorithms are well-suited to the special characteristics of WSNs. In these algorithms, routing decisions are solely based on the position of the destination and the current node. They are usually referred as localized algorithms because they only rely on local information directly available from neighbors. This makes them almost state-less and they only require a minimum memory space to maintain data structures. Their computational cost is normally low and they are very scalable which is important due to the large number of sensors a WSN could have. That is the reason why several routing protocols based on this technique were proposed in the late 80's such as MFR [11], Compass Routing [6] and GEDIR [9]. Those three algorithms use the notion of progress, first introduced by Finn in [2], to determine which neighbor to select in order to achieve the maximum advance toward the destination. However, packets may eventually reach a node with no neighbor providing advance toward the destination, making the algorithm fail. A variant of MFR described in [4] that proposes to adjust transmission power to reach only the selected neighbor has the same problem. To avoid that problem face routing was proposed in Greedy-Face-Greedy(GFG [1]). A similar scheme is proposed in the GPSR [5] protocol.

Based on GFG and GPSR and using different energy metrics, authors have proposed different energy efficient geographic routing protocols. The most common energy metric can be found in the work done by Rodoplu and Meng in [7]. They assume that the energy needed to send a message from a node u to one of its neighbors v located at distance d is proportional to d^α being α $(2 \leq \alpha \leq 6)$ the power attenuation factor.

GFG and GPSR usually select neighbors providing more advance towards destinations but this might not be an energy optimal decision. Stojmenovic defined a general framework called cost over progress [8] in where different approaches can be taken into account for selecting the best next forwarder. The same concept is used by the same author to design in [10] a location-based energy efficient algorithm for WSN called Iterative Power Progress (IPOW). This algorithm selects as best next hop neighbor the one minimizing cost over progress ratio, being the cost the energy needed to reach such neighbor. After the selection is done, an iterative process tries to optimize the decision. The optimization can be achieved if another neighbor can be used as relay to reach the previously selected and doing it in two hops needs less energy than a direct transmission. In this algorithm, when there is no neighbor providing advance towards the destination, standard face routing [5] is applied to get over the local minima. To the best of our knowledge, this algorithm is the best in this field.

In this paper we present LOSR which is a a new localized and energy-efficient geographic routing algorithm for wireless sensor networks. In LOSR the current node processing a message computes the energy shortest path to the neighbor closest to the destination and follows it until a node closer to the destination than itself is found. After the selection of the next forwarder is made, we use the Source Routing (SR) to force the message to follow that energy efficient path to reach it. That is, the source routing header includes the usually short list of nodes that need to be used hop by hop. One of the key aspects of our proposed scheme is the use of source routing to exploit the local knowledge in a node's neighborhood to save energy. LOSR uses Dijkstra Shortest Path algorithm considering as link weights the energy required to send a message from one of the endpoints to the other one. Thus, Dijkstra's algorithm computes the local energy shortest path using only local information (i.e. the position of the node's neighbors). However, as in any greedy algorithm, it may happen that the locally optimal decision might not be globally optimal. This is the reason why we take the decision of not reaching the node providing the greatest advance but the first one providing advance in the locally optimal path to reach it. Our scheme guarantees that it is possible to correct the routing direction in case the first decision was not good enough (normally due to the lack of global knowledge about nodes ahead of the neighborhood).

As we mentioned before, routing in greedy mode means that packets may reach a node which has not got any neighbors providing advance. In our case, we also use face routing in those situations, but we also use the minimum energy path to reach the next hop in face mode and use SR to reach it. We show by simulation that our algorithm outperforms IPOW algorithm, which was the best energy-efficient localized routing protocol to date.

The rest of the paper is organized as follows: section 2 defines the physical model used. Our proposed algorithm is described in section 3. In section 4 we show an analysis of the performance of our solution. Finally, section 5 provides some conclusions and discusses open issues.

2 Physical Model

2.1 Network Model

Following the generally accepted unit disk graph (UDG) model, we represent a WSN as an undirected graph $G = (V, E)$ where V is the set of vertices and E is the set of edges. We assume that every node, represented by a vertex $v \in V$, is embedded in the plane, i.e. there are no great differences in height between nodes. Each node $v \in V$ has a maximum transmission range r that can be considered, without losing generality, the same for all nodes. Let $dist(v_1, v_2)$ be the Euclidean distance between two vertices $v_1, v_2 \in V$. An edge between two nodes $v_1, v_2 \in V$ exists $\Longleftrightarrow dist(v_1, v_2) \leq r$ (i.e. v_1 and v_2 are able to communicate directly).

2.2 Energy Model

There are different energy models that can be used to estimate the energy required by a node n to send a message far enough to reach a specific neighbor placed at distance d. In this work we follow the model proposed by Rodoplu and Meng in [7]. In this model, the energy consumption for transmitting a fixed size message at distance d is:

$$E(n, d) = d^{\alpha} + C$$

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.

3 Routing with Locally Optimal Paths

The basic idea of this algorithm is to progress as much as possible in each step but using as low energy as possible. To do it, the algorithm is as conservative as possible about the goodness of the direction locally selected in each decision. Our intuition is that progressing as much as possible in each step might not be globally optimal. The routing algorithm works as follows. A node a currently holding the message uses Dijkstra's shortest path, to compute the minimum energy path towards b the neighbor placed closest to the destination among those which are closer than a. Then, the next hop selected is the first in that path being closer to the destination than a. Finally, Source Routing (SR) is used to force the packets to follow the computed path between a and c.

When the node a has no neighbor providing advance towards the destination, it switches to face routing. In face routing, nodes locally derive a planar subgraph of their neighbors and select the next hop applying the right-hand rule over it. Once that next hop is selected, the local energy shortest path between current node and the next hop is computed in order to reach it using as low energy as possible. If a shortest energy path is found, the SR header is inserted in the message. By doing that, we can also save energy in face mode. In the next subsections, we explain in detail the whole process.

3.1 Greedy Routing

The well-known Dijkstra algorithm, to find the shortest path between two nodes in a graph, can be used to find energy shortest path as long as edge weights reflect the energy needed to send messages between nodes connected by those edges. Instead of using the complete topology (which would not satisfy the locality requirements of the protocol) we use this algorithm locally to find out the shortest energy path to a neighbor of a node. The idea is to compute this path to one of the neighbors providing advance towards the destination and then follow the path. This behavior guarantees that each hop is saving as much energy as possible, but the problem is that globally that path may not resemble the energy shortest path between source and destination. The reason is that decisions are taken trying to get advance without global knowledge. In fact, in geographic routing providing advance is a must to avoid routing loops. However, trying to advance too much on each step can lead to a bad overall decision. In our solution, we choose the first node in the path being closer to the destination than current one. This guarantees the avoidance of loops and at the same time we are following the best possible path with the known (local) information. Once the selected relay is reached, a new decision can be taken with new information about its neighbors which was not available to previous nodes. Hence, a better decision can now be taken based on the new information known by the new current node. The message is sent including in its header the list of nodes in the shortest path that the message must traverse as in IP Source Routing (SR). Nodes receiving a message with a SR header on it do not compute the next hop. Instead, they remove themselves from the SR header and forward the message to the next hop in the SR header.

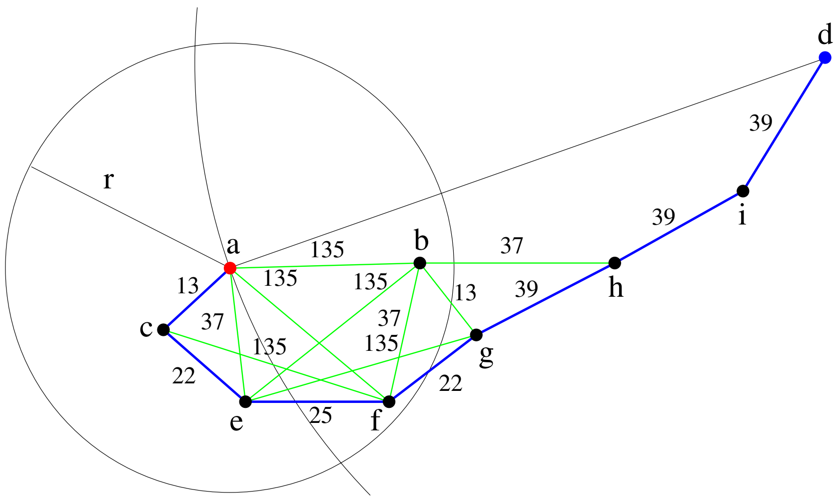

Fig. 1. Node a routing to d selects node c as next forwarder

Fig. 1 shows an example in which node a currently holding the packet has to select the next forwarding node to route the message to node d. Each link is labeled with the cost in energy of sending a message through it. From the point of view of a, b is the neighbor that provides most advance towards the destination d whereas nodes c and e do not provide any advance. But if node a computes the energy shortest path to reach b, the resulting path is a, c, e, f, b. Notice that, globally, the energy shortest path includes also node g but, g is not a neighbor of a, therefore, it does not know about its existence and can not include it in the computation of the path. Following this path completely is the local optimal decision to reach node b. That is, the best local decision with the knowledge that node a has. However, going to b using that path may not be the best global decision. Our algorithm selects f as next hop node because it is the first node in the local path whose distance to d is lower than the distance from a. The reason for doing that is that the deviation from the globally best path can be reduced. Therefore a creates a message including in the header the path that the message should follow to reach f using the previously computed energy shortest path. The list included in the message is c, e because it is not necessary to include the origin nor the destination of the SR as they are already included in the header of the message. When node c receives the message, it checks if it has a SR header or not. In our example, the header exists so, c removes himself from the list and forwards the message to the next node in the list (e) that repeats the process. At node f source routing ends and then, it can recompute the next best hop. Node f has more information than node a because it knows of the existence of node g. Here we can see how the conservative election of a allows us to take a better decision. In the next step, node f selects g and finally g passes the message to h which forwards it to i and finally to d.

Not being conservative would have lead us to reach b in a locally optimal way but after that, the shortest path to d from b would have gone through g which is not globally optimal. Our approach takes advantage of the progressive increment in knowledge that nodes located closer to the destination have. In fact, the further away the next hop selected, the greater the error that may be incurred. On the other hand, selecting nodes providing the lowest advance towards the destination does not represent much error but it is not useful because it only delays the moment of the real decision. In our case, we reach a trade-off. We only follow the path to the first point in which a new evaluation might be better than the current.There is also another reason for not following the complete energy shortest path towards most promising neighbor. Including large SR headers in the message implies augmenting the bandwidth usage and at the same time the energy consumption.

3.2 Face Routing

We now explain how to deal with the situation commonly-known as local minima. As mentioned above, routing in greedy mode can end up reaching a node where no neighbor provides advance towards the destination. As previous geographic routing algorithms, we use face routing to get over this situation. However, to further reduce energy consumption we compute the shortest energy path towards the node selected by face routing, and again we use source routing to reach it. In order to maintain face routing behavior as it is defined, it is necessary to extend the face routing specific header. This header includes the node where face routing started, the edge used to enter the current face being used, etc. We add to this header the node where SR started. Notice that in an standard face routing node a, selecting node b as its next face hop, would be the sender of the message arriving at b. In our case, when there exist an energy shortest path between a and b, the sender of the message eventually received by b might not be

a. As face routing needs to know the previous node in the face path to compute the next one, we need this information to be carried in the message.

4 Experimental Results

We have performed a simulation-based analysis to assess the performance of the proposed scheme. Simulations have been performed with a custom-made java simulator for geographic routing, which is able to simulate very large topologies consisting of thousands of nodes. Each simulation has been performed for different network densities, that is, mean number of neighbors per node. Nine different densities have been simulated between 9 and 45. Thus, to fix the simulation area, the total number of nodes is changed accordingly having as a result a value between 320 nodes for a density of 9 and 1600 nodes for a density of 45. In all the scenarios tested the radio range is equal for all the nodes and fixed to 50m and the attenuation factor and C constant considered to calculate the energy of radio transmissions are α=4 and C = 100000 as in [7]. The size of the scenarios is fixed at $500m^2$ and, in each scenario, the source is placed at top left corner and the destination at the bottom right corner. For each density 50, different scenarios have been evaluated giving a total of 450 simulation runs for each of the tested protocols. We have simulated our new algorithm LOSR and its variant without Source Routing as well as Iterative Power Progress (IPOW) and its variant with SR. We have also simulated a centralized version of the Dijkstra algorithm to find out the global energy shortest path called ESP.

The main performance metric has been the mean energy consumed but also the percentage of messages sent in perimeter mode. The results presented below have a confidence interval of a 95% not sohwing in the curves to improve readability.

4.1 Energy Saving Due to Source Routing

The use of Source Routing reduces the energy hop by hop. To measure the amount of energy saved by the use of this technique we have simulated our algorithm without using SR, i.e., the algorithm forwards the messages to the neighbor that provide the most advance towards the destination, using SR from the node to the selected neighbor and using SR only up to the first node in the path providing advance towards the destination. The first variant of the algorithm selects the next hop in the same way (the neighbor closest to the destination) but it does not compute the energy shortest path to reach the relay in greedy nor in face mode.

Fig. 2 shows that the higher the density the higher the improvement achieved using SR. The energy reduction achieved is between a 50% and a 86%. Moreover, stopping the SR in the one-hop neighbor that would be the first node, that is closer to the destination than the current node, on the minimum energy path to the one-hop neighbor selected as forwarder, reduces the energy consumption between a 1% and a7% more. As we can see, at lower densities the energy

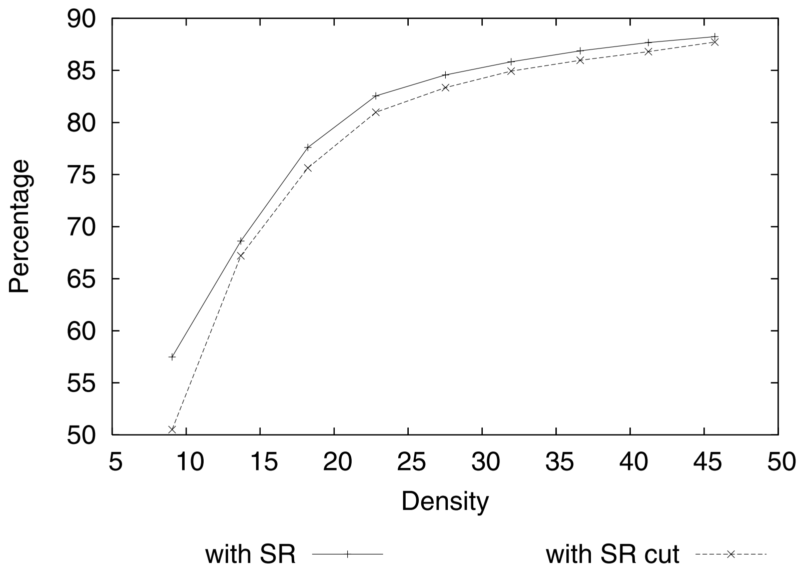

Fig. 2. Improvement by using Source Routing

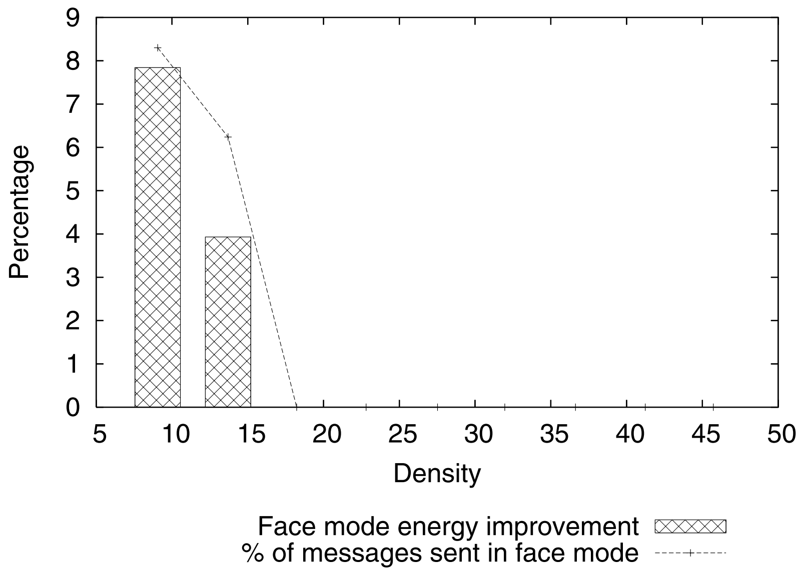

Fig. 3. Energy saving in face mode due to Source Routing

reduction is low. For lower densities it is difficult to find alternative energy efficient paths as the number of nodes is low whereas for higher densities the probability of finding nodes to build the Dijkstra path is higher.

In Fig. 3 we can see the reduction of energy consumption achieved applying SR to Face Routing against the ratio of messages sent in this mode. As it is shown, the percentage of messages sent in face mode decreases to 0 when the mean density goes over 14. Thus, only up to that density, the improvement can be of any significance. The reduction of energy achieved taking into account only the one used in face routing mode is up to a 8%. Taken into account the percentage of messages sent in face routing, the overall energy reduction due to the application of SR in face routing is under 1%. Obviously, the scenarios in which face routing is applied are the ones with lower densities. Building energy-efficient paths with only a few neighbors is difficult. That is the case in those scenarios, therefore, the improvement achieved is low but also important.

4.2 Performance Against Iterative Power Progress

Simulations of Iterative Power progress have been made using the same sets of graphs in order to compare the energy needed by each protocol. Fig. 4 shows the total amount of energy needed by each protocol at increasing densities. It also shows with column bars the percentage of energy that each protocol uses in perimeter mode with the exception of ESP that does not uses that mode. As it can be seen, the density has the same effect on the three protocols. The higher the density the lower the energy used. The reason is that at higher densities it is possible to find better paths through multiple nodes. These paths usually have more nodes than the ones built at lower densities whereas the total distance between source and destination remains very similar. Including more hops in a path means reducing the inter-hop distance and thus reducing the energy consumption up to a limit. That limit is given by the constant C of the formula for the energy in 2.2. Having a $C \neq 0$ guarantees that the best path is not the one made with infinite hops.

As expected, the higher the density the closer all protocols are to the best one (ESP). However, LOSR is better than IPOW when the mean density is higher than 14, and the difference increases with the density as expected. Having more neighbors per node allows us to locally compute a better energy shortest path saving much more energy than IPOW that only takes advantage of energy reductions achieved by adding a single node to the path. At lower densities, IPOW is better than LOSR because as figure 5 shows, the percentage of messages sent in perimeter mode by IPOW is lower than LOSR. Even though LOSR is reducing the energy of the messages sent in perimeter mode, the selection of the next forwarder based only in distance to the destination make the protocol enter more frequently in perimeter mode than the complex selection function of IPOW does.

With these results we decided to apply our energy reduction method to IPOW in order to test how much can SR reduce the energy if IPOW. In each step of IPOW algorithm an iterative process looks for a node whose cost of being reached directly could not be reduced adding another one in the middle and making two hops instead of only one. Obviously, it might exist a longer path with less energy consumption.

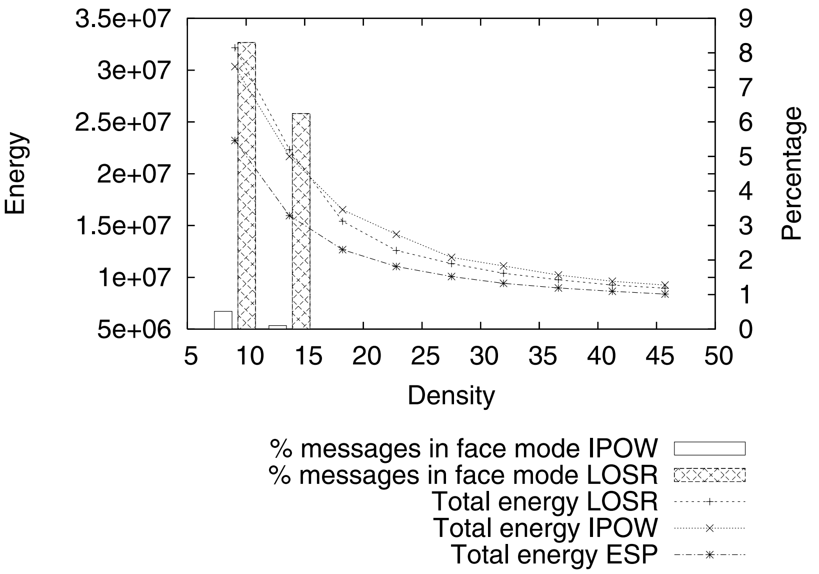

Fig. 4. Total Energy consumption

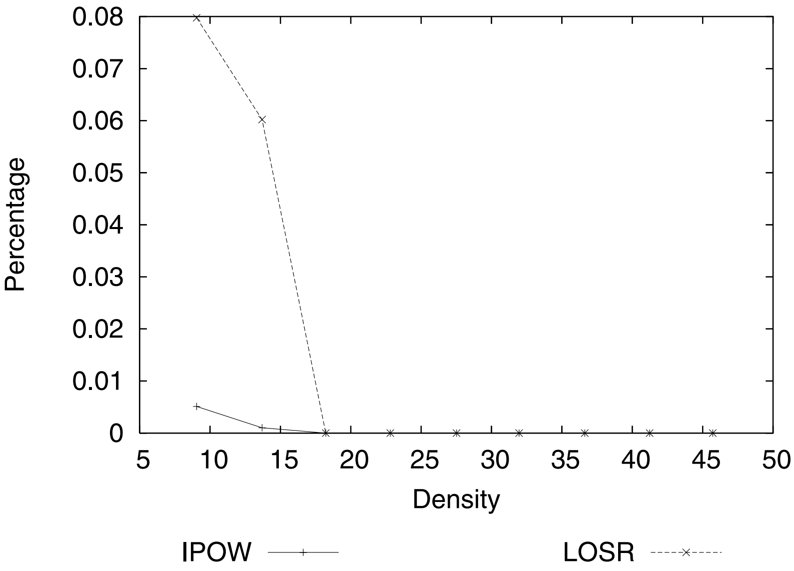

Fig. 5. Percentage of messages sent in perimeter mode

Fig. 6 shows the total energy consumed by IPOW and the SR variant of IPOW and the percentage of improvement that the SR variant achieves over the original one. The improvement is greater at lower densities because the original IPOW

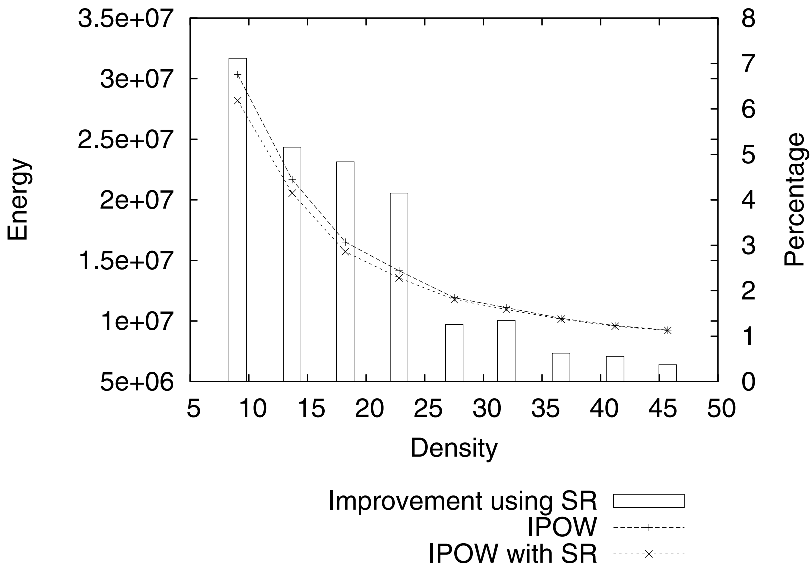

Fig. 6. Energy saving improvement over Iterative Power Progress

algorithm only selects as forwarders neighbors closer to the destination than the node taken the decision. Adding SR allows the protocol to use also the neighbors that does not provide advance towards the destination. Therefore, less energy-consuming paths are found to reach the original forwarder neighbor selected. At higher densities, SR has almost no effect because having enough neighbors allows IPOW to chose almost every time the one that provides advance and at the same time, the cost of sending a message directly to it is lower than through any other path.

5 Conclusions and Future Work

We have introduced a new localized and energy-efficient geographic routing algorithm for wireless sensor networks which as density increases outperforms Iterative Power Progress. We have also shown that for scenarios with lower densities the best approach is to apply our SR technique to Iterative Power Progress. Thus, we have shown that the use of the well-known Source Routing technique can save energy when it is applied in conjunction with a locally computed Dijkstra's energy shortest path regardles of the original next forwarder selection function used. The main conclusion is that locally made decisions have to be carefully taken as they can be wrong due to the lack of global knowledge. Thus, it is better not to follow initial selections till the end. Rather, new information obtained after a shorter advance might correct the initial decision. Our approach of taking the minimum part of the initial decision has really good results improving IPOW as density increases. For future works we are studying how to deal with more realistic scenarios in which errors play an important role as well as the possibility of adapting this algorithm to multicast.

References

1. P. Bose, P. Morin, I. Stojmenovic, and J. Urrutia. Routing with Guaranteed Delivery in Ad Hoc Wireless Networks. *Wireless Networks*, 7(6):609–616, 2001.
2. G. G. Finn. Routing and Addressing Problems in Large Metropolitan-scale Internetworks. Tech. Rep. ISI/RR-87-180, University of Southern California, Information Sciences Institute, March 1987.
3. G. Halkes, T. van Dam, and K. Langendoen. Comparing Energy-Saving MAC Protocols for Wireless Sensor Networks. *Mobile Networks and Applications*, 10(5):783–791, 2005.
4. T.-C. Hou and V. Li. Transmission Range Control in Multihop Packet Radio Networks. *IEEE Transactions on Communications*, 34(1):38–44, 1986.
5. B. Karp and H. T. Kung. GPSR: greedy perimeter stateless routing for wireless networks. In *Proc. 6th annual ACM/IEEE International Conference on Mobile Computing and Networking (MobiCom '00)*, pages 243–254, New York, NY, USA, 2000. ACM Press.
6. E. Kranakis, H. Singh, and J. Urrutia. Compass Routing on Geometric Networks. In *11th Canadian Conference on Computational Geometry (CCCG '99)*, pages 51–54, Vancouver, August 1999.
7. V. Rodoplu and T. Meng. Minimum Energy Mobile Wireless Networks. *IEEE Journal on Selected Areas in Communications*, 17(8):1333–1344, 1999.
8. I. Stojmenovic. Localized Network Layer Protocols in Wireless Sensor Networks based on Optimizing Cost Over Progress Ratio. *IEEE Network*, 20(1):21–27, 2006.
9. I. Stojmenovic and X. Lin. Loop-Free Hybrid Single-Path/Flooding Routing Algorithms with Guaranteed Delivery for Wireless Networks. *IEEE Transactions on Parallel and Distributed Systems*, 12(10):1023–1032, 2001.
10. I. Stojmenovic and X. Lin. Power-Aware Localized Routing in Wireless Networks. *IEEE Tran. on Paralell and Distributed Systems*, 12(10):1122–1133, October 2001.
11. H. Takagi and L. Kleinrock. Optimal Transmission Ranges for Randomly Distributed Packet Radio Terminals. *IEEE Transactions on Communications*, 32(3):246–247, March 1984.