LEHP: Localized Energy Hole Profiling in Wireless Sensor Networks

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***Abstract*—Wireless Sensor Networks (WSN) invariably display non-uniform energy usage distribution. This is mainly induced by the sink centric traffic or by non-uniform distribution of sensing activities and manifests as *energy holes* throughout the WSN. Holes can threaten the availability of the WSN by network partitioning and sensing voids. They are hard to predict, and consequently, proper function of the network requires systematic maintenance. Unfortunately, existing approaches do not systematically profile holes and focus only on one specific type of holes. In this work we present new distributed energy profiling algorithms for generalized types of energy holes. The algorithms search for boundary nodes and use them as a reference to calculate the energy needs of nodes within the hole. These when aggregated create angular and radial energy profiles. Extensive simulations show that the algorithms, when used for WSN maintenance, significantly help to extend the lifetime of the network.**

***Keywords*-Wireless Sensor Networks; maintenance; energy profiling; energy holes;**

I. Introduction & Contributions

Wireless Sensor Networks (WSN) constitute a rapidly developing area in the fields of communication and computation. Typical WSNs consist of multitudes of battery powered autonomous devices equipped with processing units, capable of sensing environmental changes and communicating wirelessly, allowing high flexibility for deployment. Unfortunately, the constrained energy supply imposed by using batteries and its quick depletion arising from wireless communication, limits the network lifetime.

The WSN lifetime estimation is complicated as the energy consumption within the network tends to show non-uniform distribution leading to network partitioning and degradation of sensing and communication coverage. An example of such behavior is sink centered energy hole problem [2]–[5]. The sensor nodes (SN) placed in close proximity of the sink deplete their energy at a faster rate as, besides their own operations, they forward most of the WSN traffic. Although most of the SNs still retain significant amounts of energy, the loss of sink neighbors renders the entire network inoperable.

In more complex WSN deployment scenarios, the non-uniform energy consumption distribution is not only induced by the topology but also significantly by spatially correlated sensing activities. At the locations where the phenomenon occurs, the SNs adapt their sampling and sample reporting rates in order to meet desired accuracy. Higher frequency of reports, with associated higher message traffic, leads to accelerated energy depletion in the phenomena region. The distribution of the energy usage mimics the distribution of monitored physical phenomena, which usually shows high spatial correlation. Monitoring mostly takes place in the unknown areas with the actual goal of discovering the distribution of the phenomena intensity.

This problem could be alleviated by deploying SNs with higher density [5] in the threatened region. Unfortunately, barring a few trivial cases, communication load and energy consumption patterns cannot be predicted in the pre-deployment stage. Thus, the formation of sensing and communication coverage holes remain serious threats to WSN. To avoid/delay the manifestation of WSN holes, a suitable proactive profiling and maintenance actions are desirable.

Unfortunately, most existing solutions for energy holes do not accurately profile the hole and are reactive [17]–[22]. Current techniques allow only estimating the holes periphery, which does not provide insight into the hole dynamics. The energy hole growth rate and the increased energy usage causing the hole are neglected. Only a static picture of the hole (its size and shape) is provided but not its internal distribution required to estimate its future energy needs. Typical remedies for holes are to opportunistically reposition movable SNs, or place new SNs to cover the hole. The actual amount of needed energy is often not considered. If energy added is significantly higher than the energy needed, resources are wasted; if it is lower then the hole may reoccur negating the overall efforts.

A. Paper Contributions & Structure

An effective maintenance should handle the cause of the problem and not its symptoms. A fundamental step is to have a proactive systematic profiling of the threatened area. In this paper we make the following contributions. To our knowledge this is the first work to propose an effective proactive algorithm for profiling energy needs to repair the energy holes. Our technique, i.e., Localized Energy Hole Profiling (LEHP):

- is based on an efficient, balanced and accurate profiling of the energy needs within the hole,
- uses an in-network aggregation strategy that provides for an angular and radial profiling resulting in a compact profile,

- is proactive allowing for prevention and proactive maintenance, and may be easily combined with existing maintenance strategies,
- applies for generalized energy holes with different sizes, shapes and energy spatial distributions.

The remainder of the paper is structured as follows. Related work is discussed in Section II. Following the system model in Section III, Section IV details the LEHP profiling algorithm, the paper's main contribution. The evaluation of the algorithm is presented in Section V. Section VI concludes the paper.

II. Related Work

WSN holes present an abstraction to describe degenerations in network conditions. They have recently received wide attention in the WSN community [1]–[11]. The survey [1] defines several classes of holes, e.g., coverage holes, routing holes, jamming holes and sink/black/worm-holes. The coverage (sensing) and routing (communication) holes are of main interest in this paper. The other sink/black/worm-holes are virtual type of holes (e.g. induced by security attacks) and are not considered here. Here, the jamming holes can be seen as special case of coverage holes, where profiling is inherently impossible.

[2], [5] describe the problem of non uniform depletion of energy around the sink. They exploit the fact that distribution of this kind of energy holes is predictable and propose, proportionally to the expected traffic, to increase the density of the SNs around the sink. [3] delivers an analytical description of the energy hole built up around a centrally located sink. The solution proposes to provide additional resources at the endangered region by the deployment of assistant nodes. As an additional optimization traffic compression is suggested. In [4] authors handle the same problem and propose another solution, i.e., balancing energy usage by increasing the transmission range of SNs farther from the sink, to ease the traffic burden on the SNs closest to sink. [2]–[5] take important steps in handling the energy holes. However, they can be applied only to a subset of energy holes, while our approach targets generalized type of holes.

[8]–[11] propose efficient techniques for detection of hole boundary. [6] [7] model the perimeter of the hole to prevent occurrence of the local minimum problem in geographic routing. While these techniques are useful for event detection and routing, the lack of holes interior profile considerably limits their applicability for proactive maintenance.

For addressing maintenance and network reconfiguration, a number of approaches have been proposed. The common options are to reposition SNs [16]–[18] [22]–[24], to deploy redundant SNs that can be activated or added on demand [20] [21], increase the transmission range, or combinations [19]. These works are well suited to react on drop of connectivity or coverage resulting from failure of single SNs. Such strategies have opportunistic character, while effective in short term, they do not prevent the reoccurrence of the hole. In contrast, our solution systematically profiles energy holes and provides a necessary basis for proactive maintenance. Only two prior works [16] [24] present proactive approaches. However, both are limited to node-level profiling. A non-systematic profiling usually leads to inaccurate and short term effective maintenance/reconfiguration. We show that the application of our systematic/generic profiling of holes provides a major improvement over existing maintenance approaches in terms of effectiveness.

III. System Model

Similarly to existing WSN models [2]–[5], we assume a WSN consisting of a large number of static resource constrained SNs and a sink. The SNs are powered by limited capacity batteries. The communication range r is limited, and two neighboring SNs can communicate only if the Euclidean distance between them is smaller than r. The distribution of the SNs in the deployment area follows the uniform random distribution. The SNs know their position using on board GPS receivers or alternative measure of localization [25]. The only considered cause of SNs failure is their energy depletion.

SNs can increase their sampling rate, operate longer in active mode, and transmit more data reflecting the dynamics of the phenomena being monitored. This implies that SNs placed in the region of high activity of phenomena consume energy at a higher rate. We assume the spatial correlation of physical phenomena and consider the following three spatial distributions: Exponential, Pareto and Normal. Accordingly, SNs perceive the phenomenon and generate a message with the following probability $p = f(d)$, where d is distance to the center of the phenomena (Hotspot model [15]). The non-uniform distribution of physical phenomena manifests as a non-uniform energy depletion among SNs and leads to the emergence of energy holes. We assume a local extremum (energy minimum) close to the epicenter of the hole. This local minimum is surrounded by irregular rings of energy levels (Fig. 1, darker shades denote lower energy levels).

IV. LEHP: Localized Energy Hole Profiling

In order to avoid or delay the drops in sensing and communication coverage, the energy holes should be systematically profiled by collecting information about the hole's shape and energy distribution. In this section, we present novel algorithms for such hole energy profiling.

A. Overview of our LEHP Approach

The main objective of LEHP is to create an accurate profile of the necessary energy to be injected into a given WSN energy hole in order to maximize the network lifetime. Our approach/contribution is to determine the energy needed to distribute over the hole to prevent hole reoccurrence during the lifetime of the rest of the network. LEHP consists

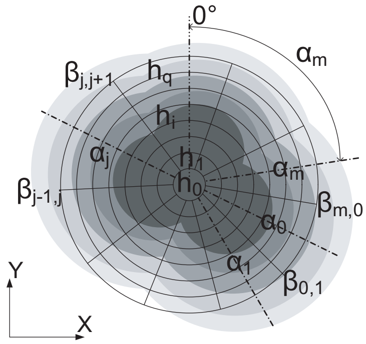


Figure 1. Angular and radial profiling

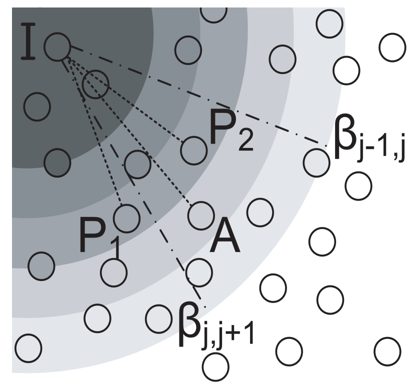
of two phases. First, an initiator node *I* from interior of hole starts a discovery phase to identify the energy reference level on the hole's border and to build a spanning tree rooted at *I*. Second, through efficient in-network and tree-based aggregation, the profile of the energy needs within the hole is collected at *I*. The SNs located closest to the epicenter of monitored phenomena are usually the first to reach a given energy threshold E_{TH} (Alg. 1 lines 2-5). The value of E_{TH} can be set arbitrarily but more desirable is to determine it based on the energy depletion rate of SNs as well as the required time scale for pro-active maintenance. The first SN to approach the threshold triggers profiling activity.

In order to provide highly accurate profiling, we develop an aggregation technique that models the hole as sectors and concentric rings around the local extremum. Accordingly, we aggregate the energy levels at quantified distances (h_i, for $0 \leq$ i $\leq$ q) (Fig 1). As energy redeployment requires not only the distribution of needed energy, but also the values representing its amount, we cannot limit the reports to simple contours of rings as in [14]. Also, as the hole often shows irregular shapes (shading represents the energy distribution), relying only on distance aggregation may prove inaccurate. To alleviate this problem we separately aggregate reports at different angles (α_j, for $0 \leq$ j $\leq$ m) as shown in Fig 1. The radial positions (α_i) are defined by the positions of 1-hop neighbors of *I* as they are the roots of *I* subtrees. The width of the arcs ($\widehat{\beta_{j-1,j}\beta_{j,j+1}}$) corresponds to the minimal and maximal angles of SNs belonging to the subtree. This approach allows us to accurately identify the energy needs for different positions in the hole.

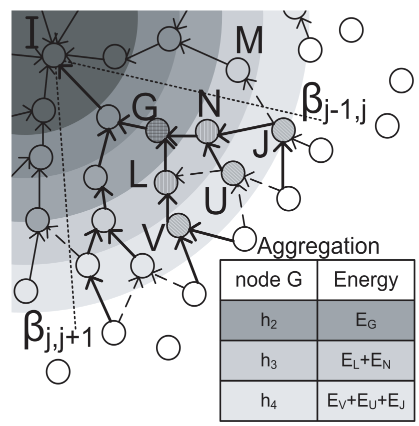
B. *Profiling*

In the following we detail the two operational phases as well as some optimizations of LEHP.

1) Phase 1 of LEHP: Detecting Hole Border and Establishing the Aggregation Tree: This phase is inspired by route discovery [13] and introduces new optimizations to increase the accuracy of angular profiling. The initiator *I*, located close to the hole epicenter, propagates a request (including its position and a unique profiling ID) for the spanning tree construction by traversing the areas of different energy levels (Fig. 2(a)) and counting the number of hops traveled.



(a) Tree construction



node G	Energy
h_2	E_G
h_3	E_L+E_N
h_4	E_V+E_U+E_J

(b) Aggregation

Figure 2. Operational phases of LEHP

As detailed in Alg. 1, the SNs upon receiving the request message check whether the entry in the profiling-specific routing table for profiling ID exists (Alg. 1 line: 9). If not, a new entry is created storing the ID of the parent node (the address of immediate sender of the request message), the hop distance to *I* (that the message traveled so far) and the position of *I*. In case that the entry already exists, its content is evaluated against current message. If the hop distance traveled by the message is greater than contained in the entry, then the message is discarded (i.e., a route shorter was already propagated) and not forwarded (Alg. 1 lines: 11 and 16). When the hop distance of the message is smaller, the message information replaces information stored in the entry and the message is forwarded (Alg. 1 lines: 14 and 22). If the hop distances indicated by the message and table entry are equal, further evaluation takes place as detailed in the following.

To support the desired angular profiling, a SN should select its parent node in the same sector, i.e., belonging to a proper arc $\widehat{\beta_{j-1,j}\beta_{j,j+1}}$ as depicted in Fig. 1 and Fig 2. A node *A* (Fig. 2(a)) selects the closest parent (P_i) in the angular distance, to minimize the angle $\angle$AIP$_i$. Assuming that the current parent of the node *A* is P_1 and the currently processed message was sent by P_2, then if the $\angle$AIP$_1$ is larger than $\angle \mathrm{AIP}_2$ the entry is replaced (Alg. 1 lines: 13-14). This indirectly increases the chance that the SN will belong to the branch of subtree representing the arc to which its child nodes geometrically belong. Node *A* does not forward a request message as the hop distance does not change.

Algorithm 1 Hole Discovery & Aggregation Tree Construction

```
1:  On Energy Change
2:  if Energy < E_TH then
3:      Node becomes Initiator;
4:      send(REQ, MAC_BROADCAST);
5:  end if
6:
7:  On Receiving a Profiling Request REQ
8:  var static routingTable;
9:  if existsEntry(REQ.profileID) then
10:     entry = extractEntryFromTable(REQ.profileID);
11:     if entry.Hop > REQ.Hop then
12:         replaceEntry(REQ.profileID, REQ);
13:     else if entry.Hop = REQ.Hop && entry.angle > REQ.angle then
14:         replaceEntry(REQ.profileID, REQ);
15:     else
16:         return;
17:     end if
18: else
19:     addEntry(REQ);
20: end if
21: REQ.Hop++;
22: send(REQ, MAC_BROADCAST);
```

In order to limit the message flooding within the hole area two approaches (broadcast break conditions) are followed.

The first approach is tailored to the hole shape. The message should propagate until the variance of energy values of SNs that message traverses drops under a certain threshold (TH_{break}). Each message carries the energy values of the two last traversed SNs. When both conditions in Eq. (1) and Eq. (2) are satisfied then break condition is met.

$$\frac{E_{hop-1}}{E_{hop-2}} < TH_{break} \quad (1) \qquad \frac{E_{current}}{E_{hop-1}} < TH_{break} \quad (2)$$

It is necessary to compare the energy from at least two preceding hops to avoid a situation where a SN selects a SN placed next to it as a parent, which, as consequence of its closeness, has similar energy value and therefore, variance can easily fall below the defined threshold.

In the second approach, the maximal number of hops for the message to travel or the maximal distance from *I* is set to a maximal value, called Time-To-Live (TTL). We use this to limit the profiling to energy holes of size that can be handled by maintenance (e.g. under maintenance cost criteria). The TTL value can be set at pre-deployment stage. We refer to *border nodes* (BN) as those SNs that, upon receiving a broadcast message, detect one of the break conditions.

2) Phase 2 of LEHP: Aggregation-based Profiling: A naive approach for profiling would be to have each SN send its individual measurement and position to *I*. Though this approach provides high accuracy profiling, unfortunately, it also causes high traffic in particular on the SNs closer to *I* which are more threatened by battery crash. Furthermore, *I* would have to process the entire aggregation on raw data, which can become complex for large holes. Accordingly, we develop the following in-network profiling strategy to realize the second phase of LEHP. The profiling technique needs to aggregate the data while retaining information about its distribution.

Algorithm 2 Aggregation-based Profiling

```
1:  On receiving a Reply Message REP
2:  var static P_REP;
3:  const T;
4:  evaluationTime = now() + T;
5:  if REP.DestID == this.ID then
6:      for i = 0; i < maxNumberOfEntries; i++ do
7:          P_REP.Energy[i] += REP.Energy[i];
8:          P_REP.Count [i] += REP.Count[i];
9:      end for
10: else if entry.Hop > REP.HopToTravel then
11:     return;
12: end if
13: P_REP.Ref = recalculateReference(P_REP.Ref, REP.Ref);
14:
15: On Data Evaluation Event Handler
16: entry = extractEntryFromTable(REP.profileID);
17: energyNeeded = estimateEnergyNeeded(P_REP.Ref);
18: P_REP.Energy[entry.Hop] += energyNeeded;
19: P_REP.Count[entry.Hop]++;
20: send(P_REP, entry.ParentID);
```

Our approach builds on tree-based aggregation [12] and uses the constructed spanning tree to implement a new efficient technique for accurate in-network profiling of the needed energy. The energy levels of BNs serve as a reference energy to quantify the energy needed for the hole. BNs initiate the aggregation phase by sending their lifetime reference value towards *I* along the spanning tree. BNs estimate their lifetime reference using a simple linear regressive model (Eq. (3)), where $E_{initial}$ is the initial energy of the node, $T_{elapsed}$ the time passed since deployment and $E_{current}$ the current energy level of the node. If needed, this model can be replaced by a more accurate one [27].

As outlined in Alg. 2, SNs collect and process the energy information received from all their child nodes. First, the received partial profiles are grouped according to their hop distance to *I*. Next, aggregation is applied to each group separately. Aggregation within LEHP is to sum up the energy need for each SN within a group (Alg. 2 lines: 6-9). We chose to use summation as we have to provide the total value of energy to deliver. After receiving messages from the child nodes, the SN estimates its energy needs given its locally estimated lifetime and energy consumption rate (Eq. (4), Alg. 2 line: 17), and the received reference lifetime of the BNs.

$$Lifetime_{REF} = \left(\frac{E_{initial}}{E_{initial} - E_{current}} - 1\right) * T_{elapsed} \quad (3)$$

$$E_{needed} = Lifetime_{REF} * \frac{E_{initial} - E_{current}}{T_{elapsed}} - E_{current} \quad (4)$$

The result of the aggregation for each group is the sum of needed energy as well as the number of SNs contributing to the sum. The messages also contain the maximal and minimal angles at which traversed SNs are located.

The message traveling towards *I* is processed not only by addressed SNs but also by the rest of the SNs belonging to the spanning tree and placed at the same or smaller hop distance from *I* than the addressed SN. These SNs do not aggregate the energy needs but extract the lifetime reference value. They calculate the average of all children intercepted reference values and use this value to estimate their own energy needs using Eq. (4). This approach allows for better approximation of the reference value, as the reference is calculated from more sources. Fig. 2 shows a few examples (dashed links). This is especially useful for those SNs that do not have any child node. Node *M* does not serve as a parent to any of the SNs, therefore, the interception of the communication between *J* and *N* is useful to receive a more accurate reference. Without this optimization *M* will use its own lifetime as a reference.

An alternative approach to the use of hop distance is to use Euclidean distance. Varying the width of rings allows for controlling the aggregation accuracy of the algorithm and also the size of messages transmitted. The smaller the width values, the higher is the accuracy but at the cost of a larger message size. If the initiator selects this method for profiling, it should disseminate the desired value for ring width length.

C. Profiling Outcome and Usage

At the end of the profiling process the initiator *I* possesses a collection of reports from different arcs $(arc_j\widehat{\beta_{j-1,j}\beta_{j,j+1}})$ of the energy hole. Before using the information, I attempts to fuse the radial information. The neighboring arcs arc_{j-1}, arc_j are inspected regarding the energy density required at certain distances. If the variance is not greater than predefined threshold value $arc_{var_{th}}$ then aggregation takes place, as described in the Phase 2. The memory required to store profile is equal to number of angles times the number of distances.

For the idealized redeployment for every SN n_i within the profiled hole we calculate the angle δ_i at which SN is positioned in relation to *I*. Then, we use the angle to select arc arc_j of energy angular profile to which a SN belongs. From the selected arc the value of energy at the $distance_i$ is divided by the amount of reporting nodes at this distance.

The obtained profile has as simple form of two matrices and can be used by SNs, or other assist nodes, or on the sink for reconfiguration or maintenance planning. The profile could be sent to the sink using the routing protocol.

D. On the Selection of the Initiator

In order to select I as close to the hole epicenter as possible and to prohibit singular (faulty) SNs to initiate profiling, we require that before initiating profiling the candidate SN queries the energy values of its 1-hop neighbors. The candidate becomes *I* only if the average of these values is below a certain threshold (E_{TH}). It is possible that two or more initiators simultaneously start profiling within the same hole. In this case the simple solution is for SNs to join the spanning tree rooted at *I* with the lowest profileID. To prevent repetition of profiling by another SN reaching E_{TH}, every SN once joining a spanning tree delays the start of a new profiling for the time required to undertake maintenance actions. It is evident that a higher connectivity degree of *I* increases the number of branches of the aggregation tree and consequently also the radial resolution of the energy needs profile. Therefore, it is meaningful to require a minimal value of connectivity degree for a SN to become *I*.

V. Evaluation

We now evaluate the performance of LEHP. First, we define the simulation settings and performance metrics. Next we present the results.

A. Evaluation Setting

For simulation we use the OMNeT++ simulator [28]. Since the accuracy of LEHP profile depends on average connectivity degree of the network, we setup the network topology to allow to evaluate its impact. Based on [26] we chose the following network parameters to vary the connectivity degree. All SNs use the same fixed communication range *r* = 25m. The SNs are deployed uniformly random over an area of size 250m x 250m. The results are provided by different connectivity degrees by deploying 250, 500 and 750 SNs. All SNs, independent of their placement, are assumed to consume energy at a constant rate (period of 25 sec) for their normal operation. Additionally, every 1.5 sec SNs perform sensing according to the hotspot model.

We consider only a single hole in the network but vary its size. We show simulation results for aggregation distances of r/3, r/2 and r and fixed hop distance. We model phenomena using Exponential, Pareto and Normal spatial distributions as discussed in Section III. If not otherwise stated, we assume a period of 25 sec for operational energy usage, Exponential distribution model of phenomena, deployment of 500 nodes, aggregation of messages using the Euclidean distance of r/2.

B. Profiling Evaluation Metrics

For evaluation of the proposed LEHP approach we simulate an ideal maintenance of the hole. We use the created profile to retrieve the energy needed for each SN. The needed energy is added to the SNs' current energy. After this operation we continue simulation and measure the lifetime of the repaired network. After applying the energy adjustment we measure the lifetime of the hole in relation to the lifetime of the rest of the network. The optimal redeployment should lead to possibly simultaneous death of the SNs inside and outside the hole. The premature death of the SNs in the hole signifies undervaluation of the energy needs, the delayed death overstocking with energy. As a metric we define the ratio of alive SNs in the energy hole to the initial number of SNs over relative time. Relative time is expressed as a percentage of the lifetime of the network without energy injection. We define the lifetime as the time of first failure of SN outside the energy hole. Consequently, if some SNs within the hole as the result of energy injection are overstocked with energy, it is possible for them to be still alive at time greater than the network lifetime. An important performance metric is the energy cost of LEHP.

C. Energy Efficiency of LEHP

In this section, we describe the energy cost of a profiling algorithm. For this consideration we neglect the computational energy expenditure and concentrate only on the costs incurred by communication, which we measure as the number of messages sent per SN. We also give an upper bound for messages length.

During the spanning tree construction phase, I starts limited flooding/broadcast that propagates through the hole. Each SN receiving the broadcast message evaluates the length of the path to I and only if this path length is shorter than the one currently stored in the routing table, the message is propagated further with increased path length. In the optimal case each SN within the hole should forward the message only once. Because of the varied propagation delays along different possible paths, SNs do not always receive the optimal path as first, therefore more than one forwarding is possible. For the described evaluation setting we measured how many forwards per SN took place in our simulations. The results show that on average 74.53% of SNs performed only a single forward, 24.27% two forwards and only 1.20% three forwards. The average is then 1.26 forwards per SN for the spanning tree construction, where the length of the transmitted message is constant.

The evaluation of the second phase is straightforward. Every SN within the energy hole aggregates received messages from its children and sends only a single message to its parent. The length of aggregation messages varies, growing on the way towards I. It contains a fixed length header for routing and a varing number of entries for each quantified distance for which aggregation is performed. The maximum length of the message payload cannot exceed L (Eq. 5), where q_{size} is the aggregation quant size (fraction of r).

$$L = max(TTL_{max}, \lceil \frac{r}{q_{size}} \rceil) \times sizeof(data\_struct) \qquad (5)$$

Summarizing, the amount of energy required per SN for performing the profiling is very limited and amounts to forwarding 2.26 messages on average. It is important to note that the profiling is performed only rarely as profile based maintenance should prevent hole reoccurrence.

D. Simulation Results

All of the presented plots share the same axes. Axis x represents relative time expressed in percents. Axis y shows percentage of SNs within the hole that have enough energy for operation over the time. The ideal curve (perfect accuracy of energy needs profiling) should be straight line at value of 100% alive SNs reaching the relative time of 100% and then instantaneously falling to 0%. Deviations from the ideal curve mean some degree of inaccuracy. The curve falling below 100% alive SNs before reaching 100% relative time indicates level of under-stocking of the network with the energy within the hole. The value above 0% alive SNs at relative time over 100% indicates level of overstocking of the network within the hole.

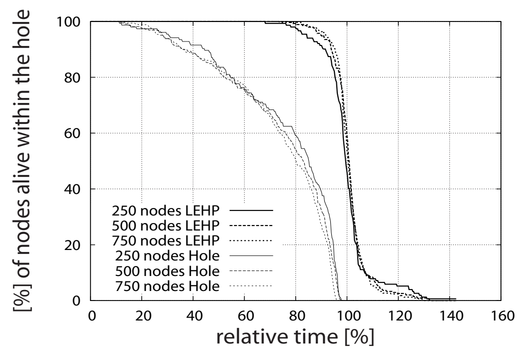


Figure 3. Impact of node density

Fig. 3 depicts how the density of the deployment impacts the accuracy of LEHP. The labels ”x nodes LEHP” and ”x nodes Hole” represent simulation with and without LEHP respectively. As expected, the network deployed with 250 SNs shows slightly lower accuracy. It is caused mostly by the fact that lower average connectivity degree degrades angular resolution. Although the network remains connected, sparse connectivity leads to the assignment of SNs to an arc which is less accurate than in denser deployments. The deployment of over 500 SNs assures high connectivity degree, therefore, higher angular resolution is reached. It results in more accurate profiling. Without energy injection, the first SNs (closest to the center of hotspot) start to fail already at time of 15% of network lifetime and the rest gradually follow. *Concluding, the accuracy of LEHP is highly independent from the density of the network.*

The impact of the aggregation step (Alg. 2) is presented in Fig. 4. As expected, the higher the granularity, the better the accuracy is achieved. Both r/3 and r/2 (step size r/3 and r/2) preform very well. The smaller area over which aggregation

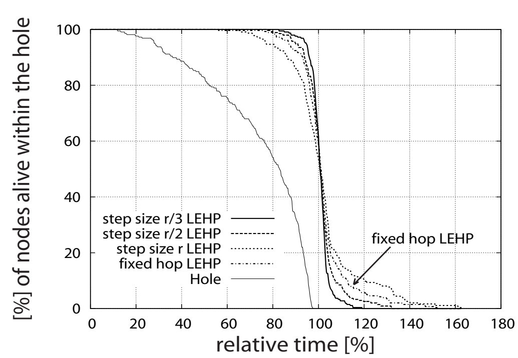


Figure 4. Impact of aggregation distance

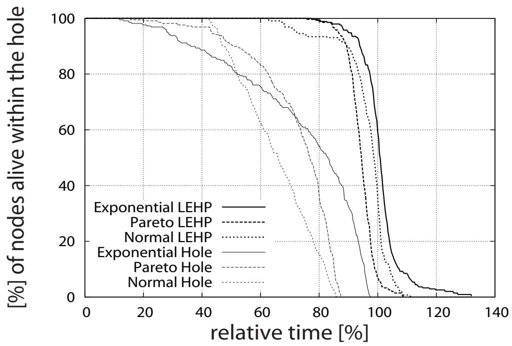


Figure 5. Impact of hole distribution

takes place the greater chances that lower variance in energy need levels, therefore lower averaging error. It is to observe that applying hop distance metric (fixed hop) outperforms Euclidean distance approach if $step = r$. When using the hop distance, the distance corresponds to shorter Euclidean distance than *r* as it would be expected by multiplying the range of communication by amount of hops. The curve *Hole* represents the failing of the SNs without energy injection. *Concluding, Euclidean based aggregation preforms better for ring widths smaller than communication range, otherwise it is more efficient to use hop based quantification.*

The best performance is achieved for the Exponential distribution model (Fig. 5). Here, the highest energy depletion is concentrated near the epicenter of the hole, what assures high accuracy of profiling for this most dynamic region. For Normal and Pareto distributions the energy is more evenly distributed, degradation of network starts later but is much steeper afterwards (Pareto Hole and Normal Hole curves), therefore, the implications of lower accuracy at greater distances are more evident. *The LEHP algorithm offers better accuracy for the distributions which show smaller variance.*

VI. CONCLUSIONS

In this work we provided the first necessary steps for making the energy based maintenance a viable option for WSN functionality conservation. The developed energy hole profiling algorithm, LEHP, is shown to be an efficient strategy for valuable early warning of likelihood of energy holes. LEHP allows the accurate positioning and size estimation of developing energy hole, which usually leads to sensing and communication coverage loss. The efficiently computed and accurate angular and radial information about the energy needs, provides means for effective maintenance actions, which optimally are long term. This assertion is substantiated by the extensive simulation results.

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