Self-Healing Wireless Sensor Networks: Results That May Surprise

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Abstract

According to a recent DARPA announcement [1], *self-healing* – the ability of a network to effectively combat coverage and routing holes and network disconnection – represents one of the most desired operational properties of wireless sensor networks (WSNs) for military applications. Although previously considered in the WSN literature, the concept of network self-healing, and specifically self-healing by means of mobile nodes, still remains a greatly understudied research area.

In this paper, by focusing on one particular type of holes - *routing holes*, the energy aspect of combating these holes through the deployment of a single mobile (super) node is discussed. The specific contributions of the paper include:

1) It is proven that although bridging a routing hole by means of a mobile node may seems very intuitive, the deployment of the mobile is often hard to formally justify. For instance, the use of the mobile turns out to be completely energy unjustifiable in all circle- and square- like shaped holes, regardless of their actual size or number of boundary nodes actively involved in routing. Accordingly, the need to consider other parameters, such as overall transmission delay or static-node failure, when deciding whether/where to deploy the mobile, is demonstrated.

2) Building on the results of 1), we propose **OPlaMoN** – a simple distributed algorithm for determining the **O**ptimal **Pla**cement of a **Mo**bile **N**ode within a routing hole of any arbitrary topology. As the name implies, the algorithm solves a rather complex optimization problem by breaking it into smaller fragments which are, then, partially solved by individual nodes. The final solution is reached through a cooperative decision-making process, assuming a minimum exchange of information among the effected nodes. The algorithm has excellent energy conserving properties and, as such, is highly suited for WSN environments.

We believe the findings of this paper can serve as a good starting point and encourage further research on the deployment of mobile nodes for the purpose of self-healing in wireless sensor networks.

1. Introduction

In recent years, wireless sensor networks (WSNs) have attracted great attention of the research community, thanks to their tremendous potential in various application fields, including: environment monitoring, security surveillance, disaster management, combat operations, etc.

A typical WSN application scenario assumes a large-scale network, consisting of inexpensive, static nodes, randomly deployed in a remote and/or hostile area, as illustrated in Figure 1. From the network-operation point of view, most application scenarios consider the use of geographic (greedy) routing[1] over a multi-hop topology.

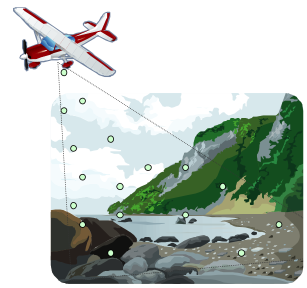

Figure 1 WSN for environment monitoring

Energy conservation is identified as the most critical issue in the design and operation of WSNs, due to its direct impact on the network efficacy and, more importantly, on the overall network lifetime. The most straightforward way to achieve effective energy conservation is: 1) by minimizing the number of required transmissions and/or 2) by utilizing optimal (i.e. optimized) routing paths through the network. Unfortunately, the implementation of 2) turns out to be a great challenge in a number of application scenarios. Namely, as indicated earlier, a typical WSN setup assumes one or more of the following:

- sensor nodes are randomly scattered throughout the deployment filed, e.g. by being disseminated from a plane;
- the deployment field is a region of irregular geographic composition, (possibly) comprising natural obstacles such as lakes or cliffs;
- sensor nodes are small, inexpensive, wireless, and battery-powered devices, prone to failure due to:
  - component malfunctioning;
  - battery depletion;
  - environmental factors: extreme heat, flooding, freezing, etc.;
  - man-caused factors: interference, accidental damage, explosion, etc..

[1] In geographic routing, nodes have to only know the locations of their nearest neighbours; packets are routed through the network by being forwarded to a neighbour that is physically closer (closest) to the destination. The main advantages of geographic over other WSN routing strategies include: 1) stateless, and therefore highly energy efficient, nature of routing, 2) fast adaptability to network's topological changes, and 3) scalability. Geographic routing, in the context of this paper, has been discussed in [2], [3], [4].

Based on the above, the network topology inevitably is, or eventually gets, plagued by serous irregularities and areas completely void of nodes – a.k.a. *routing holes* [5]. The existence of routing holes presents the major hurdle to the realization of optimal, i.e. optimized, routing, irrespective of the actual routing protocol employed in the network [2].

The techniques aimed at combating routing holes in WSNs are commonly referred to as *self-healing* techniques. A large number of these techniques has already been proposed in the literature (see [6] to [9]); however, most of them appear rather ineffective as they focus on finding alternate paths through the network, instead of attempting to directly combat the holes, e.g. by minimizing their negative effects or eliminating them completely.

2. Self-healing by means of mobile nodes

The use of mobile nodes, with the goal to improve general network coverage and connectivity, is not a new idea ([10], [11], [12]). The utilization of mobile nodes for the specific purpose of self-healing, in the framework of coverage holes, has also been previously discussed in the literature (see [13], [14]). In all these works, the deployment (i.e. availability) of a large number of mobile nodes is commonly assumed. Yet, sensor-network researchers generally agree that in an average real-world sensor network, the deployment of only few of such nodes may be feasible, given their considerably higher cost than the cost of static sensors. ([15] and [16] provide a good insight into the challenges of designing, and advantages of using, mobile micro aerial sensor nodes.)

According to our knowledge, the work presented in this paper is one of the first attempts to investigate the energy aspect of self-healing by means of mobile robots, in the framework of routing holes. In particular, our work considers a realistic large scale WSN, with only one or a few mobile nodes, and with a number of routing holes such that the deployment of only one mobile per hole is possible, as illustrated in Figure 2. (Mobile nodes are assumed to be much superior to regular static nodes - in addition to being mobile, 1) they have nearly unlimited, or easily replenishable, power supply; and 2) they can dynamically readjust their transmission power.)

The main contributions of our work include:

- Through theoretical and simulation results, we prove that the use of 'energy' as the sole criterion for deciding whether/where to place a mobile within a routing hole can often lead to surprising results - by completely failing to justify the mobile's deployment, even in the cases when the advantages of using the mobile seem very intuitive and obvious.
- We propose a simple, energy-efficient algorithm for determining the optimal location of a mobile bridge-node within a routing hole of any arbitrary topology. The algorithm is fully distributed and runs in O(n) time, where n represents the number of boundary nodes affected by sub-optimal routing.

The reminder of this paper is organized as follows. The most important network assumptions are outlined in Section 3.1. The energy aspects of self-healing by means of mobile nodes, in case of circular and rectangular holes, are presented in Sections 3.2 and 3.3. Section 4 provides an overview of OplaMoN - our distributed cooperative energy-efficient algorithm for optimal placement of mobile nodes. Section 5 summarizes our findings and outlines our future research directions.

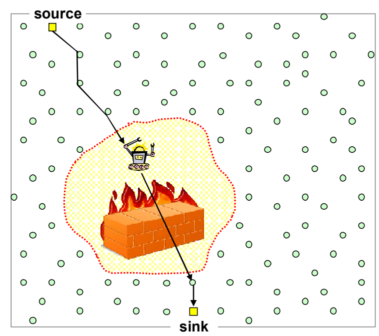

Figure 2 Self-healing by means of mobile nodes: one node per hole

3. Energy as criterion for deciding on mobile node deployment

3.1 General network assumptions

The analysis presented in the subsequent sections is based on the following assumptions concerning the structure and functionality of the observed WSN:

- The radio range of individual sensor nodes is r [units].
- Each node is aware of its location.
- One single data source and one single respective data sink exist in the network.
- The network employs geographic routing.
- The optimal path between the source and the sink (as determined by geographic routing) is intercepted by a routing anomaly – a routing hole.
- The node at which the source-to-sink traffic first encounters/touches the hole (i.e. hole boundary) is annotated by node(1) – see Figure 3. The node at which the source-to-sink traffic exits the hole boundary is annotated by node(n). Accordingly, a total of n boundary nodes, and n-1 links, are affected by (i.e. participate in) the routing of the source-to-sink traffic.
- In order to 'bridge' the hole, the use of only one mobile node is considered (see Figure 4). If/when deployed, the mobile is placed at distance r [units] from one of the affected boundary nodes, in the direction of the exit node – we will annotate this node with node(k), $k \in \{1,.., n-2\}$.[3]

[2] Traffic streams with the source- and respective sink- node on the opposite sides of a routing hole, will be forced to make a 'detour', as illustrated in Figure 2. Clearly, this phenomenon is most obvious in the case of geographic routing.

[3] Please note, we do not consider placing the mobile next to the immediate neighbour of exit node(n).

Upon its deployment, the mobile passes the traffic directly across the hole – from node(k) to exit node(n).

- Finally, for all static nodes: the minimum received-signal power required to reach a limiting SNR ratio is $P_{received}$. Accordingly, by assuming a simple free-space path loss model and path loss gradient α=2 [18], a node must emit signal with power $P_{received} \cdot r^2$, to ensure the radio range of r [units].

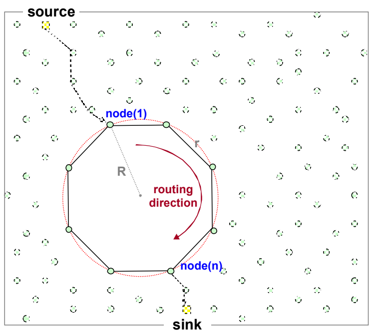

Figure 3 Circular shaped routing hole

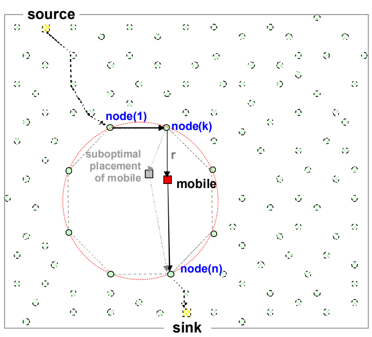

Figure 4 Circular hole bridged by a mobile node

In the subsequent sections, we will focus on two special types of routing holes: circular and rectangular shaped. According to [19], circular routing holes can be found in outdoor environments, countryside, battlefields, etc., and they are typically caused by natural obstacles such as: craters, large rocks, lakes, ponds, etc. Rectangular routing holes, on the other hand, can be found in urban environments, as they roughly correspond to buildings, large overpasses, and other man-made obstacles.

3.2 Circular shaped hole

To evaluate the possible energy benefits of using a mobile node to bridge a circular shaped routing hole, the assumptions from Section 3.1 are extended as follows:

- The routing hole, i.e. area void of sensor nodes, matches the interior of a circle of radius R [units] (Figure 3).
- Accordingly, the sensor nodes on the boundary of the hole, and their respective radio links, form a convex polygon of degree m (i.e. number of polygon sides = m), which we will annotate by P. For the simplicity of the discussion, we will assume P to be a regular polygon with all sides of equal size r [units].

Clearly, under the above assumptions, as the size of the hole increases (R increases), more nodes will fit (i.e. be found) on the boundary of the hole, ultimately increasing the degree of polygon P. In a general case, the relationship between r, R and m is given by the following formula [20]:

$$r = 2R \cdot \sin\frac{180\,[deg]}{m} = 2R \cdot \sin\frac{\pi\,[rad]}{m} \qquad (1)$$

Please note: in the worst case scenario[4], node(1) and node(n), as defined in Section 3.1, will happen to be on the opposite sides of polygon P - for an illustration, see Figure 4. Consequently, assuming m is an even number, n and k (see Section 3.1) become: $n = \frac{m}{2} + 1$ and $k \in \{1,..,\frac{m}{2} - 1\}$.[5]

3.2.a) Routing around hole

Now, let us begin the energy-related analysis by, first, considering the base case, involving no mobile node (Figure 3). The energy required to route a bit of source-to-sink traffic along, i.e. around, the boundary of the hole is annotated by $E_{1\text{-}n}$. The respective expression is provided in (2).

$$E_{1-n} = (n-1) \cdot P_{received} \cdot r^2 \qquad (2)$$

By substituting (1) in (2), (2) becomes:

$$E_{1-n} = (n-1) \cdot P_{received} \cdot (2R)^2 \cdot \left(\sin\frac{\pi}{m}\right)^2 \qquad (3)$$

3.2.b) Routing through mobile

Next, let us consider the case involving a mobile node, as shown in Figure 4. The energy required to route the traffic through the mobile - assuming it is placed next to node(k) - and across the hole, is annotated by $E_{1\text{-k-mob(k)-n}}$. The respective expression is provided in (4) and (5).

$$\begin{aligned} E_{1-k-mob(k)-n} &= E_{1-k} + E_{k-mob(k)} + E_{mob(k)-n} = \\ &= (k-1) \cdot P_{received} \cdot r^2 + P_{received} \cdot r^2 + \\ &+ P_{received} \cdot d(mob(k), node(n))^2 \end{aligned} \qquad (4)$$

$$E_{1-k-mob(k)-n} = P_{received} \cdot \left(k \cdot r^2 + d_{mob(k)-n}{}^2\right) \qquad (5)$$

In (4), $E_{1\text{-k}}$ represents the energy required to route a bit of traffic between node(1) and node(k), $E_{k\text{-mob(k)}}$ represents the energy required to route a bit of traffic between node(k) and the mobile, and $E_{mob(k)\text{-n}}$ represents the energy required to route a bit of traffic between the mobile and the exit node (node(n)). d(mob(k),node(n)) represents the Euclidean distance between the mobile and node(n). In (5), $d_{mob(k)\text{-n}}$ is a short notation for d(mob(k),node(n)). Please note, the optimal placement of the mobile – the one that minimizes $d_{mob(k)\text{-n}}$, and ultimately minimizes $E_{1\text{-k-mob(k)-n}}$ (see (5)) – is along the line that passes through node(k) and node(n), as illustrated in Figure 4.

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[4] By worst case scenario, we assume the case in which the maximum possible number of boundary nodes is affected by a given source-to-sink traffic stream.

[5] The proceeding analysis can be easily extended to odd m.

Under the optimal placement of the mobile node in the neighbourhood of node(k), as discussed above, $d_{mob(k)-n}$ can be expressed simply as:

$$d_{mob(k)-n} = d_{k-n} - r \tag{6}$$

Consequently, (5) can be rewritten into

$$E_{1-k-mob(k)-n} = P_{received} \cdot \left(k \cdot r^2 + \left(d_{k-n} - r\right)^2\right) \tag{7}$$

In (7), d(node(k),node(n))=d_{k-n} is the Euclidean distance between node(k) and node(n). As such, d_{k-n} corresponds to the $(n–k)^{th}$ diagonal of polygon P (see [20]), and is given by:

$$d_{k-n} = 2R \cdot \sin \frac{\pi\,[rad] \cdot (n-k)}{m} \tag{8}$$

By substituting (1) and (8) in (7), (7) becomes

$$E_{1-k-mob(k)-n} = P_{received} \cdot (2R)^2 \cdot \\ \cdot \left(k \cdot \left(\sin\frac{\pi}{m}\right)^2 + \left(\sin\frac{\pi\cdot(n-k)}{m} - \sin\frac{\pi}{n}\right)^2 \right) \tag{9}$$

3.2.c) Routing around hole vs. routing through mobile

From the preceding discussion, one can simply conclude: the deployment of the mobile in a circular shaped hole is energy justifiable as long as we can find a k∈ {1,.., n-1}, that satisfies the following inequality:

$$E_{1-k-mob(k)-n} < E_{1-n} \tag{10}$$

Based on (3) and (9), an equivalent form of (10) is obtained:

$$\left(\sin\frac{(n-k)\cdot\pi}{m} - \sin\frac{\pi}{m}\right)^2 < (n-k-1)\cdot\left(\sin\frac{\pi}{m}\right)^2 \tag{11}$$

By substituting (n-k) in (11) with j (j=n-1, n-2,..,2), and by annotating the left- and right- hand side of (11) with $\mathbf{f_1}$(j) and $\mathbf{f_2}$(j) respectively,

$$\mathbf{f_1}(j) = \left(\sin\frac{j\cdot\pi}{m} - \sin\frac{\pi}{m}\right)^2 \tag{11}$$

$$\mathbf{f_2}(j) = (j-1)\cdot\left(\sin\frac{\pi}{m}\right)^2 \tag{12}$$

we can finally state: the use of a mobile-bridge node in a circular shaped routing hole comprising a total of m boundary nodes is energy justifiable as long as

$$\boxed{\exists\ \mathbf{j} \in \{\mathbf{2,..,n-1}\}\ \ \textbf{such that}\ \ \mathbf{f_1}(j) < \mathbf{f_2}(j)} \tag{13}$$

Please recall, in the worst case scenario of source-to-sink traffic stream, n=(m/2)+1, and j∈ {m/2, .., 2}.

Figures 5.a) to 5.c) illustrate the relationship between $\mathbf{f_1}$(j) and $\mathbf{f_2}$(j), for different values of m. From these figures it is evident that the condition stated in (13) never gets satisfied. (The only exception is the case m=10 and j=2, which corresponds to the mobile being deployed 2 hops away from the exit node in a routing hole comprising 10 boundary nodes. We disregard this deployment scenario as being trivial.) This further leads to a rather surprising conclusion: the deployment of a mobile-bridge node in a circular shaped routing hole will never be energy justifiable, regardless of the actual size of the hole and/or the number of boundary nodes actively involved in routing. Or, put another way, if using energy as the sole criterion of efficiency, it will always be more favourable to route traffic around a circular shaped hole (even if it means routing through tens or hundreds of static sensors!), then to bridge the hole by means of a single mobile node.

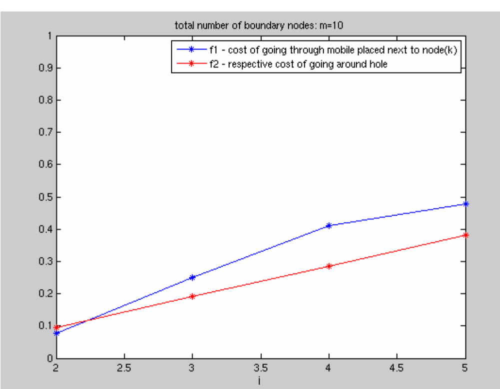

Figure 5.a) f_1(j) v.s. f_2(j), for m=10

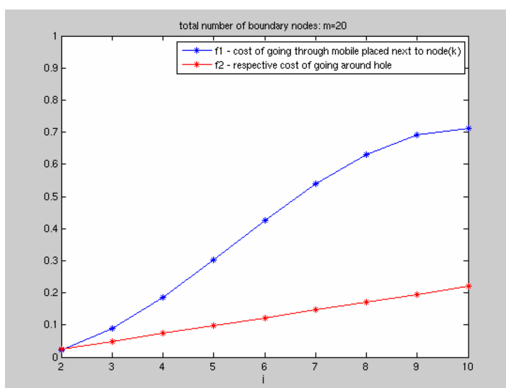

Figure 5.b) f_1(j) v.s. f_2(j), for m=20

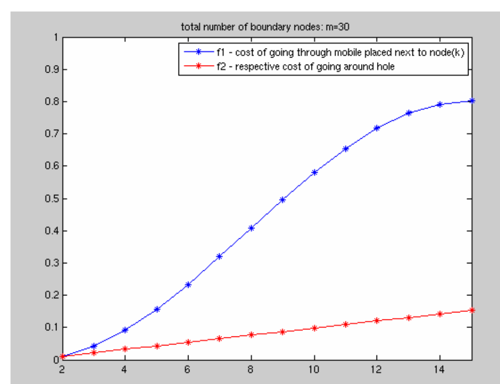

Figure 5.c) f_1(j) v.s. f_2(j), for m=30

3.3 Rectangular shaped hole

In our most recent work [17], the energy aspect of bridging a rectangular shaped routing hole by means of a mobile node is investigated. The obtained results demonstrated that the use of the mobile is, again, unjustifiable in all square, or nearly-square, shaped holes.

3.4 Summary

By generalizing the findings of Section 3.2 and 3.3, we deduce: deployment of a mobile node in any uniform-like shaped[6] hole will not be energy justifiable. Our extensive

[6] By uniform-like shape, we mean a shape whose center of gravity is also its geometric center. Circle and square are two special cases of such holes.

simulation experiments fully confirm this hypothesis. Nevertheless, we argue that in such holes, especially the ones that affect large areas and considerable number of boundary nodes, the deployment of a mobile still should not be completely abandoned. Namely, even though the path through the mobile may turn out to be more costly in terms of overall energy consumption, it is reasonable to expect that this path:

- offer lower transmission delay, by involving fewer nodes/hops, and
- prevent further enlargement of the hole, by posing less demand on the boundary nodes (as discussed in [3]).

(For an illustration, see Figure 6.)

From the above, we further postulate: any algorithm aimed at finding the optimal position of the mobile, for the sake of bridging a routing hole, should not use 'energy' as its sole criterion. Instead, the algorithm should incorporate 'transmission delay' and 'hole-enlargement phenomenon' as (equally) important parameters.

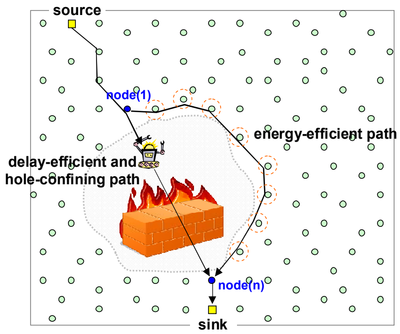

Figure 6 Energy-efficient path around the hole vs. delay-efficient ant hole-confining path through mobile

4. OPlaMoN

In this section, an overview of our algorithm for **O**ptimal **Pla**cement of **Mo**bile **N**odes (OPlaMoN) in self-healing WSNs is provided. (Many of the details are omitted due to lack of space.) The algorithm is aimed at finding the most effective location for deploying a mobile-bridge within a routing hole of any arbitrary topology. OPlaMoN is fully distributed, and it reaches the final solution through a cooperative decision-making process, assuming a minimum exchange of information among the affected sensor nodes. The essence of the algorithm is as follows: each affected boundary node (node(k), k=1,..,n) calculates the so-called bidding value (see Section 4.1), which represents the overall gain that would be obtained if the mobile is to be placed next to this node. Through local exchange of bidding values, the nodes cooperatively identify the highest bid and the respective bidder (see Section 4.2). By deploying the mobile in the vicinity of the highest-bid node, the maximum network gain is ensured.

4.1 Calculation of bidding values

Each boundary node(k), k=1,..,n, calculates its bid value – Bid(k), using the following weighted-sum formula:

$$Bid(k) = \begin{cases} -\infty, & \text{if battery level} < TH_{critical} \\ w_1 \cdot EG_k + w_2 \cdot DG_k \end{cases} \qquad (14)$$

In (14), EG_k represents the relative ***energy gain*** that would be obtained if the mobile is to be placed next to node(k), and is defined as:

$$EG_k = \frac{E_{1-n} - E_{1-k-mob(k)-n}}{E_{1-n}} \qquad (15)$$

DG_k represents the relative ***delay gain*** (i.e. reduction in transmission delay) that would be obtained if mobile is to be placed next to node(k), and is defined as:

$$DG_k = \frac{\#\,hops\ around\ hole - \#\,hops\ through\ mobile}{\#\,hops\ around\ hole} = \frac{(n-1)-(k-1+2)}{(n-1)} = 1 - \frac{k+1}{n-1} \qquad (16)$$

Note, to be able to calculate EG_k and DG_k, we assume each node knows only the following:

- its own location;
- the location of exit node(n);
- its own hop distance from node(1);
- the number of boundary nodes involved in the routing of the given source-to-sink traffic (n).

All of the above could be obtained (i.e. calculated) in a single round of information exchange along the boundary of the routing hole.

Back in (14), the weights w_1, $w_2 \in [0,1]$ determine the relative importance of EG_k and DG_k. They are meant to be adjustable, and can be fine-tuned to each specific application, either by an expert or through an automated procedure. Clearly, in applications where the energy of the mobile is scarce w_1 should be much greater than w_2, while in time-critical applications w_2 should be greater than w_1. Otherwise, $w_1=w_2=0.5$ would be a reasonable choice.

4.2 OPlaMoN Outline

4.2.a) OPlaMoN: Initialization phase

Using TENT rule [9], boundary nodes involved in the routing of source-to-sink traffic (node(1) to node(n)) identify themselves. Subsequently, the exit node (node(n)) informs other boundary nodes (node(1) to node(n-1)) of its location. The rest of the algorithm assumes that the mobile bridge-node is somewhere close to the boundary of the routing hole, and within the radio range of at least one of the affected boundary nodes (see Figure 7).

4.2.b) OPlaMoN: Steps performed at individual nodes

1st (forward) pass, from node(1) to node(n):

(1) Calculate Bid(k) according to (14).

(2) If k=1,

- *highestBid = Bid(1);*
- *higestBidderID = 1.*
- *go to (4).*

If k≠1, wait for Bid(k-1) from node(k-1).

(3.a) After receiving Bid(k-1), adjust own bid value according to:

$$Bid(k)=\begin{cases}-\infty, & if\ Bid(k-1)=-\infty \\ Bid(k), & otherwise\end{cases}$$

(3.b) Subsequently, calculate:

$$highestBid = \max\{highestBid, Bid(k)\}$$
$$highestBidderID = index(\max\{highestBid, Bid(k)\})$$

(4) send [Bid(k), highestBid, highestBidderID] to node(k+1)

2nd (reverse) pass, from node(n) to node(1):

(5) If k=n,
- *winningBid = highestBid;*
- *winningBidderID = highestBidderID.*
- *go to (6).*

If k≠n, wait for highestBid and highestBidderID from node(k+1).

(6) Broadcast [highestBid, highestBidderID].

Please note, with step (3.a), OPlaMoN ensures that the new 'shortcut' path (i.e. path through the mobile) will never involve a node with critically low battery supply. As an illustration, let us look at the example of Figure 7. Although the initial bid value of node(5) is highest, placing the mobile bridge next to this node would result in traffic being routed to the mobile via node(4), which is already close to 'dying' due to critically low battery levels. To avoid placing any further stress on node(4), OPlaMoN sets the bidding values of all nodes downstream of node(4) (node(5) to node(7)) to -∞ and, consequently, enables node(3) to win the bid.

Also, note, with steps (5) and (6), OPlaMoN ensures that the highest bid value will be propagated back along the hole boundary, until it finally reaches the mobile node.

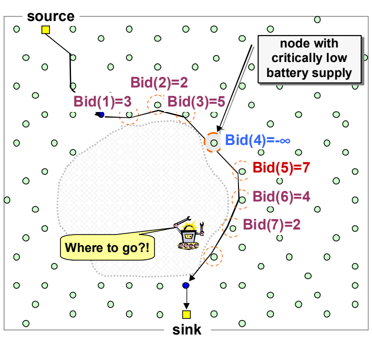

Figure 7 Boundary node with critically low battery supply

4. Conclusion and Future work

In this paper, we have shown that while bridging a routing hole by means of a mobile robot may seem intuitive, finding formal justification for the deployment of the mobile is not a trivial task. Namely, we have proven that 'energy' – the most commonly used measure of efficiency in the WSN literature – may fail to justify such a use of the mobile in a wide range of cases, including all uniformly (e.g. circle- or square- like) shaped holes. Thus, the use of other parameters, including overall transmission delay and static-node failure, may have to be considered when deciding on whether, or where, to deploy the mobile.

Based on the obtained theoretical results, a new simple distributed energy-conserving algorithm for optimal placement of mobile-bridge nodes has been proposed.

In our future work, we plan on extending the analysis presented in this paper to WSNs with multiple streams of source-to-sink traffic.

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