A Framework for Mobile Assisted Localization in Wireless Sensor Networks

Asheq Khan, Sumesh J. Philip ,Chunming Qiao and Satish K. Tripathi
Department of Computer Science and Engineering
State University of New York at Buffalo, Amherst, New York 14260
Email: {akhan6, sumeshjp, qiao, tripathi}@cse.buffalo.edu

Abstract

Location tracking has several applications in wireless sensor networks. While GPS receivers can be used for location awareness in the outdoor environment, it can be prohibitively expensive in terms of size, cost and power consumption for large scale deployment. Most of the existing work in network localization has investigated the problem of computing the locations of all nodes with the help of a limited subset of *seed* nodes, who are already aware of their own locations. In this work, we introduce the novel concept of mobile seed node assisted localization, in which a small subset of mobile sensor nodes are used for network localization. specifically, we consider the case in which the network is localized using only three mobile sensor nodes. We present efficient algorithms for network localization that optimizes the localization latency, total battery power and minimizes the maximal power consumption by any mobile sensor node.

I. Introduction

A sensor network is a distributed network consisting of a large number of small devices, each having a limited computational, communication and storage capacity. The goal of a sensor network is to do collective sensing, and efficiently disseminate sensed information for further analysis. Establishing the location information of the sensors can be very useful not only for sensing purposes, but also for the design and implementation of many higher layer protocols. For example, we can make use of the location information to activate/de-activate certain sensors such that no redundant data need to be sensed or sent/received, to create clusters/hierarchies for improved scalability and increased robustness and security, and to facilitate geographic routing [1]. Although individual sensor nodes can be equipped with a GPS receiver to track its location, it will be impractical in indoor environments and prohibitively expensive in terms of cost, size and power usage for large scale deployment.

There has been considerable research into establishing individual sensor location in the past [2],[3],[4],[5],[6], [7]. To the best of our knowledge, existing localization algorithms use some sort of static infrastructure (for e.g. fixed base stations) or *seed* nodes as reference points to compute their locations via known position estimation techniques such as triangulation or multilateration. We feel the maintenance of the fixed infrastructure is as complex as maintaining the sensor field itself. In other words, the localization infrastructure is itself power limited, and need to be replaced or upgraded from time to time, which can be expensive in terms of time and cost. In addition, the granularity of localization depends on density and placement of the reference points. For fine grained localization, the number of seed nodes or fixed nodes are quite high. Due to this limitation, we argue that current algorithms may not be suitable or resource efficient for generic scenarios for localization of stationary sensor nodes.

In this work, we propose to use seed nodes that are mobile and location aware, and more capable (in terms of hardware) than the stationary sensor nodes. The intuition to use mobile seed nodes is two fold: on one hand, the number of seed nodes that are required can be reduced considerably, by reusing the same seed nodes across the terrain. On the other hand, since the granularity of localization directly depends on the number of reference points, we can control the mobility of the seed nodes such that the number of reference points can be directly controlled. Additionally, the maintenance of the seed nodes would become tractable due to their reduced number. On the flip side, such stations may be more expensive to

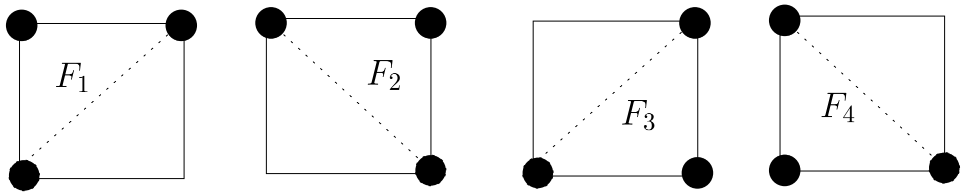

Fig. 1. The formations of the MSNs

realize than their static counterparts, but the number of such stations required is small (as few as three to four), and hence may justify the additional engineering/manufacturing cost.

We employ three sensor nodes that have additional capabilities such as mobility and are also location aware (equipped with a GPS receiver) as seeds to determine the location of the stationary sensor nodes in the network. The mobile sensor nodes traverse the rectangular sensor field as a group such that each time a subset of the stationary nodes are simultaneously exposed to the three mobile nodes. By receiving signals from three reference nodes, the exposed stationary nodes can determine their location using techniques such as triangulation or trilateration. Our goal is to derive an efficient algorithm that makes all the sensor nodes location aware while minimizing the objective function. We examine three objective functions critical for sensor nodes: i) minimization of the total distance traveled by the mobile seed nodes; ii) minimization of the localization latency; and iii) minimization of the maximal power consumption by any single mobile sensor node. By minimizing the total distance traveled by the seeds, we can minimize the total battery power of the mobile sensor nodes.

This paper is organized as follows. In section II, we define and formulate the problem. The optimal placements and movements of the mobile seeds are described in section III. In section IV, we describe the algorithm for mobile seed assisted localization. Finally, we conclude the paper in V.

II. Problem Definition

We address the problem of localization of sensor nodes in a region. To this extent, we employ a limited number of mobile sensor nodes (MSN), which has additional capabilities such as mobility, and is equipped with a GPS receiver, to determine the locations of the stationary sensor nodes (SSN) in the network. The MSNs travel as a group to allow a subset of SSNs to simultaneously receive signals from the MSNs. With three known reference points, a SSN can determine its location using techniques like triangulation or trilateration.

The problem can be formulated as follows. A rectangular sensor field is divided into smaller squares of side *r*, where *r* is the radio range of the MSNs and is much smaller than the diameter *R* of the sensor cloud. After the SSNs have been partitioned into small squares, a subset of sensor nodes in each square can be made location aware by positioning the three MSNs appropriately to form a specific triangle (called a *formation*), and by moving the MSNs so they can be re-positioned to cover the next subset. Once all the SSNs in a square have been localized, the MSNs move to a new square and repeat the process.

At each square, the MSNs are placed at three of the four corners such that they form a triangular formation. Then all the SSNs within the triangle can be localized by receiving signals from the three reference points. Figure 1 shows the four possible formations (F_1,F_2,F_3 and F_4) of the three MSNs such that each formation covers a triangle that is half of the square. Clearly, either formations F_1 and F_3, or formations F_2 and F_4 are sufficient to make all the SSNs in a square location aware.

We define a change in formation within a square as a *transformation*. In this case, a transformation occurs only between formations F_1 and F_3 and between F_2 and F_4. A transformation can be completed by a MSN to moving diagonally (Figure 2(a)) or by two MSNs moving simultaneously along the edge of the square (Figure 2(b)).As previously stated, any other transformation will be inadequate in covering a square with two formations. After the location of the nodes in a square is determined, the MSNs move

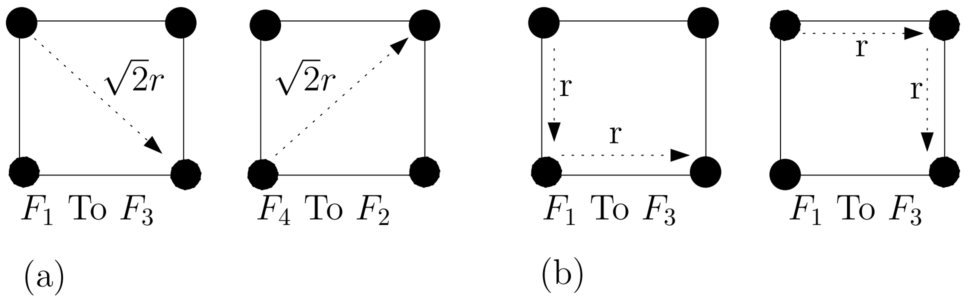

Fig. 2. Optimal transformation scheme

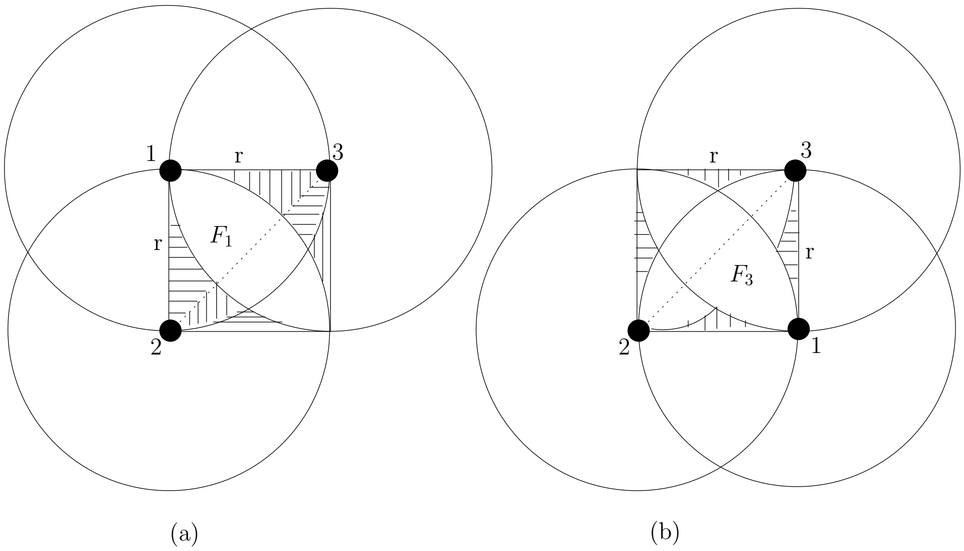

Fig. 3. Sensors not receiving signals from three MSNs

to a new square. The process of the MSNs moving from one square to another is termed as a *migration*. A migration can occur from any formation to any other formation provided its optimal.

Since the radio range of a MSN is r, which is also the length of the sides of the square, it is possible for SSNs in certain regions within the square not to be localized. This happens because SSNs in those regions may not receive signals from three reference points and hence, cannot determine their locations. For example, in formation F_1, sensors in the shaded regions of the square has not received signals from all three MSNs (Figure 3(a)). After MSN 1 has moved diagonally to form formation F_3 and all three MSNs rebroadcast their becons, the SSNs in the shaded regions (Figure 3(b)) still have received signals from only two different reference points.

This problem can be simply solved as follows. As MSN 1 moves diagonally for the transformation, it can stop at the midpoint for few miliseconds to perform a broadcast (Figure 4(a)). This allows all the SSNs in the square (including ones in the shaded regions) to receive signal from an additional reference point. For transformation along the edges of the square, each of the two moving MSNs can stop at a point on the edge and broadcast its signal such that the SSNs in the shaded regions receive signals from atleast one of them. For example, MSN 1 stops at a point closer to its origin whereas, MSN 3 stops at a point closer to its destination to broadcast additional signals (Figure 4(b)). Alternatively, MSNs 1 and 2 could have moved to complete the transformation.

With this problem solved, our goal is to find the optimal transformation and migration scheme that minimizes the total distance and time taken by the MSNs to localize the stationary nodes in the network. We also attempt to maximize the lifetime of the MSNs by ensuring that no single MSN travels significantly more distance than the others and hence, does not exhaust its power too soon.

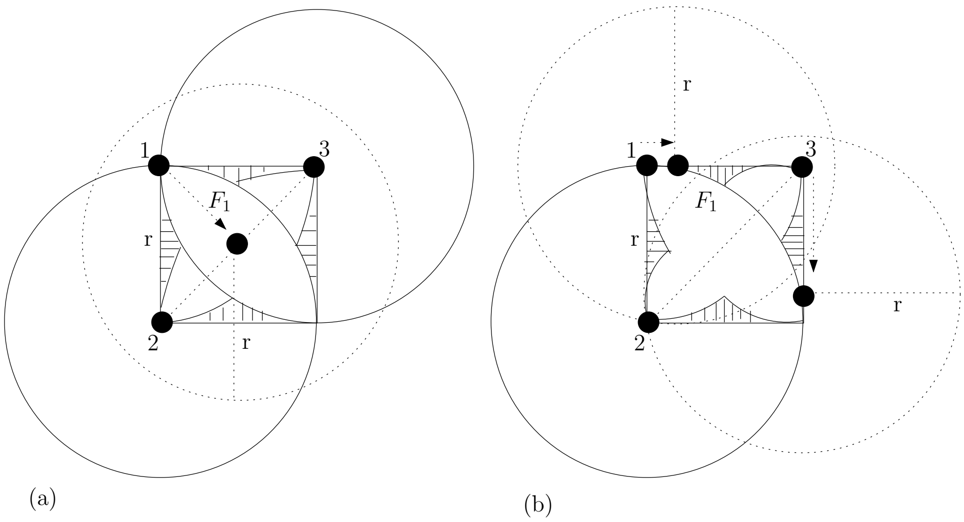

Fig. 4. Additional broadcast for a third reference point

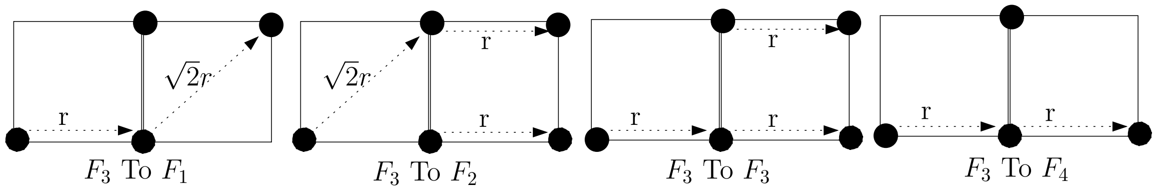

Fig. 5. Migrations from formation F_3

III. Optimal Transformation and Migration

A transformation within a square tile can occur either between formations F_1 and F_3 or between F_2 and F_4 is an *optimal transformation*. In either case, the minimum distance traveled to complete the transformation is the diagonal distance $\sqrt{2}r$ ($\sqrt{r^2 + r^2}$) (Figure 2(a)). Now, the time taken to complete this transformation is also $\sqrt{2}r$, which is not the minimum time possible. Therefore, one of the transformations in Figure 2(b) can be employed to minimize the time taken to complete the transformation. In this case, two of the MSNs can each move in parallel a distance of *r* along the edge of square and complete the transformation in *r* time.

Unlike transformation, a migration can take place from any formation to any other formation. As an example, the migrations from formation F_3 are shown in Figure 5. Among the migrations, the migration from formation F_3 to F_4 requires the MSNs to travel a total distance of *2r (r + r)* to complete the migration to the square on the right. We state that *2r* is the minimum migration distance possible between two formations and hence, the migration from F_3 to F_4 is an *optimal migration*. But, it should be noted that an optimal migration might not exist from a formation. For example, the minimum migration distance from formation F_1 is *3r* (to F_1) and hence, it is not an optimal migration (Figure 6).

In terms of latency, an optimal migration is completed in time r because two MSNs each move a

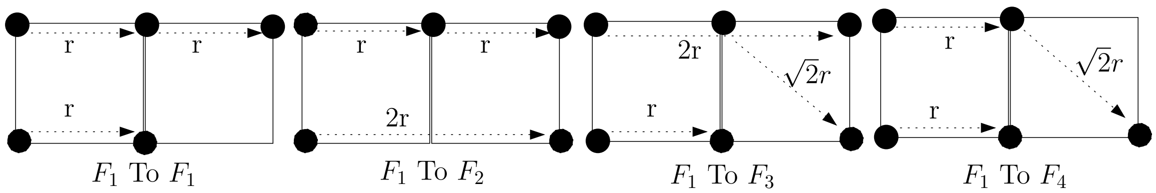

Fig. 6. Migrations from formation F_1

TABLE I
OPTIMAL MIGRATION FORMATIONS

Migration	Current	Next	Distance	Time
LEFT TO RIGHT	F2	F1	2r	r
LEFT TO RIGHT	F3	F4	2r	r
RIGHT TO LEFT	F1	F2	2r	r
RIGHT TO LEFT	F4	F3	2r	r
TOP TO BOTTOM	F3	F2	2r	r
TOP TO BOTTOM	F4	F1	2r	r
BOTTOM TO TOP	F2	F3	2r	r
BOTTOM TO TOP	F1	F4	2r	r

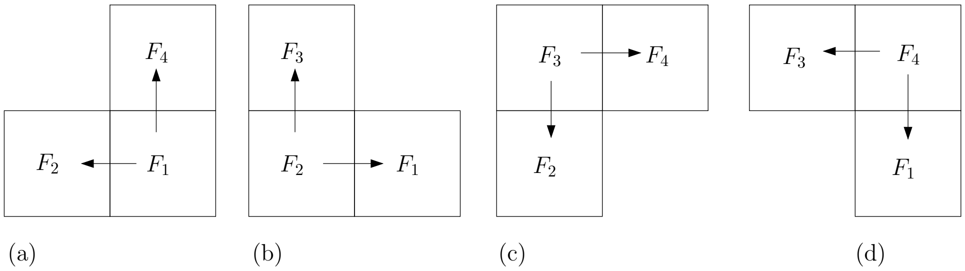

Fig. 7. Directions of optimal migration from each formation

distance r in parallel. Next, we determine the optimal migrations possible as the MSNs migrate to the square on the right, left, top or bottom (Table I). Now, the challenge is to derive an efficient algorithm that allows the MSNs to traverse the rectangular sensor field such that, each square is visited once and each transformation and migration results in an optimal formation.

IV. ALGORITHM FOR MOBILE NODE ASSISTED LOCALIZATION

We are provided with a rectangular sensor field divided into X rows and Y columns, where each cell $s_{i,j}$ (for *i*= 1..X,*j*= 1..Y) is a square of sides *r*. The goal is to derive an algorithm that allows the MSNs to start at the first square (cell $s_{1,1}$) and at a formation that allows them to traverse each square only once and also minimizes the total distance and time needed to complete the localization. The algorithm requires the MSNs to choose the transformation and migration that results in an optimal formation (Section III). Since an optimal transformation can only occur either between formations F_1 and F_3 or between F_2 and F_4, the challenge lies in migrating to an optimal formation after the transformation.

We start with an examination of the optimal migration from each formation. For formation F_1 at cell $s_{i,j}$, the two optmal migrations are to F_4 ($s_{i-1,j}$) and F_2 ($s_{i,j-1}$) (Figure 7(a)). Similarly, from F_2 at cell $s_{i,j}$, the two optimal migrations are to F_3 ($s_{i-1,j}$) and F_1 ($s_{i,j+1}$) (Figure 7(b)). And, from F_3 at cell $s_{i,j}$, the two optimal migrations are to F_2 ($s_{i+1,j}$) and F_4 ($s_{i,j+1}$) (Figure 7(c)). Finally, from F_4 at cell $s_{i,j}$, the two optimal migrations are to F_1 ($s_{i+1,j}$) and F_3 ($s_{i,j-1}$) (Figure 7(d)). Next, we determine for each starting formation, the direction of movement of the MSNs along the rows and columns that result in optimal formations.

If the MSNs start at F_1 at cell $s_{1,1}$, then the transformation within the square results in formation F_3. From F_3, the MSNs can migrate either to the square on the right,$s_{1,2}$ or to the square at the bottom,$s_{2,1}$. If the MSNs move across the row then they arrive (after transformation within the cell) at formation F_2 at cells($s_{1,2}$,$s_{1,4}$,$s_{1,6}$,..,$s_{1,MaxEvenColumn}$) and at formation F_3 at cells($s_{1,3}$,$s_{1,5}$,$s_{1,7}$,..,$s_{1,MaxOddColumn}$). Similarly, if the MSNs move down the column then they arrive (after transformation within the cell) at formation

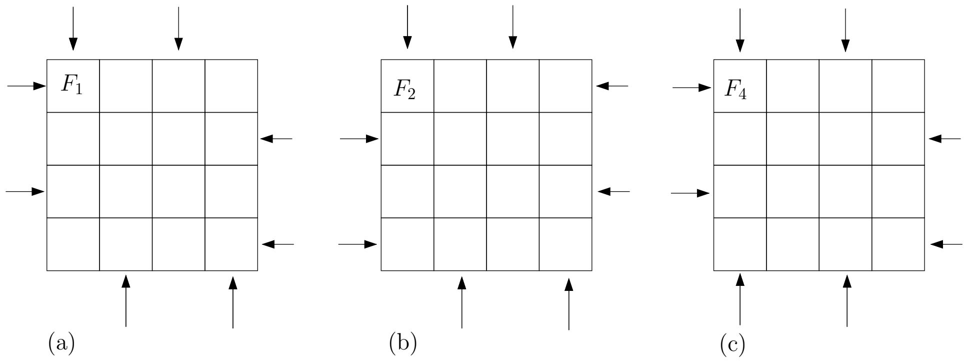

Fig. 8. Movement map for each starting formation

F_4 at cells ($s_{2,1}$,$s_{4,1}$,$s_{6,1}$,.., $s_{MaxEvenRow,1}$) and at formation F_3 at cells ($s_{3,1}$,$s_{5,1}$, $s_{7,1}$,..,$s_{MaxOddRow,1}$). Now, the MSNs arrive at formation F_3 at odd rows and columns and the optimal migration from F_3 is either right to F_4 or down to F_2 (Figure 7(c)). Therefore, we can infer that the MSNs could only traverse from column j to j+1 at odd rows and from row i to i+1 at odd columns. Similarly, it can be infered that the MSNs could only move from column j to j-1 at even rows and from row i to i-1 at even columns provided they exist. The direction map for starting formation F_1 is presented in Figure 8(a).

Now, if the MSNs start at formation F_2, then a transformation leads to formation F_4 at cell $s_{1,1}$. From F_4, the MSNs can only migrate down to cell $s_{2,1}$ since the other optimal migration to the left does not exist. If the MSNs move down the column then they arrive (after transformation within the cell) at formation F_3 at cells ($s_{2,1}$,$s_{4,1}$,$s_{6,1}$,..,$s_{MaxEvenRow,1}$) and at formation F_4 at cells ($s_{3,1}$,$s_{5,1}$,$s_{7,1}$,..,$s_{MaxOddRow,1}$). On the other hand, at an even row, say i=2, starting from F_3 at $s_{2,1}$, the MSNs can move across the row from left to right and arrive (after transformation within the cell) at formation F_2 at cells ($s_{2,2}$,$s_{2,4}$,$s_{2,6}$,.., $s_{2,MaxEvenColumn}$) and at formation F_3 at cells ($s_{2,3}$,$s_{2,5}$, $s_{2,7}$,..,$s_{2,MaxOddColumn}$). Now, the MSNs arrive at formation F_4 at odd rows and columns and the optimal migration from F_4 is either left to F_3 or down to F_1 (Figure 7(d)). Therefore, we can infer that the MSNs could only traverse from column j to j-1 at odd rows and from row i to i+1 at odd columns. On the other hand, at even rows, the MSNs arrive at F_2 at even columns and at F_3 at odd columns. Since both F_2 and F_3 have an optimal migration to the left to formations F_1 and F_4 respectively, we can infer that a change in column from j to j+1 can only occur at even rows. Similarly, it can be infer that the MSNs can only move up from row i to i-1 at even columns. Figure 8(b) shows the direction map when the MSNs start at formation F_2.

On the other hand, the MSNs can start at formation F_3. Next, a transformation within the square results in formation F_1. From F_1, the optimal migrations are either to the cell on the left or to the cell on the top. Since there is no cell to the left or top of the starting cell $s_{1,1}$, F_3 cannot be the starting formation.

Finally, the MSNs can start at formation F_4 and a transformation leads to formation F_2 at cell $s_{1,1}$. From F_2, the MSNs can only migrate right to cell $s_{1,2}$ since the other optimal migration to the top does not exist. If the MSNs move across the row then they arrive (after transformation within the cell) at formation F_3 at cells($s_{1,2}$,$s_{1,4}$,$s_{1,6}$,..,$s_{1,MaxEvenColumn}$) and at formation F_2 at cells($s_{1,3}$,$s_{1,5}$,$s_{1,7}$,..,$s_{1,MaxOddColumn}$). But, at an even column, say j=2, starting from F_3 at $s_{1,2}$, the MSNs can move down the column and arrive (after transformation within the cell) at formation F_4 at cells($s_{2,1}$,$s_{4,1}$,$s_{6,1}$,..,$s_{MaxEvenRow,1}$) and at formation F_3 at cells($s_{3,1}$,$s_{5,1}$,$s_{7,1}$,..,$s_{MaxOddRow,1}$). Now, at odd rows, the MSNs arrive at formation F_2 at an odd column and F_3 at an even column. Since both F_2 and F_3 have an optimal migration to the left to formations F_1 and F_4 respectively, we can infer that a change in column from j to j+1 can only occur at odd rows. Additionally, we can also infer that a change in row from i to i-1 will only occur at an odd column and a change in row from i to i+1 can only occur ar an even column. Finally, the formation F_4 at even rows implies that the MSNs can move from column j to j-1 only at even rows. The direction map for starting formation F_4 is presented in Figure 8(c).

After generating the movement map for each possible starting formation, we explore the possibility of

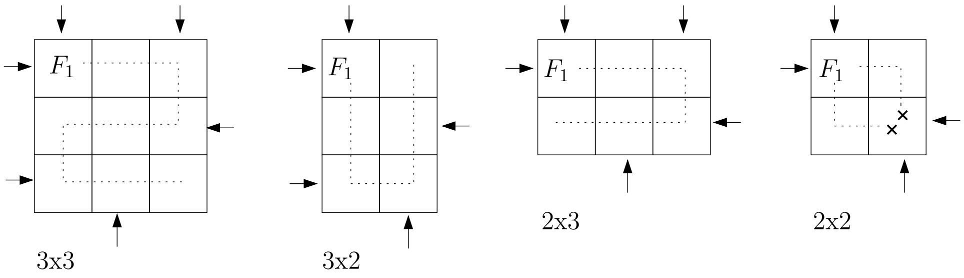

Fig. 9. Applications of F_1's movement map

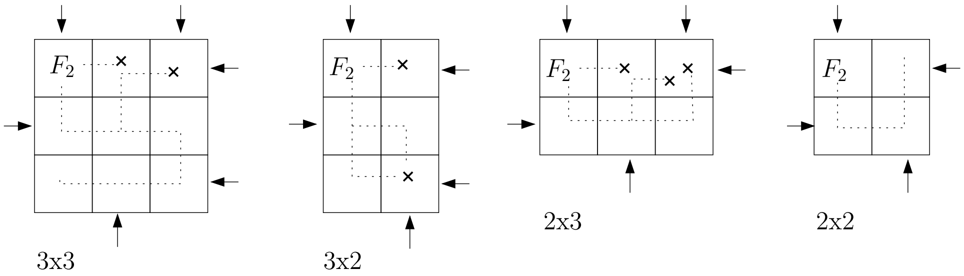

Fig. 10. Applications of F_2's movement map

applying the map to sensor fields of different dimensions. The four possible dimensions are: odd rows and odd columns, odd rows and even columns, even rows and odd columns and even rows and even columns. We want to determine whether for a particular dimension, the movement map of a starting formation can be followed to visit each square cell in the region once provided the MSNs start at the first cell. To this extent, we apply a movement map to four rectangular regions of dimensions,3x3,3x2,2x3,2x2. If the map works for a rectangular region of minimum dimension then it can also be applied to any larger dimension of the region.

We start with the movement map of F_1. For sensor fields of dimensions 3x3,3x2 and 2x3, it can be seen that an optimal path exist from the starting cell (Figure 9). But, for a 2x2 field, the MSNs cannnot find an optimal migration into the last cell $s_{2,2}$ (Figure 9). Therefore, we can conclude that the starting formation of F_1 can be applied to sensor fields of any dimension except those with even rows and columns.

Next, we observe the starting map of F_2 and find that for dimensions of 3x3,3x2 and 2x3, optimal migrations are not possible to all the cells in the field. On the other hand, an optimal migration is possible for the rectangular region of 2x2 (Figure 10). Therefore, it is understood that F_2 can be used as a starting formation only for regions with both even rows and columns.

Finally, we determine that the starting map of F_4 cannot find an optimal path for dimensions of 3x3,3x2 and 2x3 but, there exists an optimal path for the rectangular region of 2x2 (Figure 11). Hence, we can conclude that F_4 like F_2 can only be used as a starting formation for regions with both even rows and columns.

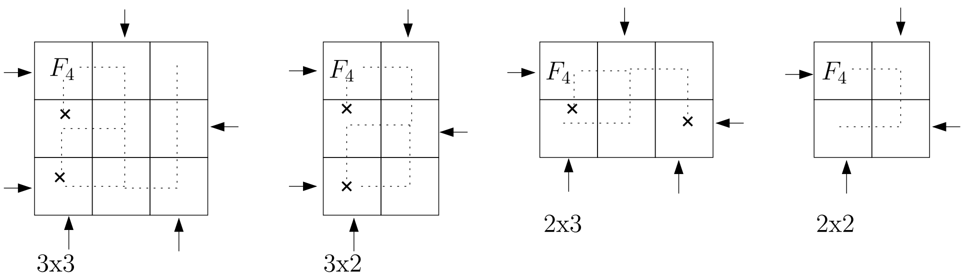

Fig. 11. Applications of F_4's movement map

After determining for each possible starting formation, the movement maps and the rectangular fields they can be applied to, the last step is to find an algorithm or set of rules that the MSNs can adhere to and discover all the optimal paths from the starting formation. Ofcourse, from any formation, if only one optimal migration is possible then the MSNs will choose that. But, a question arises when the MSNs need to choose from two optimal formations. Then the correct formation needs to be chosen such that, the MSNs do not end up at a cell from which it cannot get out without revisiting one of the already traversed cells. To eliminate this situation, we provide a set of rules for each formation at cell $s_{i,j}$ that dictates which migration formation needs to be chosen.

From formation F_1:
Rule 1: If (j-1 = 1) OR (j-2 is already traversed) Then
Migrate to F_4
Rule 2: If (i-1 = 1) OR (i-2 is already traversed) Then
Migrate to F_2
Rule 3: Otherwise
Migrate to either F_2 or F_4

From formation F_2:
Rule 1: If (j+1 = Y) OR (j+2 is already traversed) Then
Migrate to F_3
Rule 2: If (i-1 = 1) OR (i-2 is already traversed) Then
Migrate to F_1
Rule 3: Otherwise
Migrate to either F_1 or F_3

From formation F_3:
Rule 1: If (j+1 = Y) OR (j+2 is already traversed) Then
Migrate to F_2
Rule 2: If (i+1 = X) OR (i+2 is already traversed) Then
Migrate to F_4
Rule 3: Otherwise
Migrate to either F_2 or F_4

From formation F_4:
Rule 1: If (j-1 = 1) OR (j-2 is already traversed) Then
Migrate to F_1
Rule 2: If (i-1 = 1) OR (i-2 is already traversed) Then
Migrate to F_3
Rule 3: Otherwise
Migrate to either F_1 or F_3

A. Minimizing the total distance

The MSNs can employ the optimal migration algorithm descibed above with the optimal tranformation within a cell that requires a distance of $\sqrt{2}r$ (Section III) to minimize the total distance traveled to localize the sensor nodes in the field.

Theorem 1: In a wireless sensor network tiled into M unit regions of side r, the mobile seed nodes need to traverse a total distance of $\sqrt{2}Mr+2(M-1)r$ for network localization, and is minimum according to the formations specified in Section III.

Proof: The proof is by induction, and is as follows. For the base case, the number of unit regions is one and localization can be carried out in one step by moving the anchor MSN for a distance of $\sqrt{2}r$

to complete the transformation from F_1 to F_3 or F_2 to F_4 or F_4 to F_2. Thus, the bound holds true for the base case.

For the general case, if d_i is the minimum total distance to localize unit region i, then the induction hypothesis for the minimum total distance required to localize M unit regions is

$$\begin{aligned} D_M &= \sum_{i=1}^{M} d_i \\ &= \sqrt{2}Mr + 2(M-1)r \end{aligned} \tag{1}$$

With an additional unit region to localize, we have to prove that

$$\begin{aligned} D_{M+1} &= \sum_{i=1}^{M+1} d_i \\ &= \sqrt{2}(M+1)r + 2Mr \end{aligned} \tag{2}$$

and can be done as follows.

$$\begin{aligned} D_{M+1} &= \sum_{i=1}^{M} d_i + d_{M+1} \\ &= \sqrt{2}Mr + 2(M-1)r + (\sqrt{2}r + 2r) \\ &= \sqrt{2}(M+1)r + 2Mr \end{aligned} \tag{3}$$

■

B. Minimizing the total time

Similarly, the MSNs can also employ the migration algorithm with the optimal tranformation that allows two MSNs to each move in parallel a distance of r in r time (Section III) to minimize the total time needed to complete the localization of all the nodes in the field.

Theorem 2: In a wireless sensor network tiled into M unit regions of side r, the mobile seed nodes can localize the sensor nodes in the network in a total time of $Mr + (M-1)r$, and is minimum according to the formations specified in Section III.

Proof: The proof is by induction, and is as follows. For the base case, the number of unit regions is one and localization can be carried out by moving two of the MSNs in parallel in time r to complete the transformation from F_1 to F_3 or F_2 to F_4 or F_4 to F_2. Thus, the bound holds true for the base case.

For the general case, if d_i is the minimum total time to localize unit region i, then the induction hypothesis for the minimum total time required to localize M unit regions is

$$\begin{aligned} D_M &= \sum_{i=1}^{M} d_i \\ &= Mr + (M-1)r \end{aligned} \tag{4}$$

With an additional unit region to localize, we have to prove that

$$\begin{aligned} D_{M+1} &= \sum_{i=1}^{M+1} d_i \\ &= (M+1)r + Mr \end{aligned} \tag{5}$$

and can be done as follows.

$$\begin{aligned} D_{M+1} &= \sum_{i=1}^{M} d_i + d_{M+1} \\ &= Mr + (M-1)r + 2r \\ &= (M+1)r + Mr \end{aligned} \tag{6}$$

■

C. Maximizing the lifetime of the mobile seeds

The lifetime of the MSNs is defined as the time until one of the MSNs drains out of energy. The energy of a MSN will depend on the distance traveled by the MSN. Therefore, it is important to ensure that each of the three MSNs travel similar distance in completing the localization. The total minimum distance theorem cannot gurantee that each of the three sensors will travel an equal or near-equal distances because the anchor MSN of a formation needs to travel a distance of $\sqrt{2}r$ diagonally to complete a transformation when the other two remain stationary. Additionally, a migration requires a distance of 2r. Since the migration and the transformation require different distances to be traveled by the MSNs, it is not possible to ensure that each of the three MSNs will travel similar distances.

Therefore, we can ensure that each of the three MSNs travel similar distances by considering the transformation where two of the MSNs each travel a distance of r to complete the transformation. This will ensure that both the migration and transformation each require two of the MSNs to move r distance each. Then for each MSN to travel similar distance, it has to be ensured that the same two MSNs are involved in successive movements only if no other combination of MSNs can move to that formation by traveling a total distance of 2r. That is, if MSNs 1 and 2 have just moved to complete a transformation then either MSNs 1 and 3 or 2 and 3 will participate in the migration unless only MSNs 1 and 2 can complete the optimal migration. With this scheme, we will ensure that each MSN move an equal distance if ($2M$-1) is a factor of 3. For every other case, either two of the MSNs or one of the MSN will move an extra r distance more than one or two of the MSNs respectively. Therefore, we state that the maximum difference in the total distance traveled by each MSN will not be greater than r.

Theorem 3: In a wireless sensor network tiled into M unit regions of side r, the mobile seed nodes can traverse a total distance of $2Mr + 2(M-1)r$ that maximizes the lifetime of the mobile seed nodes by ensuring that the maximum difference in the total distance traveled by each MSN will not be greater than r, and is minimum according to the formations specified in III.

Proof: The proof is by induction, and is as follows. For the base case, the number of unit regions is one and localization can be carried out in one step by moving the anchor MSN for a distance of $2r$ to complete the transformation from F_1 to F_3 or F_2 to F_4 or F_4 to F_2. Thus, the bound holds true for the base case.

For the general case, if d_i is the minimum total distance to localize unit region i, then the induction hypothesis for the minimum total distance required to localize M unit regions is

$$\begin{aligned} D_M &= \sum_{i=1}^{M} d_i \\ &= 2Mr + 2(M-1)r \end{aligned} \tag{7}$$

With an additional unit region to localize, we have to prove that

$$\begin{aligned} D_{M+1} &= \sum_{i=1}^{M+1} d_i \\ &= 2(M+1)r + 2Mr \end{aligned} \tag{8}$$

and can be done as follows.

$$\begin{aligned} D_{M+1} &= \sum_{i=1}^{M} d_i + d_{M+1} \\ &= 2Mr + 2(M-1)r + (2r + 2r) \\ &= 2(M+1)r + 2Mr \end{aligned} \tag{9}$$

■

V. CONCLUSION

Localization of sensor nodes can serve many useful purposes. In this paper, we have presented a framework where mobile seed nodes are employed to determine the locations of all the sensors in a sensor field. The uniqueness of our approach is that we utilize only three mobile sensor nodes to determine the locations of all the stationary sensor nodes in the network. While making all the sensor nodes location aware, we attempted to minimize total distance traveled and the time needed by the mobile seeds to complete the localization. We have found that both of these objectives cannot be satisfied using the same transformation scheme. Finally, we aimed to maximize the lifetime of the mobile seeds by ensuring that one of the them does not drain out of power too quickly by traveling significantly more distance than the others. As a result, we also propose a scheme where the difference in distance traveled by any two mobile seed is not greater than r. The later scheme also minimizes the total localization latency.As future work, we will examine how to provide reliability for the mobile seeds incase of failures.

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