COMBATING ROUTING MICROHOLES IN HYBRID WIRELESS SENSOR NETWORKS

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ABSTRACT
In this paper we propose a new technique for dealing with routing holes found in Wireless Sensor Networks (WSNs) with the help of mobile sensor nodes that are deployed alongside the static nodes. In a nutshell, our technique involves using mobile nodes in order to bridge the gaps created by routing holes, shortening the average hop distance of routing paths, and thereby leading to significant energy gains. We also introduce a new routing anomaly which we term the *microhole*. Microholes are very small imperfections in the routing path and are not classified as routing holes by the traditional routing hole definition. We evaluate our approach with respect to microholes while using energy as the primary metric and show that our approach can provide a reduction in energy consumption in certain WSNs deployment scenarios. Based on our finding, we propose DARMA - an algorithm for combating microholes.

KEY WORDS
Hybrid Wireless Sensor Networks, Mobility Support, Self Configuration, Routing Holes, Energy Efficient design

1. Introduction

Wireless Sensor Networks (WSNs) are comprised of small, inexpensive, resource constrained electronic devices. These devices are generally capable of sensing the environment, performing simple computations, and are equipped for internodal wireless communication. Once a group of sensors is deployed over an area, they distributively self-organize into a multihop network in which routing is usually accomplished using geographic routing (also known as greedy routing or compass routing) protocols. In geographic routing, nodes forward packets to nodes which are closer to the destination than themselves. Geographic routing protocols are genrerally considered most suitable for WSNs since they are conservative of the networks' resources, scalable, and adapt rapidly to the networks' topological changes [1].

Node positioning is very important for successful and efficient WSN operation, yet it is often impossible to gurantee precise node deployment. The imprecisions in WSN deployment can lead to a number of anomalies that may diminish or prevent normal network operation. These anomalies are caused by areas devoid of nodes which are collectively known as *holes*. In our work, we have concentrated on dealing with *routing holes*, which prevent nodes from communicating due to lack of nodes along the optimal routing path [2]. In particular, we have studied mechanisms for combating routing holes in WSNs that use geographic routing. When greedy geographic routing is used, a routing hole may be facilitated by a local minimum phenomenon where none of a node's neighbors are closer to the destination than the forwarding node itself, causing forwarded packets to get stuck at the local minimum node [3]. Routing holes are also detrimental since they can create inefficient routing paths as information is forced around the perimeter of the routing hole. This may lead to poor load distribution, longer routes and bottlenecks. Aside from delays in packet delivery, nodes along the boundaries of the routing holes may become strained beyond their intended design, which may result in an untimely discharge of their limited resources, causing the hole to grow bigger, possibly to a point where the network becomes partitioned [4].

In this paper we describe a new approach for combating geographic routing holes in WSNs. We propose to deploy a number of mobile nodes along side the static nodes - transforming the WSN into a Hybrid WSN - and use the mobile nodes to bridge the gaps towards the nodes on the opposite sides of the routing holes, therefore mitigating or eliminating the holes entirely. Using mobile nodes in order to combat routing holes offers a unique advantage over other techniques because it is the only way through which the average hop distance of a routing path can be reduced. Accordingly, it is reasonable to assume that by using mobile nodes we can also achieve better load distribution, fewer bottlenecks, improved fault tolerance, reduced packet delivery delays and decreased energy consumption. Though other approaches for dealing with routing holes exist, to our knowledge no other approach makes use of mobile nodes in order to try and solve this problem.

Later in this paper we introduce an augmentation to the concept of a routing hole by defining the new concept which we term a *microhole*. We argue that even though a working routing path may exist between a sender and a receiver in a WSN, the path could contain many inefficiencies that are admitting to optimization. We also show that hole detecting algorithms such as TENT are disadvantaged by their inability to detect microholes. Overall, since our research is still in its early stages, the work described in this paper is meant to serve as stepping stone for our future efforts. Therefore, we focus on applying our technique to microholes as they can be seen as the simplest cases of routing holes, allowing for a straight forward analysis and serving as a proof of concept for our approach.

We finally introduce a Distributed Algorithm for Routing Microhole Abolishment or DARMA. Using DARMA, static nodes are able to distributively detect and map microholes. Next, microhole information is forwarded to the mobile nodes, which use this information to decide on deployment locations that minimize the negative effects caused by the microholes.

The rest of the paper is organized as follows: Section 2 summarizes related work. Section 3 introduces the concept of a microhole and its importance with respect to the current definition of a routing hole. Section 4 simulates our approach with real world data and analyzes the feasibility, justifiability and effectiveness of using mobile nodes in order to combat microholes while using energy as the primary metric. Section 5 introduces DARMA. Section 6 discusses some additional possible advantages, disadvantages and tradeoffs of using mobile nodes in order to alleviate the routing hole problem. Section 7 concludes the paper with our possible future undertakings.

2. Related Work

Our study is largely based on two areas of research which we attempt to bring together: 1) methods for bypassing routing holes in static WSNs, and 2) research in which mobile nodes are used to improve various performance aspects of Hybrid WSNs.

A number of approaches attempt to mitigate the impact of routing holes in WSNs. Some of these approaches simply find a way to prevent packets from getting stuck at local minimums and route these packets around the boundaries of routing holes [3, 5–7]. The disadvantage of these approaches is that all of the incoming packets are likely to be routed around the boundary of the routing hole, therefore straining these nodes disproportionately to the rest of the network and causing delays and premature energy depletion. Also, all of the referenced techniques (except [8]) rely on some form of global knowledge of the network topology, which is often not readily available in WSNs.

To avoid the problem of routing along the boundary of the routing holes some approaches try to find alternative paths that do not traverse the boundary [4, 9].

The common disadvantage the solutions described above is that they cannot physically alter the topology of the network. However, if mobile nodes are part of the WSN as envisioned in [10–15], they can be used to augment the network and optimize its routing paths. Our approach builds on such an assumption of a Hybrid WSN in order to lessen or eliminate the negative effects of routing holes. By using the mobile nodes as relays, we can achieve shorter routes and a reduction in energy consumption. We also believe that better traffic load distribution, fewer delays, and improved fault tolerance are some of the additional benefits that can result from our approach.

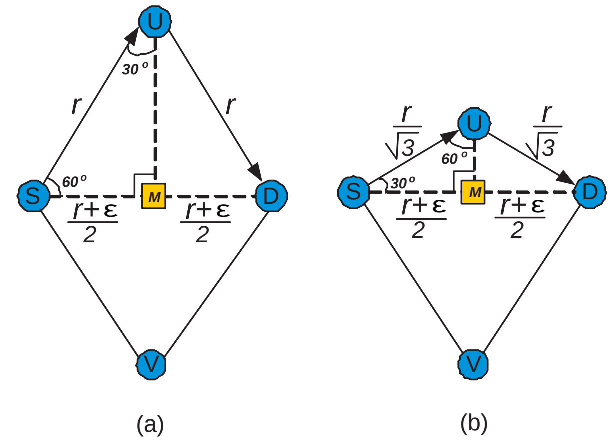

Figure 1. (a) A nodal configuration limit of a microhole. Microholes approaching this limit will benefit the most from the deployment of the mobile node M due to the large difference between the pre and post deployment average hop lengths. (b) A nodal configuration limit past which the microhole becomes a hole. If, however, node V is also moved towards the bisector SD, it could at one point (depending on the position of U) become a neighbor of U, and therefore this configuration could remain a microhole.

3. Microholes

3.1 Definition and Analysis of Microholes

In WSNs that employ geographic routing, routing holes are generally manifested through the so-called 'local routing minima'. Algorithms such as TENT and BOUNDHOLE [8] may be used to distributively discover and map routing holes by identifying the points of local routing minima. Nevertheless, we argue that even in the absence of routing holes (in the traditional sense), the routing paths of a WSN could still be riddled with inefficiences. We call these inefficienceis *microholes* and define them as follows:

Definition 3.1. *Microholes* are areas on the routing paths that do not prevent correct geographic routing (i.e. do not contain local minima with respect to the main routing directions) but can still be optimized by augmenting the topology of the area in question.

We illustrate the concept of the microhole by referring to the network configurations shown in Figure 1. We assume that the maximum communication range of the nodes is r, and node S is the source node sending packets to destination D. Also, we assume that the distance between SD is fixed and slightly greater than r ($r + \epsilon$, where $\epsilon > 0$), thereby forcing the information to travel through either one of the intermediate nodes, U or V.

By the TENT rule, a node is considered a local routing minimum (i.e. a node on a boundary of a routing hole where a packet could possibly get stuck) if it forms an angle $\geq 120°$ with its neighbors. Referring to Figure 1a, it can be seen that this topology corresponds to a boundary case of a hole as the angle VSU is exactly 120°. Now, we could theoretically move node U (or V) towards the bisector of SD. As node U is moved towards the bisector of SD, angle VSU would grow smaller and angle SUD would increase accordingly, up to the point when it reaches 120° and node U becomes a possible local minimum (see Figure 1b). Any intermediate node configuration between those two limiting configurations would not contain any angles $\geq 120°$ and therefore would not be considered a hole. Furthermore, if we were also to move node V towards the bisector SD, it could become within the communication range of U, causing the TENT rule to fail. Still, any of these intermediate configurations would, clearly, be suboptimal in the routing sense. We identify and term, these routing inefficiencies - the microhole.

Theorem 3.1. Placing a mobile node in a microhole on the bisector between the source and the destination of the microhole will reduce the average hop length between 50% (occurs in case (a) of Figure 1) and 0% (occurs in case nodes U and V are positioned on the bisector of SD).

Proof: Through simple trigonometric analysis it can be seen that that the average hop distance for the limiting scenario of Figure 1a is r. The other limiting scenario includes the case where both nodes U and V are found on the bisector of SD. In such a case the average hop distance would be $\frac{r}{2}$. However, if the mobile node M was to be placed on the midpoint between SD, the average hop distance would be reduced to $\frac{r}{2}$ (since the mobile node would relay the data). Therefore, placing a mobile node in a microhole on the bisector between the source and the destination would shorten the hop distance anywhere between 0% to 50%.

In the following section we will demonstrate that reduced hop distance can provide substantial energy savings, provided the transmission power can be adjusted at the sender.

4. Approach Simulation and Analysis

In WSNs, the most energy expensive operation is communication. Due to the nature of signal propagation (i.e. path loss), communication energy cost increases exponentially with relation to the distance between the sender and the receiver. Path loss is greatly dependent on the properties of the medium through which the signal propagates [16]. Therefore, we hypothesized that by reducing the hop distance with the help of mobile nodes we can achieve significant savings in terms of energy consumption throughout the lifetime of a WSN.

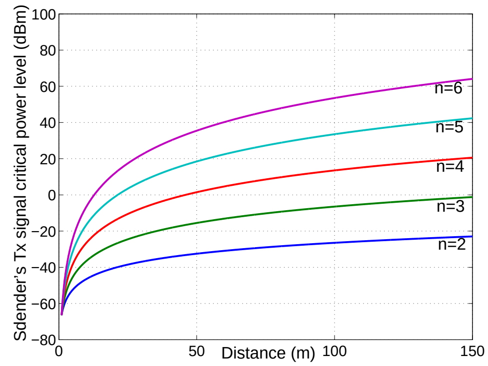

Figure 2. The Tx power required for signal detection in various environments by a receiver at a distance d, assuming log-distance path loss model without shadowing, constant Rx sensitivity of Pr = -98 dBm and path loss exponent n.

4.1 Effects of Distance and Environmental Conditions on Signal Power

We demonstrate the feasibility of our approach as discussed in Section 3 by firstly examining the difference in the required transmission power of a sender with respect to distance to the receiver under variable environmental conditions. Here and throughout the rest of the paper we use a typical commercial sensor system parameters (Crossbow MPR500CA: 900 Mhz (868/916 MHz); Tx power: -20 to +5 dBm; Rx sensitivity: -98; dBm Range: 152.4 m) [17].

4.1.1 Link Design Using a Log-distance Path Loss Model

In our analysis we use the following simple Log-distance Path Loss model [16] in order to estimate the sender's *critical transmission power* (i.e. the minimum required transmission signal power with which the sender can transmit a message to the receiver given a particular receiver sensitivity):

$$P_t(d)[dBm] = P_r[dBm] - G_t + \overline{PL}(d)[dB] - G_r \quad (1)$$

where, P_t = transmitter power; G_r = receiver antenna gain; G_t = transmitter antenna gain, and $\overline{PL}(d)$ = average path loss at a distance d from the transmitter, given by the following:

$$\overline{PL}(d)[dB] = \overline{PL}_o(d_o) + 10nlog_{10}\left(\frac{d}{d_o}\right) \quad (2)$$

$$\overline{PL}_o(d_o) = 20log_{10}\left(\frac{4\pi d_o}{\lambda}\right) \quad (3)$$

In (2) and (3), $\overline{PL}(d)$ = average path loss at a distance d from the transmitter; $\overline{PL}_o(d_o)$ = free space path loss at a reference distance d_o; λ = wavelength of the carrier; n = path loss exponent (dependent on the signal propagation environment)

The results in Figure 2 are based on transmitter and receiver gains (G_t and G_r respectively) of 0 dBi, receiver sensitivity of -98 dBm, operating frequency of 900 Mhz

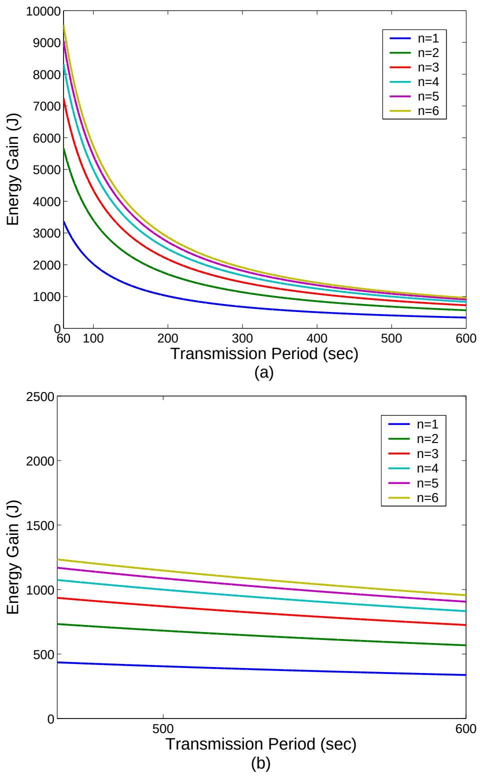

Figure 3. (a) Energy gained over half a year lifetime of a WSN resulting form placing a mobile node in an average size microhole in different environments. (b) Zoom in on (a).

and a number of different typical path loss exponents (2 (free space) to 6 (obstructed indoor environments) [16]). We ignore shadowing since it is highly dependent on the particular environmental conditions. As a note, we were unable to find link design parameters and path loss models that were tailored specifically for WSNs. Measuring such parameters and developing WSN specific path loss models could prove to be an important future research task.

Figure 2 highlights the significant effects of distance and the environment on the critical transmission power. As it can be also observed that as the path loss exponent increases by a single unit, the amount of power required to transmit a signal increases by more than 2 orders of magnitude. Depending on the value of the path loss exponent, increasing the distance between the transmitter and receiver only twice requires an increase in the transmission power of approximately of 1 to 2 orders of magnitude. Similarly, shortening the distance between the transmitters and the receivers could provide significant energy gains, especially in transmission intensive wireless networks.

4.1.2 Energy Gains Due to Mobile Node Deployment

The results in Figure 3 demonstrate energy gains that may be achieved over the lifetime of a WSN by placing a mobile node in a microhole. Energy gain is equivalent to the energy that is used by the sender and the forwarding node when the mobile node is not deployed, less the energy that is used by the sender and the relay mobile node once the mobile node is deployed. For this particular case we assumed a microhole in which the hop distance will be reduced by 31.7% when the mobile node is deployed. The parameters for our calculations are based on a typical commercial wireless sensor (Crossbow MPR500CA), and the Great Duck Island (GDI) bird habitat monitoring experiment, which is one of the most widely publicized and successful deployments of WSNs [18].

In our calculations, we set the network lifetime to be half a year, the transmission rate 34.2 baud and message size 30 kB. As can be seen from Figure 3, we calculated the energy gains for a range of transmission periods and for various values of path loss exponent. We have also assumed our network to be more transmission intensive than in the GDI experiment by setting the packet size to 30 kB as opposed to 36 bytes.

There are a two important observations about Figure 3: 1) As transmission period increases (i.e. data is transmitted less frequently), energy gains decrease, and vice versa. This is to be expected as a smaller transmission period implies that a greater amount of data is being forwarded by the mobile node during the lifetime of the network, leading to greater energy savings. More interestingly, however, is the observation that 2) a n increases, greater energy savings are achieved. This leads to the following important point: due to the properties of signal propagation as described in Section 4.1.1, shortening the hop distance by the same relative amount for networks communicating in environments with greater values of n produces larger energy savings than for networks communicating in environment with smaller values of n.

4.2 Feasibility, Justifiability and Effectiveness Evaluation of Our Approach

For our approach to be employed in a real world scenario it has to be *feasible*, *justifiable* and *effective*. By feasible we imply that a mobile node possesses the physical capacity needed to be deployed to a microhole, by justifiable we mean that the network benefits from the implementation of our approach, and by effective we denote the probability with which a mobile node will be successful in meeting its mission goals.

4.2.1 Feasibility Evaluation

For our approach to be feasible, the following condition (4) has to be satisfied. To explain, (4) states that the total energy available to a mobile node ($E_{battery}$) cannot be less than the energy that is required for a mobile to locomote to a microhole location ($E_{move-feasible}$) and to operate there for a period of time P ($E_{op}(P)$).

$$E_{battery} \geq E_{move-feasible} + E_{op}(P) \quad (4)$$

We can expand expression (4) to (8), by using the following expressions (5), (6) and (7),

$$E_{move-feasible} = d_m \times E_{cost/unit} \quad (5)$$

where, d_m = distance a mobile node locomotes; $E_{cost/unit}$ = energy a mobile node consumes for locomotion per unit distance.

$$E_{op}(P) = P_{Rx} \times R^n \times P + c \quad (6)$$

where,

$$P_{Tx} \approx P_{Rx} \times R^n \quad (7)$$

Above, (6) represents a simple energy model in which the constant c accounts for energy used when the node is in states such as idling, sleeping, sensing or processing the received information. (7) approximates transmission power (P_{Tx}) assuming a fixed receiving power (P_{Rx}) and is essentially a simplified version of (1) discussed in Section 4.1.1. R is the distance between a transmitter and a receiver, and n is a path loss exponent.

By substituting (5) and (6) into (4), (8) is obtained,

$$E_{battery} \geq d_m \times E_{cost/unit} + P_{Rx} \times R^n \times P + c \quad (8)$$

By rearranging (8) we can get the following expression:

$$d_m \leq \frac{E_{battery} - P_{Rx} \times R^n \times P - c}{E_{cost/unit}} \quad (9)$$

From (9), one can also notice that the maximal feasible locomotion distance d_{f-max} is strongly dependent on two network/environment parameters: R - a parameter directly related to the current inter-nodal distance in the WSN, and n - path loss exponent. Specifically, higher values of either of the two parameters would result in increased power consumption of the mobile node upon its deployment in the microhole - $E_{op}(P)$ (see (6)), leaving less energy for locomotion. Or, put another way, with a higher $E_{op}(P)$ a stricter bound would be placed on $E_{move-feasible}$ in order to satisfy (4), ultimately resulting in shorter maximal feasible locomotion distance (d_{f-max}).

4.2.2 Justifiabilty Evaluation

Assuming that the feasibility constraint (4) is satisfied, it is still possible that moving the mobile into the microhole is not justifiable. Specifically, if the energy consumed for the mobile's locomotion exceedes the energy gain $G_e(P)$ obtained by the mobile's deployment for a period P, then the justifiability of the entire operation becomes questionable. We quantify this 'justifiability criteria' in (10).

$$E_{move-justified} \leq G_e(P) \quad (10)$$

Based on this we can calculate maximum justifiable locomotion distance d_{j-max} as follows:

$$d_{j-max} = \frac{G_e(P)}{E_{cost/unit}} \quad (11)$$

We can expand expression (11) to get (16) by using the following expressions (12), (13), (14) and (15),

$$G_e(P) = E'(P) - E(P) \quad (12)$$

where, $E'(P)$ = total energy expanded for communication by the nodes comprising a microhole in a period of time P; $E(P)$ = total energy expanded for communication in a period of time P after a mobile node is deployed to a microhole.

$$E'(P) = 2 \times (P_{Rx} \times (R')^n + c) \times P \quad (13)$$

$$E(P) = 2 \times (P_{Rx} \times R^n + c) \times P \quad (14)$$

The above (13) and (14) are calculated based on the microhole definition from Section 3. $(R')^n$ and R^n are microhole inter-hop communication distances prior and after a mobile node deployment accordingly. By substituting (13) and (14) into (12),

$$G_e(P) = 2P_{Rx} \times ((R')^n - R^n) \quad (15)$$

By substituting (15) into (11),

$$d_{j-max} = \frac{2P_{Rx} \times ((R')^n - R^n)}{E_{cost/unit}}) \quad (16)$$

From (16), d_{j-max} appears to be sensitive to changes in R, R' and n. Specifically, larger difference between R' and R would result in a significant gains in energy and would provide for a large d_{j-max}. Smaller difference would result in insignificant energy gains and therefore a small d_{j-max}. From the network design perspective, it is desirable to have $d_{f-max} \geq d_{j-max}$, since this would imply that the ultimate goal of the network - to deploy the mobile node in a selected microhole - is not bounded by the feasibility constraint of the mobile.

4.2.3 Effectiveness Evaluation

Knowing whether deploying a mobile node to a microhole will be feasible and justifiable is only possible if the precise deployment location of the microhole and the mobile node can be predicted. In a real deployment scenario this may not be possible. Nevertheless, it is important to be able to approximate the effectiveness of our approach prior to Hybrid WSN deployment since the cost of deploying an ineffective network could be very high.

For evaluating the effectiveness of our approach we suggest a simplified version of a Hybrid WSN deployment scenario which could be augmented in the future so to provide for a better evaluation. We propose to use a single mobile node, which locomotion coverage area is contained within a rectangular WSN area, where the static node density is $\sigma = \frac{1}{R^2}$, where R represents the radio range of individual sensor nodes. Assuming that the static nodes form a fixed rectangular network lattice of $N \times N$ nodes, our network area would be $A_{WSN} = ((N-1) \times R)^2$ (see Figure 4).

In order to evaluate the effectiveness of our approach we try to find the probability with which only a single static node fails (i.e. a single microhole is created) and it is within the mobile node's feasible or justifiable locomotion distance (depending on the requirement). To explain, if on average, only one microhole could be found in the network, but it happens to at a distance greater than d_{f-max}

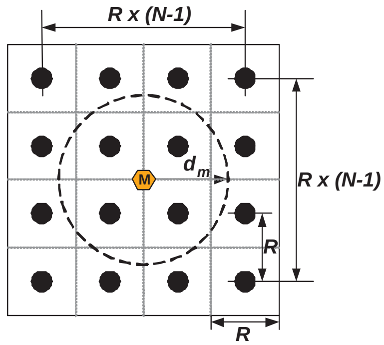

Figure 4. Simplified Hybrid WSN deployment scenario with $N \times N$ static nodes having a node density of $\frac{1}{R^2}$. A mobile node M is initially placed so its maximum locomotion area $\pi \times d_m^2$ is contained within the network area.

or d_{j-max} from the mobile, the mobile locomotion would be unfeasible or unjustifiable. On the other hand, if more than one microhole would be created on average regardless of their location, the mobile node could be deployed to at most one of the microhole locations, leaving the other microholes unfixed. In both cases the approach effectiveness would be less than optimal. We summarize this in using the following expression:

$$P_{mobile-effective} = P_{one-node-fails} \times P_{node-near-mobile} \quad (17)$$

where, $P_{one-node-fails}$ = probability that exactly one static node fails in the network (i.e. exactly one microhole is created); $P_{node-near-mobile}$ = probability that the single failed node, i.e. respective microhole, is within the locomotion distance from the mobile. (Here, the locomotion distance represents d_{f-max} or d_{j-max}, whichever is less.) We can expand expression (17) to get (20) by using the following expressions (18) and (19),

$$P_{one-node-fails} = N^2 \times (p_{fail} \times (1 - p_{fail})^{N^2-1}) \quad (18)$$

where p_{fail} is the probability that a node fails and a microhole is created.

$$P_{node-near-mobile} = \frac{d_m^2 \times \pi}{((N-1) \times R)^2} \quad (19)$$

The above expression (19) finds the probability that a microhole is within locomotion distance of the mobile node by dividing the circular area or radius d_m that the mobile node can locomote by the total network area (this is only an approximation since we are trying to compare a circular area to a square area). Substituting (18) and (19) into (20),

$$P_{mobile-effective} = N^2 \times (p_{fail} \times (1 - p_{fail})^{N^2-1}) \times \frac{d_m^2 \times \pi}{((N-1) \times R)^2} \quad (20)$$

Expression (20) does not lend itself to simple analysis due to the complex, non-linear interaction of its parameters. However, in a real world scenario when some of the parameters known and fixed, we speculate that it should be possible to use optimization techniques in order to derive optimal parameter ratios.

5. Distributed Algorithm for Routing Microhole Abolishment

In this section we propose DARMA - a Distributed Algorithm for Routing Microhole Abolishment. It is divided into two main phases. In the first phase the static nodes found along the routing path distributively detect microholes and forward this information to the mobile nodes. In the second phase the mobile nodes use the microhole information in order to come to a deployment decision.

5.1 Distributed Microhole Detection

Microhole detection should occur reactively along routing paths only once they have been established (i.e. only along active routing paths) since detecting microholes along all possible routing paths would be impractical. When a routing path has been established, microholes along this path can be detected by having each node on the path send a *microhole discovery packet*, or MD_pkt for short, to its downstream forwarding neighbor. Since the forwarding neighbor is aware of its upstream neighbor's coordinates, it will attach these coordinates to the MD_pkt and forwards it further to its downstream neighbor (i.e. the destination node). Upon receiving the MD_pkt, the destination node will use the coordinates of its two upstream neighbors in order to calculate the deviation in the angle between itself, the source node and the forwarding node, and based on this information it will be able to make the decision whether there is a microhole present. To clarify, looking at Figure 1, if node S were to send a MD_pkt to node U, node U would forward this packet to node D, which would be able to calculate the angle DSU. If this angle is greater than 0°, microhole is present. Also, in order to avoid a very large number of microholes being detected, it is possible to exacerbate the criterion for microhole detection by setting a condition that the angle DSU has to be greater than a certain value β where $0^\circ \leq \beta < 120^\circ$.

If a destination node concludes from the MD_pkt that a microhole exists, it will send a *microhole repair request* packet or MR_req for short, containing the coordinates of the microhole nodes and a sequence number to all its neighbors. The neighbors will forward MR_req to all their neighbors unless they have already forwarded this MR_req. The MR_req flooding guarantees that every mobile node in the network will be aware of all the microholes, their locations and severities, and will be able to make a deployment decision based on this information.

5.2 Distributed Mobile Node Deployment

Mobile nodes will listen for MR_req packets and aggregate them. When the mobile nodes no longer receive MR_req packets or after MR_req packet aggregation timer had expired, each mobile node will pick its deployment candidate microholes. For a mobile node to even consider a microhole for deployment, both of the following conditions have to be satisfied:

$$|C_d(P) + C_{mv}| \le E_m \quad (21)$$

$$|C_{mv}| < G_e(P) \quad (22)$$

where, P = period of deployment; $C_d(P)$ = cost that the mobile node incurs at the microhole during the deployment period P; C_{mv} = cost that the mobile node incurs during locomotion to the deployment location; E_m = total energy of the mobile node; $G_e(P)$ = energy gained from having the mobile node deployed at the microhole for the period P.

Condition 1: a mobile node should not consider deploying to a microhole if it does not have enough energy to locomote and stay there for the period P. (21) Condition 2: a mobile node should not be consider deploying to a microhole unless the energy gained from its deployment, for the period P, exceed the cost of its locomotion. (22) It is also important to note that at the moment the mobile nodes use energy as the sole metric for decision making, however in the future we expect that other types of metrics may be incorporated into the decision making process. This may also require the MR_req to carry additional information besides the microhole node coordinates.

Once all the deployment candidate microholes are chosen, they are ranked according to the following criterion:

$$Rank_i = G_e(P) - C_{mv} \quad (23)$$

where, $Rank_i$ = rank of the deployment candidate microhole i; $G_e(P)$ = energy gained from having the mobile node deployed at the microhole for the period P; C_{mv} = cost that the mobile node incurs during locomotion to the deployment location.

Criterion 3: the rank of a deployment candidate microhole is the energy that will be gained from having the mobile node deployed at the microhole for the period of time P minus the cost of locomotion. Therefore, the deployment candidate microhole with the highest ranking is most desirable for deployment. (23)

Since there could be many mobile nodes deployed throughout the WSN, some of the mobile nodes may be in a more favorable deployment positions than other mobile nodes with respect to a particular microhole. Also, mobile nodes do not initially know what the other mobile nodes plan on doing and therefore there is the possibility that a number of mobile nodes will deploy to the same microhole. To solve these issues some form of coordination between the mobile nodes is required. Therefore, mobile nodes will flood the network with their *microhole list packets* or ML_pkt for short, containing a unique identifier, microhole coordinates with their appropriate rank, and a random number for tie resolution. This will enable mobile nodes to know exactly what the other mobile nodes are planning on doing and adjust their actions accordingly. For example, if mobile node M_1 wants to deploy to microhole i but receives a ML_pkt from mobile node M_2 which has a higher rank for the same microhole, M_1 will choose its next lower ranked microhole to deploy to since it knows that M_2 makes for a better deployment candidate.

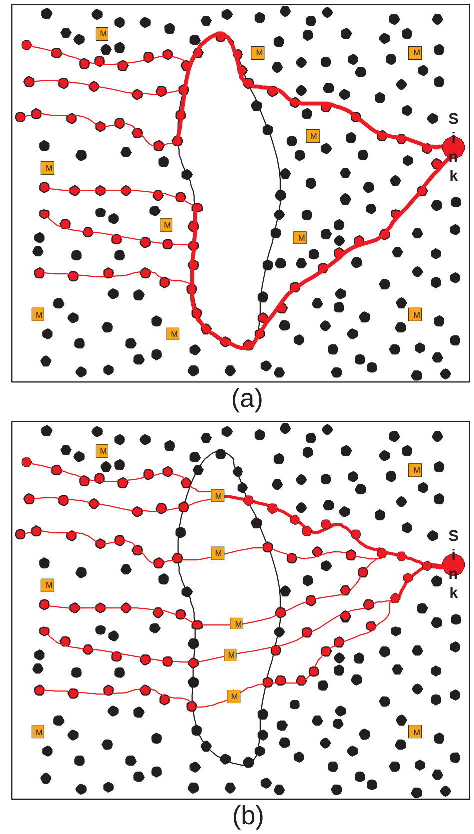

Figure 5. (a) Possible routing hole effect on data distribution in a Hybrid WSN. Round dots are static nodes; square dots are mobile nodes. (b) Relay mobile nodes provide for a better traffic load distribution.

6. Discussion

When considering our approach with respect to routing holes in general (i.e. not necessarily microholes), energy gains are just one type of the benefit that may emerge. Therefore, evaluating our approach solely on this criterion is likely to prove erroneous. We believe that even though in certain cases energy gains alone might not justify the deployment of mobile nodes, when incorporated with other possible benefits, mobile node deployment could become justified. For example, one such possible benefit is improved data load distribution. Figure 5a presents a plausible routing hole scenario. Many data streams initiated at different sources are forced to converge on the same routing paths because of the unfortunate location, size and orientation of the routing hole. This in turn is likely to lead to congestion and bottlenecks, creating delays and possible data loss. Also, the nodes along the converged paths, which include the boundary of the routing hole, will be strained to a much larger extent than other nodes in the network. Therefore, these nodes will tend to expire prematurely due to hardware failure and resource consumption. This will cause the boundaries of the routing hole to grow and eventually partition the network. With our approach, as can be seen in Figure 5b, if some of the mobile nodes were to deploy inside the routing hole, they could provide for better traffic load distribution. This would reduce the problem of routing path convergence and therefore would also mitigate the aforementioned problems. As a side effect, the overall network fault tolerance might increase as well, since if a mobile node fails, the data can still be routed around the routing hole or through some of the other mobile nodes.

Despite the advantages, disadvantages and alternative approaches have to be carefully considering and weighed against our approach when designing a WSN. One of the things to consider is that mobile nodes are significantly more expensive than static nodes. It might be more beneficial to simply deploy greater numbers of small, inexpensive static nodes. Improved routing algorithms that are sensitive to traffic load distribution and resource consumption are another type of solution that could be used. On the other hand, Hybrid and mobile WSNs have the unique advantage of dynamic control over the network topology, which as a consequence might prove indispensable in mission critical scenarios where a routing path is broken and needs to be reestablished in the least amount of time or without human intervention.

7. Conclusion and Future Work

In the future we would like to continue developing our approach. We would like to develop an accurate, working simulation of DARMA. We would also like to extend DARMA to include the ability to combat regular routing holes. This will likely pose many new challenges, but we are confident that the combined benefits of our approach will prove to be significant and useful in certain real world deployment scenarios. Another task is to find ways to quantify the various benefits and disbenefits of our approach (besides energy consumption) and incorporate those parameters into our gain functions. Finally, an actual real world implementation of our approach would be desirable.

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