Combating routing holes by means of mobile nodes: Should energy really matter!?

Natalija Vlajic, Nelson Moniz, Michael Portnoy

Department of Computer Science and Engineering, York University, Toronto, Canada

Abstract — **In this paper, some fundamental aspects of self-healing in large-scale WSNs are discussed. Namely, 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 examined. The obtained results indicate that, even though 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 uniformly (e.g. circle- or square- like) shaped holes, regardless of their actual size or number of boundary nodes actively involved in routing. This further implies the need to consider other parameters, such as overall transmission delay or static-node failure, when deciding whether, or where ultimately, to deploy the mobile.**

Index Terms — **energy conservation, mobile node, self-healing, wireless sensor network.**

I. Introduction

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 by utilizing optimized routing paths through the network. Unfortunately, this 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.;

Due to the above, the network topology inevitably gets plagued by serous irregularities and areas completely void of nodes – a.k.a. *routing holes* [1]. The existence of routing holes presents the major hurdle to the realization of optimized routing, irrespective of the actual routing protocol employed in the network (see Fig. 1).

The techniques aimed at combating routing holes are commonly referred to as *self-healing* techniques. A large number of these techniques has already been proposed in the literature ([2] to [5]); 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 effect or eliminating them completely.

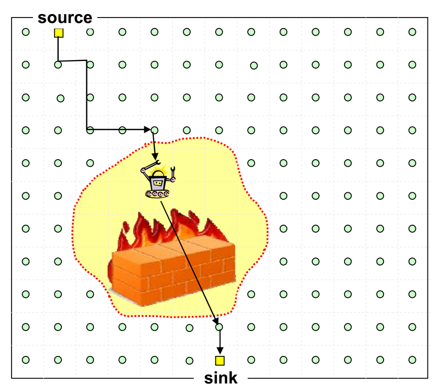

Fig. 1. Self-healing by means of mobile nodes

According to our knowledge, the work presented in this paper is the first attempt 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 Fig. 1.

The reminder of this paper is organized as follows. The most important network assumptions are outlined in Section II.A. In Section II.B, the details of our energy-related single mobile node deployment analysis are presented. Section III summarizes the key findings from Section II.

II. ENERGY AS A CRITERION FOR DECIDING ON MOBILE NODE DEPLOYMENT

A. Network Assumptions

The assumptions concerning the structure and functionality of the observed WSN include:

- Sensor nodes are organized into a grid of size NxN. The radio range of individual sensor nodes is r [units]. Each node can directly communicate with four of its nearest neighbours. 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 is intercepted by a routing anomaly – a hole.
- The overall area affected by the routing hole can be modeled as a rectangle of dimensions axb, where a and b are two arbitrary real numbers ($a, b \in R$).
- The node at which the source-to-sink traffic first encounters/touches the hole (i.e. hole boundary) is annotated by node(1). 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 the routing of the source-to-sink traffic.
- In order to 'bridge' the hole, the use of only one mobile node is considered (see Fig. 2).
- If/when deployed, the mobile is placed at distance r [units] from one of the boundary nodes - node(k) ($k \in \{1,..,n\}$). Upon its deployment, the mobile passes the traffic directly across the hole - from node(k) to the exit node (node(n)).
- Finally, for all 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 of $\alpha=2$ [18], the sending node must emit signal with power $P_{received} \cdot x^2$, in order to effectively communicate with another node at distance x [units].

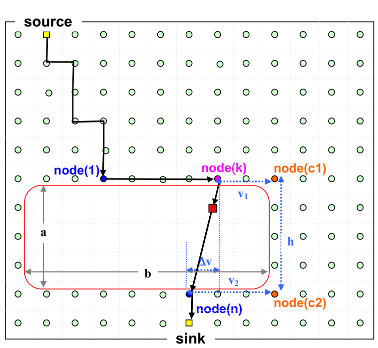

Fig. 2. Routing hole bridged by a mobile node

B. Is The Use Of The Mobile Node Energy Justifiable?

In this section, we aim to answer the fundamental question: Is it energy justifiable to employ a mobile node in the interior of an observed routing hole for the purpose of bridging (i.e. shortcutting) the hole.

We begin the analysis by considering the base case, involving no mobile node. The energy required to route a bit of source-to-sink traffic around, the boundary of the hole is annotated by E_{1-n}, and corresponds to

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

Now, let us consider the case involving a mobile node, shown in Fig. 2. The energy required to route the traffic through the mobile and across the hole is annotated by $E_{1-k-mob(k)-n}$, and given in (2) and (3).

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

$$E_{1-k-mob(k)-n} = P_{received} \cdot \left(k \cdot r^2 + d_{mob(k)-n}{}^2\right) \tag{3}$$

In (2), E_{1-k} represents the energy required to route a bit of traffic between node(1) and node(k), $E_{k-mob(k)}$ represents the energy required to route a bit of traffic between node(k) and the mobile, and $E_{mob(k)-n}$ represents the energy required to route a bit of traffic between the mobile and the exit node (node(n)). $d(mob(k),node(n))=d_{mob(k)-n}$ represents the Euclidean distance between the mobile and node(n).

Clearly, for a fixed node(k), the optimal placement of the mobile - the one that minimizes $d_{mob(k)-n}$, and ultimately minimizes $E_{1-k-mob(k)-n}$ (see (3)) - is along the line that passes through node(k) and node(n). Thus, $d_{mob(k)-n}$ can be expressed simply as $d_{mob(k)-n} = d_{k-n} - r$, where $d(node(k),node(n))=d_{k-n}$ is the Euclidean distance between node(k) and node(n). Consequently, (3) becomes

$$E_{1-k-mob(k)-n} = P_{received} \cdot \left(k \cdot r^2 + (d_{k-n} - r)^2\right) \tag{4}$$

Based on (1) and (4), one can simply conclude: the deployment of the mobile is justifiable as long as we can find a k, i.e. a node(k), $k \in \{1,..,n\}$, that satisfies the following inequality.

$$E_{1-n} > E_{1-k-mob(k)-n} \tag{5}$$

By substituting (1) and (4) into (5), the condition (5) can be rewritten as (6).

$$(n-k-1) \cdot r^2 > (d_{k-n} - r)^2 \tag{6}$$

In the remainder of this section, we investigate under which conditions any of the boundary nodes affected by the source-to-sink traffic will satisfy (5), i.e. (6). To facilitate our analysis, we annotate the nodes in the upper right and lower right corner of the observed routing hole with node(c1) and node(c2) (Fig. 2). Within the boundary nodes affected by the source-to-sink traffic (node(1) to node(n)), the following three groups are identified and separately studied:

Group 1: node(1) to node(c1);
Group 2: node(c1) to node(c2);
Group 3: node(c2) to node(n).

B.1) Placing Mobile Bridge Next To A Node Of Group 1

In this section, the following auxiliary notation is employed (see Fig. 2):

v_1 – Number of hops between node(k) and node(c1).

h – Number of hops between node(c1) and node(c2). Note, h is directly proportional to the dimension a of the routing hole, hence $h=\lceil a/r \rceil$. For the simplicity of our discussion, we will assume that h=a/r.

v_2 – Number of hops between node(c2) and the exit node (node(n)).

$\Delta v = (v_1 - v_2)$ – Defined in this way, Δv could be any integer number. E.g., if $\Delta v>0$ node(k) is 'above' and 'left of' the exit node (node(n)), if $\Delta v=0$ node(k) is 'just above' the exit node, and if $\Delta v<0$ node(k) is 'above' and 'right of' the exit node. The case presented in Fig. 2 corresponds to a negative Δv.

For the nodes of Group 1, (6) becomes:

$$(v_1 - 1 + h + v_2)\cdot r^2 > (d_{k-n} - r)^2 \quad (7)$$

By substituting v_1 by $v_2+\Delta v$, (7) gets transformed into

$$(\Delta v + 2v_2 + h - 1)\cdot r^2 > (d_{k-n} - r)^2 \quad (8)$$

Given $d_{k-n} \geq r$, the following inequality applies

$$d_{k-n}^{\;2} - r^2 = (d_{k-n} - r)\cdot(d_{k-n} + r) > (d_{k-n} - r)^2 \quad (9)$$

Accordingly, (8) will hold as long as (10) is satisfied:

$$(\Delta v + 2v_2 + h - 1)\cdot r^2 \geq d_{k-n}^{\;2} - r^2 \quad (10)$$

For the nodes of Group 1, d_{k-n} can be represented as

$$d_{k-n}^{\;2} = (\Delta v \cdot r)^2 + (h \cdot r)^2 \quad (11)$$

Thus, by employing (11) in (10), and then dividing both sides of (10) by r^2, (10) becomes:

$$\Delta v + 2v_2 + h - 1 \geq \Delta v^2 + (h^2 - 1) \quad (12)$$

Finally, (12) can be transformed to (13).

$$f(\Delta v, v_2) = \Delta v^2 - \Delta v - 2v_2 + (h-1)\cdot h \leq 0 \quad (13)$$

Note, (13) represents an alternative version of (6), i.e. (5), adjusted to suit the nodes of Group 1.

In order to identify the conditions under which (13) will be satisfied, let us observe that $f(\Delta v,v_2)$ in (13) is a linear function of v_2 and a convex function of Δv – see Fig. 3. The zeros of $f(\Delta v,v_2)$, with respect Δv, are:

$$\Delta v_{1,2} = \frac{1 \pm \sqrt{1 + 8v_2 - 4(h-1)h}}{2} = \frac{1 \pm \sqrt{h(v_2)}}{2} \quad (14)$$

Based on the above, a condition necessary for (13) to be satisfied is that $\Delta v_{1,2}$ exist and are 'real'. $\Delta v_{1,2}$ will exist and be real as long as the value under the square root in (14) is positive, as indicated in (15).

$$h(v_2) = 1 + 8v_2 - 4(h-1)h \geq 0 \quad (15)$$

Finally, (15) will be satisfied provided the following holds

$$v_2 \geq \frac{4h^2 - 4h - 1}{8} \quad (16)$$

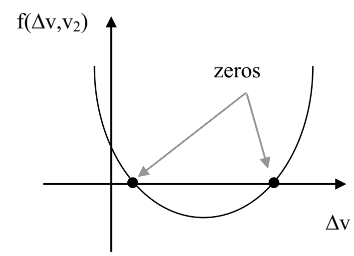

Fig. 3. $f(\Delta v,v_2)$ assuming a fixed v_2

B.2) Placing Mobile Bridge Next To A Node Of Group 2 or Group 3

By conducting a procedure similar to the one presented in Section II.B.1), it can be easily proven that the deployment of the mobile 'next to' a node of Group 2 or 3 will never be justifiable.

B.3) Theorems Arising From B.1) and B.2)

Theorem 1 – Assume h (h=a/r) of a hole is given. Then, the deployment of the mobile is energy justifiable only if both of the following two conditions are satisfied:

C.1) The exit node (node(n)) lies at a specific hop distance v_2 from node(c2), where

$$v_2 \geq \frac{4h^2 - 4h - 1}{8} \quad (17)$$

C.2) The mobile is deployed at/near some node(k) that happens to be on the opposite side of the exit node and anywhere between $v_2+\Delta v_1$ and $v_2+\Delta v_2$ from node(c1), where

$$\Delta v_1 = ceil\left(\frac{1-\sqrt{1+8v_2-4(h-1)h}}{2}\right) \quad (18.a)$$

$$\Delta v_2 = floor\left(\frac{1+\sqrt{1+8v_2-4(h-1)h}}{2}\right) \quad (18.b)$$

Proof – In order to prove Theorem 1, let us consider the consequences of either C.1) or C.2) being violated.

- As shown in section II.B.1), the placement of the exit node at v_2 that contradicts C.1) will result in $f(\Delta v, v_2)>0$ for the entire domain of Δv. Accordingly, (13) will never be satisfied and the deployment of the mobile will not be energy justifiable.
- The placement of the mobile at/near any boundary node other than the ones given by C.2) will again result in $f(\Delta v, v_2)>0$ - even if C.1 alone happens to be satisfied and $f(\Delta v, v_2)$ takes on negative values for some Δv . This, again, implies that (13) will never hold, and the deployment of the mobile will not be energy justifiable.

Theorem 2 – Let us consider a routing hole of size S=axb. If the deployment of a mobile bridge in such a hole is to be energy justifiable, then the hole's dimensions a and b must satisfy (19),

$$b \neq k \cdot a \quad (19)$$

where k is a small constant close to 1. ((19) implies that a and b must not be proportional to each other.)

Proof – In the view of the discussion from Section II.B.1), one dimension of the hole (say dimension a) determines the value of h, while the other dimension (dimension b) determines the range of all possible positions v_2 of the exit node (node(n)):

$$h = \frac{a}{r} \quad (20.a)$$

$$1 \leq v_2 \leq \frac{b}{r} \quad (20.b)$$

To prove Theorem 2, let us assume (19) is incorrect, and a and b are directly proportional to each other (b=k·a). By employing b=k·a and a=h·r in (20.b), the following is obtained:

$$1 \leq v_2 \leq \frac{b}{r} = \frac{k \cdot a}{r} = \frac{k \cdot (r \cdot h)}{r} = k \cdot h \quad (21)$$

v_2 as given above ($v_2 \leq k \cdot h$), will not satisfy condition C.1) of Theorem 1, except for very small values of h. Consequently, the deployment of the mobile in a hole where b=k·a will not be energy justifiable.

III. Conclusions

By generalizing Theorem 1 and 2, from Section II.B.3), we deduce that the deployment of a mobile node in any uniform-like shaped hole (e.g. square, circle) will never be energy justifiable, regardless of the hole's actual size and/or the number of boundary nodes actively involved in routing - even if it means routing through tens or hundreds of static sensors! Our further theoretical investigation and extensive simulation experiments fully confirm this hypothesis (see [6]). 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, it is reasonable to expect that the path through the mobile:

- offer lower transmission delay, by involving fewer nodes/hops, and
- prevent further enlargement of the hole, by posing less demand on the boundary nodes. (For an illustration of the above, see Fig. 4.)

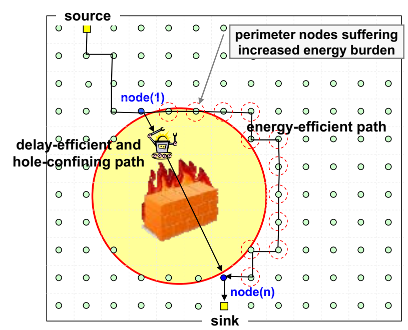

Fig. 4. Energy-efficient path around the hole vs. delay-efficient & hole-confining path through mobile

References

[1] N. Ahmed, S. S. Kanhere, and S. Jha, "*The holes problem in wireless sensor networks: a survey*", *SIGMOBILE Mob., Comput. Commun. Rev.*, vol. 9, no. 2, pp. 4–18, 2005.

[2] B. Karp and H. T. Kung, "*Gpsr: greedy perimeter stateless routing for wireless networks*", The 6th Conference on Mobilecomputing and Networking (MobiCom '00), New York, NY, USA, 2000.

[3] Q. Fang, J. Gao, L. Guibas, V. de Silva, and L. Zhang, "*GLIDER: Gradient landmark-based distributed routing forsensor networks*", The 24th Conference of the IEEE Communication Society (INFOCOM), March 2005.

[4] F. Kuhn, R. Wattenhofer, Y. Zhang, and A. Zollinger, "*Geometric ad-hoc routing: of theory and practic*e", PODC 2003, Boston, MA, USA, July 2003.

[5] Q. Fang, J. Gao, and L. Guibas, "*Locating and bypassing routing holes in sensor networks*", The 23rd Conference of the IEEE Communications Society (Infocom), March 2004.

[6] N. Vlajic, N. Moniz, M. Portnoy, "*Self-Healing wireless sensor networks*", Book Chapter in "Cooperative Wireless Communications", Editors: Y. Zhang, H.H. Chen, M. Guizani, to be published by Auerbach Publications, CRC Press, Taylor&Francis Group (2007).