Self Aware Actuation for Fault Repair in Sensor Networks

Saurabh Ganeriwal, Aman Kansal and Mani B. Srivastava

Networks and Embedded Systems Lab (NESL)
University of California Los Angeles
56-125B Eng. IV, UCLA EE Dept., Los Angeles, CA 90095

{saurabh, kansal, mbs}@ee.ucla.edu

***Abstract* - Actuation ability introduces a fundamentally new design dimension in wireless ad-hoc sensor networks, allowing the network to adaptively reconfigure and repair itself in response to unpredictable run-time dynamics. One of the key network resources in these systems is energy and several uncontrollable factors lead to situations where a certain segment of the network becomes energy constrained before the remaining network. The performance gets limited due to the constrained sections. We argue that in this scenario, instead of rendering the complete network useless, the remaining energy resources should be reorganized to form a new functional topology in the network. We present methods for the network to be aware of its own integrity and use actuation to improve performance when needed. This capability of the system is referred to as "self aware actuation".**

In this paper, we consider a network where nodes (or a subset of the nodes) have traction ability. The network uses mobility to repair the coverage loss in the area being monitored by it. We present a completely distributed energy aware algorithm (referred to as *Co-Fi*) for coordinated coverage fidelity maintenance in sensor networks. The energy overheads of mobility are incorporated in the algorithm, thus leaving no hidden costs. Our preliminary analysis shows that Co-Fi can significantly help improve the usable lifetime of these networks.

Index Terms – Wireless ad-hoc sensor networks; Coverage; Actuation; Mobility; Sensing range.

I. INTRODUCTION

The applications envisioned for sensor networks vary from monitoring inhospitable habitats and disaster areas to operating indoors for intrusion detection and equipment monitoring [1]. In most cases the network designer would have little control over the exact deployment of the network. Thus an irregular deployment of sensor nodes is the assumed norm for these networks. Even if the nodes are deployed uniformly at the onset of the network, as time progresses, nodes will die randomly due to varying traffic characteristics, resulting in a non-uniform network topology. Other factors such as edge effects also make the energy distribution in these networks to be non-uniform. The cumulative effect of all these factors often results in scenarios where a certain segment of the network becomes energy constrained before the remaining network. If a section of the network becomes non-functional, a large number of nodes may be active in another region, the system is no longer able to meet the performance criterion, and hence is rendered useless. Thus, these energy-constrained regions (referred to as *holes*) become bottlenecks in deciding the lifetime of the network. This makes the location of the live nodes very important in addition to the number of live nodes.

A proactive method of utilizing the total available energy is to place nodes and assign tasks such that holes are never formed in the network. Though this approach might give optimal solutions, we believe that such an approach is completely impractical for sensor networks, as it requires a-priori knowledge of the future behavior of the environment to be sensed and the resultant network activity. Few applications have utility for sensing a completely known environment with predictable behavior. Instead, we assume such knowledge is not available and take a reactive and practical approach of responding to these holes as they form. If we render the network to be useless when the first holes are created in the network, all the network resources remaining at that point in time, including the energy in active nodes, are wasted. We propose using self-aware actuation to allow a network to reorganize its available resources and form a new functional topology in the face of run-time dynamics. We call this approach "self-aware" as the actuation is not governed by a user command or application but initiated by the network to salvage its own performance.

In this paper, the performance criterion that we consider is coverage, defined as the fraction of the total intended area actually covered by sensor network [2]. We consider a network where nodes (or a subset of the nodes) can move in a controlled manner, possibly at high energy expense. We propose an algorithm referred to as COverage FIdelity maintenance algorithm (Co-Fi) that uses mobility as an adaptive actuation facility for automated deployment repair of the network with the sole objective of salvaging the lost coverage in the network. There have been a number of proposals of how mobility [3, 4] can be used to enhance the efficiency of ad hoc networks. In this paper, we utilize the mobility of nodes to set up a virtual flow of energy from one part of the system to another, creating an ad-hoc self sustainable system that can last until the whole system become energy constrained rather than losing utility when only a few small regions of the system have been drained. As shown in Figure 1, when holes are created in the network, we physically move the nodes from other parts of the network to these holes so that the network continues to function efficiently with this newly formed topology. Co-Fi can be seen as an extreme case of collaboration among the sensor nodes where a sensor node may sacrifice its existing role and expend energy on moving, to bring about a potential performance enhancement of the network as a whole. Our simulations based on realistic mobility costs [5] show that Co-Fi significantly improves the network lifetime.

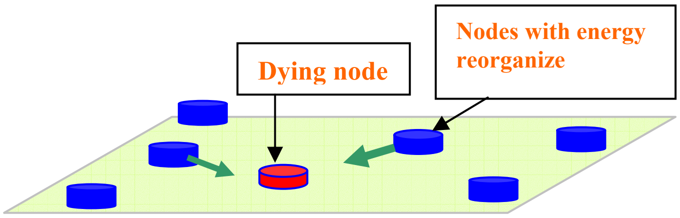

Fig. 1: Use of actuation to salvage performance and conteract holes

II. Related Work

Topology management refers to the class of algorithms that try to enhance the network lifetime by trading off energy with latency, density or performance. The idea is to keep minimum number of nodes in the active state so that minimum energy is consumed. The underlying constraint is to either maintain radio connectivity [6], complete coverage [7] or different degrees of coverage [8] throughout the network. However, when holes are created in the network, forming a working topology with the given set up becomes infeasible. In such cases, these schemes are no longer able to extract functionality from the residual resources. Co-Fi can be added in as a topology repair algorithm, which exploits actuation to overcome the limitations of static nodes.

A similar problem was addressed by authors in [9], where the formation of holes was handled by installing energy docking stations in the network. When a node is about to die, it replenishes its energy by physically moving to the docking station or a mobile node delivers energy from the docking station to the dying node (the technology for achieving this is not yet implemented). In Co-Fi, the network reorganizes its own available resources. Note that Co-Fi will work only if small parts of the network become energy constrained relatively to the other parts network and there are still available resources in the network to salvage this loss. In case, the whole network becomes resource-constrained the algorithm proposed in [9] can be used to utilize infrastructure resources such as energy docking stations when feasible.

III. Problem Formulation

A. Motivation

Nodes in the network do not die at the same time, for a variety of reasons. The activity, which the sensor network is detecting, may itself be non-uniform. For instance a network may be detecting the birdcalls in a particular ecological application. These birdcalls may occur close to a stream running through the deployment region of the network, causing much greater activity close to the stream. On the other hand, for a sensor network deployed to monitor temperature, uniform traffic is expected. Even in these scenarios nodes in the centre are likely to die faster as they lie on more data forwarding routes (this phenomenon is referred to as an edge effect). From an application perspective, the network loses utility when it does not provide the required coverage (holes are formed) and the remaining energy in the system is completely wasted. If some of the remaining energy can be transferred to these holes, albeit incurring transportation overhead, this wastage could be reduced and the network lifetime could be increased. However, the cost of transportation itself reduces energy in the system and hence a method is needed to determine when incurring such a cost actually improves system utility. Co-Fi attempts to solve this problem without assuming knowledge about future activity and without using a global system state.

B. System Model

We have a set of sensor nodes scattered randomly in an area. In the network initialization phase, every node acquires information about its location and communication neighbors by running a localization protocol [10] and link level neighbor discovery protocol [11] respectively. These are essential services for most applications and we do not consider this as an overhead specific to our algorithm. We assume that all the nodes in the network are equipped with the capability of movement. There exist several platforms with this ability [5]. Co-Fi will continue to work even if only a subset of nodes is equipped with this capability, albeit the relative benefits may be lower. We assume that nodes know their initial energy content and can keep a track of their energy expenditure [12]. Thus a node can predict its own death.

In this paper, we assume the binary coverage disc model proposed in [7, 8]. A location p is covered (monitored) by a node v if the Euclidian distance between p and v is less than the sensing range of v, Rs, *i.e.*, $|pv| < Rs$. This model is accurate when the sensor's capability to detect falls off with distance and detection takes place only above a certain sensor value threshold. We decided to adopt the binary coverage model due to its simplicity. We later consider the effect of obstacles in the environment, which introduce uncertainty in detection even within the sensing radius Rs. While proposing Co-Fi, we shall make an assumption that every node knows its sensing range, Rs. This can be easily accomplished through a training phase at the onset of the network, in which a known target is moved along a known path in the network. We would like to emphasize that Co-Fi does not rely on the homogeneity of nodes i.e. nodes may have different sensing radius. We show an example of such a scenario in simulations.

We assume that any two nodes u and v can directly communicate with each other if their Euclidian distance is less than a communication range Rc, *i.e.*, $|uv| < Rc$. Although a network can be rendered useless if it looses connectivity, we characterize the lifetime of the network by just observing the coverage provided by it. If $Rc >= 2Rs$, then it was shown in [7] that a fully covered network implies network connectivity too. In this case, Co-Fi provides connectivity in the network as an auxiliary benefit. However, if $Rc < 2Rs$, then Co-Fi would have to be modified to take connectivity into account.

C. Definitions

Sensing circle: The sensing circle $C(v)$ of node v refers to the boundary of v's idealized coverage region. It is a circle centered at the node's physical location v, having a radius equal to the sensing range, Rs. According to the binary coverage model, any point p lying on or outside the circle $C(v)$

(*i.e.*, $|pv|>=Rs$) is not covered by *v*. This definition can be extended to a convex region *A*; *A* is covered by node *v* if and only if whole region *A* lies inside the sensing circle of node *v*.

Intersection points: A point *p* is called the intersection point of nodes *u* and *v* if it lies on the sensing circle of both the nodes (*i.e.*, $|pv|=|pu|=Rs$).

Sensing neighbors[2]: The sensing neighbor set of node *v*, $N_s(v)$, includes all the active nodes that are within a distance of twice the sensing range, *i.e.*, $N_S(v) = \{u : |uv| < 2Rs\}$.

Coverage region[2]: The coverage region, $C_N(v)$, of a node *v* is defined as the region within the sensing circle of *v* exclusively covered by this node *i.e.*, $C_N(v) = \{A : (A \text{ is covered by } v) \ \& \ (A \text{ is not covered by } u: u \in N_S(v))\}$. This implies that if node *v* dies, coverage is lost in the region $C_N(v)$.

Figure 2 illustrate these definitions.

III. Coverage Fidelity Maintenance Algorithm

A. Basic concept

Co-Fi works in the following steps:

Initialization phase: Every node learns about its sensing neighbors and calculates its coverage region.

Panic Request Phase: A dying node requests for updating the network topology.

Panic Reply Phase: Sensing neighbors of the dying node respond to this request.

Decision phase: Network topology is updated accordingly.

B. Initialization Phase

In this phase, a node calculates its coverage region. Every node broadcasts a packet containing its physical location, which is heard in its one hop neighborhood. This could also be coupled with the link level neighbor discovery protocol [11]. In this paper, we assume that all sensing neighbors are within one-hop (*i.e.*, $2Rs >= Rc$) for simplicity. Co-Fi will continue to work even if $2Rs < Rc$. However, in such a scenario every node would have to perform limited flooding to reach all its coverage neighbors. A node *v* calculates its coverage region as follows:

- Form the set $N_s(v)$ containing the location of all the coverage neighbors, *i.e.*, $N_s(v) = \{u : (|u-v| <= 2Rs)\}$.

- Form the set $I(v)$ containing the intersection points between *v* and its coverage neighbors and also between any two coverage neighbors of *v*, *i.e.*, $I(v) = \{p : (p \text{ is an intersection point of nodes } i \text{ and } j) \ \& \ ([i, j] \in \{N_s(v) \cup v\})\}$.

- Form the set $\hat{I}(v)$ containing those intersection points which exclusively lie inside/on the sensing circle of *v*, *i.e.*, $\hat{I}(v) = \{p : (p \in I(v)) \ \& \ ([p \text{ is covered by } v] \text{ or } [p \text{ lies on } C(v)]) \ \& \ (p \text{ is not covered by } u: u \in N_s(v))\}$.

Figure 3 demonstrates the coverage region of two nodes, *A* and *D*. Although we have assumed till now that coverage region is contiguous, more complex scenarios might exist as shown for node *D* in Figure 3. The coverage region, $C_N(D)$, is a union of two triangles. Clearly, it is non-trivial to obtain this region from the set $\hat{I}(D)$ constituting of the six points shown in Figure 3. However, as we shall show later, Co-Fi only requires a binary answer to the following question, "Whether a node *v* covers any exclusive area in the sensor terrain?" This answer can be obtained by just checking whether $\hat{I}(v)$ is a non-empty set or not. Co-Fi does not requires the calculation of the actual coverage region, $C_N(v)$, of a node.

C. Panic Request Phase

In this phase, a dying node notifies the network of its death. In this paper, we try to provide 1-degree coverage throughout the sensor terrain. This implies that if a dying node does not have any exclusively monitored area ($C_N(v) = \hat{I}(v) = \emptyset$), there is no need to update the topology. In this case, a dying node just broadcasts a message, notifying the coverage neighbors of its death so that they can recalculate their coverage region. However, if a node has some exclusively monitored area ($\hat{I}(v) \neq \emptyset$), it broadcasts a panic request message triggering the update of the network topology so that the lost coverage, $C_N(v)$, can be restored.

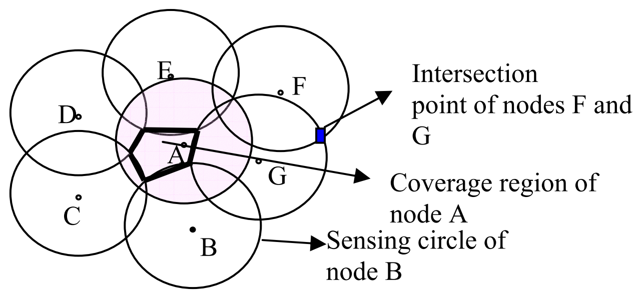

Fig. 2: Node A and its sensing neighbours

The panic request message contains the points that bound the ***mobility region*** of node *v*. Mobility region, $M(v)$, of a node *v* is defined as the region such that if a node *u* is moved to any point lying inside this region, the coverage region of node *v*, $C_N(v)$, lies completely inside the new coverage region of node *u*, $C_{N-\{v\}}(u)$. To get a physical implication of this definition, imagine a situation when a node *v* dies. By earlier definition, coverage is lost in the region $C_N(v)$. However, now if a node *u* is placed anywhere in $M(v)$, this lost coverage is restored in the new network not containing node *v*. A node *v* calculates its mobility region as follows:

- For every point *p* bounding the coverage region of node *v*, *i.e.*, ($p \in \hat{I}(v)$), draw a circle K_p, cantered at *p* of radius *Rs*.

- The mobility region is obtained by the intersection of all these circles, *i.e.*, $M(v) = \{\text{intersection } K_p \ \forall p \in \hat{I}(v)\}$.

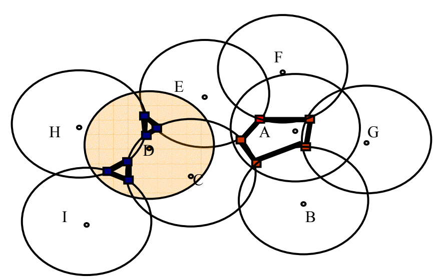

Fig. 3: Coverage region of node A and D

Note that the intersection of circles is a well-defined operation in geometry. Moreover, unlike the coverage region, mobility region will always be a single continuous convex region in the sensor terrain.

Proposition 1: *Every point belonging to $\hat{I}(v)$ is covered by a node u placed at any point in the mobility region, M(v).*

Proof: We prove it by contradiction. Let the new node *u* be placed at a random point *x* in the mobility region of node *v*, *M(v)*. Suppose there exists a point $y \in \hat{I}(v)$, which is not covered by this node. This implies $|xy| > Rs$.

By definition, *M(v)* is formed by the intersection of circles centered at points of the set $\hat{I}(v)$. Thus any point in *M(v)* has to lie within the circle cantered at *y* of radius *Rs*. This implies $|xy| <= Rs$. This is a contradiction and hence no such point exists.

Proposition 2: *If a node u covers every point belonging to the set* Î *(v), then the node also covers the coverage region of node v,* $C_N(v)$.

Proof: We have to prove that if some discrete points ($\hat{I}(v)$) lie inside a circle (sensing circle of node *u*), than all possible and even discontinuous regions ($C_N(v)$) formed by the random combination of them also lie within the circle. We prove it by induction.

The minimum cardinality of $\hat{I}(v)$ is 3 and in this case it trivially follows that $C_N(v)$ is a triangle. In this case, every edge of the triangle lies in one of the three sectors (corresponding to the sensing circle of node *u*) formed by choosing any two points in a pair and hence, the triangle lies within the circle.

Suppose the cardinality of $\hat{I}(v)$ is 4. We can subdivide this into all possible permutations of 3 points. If the points lie within the circle, than by the above proof, all the triangles formed by these points also lie within the circle. Clearly, $C_N(v) \subseteq (\cup \text{ all triangles})$ and hence, $C_N(v)$ also lie within the sensing circle of node *u*. Similarly, using induction, it can be extended for any random cardinality of $\hat{I}(v)$.

D. Panic Reply & Decision Phase

If a node, *w*, gets the panic request message of the dying node, *v*, it should decide whether it should move to a new location in *M(v)* or not. In this paper, we use a simple approach of not restoring the lost coverage, $C_N(v)$, at the cost of coverage, $C_N(w)$, in some other region of the network. Thus, if a node *w* covers some exclusively monitored area ($\hat{I}(w) \neq \emptyset$), it responds to the panic request message only if it can move without losing coverage in $C_N(w)$. A possible extension of this approach is to make this decision based on the relative magnitudes of $C_N(v)$ and $C_N(w)$. However, this will require the calculation of the exact coverage region, which, as explained in section B, is non-trivial. On the other hand, if a node *w* does not cover any exclusively monitored area ($\hat{I}(w) = \emptyset$), it always send back a message to the dying node. This reply from the node *w* is to notify the dying node *v* about its intent of being moved in the network. In this message, node *w* sends its residual energy and the shortest distance from its current location to the mobility region of *v*, which determines the mobility cost of the node.

During the decision phase, the dying node chooses the node with the maximum utility (residual energy minus the mobility cost). This greedy approach is optimal from a global perspective. After taking the decision, the dying node notifies the chosen node to move.

E. Discussion

We would like to point out that Co-Fi operates in a completely localized and distributed fashion. During every phase of the algorithm, each node just relies on local information gathered by it. This makes Co-Fi completely scalable. Scalability is a major concern for sensor networks. It is very expensive to maintain global state in such systems. Further, we incorporate mobility cost in the decision step of Co-Fi, thus leaving no hidden cost in the algorithm.

Co-Fi can easily be extended to a scenario where nodes have different sensing ranges. During the initializing phase, a node gathers location as well as range information of all its neighbors and hence, can still calculate its coverage region. However proposition 1 does not hold any more when the sensing range of node *u* is less than the sensing range of node *v*. In order to handle this, a node should calculate the mobility region using the minimum of all the possible sensing ranges in its neighborhood.

We note that our proposed solution is highly geometric in nature and we use the disc model extensively. This indeed is necessary as several optimizations are available in geometry to efficiently operate on circles. If the ranging model is not circular, more complex algorithms will have to be used. Other than battery depletion, sensor nodes can also be destroyed accidentally or deliberately. All these factors can potentially result in coverage loss in parts of the network, thus creating holes. In its current form, Co-Fi works in a reactive mode where a dying node explicitly asks for updating the network topology and hence, is not applicable to this scenario. Another typical case exists when a sensor stops functioning, although the node has significant residual energy. Co-Fi considers this scenario to be analogous to a dying node, as the metric used in this paper is coverage. Thus, on realizing the malfunctioning of its sensor, a node broadcasts the panic request message.

IV. Simulation Results

A. Simulation set up

Nodes are randomly distributed over a sensor terrain of 200x200m. Every node is equipped with the capability of movement. Our simulations try to closely model real settings. Table 1 details the setting of different simulation parameters.

Co-Fi will perform extremely well if the energy distribution is non-uniform in the network. However, we deliberately consider a pessimistic simulation model, whereby event locations are uniformly distributed in the network. This was done to show the wide applicability of Co-Fi. The energy consumption in a node falls steeply (tenth power) with the distance from the event location. After choosing an event location, we wait for the death of at least a single node before another event occurs at a new location. The mobility cost as well as the overhead of control messages in Co-Fi has been incorporated in the node energy consumption module, thus leaving no hidden costs. The simulation results are averaged over 20 independent runs.

Table 1: Simulation parameters

Parameter	Value	Reasoning
Communication range	40m	Typical ranges observed in indoor environments using Berkeley motes
Sensing range	20m	Communication range is twice the sensing range
Mobility cost	8.267j/m	Robomote I [5]
Packet transmission cost	0.075J/s	25mA (Tx) at 3V from Berkeley motes [13]
Packet reception cost	0.030J/s	10mA (Rx) at 3V, motes
Idle cost	0.025J/s	8mA (processor) at 3V, motes
Maximum energy consumption in motes	324J/hr	8mA (processor) + 15-20 mA (exclusively Tx) + 2-5mA (sensor board) at 3V, Berkeley motes
Total initial energy	32400J (100 hr)	3000 mA at 3V, capacity of alkaline battery

B. Network Density

Co-Fi will bring significant gains in dense network scenarios. Note that even in coarse network deployments, the introduction of Co-Fi will not degrade the performance any further. This is because the constant overhead of Co-Fi, the control messages, is very low. The most significant overhead of Co-Fi is in moving the nodes. However, nodes will be moved only if they can bring a performance upgrade to the system. Figure 4 plots the fraction of lost coverage v/s the fraction of the dead nodes in the network.

As shown in Figure 4, the efficiency of system increases with the death of nodes in the network. This clearly highlights the self-configuration ability of Co-Fi. As anticipated, Co-Fi performs better in higher network densities. For example when 25% of the nodes die, Co-Fi gives a 1.5x, 4x and 6x improvement respectively for sensing density[1] of 2 (not shown in Figure 4), 5 and 10 respectively.

C. Realistic Coverage Model

Sensor networks will be deployed in several regions where the environment has physical obstacles to sensing, as a result of which, the effective coverage area of a node decreases. We wanted to see the impact of these obstacles on Co-Fi. We model the obstacles by a line in a two dimensional plane. If this line lies in the sensing circle of a node, the node losses coverage in the region shadowed by this line (Figure 5).

Figure 6 shows the results after introducing 40 obstacles in the network. The lengths of obstacles were uniformly distributed between 40m and 60m. As anticipated, coverage falls. However, an interesting thing to observe is that even in such a harsh setting, the performance of the system with Co-Fi always increases compared to when Co-Fi is not used. Note that in these simulations, the radio propagation was still allowed across the obstacles. We have also simulated probabilistic radio link failures. However, as the nodes broadcast all the control packets, a few link failures do not impact the performance of Co-Fi significantly.

[1] Average number of nodes covering a point in the network.

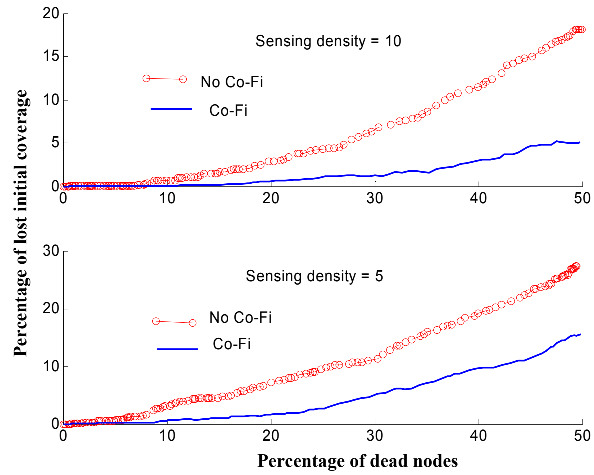

Fig. 4: Performance of Co-Fi with varying sensing density

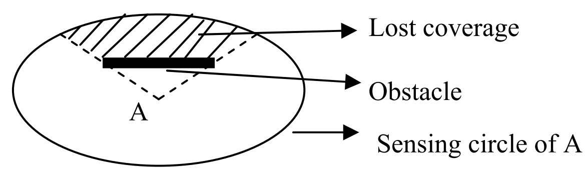

Fig. 5: Realistic coverage model

Lastly, we simulated a heterogeneous network scenario in the absence of any obstacles. Nodes have sensing ranges randomly distributed in the interval {15, 25}. As mentioned in Section IV.F, the most accurate (though pessimistic) approach is to calculate the mobility region using the minimum of the many possible sensing ranges in the neighborhood. The normal behavior is for the dying node to just use its own sensing range in the calculations. As shown in Figure 7, the obtained results are almost similar for both the approaches. The most important observation is that Co-Fi yields advantage even in a heterogeneous network scenario.

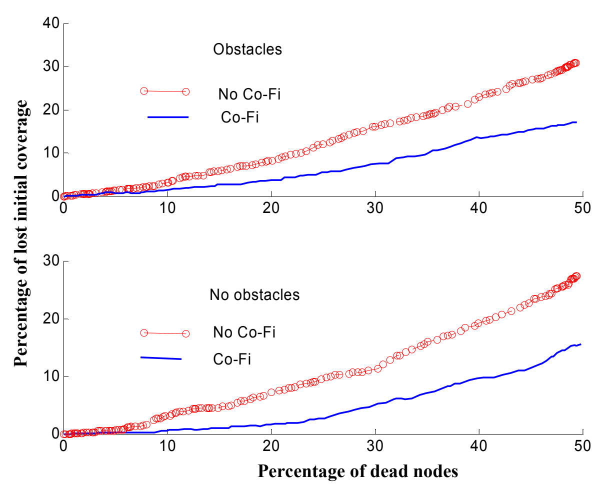

Fig. 6: Performance of Co-Fi in presence of obstacles

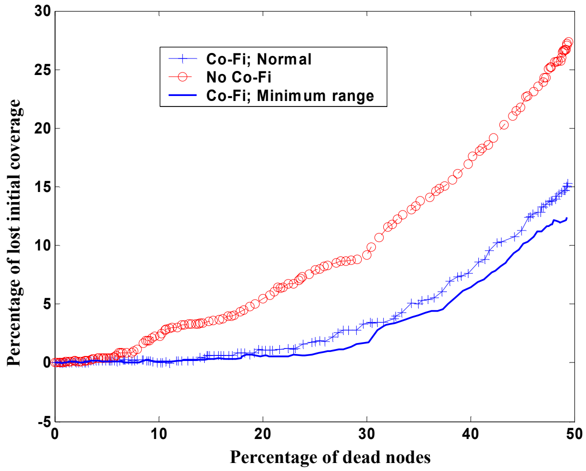

Fig. 6: Performance of Co-Fi in hetrogeneous sensor networks

IV. Conclusions

In this paper, we argue that actuation ability allows a sensor network to adaptively reconfigure and repair itself in order to improve its own performance. Based on this concept of self-configuration, we develop a scheme for maintaining coverage fidelity in sensor networks using mobility of sensor nodes. When a few sections of the network become resource constrained, instead of rendering the complete network useless, Co-Fi explicitly move the nodes to form a new efficient topology in the network. Co-Fi is a fully distributed and localized algorithm. We show that even if the energy distribution is uniform in the network (worst case scenario for Co-Fi), the system performance improves by a factor of 2-6 depending on the network density. The relative performance of Co-Fi remains unaffected by introducing ambiguities (obstacles or varying sensing ranges) in the coverage model of a node.

We believe that we have just scratched the surface in the realm of self-aware actuation. In this paper, we use the approach of self-aware actuation for coverage maintenance in sensor networks. However, future systems can use this approach to improve on other aspects such as connectivity, sensor calibration or data security. We believe that self-aware actuation presents a fundamentally new dimension in the design of wireless sensor networks and can help solve many problems in realizing the full potential of these resource-constrained systems.

Acknowledgment

This material is based upon work supported by the National Science Foundation (NSF), Center for Embedded Networked Sensing (CENS), a NSF Science & Technology Centre, and by the Office of Naval Research (ONR) under the AINS Program. Any opinions, findings and conclusions or recommendations expressed in this material are those of the author(s) and do not necessarily reflect the views of the NSF, CENS or the ONR.

References

[1] D. Estrin, R. Govindan, J. Heidemann, S. Kumar, “Next Century Challenges: Scalable Coordination in Sensor Networks”, *ACM Mobicom*, Seattle, WA, August 1999.

[2] S. Meguerdichian, K. Farinaz, P. Miodrag, M. B. Srivastava, “Coverage Problems in Wireless Ad Hoc Sensor Networks,” *IEEE ICC,* 2001.

[3] S. Capkun, J. P. Hubaux, L. Buttyan, “Mobility helps Security in Ad Hoc Networks”, *ACM Mobihoc,* Annapolis, MD, June 2003.

[4] M. Grossglauser, D. Tse, “Mobility increases the capacity of ad hoc wireless networks”, *ACM/IEEE Transactions on Networking,* 10(4), 477-486, 2001.

[5] G. T. Sibley, M. H. Rahimi, G. S. Sukhatme, “Robomote: A Tiny Mobile Robot Platform for Large-Scale Sensor Networks", *IEEE ICRA*, 2002.

[6] C. Schurgers, V. Tsiatsis, S. Ganeriwal, M.B. Srivastava, “Optimizing sensor networks in the energy-density-latency design space”, IEEE Transactions on Mobile Computing (TMC), January-March 2002.

[7] Xiaorui Wang, Guoliang Xing, Yuanfang Zhang, Chenyang Lu, Robert Pless, and Christopher Gill, “Integrated Coverage and Connectivity Configuration in Wireless Sensor Networks*”, ACM SenSys Conference,* Los Angeles, CA, November, 2003.

[8] Ting Yan, Tian He, and John A. Stankovic, “Differentiated Surveillance for Sensor Networks”, *ACM SenSys Conference,* Los Angeles, CA, November, 2003.

[9] M. Rahimi, H. Shah, G. Sukhatme, J. Heidemann, D. Estrin, “Energy Harvesting in Mobile Sensor Networks”, *IEEE ICRA*, Taipai, Taiwan, May, 2003.

[10] A. Savvides, C. C. Han, M. B. Srivastava, “Dynamic fine-grained localization in ad-hoc networks of sensors”, *ACM MobiCom*, Rome, Italy, pp.166-179, July 2001.

[11] S. Borbash, M. McGlynn, "Birthday Protocols for Low Energy Deployment and Flexible Neighbor Discovery in Ad Hoc Wireless Networks", *ACM MobiHoc*, Long Beach, USA, 2001.

[12] R. Neugebauer, D. McAuley, “Energy is just another resource: Energy accounting and energy pricing in the nemesis OS,” *Proceedings of the 8th IEEE workshop on Hot Topics in operating Systems,* Germany, May 2001.

[13] J. Hill and D. Culler, “A Wireless Embedded Sensor Architecture for System-level Optimization.” *Technical report*, U.C. Berkeley, 2001.