Fault Tolerant Connected Sensor Cover with Variable Sensing and Transmission Ranges

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Abstract— **Sensor networks are often deployed in a redundant fashion. In order to prolong the network lifetime, it is desired to choose only a subset of sensors to keep active and put the rest to sleep. In order to provide fault tolerance, this small subset of active sensors should also provide some degree of redundancy. In this paper, we consider the problem of choosing a minimum subset of sensors such that they maintain a required degree of coverage and also form a connected network with a required degree of fault tolerance. In addition, we consider a more general, variable radii sensor model, wherein every sensor can adjust both its sensing and transmission ranges to minimize overall energy consumption in the network. We call this the variable radii k_1-Connected, k_2-Cover problem. To address this problem, we propose a distributed and localized Voronoi-based algorithm. The approach extends the relative neighborhood graph (RNG) structure to preserve k-connectivity in a graph, and design a distributed technique to inactivate desirable nodes while preserving k-connectivity of the remaining active nodes. We show through extensive simulations that our proposed techniques result in overall energy savings in random sensor networks over a wide range of experimental parameters.**

I. Introduction

Fundamentally, a sensor node's responsibility is to observe the physical space around it, and measure some physical signals or detect various phenomena of interest. This gives rise to the well-known *coverage* problem [1], where the issue is to study how well a sensor network of nodes is able to monitor the given region of interest, and the minimum resources (in terms of hardware and battery energy) needed to provide the desired coverage. The metric that defines the coverage quality is very much sensor and application specific, and is generally related to the sensor's charateristic response to a signal source at a distance. The issue of providing sufficient coverage is further complicated in presence of node failures or noise (in sensor electronics or the propagation environment). In such cases, collaborative signal processing techniques are used to combine the data from multiple sensors that are in physical proximity of the signal to increase the accuracy of the observed data.

In this article, we address the problem of providing an appropriate coverage from an energy efficiency point of view. In particular, our goal is to design efficient distributed algorithms to construct a connected topology in a sensor network that is (i) fault-tolerant in terms of its connectivity [2], (ii) able to provide the desired quality of coverage, but uses only a small amount of sensing and transmission energy. Forming a connected topology is important, as the data gathered in the network need to be transported to a central sink node for storage and/or analysis. The fault-tolerant connectivity requirement ensures connectivity even in adverse conditions wherein some nodes and links may fail. Also, our notion of coverage is quite general and allows for the use of multiple sensors to improve confidence.

Energy is optimized by three mechanisms. First, some sensor nodes can be simply inactivated. This is possible as sensor networks are typically deployed in a highly redundant fashion, since the deployment cost is expected to be more than the hardware cost. Second, the transmission power of individual sensor nodes can be reduced while preserving connectivity requirements. Similarly, the *sensing region* can be reduced as long as the desired coverage quality is maintained [3]. The last strategy of reducing the sensing range of a sensor node is relatively uncommon. It hinges on the fact that for higher sensing range, more energy is needed for noise filtering and signal processing to improve the signal-to-noise ratio. We envision that sophisticated sensors in future will allow adjustment of sensing ranges in a similar manner as the transmission range. Even with the current technology control of the sensing range is still useful. Take the example of a wireless network of RFID (radio-frequency identification) [4] readers that detect RFID tags in a large factory floor. If the tags are passive, the only way to read the tags is via RF energy emitted from the reader device that is backscattered from the tags. The RF power is controlled to control the effective read range (sensing range in our terminology).

Overall, we take a unified view of coverage, connectivity, and energy efficiency, and use the available tools – exploiting redundancy, and adjusting sensing and transmission ranges – to arrive at an energy efficient topology. The approaches in our work uses discrete algorithms. Thus, we need to model the problem using a notion of coverage that is both general and amenable to such approaches. To this end, we use the notion of *sensing region* of a sensor that signifies a region around the sensor such that the sensor can sense the physical signal of interest anywhere in this region with a given confidence. For tractability, we have assumed that the sensing region is circular (with radius equal to the sensing range). However, in certain cases this assumption can be relaxed. Coverage requirment is modeled by requiring that each point in the physical space of interest to be within the sensing region of at least k sensors. The value of k depends on the desired accuracy of

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observed data and fault tolerance. The fault tolerant aspects of connectivity is modeled by making the network k-connected, i.e., the network remains connected even if k nodes fail, or equivalently there exist k node-disjoint paths between every pair of nodes in the network. We allow the possibility of using different k values for connectivity and coverage. Thus, our goal is to construct a k_1-connected k_2-cover set of sensors with assigned transmission and sensing ranges.

The rest of the paper is as follows. We start with giving a formal definition of the problem addressed in our article. The next section presents a discussion of related work. In section IV, we present some topology control schemes that preserve k-connectivity. We present the Voronoi-based distributed approach in Section V. We conclude with performance comparison of various approaches in Section VI, and concluding remarks in Section VII.

II. Problem Formulation

In this section, we formulate the connected cover problem addressed in this paper. We begin with the variable radii sensor model.

We view each sensor I as a stationary node associated with a maximum sensing radius S^* and a maximum transmission radius T^*. We assume that the maximum radii associated are same for all the sensors in the network. Each sensor has associated with it a sensing disk, with radius $S(I)$ chosen from the range $[0, S^*]$; and a transmission range, with radius $T(I)$ chosen from the range $[0, T^*]$. Any point is *covered* by a sensor I if it falls within distance $S(I)$ from I. Sensor I can communicate to any other sensor within the range of $T(I)$. We use $\theta(I)$ to denote the assigned sensing disk of sensor I. This variable radii sensor model is justified in [3].

Now we formally define the k_1-connected k_2-cover (VRKCKC) problem. First, we describe some necessary definitions.

Definition 1: (Energy Cost) Consider a sensor I with an assigned sensing radius of $S(I)$ and a transmission radius of $T(I)$. We model the energy cost of I as $E(I) = f(S(I)) + g(T(I)) + C$, where $f(x)$ and $g(x)$ are non-decreasing functions in x, and C is a constant that represents the idle-state energy cost. □

Definition 2: ((Full) Communication Graph) Given a set of sensors M in a sensor network, the *communication graph* of M is a graph with M as the set of vertices and an edge between any two sensors if they can directly communicate with each other using their *assigned* transmission radii. The *full-communication graph* of a set $\mathcal{I}$ of sensors is the communication graph of $\mathcal{I}$ when each node in $\mathcal{I}$ is assigned the maximum transmission radius T^*. □

Definition 3: (Communication Distance) A path of nodes/sensors between I_i and I_j in the communication graph is called a *communication path* between the sensors I_i and I_j. The *communication distance* between two sensors I_i and I_j is the weight of the minimum node-weighted path between I_i and I_j in the communication graph, where the weight at an intermediate sensor node I is the transmission energy cost $g(T(I))$ of the sensor node. □

Definition 4: (k-Connectivity) The communication graph of a given set of sensors M is *k-connected* if for any two vertices I_i and I_j in M, there are k vertex-disjoint paths from I_i to I_j. A equivalent definition is, after the removal of any $k-1$ nodes the communication graph of M is still connected. □

Definition 5: (Variable Radii k_1-Connected k_2-Cover) Consider a sensor network consisted of a set $\mathcal{I}$ of sensors and a query region R_Q. A set of sensors $M \subseteq \mathcal{I}$, $M = I_1, I_2, \ldots, I_m$, is chosen to be active, where each sensor I_j is assigned a sensing radius $S(I_j)(\leq S^*)$ and a transmission radius $T(I_j)(\leq T^*)$. M is said to be a *k_1-connected k_2-cover* for the query region R_Q if the following two conditions are satisfied:

1) each point p in R_Q is covered by at least k_2 distinct sensors in M.
2) the communication graph induced by M is k_1-connected.

□

Variable Radii k_1-Connected k_2-Cover Problem: Given a sensor network and a query region R_Q over the network, the variable radii k_1-connected k_2-cover problem is to find a VRKCKC such that the total of the energy cost of the sensors is minimized. This problem is NP-hard as it is a generalization of the variable radii 1-connected 1-cover problem, which is already known to be NP-hard [3].

III. Related Work

Research in connectivity and coverage is not new in ad hoc or sensor networks, though combining these issues together has been relatively uncommon. In this section, we briefly review existing work on connectivity and coverage issues.

Many schemes have been proposed to conserve energy while maintaining connectivity in the network topology. One of the most related problem in the above context is the *minimum connected dominating set* problem [5]. The work in wireless network research community ([6], [7], [8], [9], [10], [11], [12]) has primarily focused on developing energy-efficient distributed algorithms to construct a near-optimal connected dominating set. All the above works assume fixed transmission range for each sensor node. The works in [13], [14], [15], [16] address the related NP-complete problem of constructing a minimum energy broadcast tree in a network, where every node can adjust its transmission power/range. Along the same line, some recent works address the problem of fault tolerant topology control [17], [18], [2], [19]. Of particular interest to us is the protocol in [18] that proposes a cone based topology control (CBTC) scheme. The CBTC scheme is to assign the minimum transmission range to a node I such that the maximum angle between any pair of its two consecutive neighbors is at most $2\pi/3k$. It is shown that the CBTC scheme preserves the k-connectivity of the given network. In [2], the authors propose a scheme that minimizes the maximum power assigned to any node while preserving k-connectivity. None of the above described works involve any notion of sensing range or coverage.

A set of independent research has addressed the coverage problem in sensor networks. In [20] the authors have designed a centralized heuristic to select mutually exclusive sensor covers that independently cover the network region. In [21], the authors have investigated linear programming techniques to optimally place a set of sensors on a sensor field (three dimensional grid) for a complete coverage of the field. Meguerdichian et al. ([22], [23]) have considered a slightly different definition of coverage. They address the problem of finding maximal paths of lowest and highest observabilities in a sensor network. A localized protocol is proposed in [24] that aims at choosing a minimal set of sensors to be active at any time point, while guaranteeing the coverage of the grid points. Some articles ([25], [26], [27]) try to address the asymptotic coverage problem, in which they derive the necessary conditions such that a geographic region can be covered with high probability, while using a simple scheduling scheme to coordinate sensor nodes duty cycles. However, these works only consider fixed sensing ranges. Besides, connectivity is not involved.

Recently, researchers have also considered connectivity and coverage in an integrated platform. In particular, the authors in [26] consider an unreliable sensor network, and derive necessary and sufficient conditions for the coverage of the region and connectivity of the network with high probability. The PEAS protocol [28] considers a probing technique that maintains only a necessary set of sensors in working mode to ensure coverage and connectivity with high probability under certain assumptions. Wang et al. [29] present a localized heuristic in which they use the SPAN [30] protocol to maintain connectivity, and a separate CCP protocol to maintain coverage. In [1] we have proposed a greedy approximation algorithm that delivers a connected sensor cover for a sensor network with fixed transmission and sensing ranges. In [31] we have extended the above work by considering k-coverage. In [3], we have considered sensors with variable transmission and sensing ranges. In the present paper, we introduce the notion of fault tolerance to this model. Our goal is to use variable transmission and sensing ranges, but construct k_1-connected, k_2-cover. This is the first time that fault tolerant connectivity and coverage have been combined in the same framework.

IV. k-Connectivity Preserving Topology Control

In highly redundant sensor networks, we wish to keep only a subset of sensors active. In addition, to save total energy cost, we can adjust the transmission powers of the active sensor nodes, while preserving desired connectivity properties of the communication graph. In this section, we present topology control strategies to delete edges or nodes in the network, while maintaining k-connectivity of the remaining network. We would use the results presented in this section to design an efficient distributed algorithm for computing a VRKCKC in Section V.

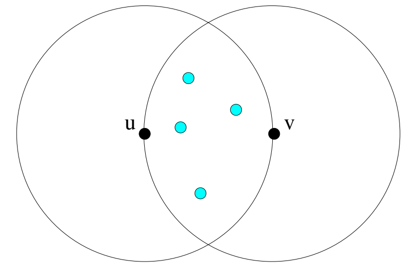


Fig. 1. k-RNG example. Given that (u, v) is an edge in the original graph, (u, v) is a k-RNG edge only if there exist less than k nodes within the common area.

A. Topology Control by Deletion of Edges

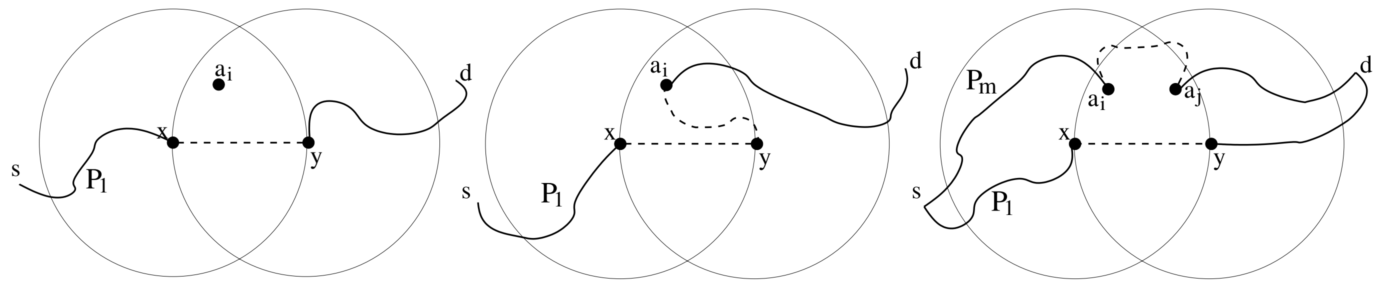
In this subsection, we generalize the RNG (relative neighborhood graph) structure [15] to the k-RNG structure, which allows us to delete longer edges in the graph in a distributed and localized manner while preserving k-connectivity of the graph. Deletion of longer edges allows us to reduce the transmission powers of the nodes in the network, and thus, reducing the total energy requirement of the network while preserving the desired k-connectivity requirement. We start with recollecting the definition of the RNG structure.

Definition 6: (Relative Neighbor Graph (RNG)) Given a network of nodes with uniform transmission radius, the *relative neighbor graph* is the network communication graph where an edge exists between any two nodes u and v *iff* the following two conditions are satisfied: 1) there exists no node w which is closer to u as well as v than the distance between u and v, i.e., there is no node w that satisfies $d(u, w) < d(u, v)$ and $d(v, w) < d(u, v)$ simultaneously; 2) edge (u, v) exists in the original graph, i.e., $d(u, v) < T^*$, where T^* is the uniform transmission radius. □

It can be easily shown that for unit-disk graphs, i.e., full-communication graphs of networks where each node has the same transmission radius, the relative neighborhood graph is connected if the full-communication graph of the network is connected. Note that RNG can be constructed efficiently in a distributed and localized manner. Construction of RNG helps in transmission power control, since each node can adjust its transmission power to directly transmit with only its RNG neighbors. We now generalize the above RNG structure to k-RNG structure which can also be constructed in a distributed and localized manner while preserving k-connectivity of the network.

Definition 7: (k^{th} Relative Neighbor Graph (k-RNG)) Given a network of n nodes with uniform transmission radius, the k^{th} *relative neighbor graph* is the network communication graph where an edge exists between two nodes u and v *iff* the following two conditions are satisfied, 1) there are at most $(k-1)$ nodes w that satisfy the condition $d(u, w) < d(u, v)$ and $d(v, w) < d(u, v)$ simultaneously; 2) (u, v) is an edge in the original graph. An example is shown in figure 1. □

Theorem 1: Given a network of nodes with uniform transmission radius, if the full-communication graph of the network is k-connected, then the k-RNG is also k-connected.



(a) Case 1: There exists a node a_i that is not contained in any path.

(b) Case 2: There exists a node a_i on path P_1.

(c) Case 3: There exist at least two nodes a_i and a_j on a single path P_m.

Fig. 2. Three cases in the proof of theorem 1.

Proof: Lets consider two nodes x and y such that there are at least k nodes $a_1, a_2, \ldots, a_k$ that satisfies the condition $d(x, a_i) < d(x, y)$ and $d(y, a_i) < d(x, y)$ simultaneously. Let the full-communication graph of the network be G, and let G' be the graph G without the edge (x, y). Below, we show that G' is k-connected, assuming G is k-connected.

Consider an arbitrary pair of nodes s and d in G. Let $P_1, P_2, \ldots, P_k$ be the k node-disjoint paths between s and d in the graph G. We try to show that there exist k node-disjoint paths between s and d in G' also. If (x, y) does not belong to any P_i $(1 \leq i \leq k)$, then s and d trivially have k node-disjoint paths in G'. Without loss of generality, let us assume that (x, y) belongs to P_1. Now, there are three cases:

- There is a node a_i $(1 \leq i \leq k)$ that is not contained in any of the other paths $P_2, P_3, \ldots, P_k$. See Figure 2 (a). In this case, the edge (x, y) in P_1 can be replaced by (x, a_i, y) to yield $P_1^{'}$, and the set of k node-disjoint paths in G' connecting s and d are $P_1^{'}, P_2, P_3, \ldots, P_k$.
- There is a node $a_i (1 \leq i \leq k)$ that is contained in P_1. See Figure 2 (b). In this case, the path P_1 can be changed to yield a shorter path $P_1^{'}$ which is node-disjoint from all other paths $P_2, P_3, \ldots, P_k$. If P_1 is of the form $(s, \ldots, x, y, \ldots, a_i, \ldots, d)$, then $(s, \ldots, x, a_i, \ldots, d)$ can be chosen as $P_1^{'}$. Similarly, if P_1 is of the form $(s, \ldots, a_i, \ldots, x, y, \ldots, d)$, then $(s, \ldots, a_i, y, \ldots, d)$ can be chosen as $P_1^{'}$.
- There are two nodes a_i and a_j that are contained in the same path P_m $(2 \leq m \leq k)$. See Figure 2 (c). In this case, P_1 and P_m can be changed to yield two node-disjoint paths that are also node-disjoint from other paths. In particular, if P_1 is of the form $(s, P_1^{sx}, x, y, P_1^{yd}, d)$ and P_m is of the form $(s, P_m^{sa_i}, a_i, P_m^{a_i a_j}, a_j, P_m^{a_j d}, d)$, then we can construct two paths $P_1^{'} = (s, P_1^{sx}, x, a_j, P_m^{a_j d}, d)$, and $P_m^{'} = (s, P_m^{sa_i}, a_i, y, P_1^{yd}, d)$. It is easy to see that the set of k paths $P_1^{'}, P_2, \ldots, P_l^{'}, \ldots, P_k$ exist in G' and are node-disjoint.

Note that the above three cases cover all possibilities. Thus, the above analysis shows that G' is k-connected.

Note that in the above analysis, the new edges introduced in the paths connecting s and d are strictly shorter than (x, y). Thus, to show that the k-RNG graph is k-connected, we can apply the above analysis for one edge removed from G at a time, in the descending order of the edge lengths. ■

One of the other distributed and localized schemes proposed in the literature for transmission power control while preserving k-connectivity is the CBTC [18] (cone based topology control) approach. In the CBTC approach, each node u picks the minimum transmission radius t_u such that there is a node w with $d(u, w) < t_u$ in *every* cone of angle $2\pi/3k$ around u. It is shown in [18] that the resulting graph considering only the undirected edges is k-connected. Below, we show that the k-RNG structure is actually a subgraph of the graph generated by the CBTC approach in unit-disk graphs.

Theorem 2: Consider a network of nodes with uniform transmission power. The k-RNG is a subgraph of the graph resulting from the CBTC approach.

PROOF. We prove the theorem by showing that if an edge (u, v) does not exist in the CBTC graph, then (u, v) is not in k-RNG. Let t_u and t_v be the transmission randii of u and v respectively resulting from the CBTC approach. Since (u, v) is not an edge in the CBTC graph, we know that either $t_u < d(u, v)$ or $t_v < d(u, v)$. Without loss of generality, let us assume that $t_u < d(u, v)$.

Now, consider the circles C_u and C_v with centers u and v respectively and radii $d(u, v)$, and the intersection region R_{uv} of the circles C_u and C_v as shown in Figure 3. Let p_1 and p_2 be the points of intersection of the two circles. Note that $\angle p_1 u p_2 = 2\pi/3$ and $d(u, p_1) > t_u$. By definition of CBTC, since there is a node w in every cone of angle $2\pi/3k$ around u such that $d(u, w) < t_u$, there are at least k nodes $w_1, w_2, \ldots, w_k$ in the cone confined by segments $u\bar{p}_1$ and $u\bar{p}_2$ such that $d(u, w_i) < t_u$ for each w_i. The above implies that there are k nodes in the region R_{uv}, and hence, (u, v) is not an edge in k-RNG. ■

B. Topology Control by Deletion of Nodes

In [12], Wu and Dai propose several schemes for distributed computation of connected dominating sets. The general strategy of their schemes was to delete nodes I that satisy the condition that for every pair of neighbors u and v there is a

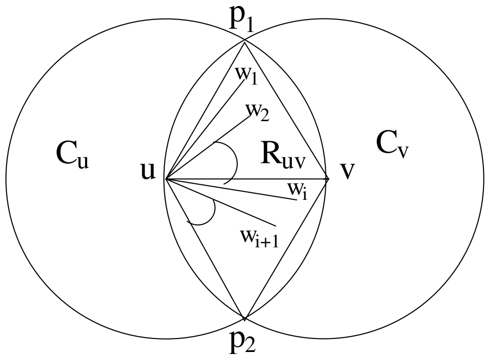


Fig. 3. Proof of theorem 2. If (u, v) is not a CBTC edge, then there are at least k nodes in the region R_{uv}.

path (called a *replacement* path) containing nodes with priority (which could be the unique node ID) higher than that of I. The above condition can be tested in a distributed and localized manner by requiring the replacements paths to exist in the d-hop neighborhood of each node I. They show that after deletion, the remaining nodes form a connected dominating set. Below, we generalize their approach to construct a k-connected dominating set in a distributed manner. In particular, we propose inactivation of a nodes I that satisfy the below defined k-delNode, and show that the set of remaining active nodes form a k-connected dominating set.[1]

Definition 8: (k-delNode condition:) A node I is said to satisfy the *k-delNode condition* if for every pair of active neighbors u and v of I, there exists k node-disjoint paths $P_1, P_2, \ldots, P_k$ containing only higher-priority (relative to I's priority) active intermediate nodes. □

Theorem 3: Given that the full-communication graph of a given set of active sensors is k-connected. After iterative inactivation of nodes that satisfy the k-delNode condition, the full-communication graph of the remaining active nodes is still k-connected. □

In work done concurrently with ours, Wu and Dai [32] have shown an even stronger result that the remaining active nodes that do not satisfy the k-delNode[2] form a k-connected k-dominating set. We refer the reader to [32] for a proof of the above theorem.

V. Voronoi-based Approach

In this section, we present a distributed and localized Voronoi-based algorithm for the variable radii k_1-connected k_2-cover problem. The geometric concept of k^{th}-order voronoi diagram and the k-connectivity preserving schemes described in section IV form the basis of our Voronoi-based algorithm. We start with some definitions.

Definition 9: (l-hop Active Neighborhood) The l-hop active neighborhood of an active node I, denoted as $N(I, l)$, is defined as the set of active nodes that are at a distance of at most l hops from I in the unweighted full-communication graph of the entire sensor network. Here, I is also included in $N(I, l)$. □

Definition 10: (k^{th}-order Voronoi Diagram/Cell/Neighbor) Given n nodes in a plane, the *k^{th}-order voronoi diagram* is defined as the partitioning of the plane into regions that have the same set of k nearest nodes [33]. The *k^{th}-order voronoi cell* of a node I is defined as the union of the regions that have I as one of their k nearest nodes. In other words, for any point p inside the k^{th}-order voronoi cell of I, there are less than k other nodes that are closer to p than I. Two nodes are called *k^{th}-order voronoi neighbors* if their k^{th}-order voronoi cells intersect or share common edge. □

Definition 11: (k^{th}-order Local Voronoi Cell/Neighbor) The *k^{th} order local voronoi cell $LV(I)$* of a node I is the k^{th}-order voronoi cell of I in the k^{th}-order voronoi diagram over the set of nodes $N(I, l)$. That is, for any point $p \in LV(I)$, there exist at most $k-1$ other nodes J in $N(I, l)$ such that $d(p, J) < d(p, I)$.

A node J is a *k^{th}-order local voronoi neighbor* of I if J is a k^{th}-order voronoi neighbor of I in the voronoi diagram over the set of nodes $N(I, l)$. Note that the k^{th}-order local voronoi neighbor relationship is not symmetric. We use $LN(I)$ to denote the set of k^{th}-order local voronoi neighbors of I. □

For any k, the k^{th}-order voronoi diagram over $N(I, l)$ can be calculated using the arrangement of planes tangent to the paraboloid above the nodes of $N(I, l)$ in time $O(|N(I, l)|^3)$ [33]. In our simulations, we use the polygon clipping method [34] to calculate the k^{th}-order local voronoi cell of I.

Note that the choice of l can affect the result of the constructed k^{th}-order local voronoi neighbor at any node. However, it is difficult to decide what value l should take. A low l can result in construction of inaccurate voronoi cells, which does not affect the correctness of our algorithm but degrades the performance. A large l can result in a high construction cost. In the experiments, l is chosen as $2S^*/T^*$, a compromise between the construction cost and the energy efficiency of the resulting sensor cover set. In the rest of the discussion, we view l as a constant to a sensor network.

The following procedure to assign radii to all the active sensor nodes form the core of our Voronoi-based algorithm.

V-R Assignment of Radii. Consider a set of active sensors A in a sensor network. The set of sensors whose maximum sensing region intersect with the given query region is M. The V-R assignment of sensing and transmission radii is as follows. Each sensor I in M is assigned a sensing radius to cover its k_2^{th}-order local voronoi cell or S^*, the maximum sensing level, if its k_2^{th}-order local voronoi cell is larger than its maximum sensing region. The transmission radius of I is assigned so as to support all the edges in the k_1-RNG graph of M. The sensors that are not in M are assigned zero sensing and transmission radius. Below, we show that the V-R assignment of radii guarantees k_1-connectivity and k_2-coverage.

Theorem 4: Given a set of active sensors A and a query region in a sensor network such that the query region is k_2-

[1]For application of the k-delNode condition to the problem addressed in this article, we do not need the dominating property of the non-deleted nodes.

[2]They refer to the k-delNode condition as the k-coverage condition.

covered by the union of the maximum sensing regions of nodes in A, the V-R assignment of sensing radii ensures k_2-coverage of the query region.

Let the set of sensors whose maximum sensing region intersect with the given query be M. If the full communication graph of M is k_1-connected, then the V-R assignment of transmission radii ensures k_1-connectivity of M.

PROOF. It is easy to see that $(V(I) \cap R_Q) \subseteq LV(I)$, where $V(I)$ is the k_2^{th}-order voronoi cell of I, R_Q is the query region, and $LV(I)$ is the k_2^{th} order local voronoi cell of I. Consider a point p in the query region, and let $\mathcal{I}_p$ be the k_2 nearest active sensor nodes to p. Now, for any $I \in \mathcal{I}_p$, $p \in V(I)$ and hence, $p \in LV(I)$. Since p is covered by the maximum sensing region of at least k_2 active sensor nodes, it is covered by the maximum sensing region of each node in $\mathcal{I}_p$, and hence, it is covered by the assigned sensing region of each node I in $\mathcal{I}_p$.

As k-RNG preserves the k-connectivity of the original graph, the V-R assignment ensures k_1-connectivity of M. ∎

Voronoi-Based Algorithm Description. The V-R assignment of sensing and transmission radii is key in the design of the Voronoi-based algorithm. Informally, the Voronoi-based algorithm works as follows. We start with all sensors in the network as active nodes, and use the V-R assignment method to assign their sensing and transmission radius. At each stage, certain sensor nodes become inactive, and the assignment of sensing and transmission radii is redone for the remaining active nodes. A sensor node is chosen to become inactive only if the remaining active sensors are capable of k_2-covering the query region and maintaining k_1-connectivity of their communication graph. We use an appropriately defined concept of "benefit" to choose the best sensor nodes to become inactive. The algorithm terminates when no more sensors can be made inactive. In the end, the set of active sensor nodes with their assigned radii form a variable radii k_1-connected k_2-cover. Formally, our proposed Voronoi-based algorithm consists of the following steps.

1) Initially, each sensor node in the sensor network is active, and gathers locations of all the nodes in the l-hop active neighborhood.
2) Each active sensor node computes its k_2^{th}-order local voronoi cell, and the neighbors in the k_1-RNG over active nodes. It uses the V-R assignment method to assign itself a sensing and a transmission radius.
3) Each node I computes its *sleeping benefit* (formally defined later), which is the decrease in the total energy cost of the "local" active sensors if I is inactivated.
4) A sensor node I is considered *removable*, if it satisfies the following two conditions.
   - Node I satisfies k_1-delNode condition.
   - The region $(LV(I) \cap \theta(I))$ is k_2-covered by the union of the maximum sensing regions of the k_2^{th}-order local voronoi neighbors of I. We show in Theorem 5 that the above condition ensures coverage of the query region, if I is made inactive.
5) If I is removable and has the most *sleeping benefit* among all its local voronoi neighbors, then I becomes inactive.
6) Go to Step 2.

The above described algorithm can be easily implemented in a distributed setting, where the communication model is reliable. To ensure correctness in an unreliable communication model, we need to add certain tedious steps as discussed in [3].

Calculating Sleeping Benefit. The calculation of sleeping benefit has been described in [3]. For completeness, we include the discussion here.

The *sleeping benefit* $B(I)$ of an active node I is defined as the decrease in total energy cost of the set of active sensors in the networks due to inactivation of the node I. More precisely,

$$B(I) = E(I) - \sum_{J \in LN(I)} (E_{new}(J) - E(J)),$$

where $E(X)$ is the current energy cost of a node X, $LN(I)$ is the set of local neighbors (local voronoi neighbors union 1-hop communication neighbors) of I, and $E_{new}(X)$ is the new energy cost of a node X after inactivation of I. Each node I is aware of the current assignment of sensing and transmission radii (and hence, the energy cost) of all its local neighbors. Thus, to compute its sleeping benefit, a node I only needs to compute the increase in sensing and transmission radii of nodes in its local neighborhood.

Based on the V-R assignment, only the local voronoi neighbors of I need to increase their assigned sensing radius when I is inactivated. The local voronoi neighbors increase their sensing radii to cover the local voronoi cell $LV(I)$ of I, and the increase in sensing radius of a local voronoi neighbor can be computed using the polygon clipping method [34]. Note that only the nodes in $N(I, 1)$ may increase their transmission radius due to inactivation of I, and the increase in transmission energy cost of the nodes in $N(I, 1)$ can be easily computed by first constructing the induced subgraphs of RNG over $N(I, 1)$, with and without I.

Coverage Guarantee. Now, we show that the above described algorithm maintains k_2-coverage of the query region, if the query region was initially k_2-covered by the active sensors. We use $\theta^*(I)$ to represent the maximum sensing region (corresponding to the maximum sensing radius S^*) of I. Also, recall that $LN(I)$ is the set of local voronoi neighbors of I. We start with a lemma.

Lemma 1: Consider the k_2^{th}-order local voronoi cell $LV(I)$ of a sensor node I. For any point $p \in LV(I)$, the line segment $\overline{pI}$ lies completely within $LV(I)$.

PROOF. Let us assume that there exists a point $q \in \overline{pI}$, such that $q \notin LV(I)$. Then there must exist a node J, such that $d(p, J) > d(p, I)$ and $d(q, J) < d(q, I)$. Now, according to triangular inequality $d(p, J) < d(p, q) + d(q, J)$, which gives $d(p, J) < d(p, q) + d(q, I) = d(p, I)$ — a contradiction. ∎

Lemma 2: Let I be an active sensor, and $\theta(I)$ be the sensing region assigned by the V-R assignment. If $LV(I) \cap \theta(I)$ is k_2-covered by $\bigcup_{j \in LN(I)} \theta^*(j)$, then $\theta^*(I)$ is also k_2-covered by

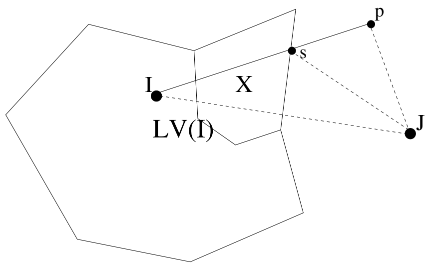


Fig. 4. Proof of lemma 2

$\bigcup_{j \in LN(I)} \theta^*(j)$. Here, $LV(I)$ is the k_2^{th}-order local voronoi cell of I.

PROOF. We show that any arbitrary point p in $\theta^*(I)$ is covered by the maximum sensing region of at least k_2 distinct sensor nodes in $LN(I)$. We consider two cases depending on whether p is in $LV(I)$.

If $p \in LV(I)$, then $p \in \theta(I)$. Thus, $p \in (LV(I) \cap \theta(I))$ and hence, is k_2-covered by $\bigcup_{j \in LN(I)} \theta^*(j)$.

Let us now consider the case when $p \notin LV(I)$. From Lemma 1, we know the line segment $\overline{pI}$ intersects the border of $LV(I)$ at only one point s, as illustrated in Figure 4. Define *subcell* as the region that has the same k_2 nearest nodes, and we denote the first subcell that $\overline{pI}$ traverses inside $LV(I)$ as X; the set of k_2 nearest nodes relating to X as N_X (note that $I \in N_X$). Because s is at the border of $LV(I)$ and X, there exists a node $J \notin N_X$ such that $d(s,J) = d(s,I)$, and thus J is in $LN(I)$ according to the definition of $LN(I)$. Hence $d(p,J) < d(p,s)+d(s,J) = d(p,s)+d(s,I) = d(p,I) \leq S^*$. Also, for any node $u \in N_X$, we know $d(s,u) \leq d(s,J)$. Thus,

$$\begin{aligned} d(p,u) &< d(s,u) + d(p,s) \\ &\leq d(s,J) + d(p,s) \\ &= d(s,I) + d(p,s) \\ &= d(p,I) \\ &\leq S^* \end{aligned}$$

Thus, p lies in the maximum sensing region of at least k_2 distinct nodes in $LN(I)$, that is, node J and the nodes in set $N_X - I$. ■

Theorem 5: Given a set of active sensors A and a query region in a sensor network, such that the query region is k_2-covered by the union of the maximum sensing regions of nodes in A, the Voronoi-based algorithm ensures k_2-coverage of the query region.

PROOF. We showed in Theorem 4 that the V-R assignment preserves the k_2-coverage of the query region. Below, we show that at any stage of the algorithm, for every point p in the query region, there are at least k_2 distinct active sensor nodes covering p using their maximum sensing region that cannot be inactivated.

Let $C(p)$ denote the set of active sensors that can cover a point p using their maximum sensing regions. Consider a point p in the query region such that $|C(p)| \geq k_2$. Let I be a sensor node in $C(p)$ such that its sleeping benefit is more than the sleeping benefit of at most $k_2 - 1$ other sensor nodes in $C(p)$. We show that the sensor node I will not be inactivated by the Voronoi-based algorithm. Let us assume the contrary that the sensor node I is inactivated, which means that $LV(I) \cap \theta(I)$ is k_2-covered by $\bigcup_{j \in LN(I)} \theta^*(j)$, and the sleeping benefit of I is maximum among all nodes in $LN(I)$. From Lemma 2, there is a set of nodes $\mathcal{H} \subseteq LN(I)$ such that $|\mathcal{H}| = k_2$ and each sensor node in $\mathcal{H}$ covers p with its maximum sensing region. Thus, $\mathcal{H} \subseteq C(p)$. Also, since $\mathcal{H} \subseteq LN(I)$, I's sleeping benefit is more than the sleeping benefit of any node in H. Thus, I's sleeping benefit is more than at least k_2 other sensors in $C(p)$, which contradicts our hypothesis. ■

K_1-Connectivity Guarantee. Theorem 3 states that removal of nodes that satisfy the k_1-delNode condition preserves the k_1-connectivity of the full-communication graph of the remaining nodes. Also, since the V-R assignment of radii preserves the k_1-connectivity, the solution returned by the Voronoi-based algorithm is k_1-connected.

A. Relaxation of Assumptions

The techniques presented above appears to use a set of idealized assumptions. We argue below how such assumptions can be relaxed and the techniques can be applied to practical cases.

Circular Sensing Range. Our Voronoi-based approach assumes that each sensor has the same circular, maximum sensing region. However, in reality, the maximum sensing regions may not be identical and they may not be circular. This may be true even when a homogenous network is used. Difference is ranges can result from noise properties, occlusion etc. In a general scenario, each sensor node has associated with it h different sensing regions (not necessarily circular) each with an associated energy cost. Our designed Voronoi-based algorithm is still applicable in this general scenario, by choosing the minimum-energy sensing region that contains the local voronoi cell at any stage.

Omnidirectional Transmission Ranges. The k-connectivity preserving topology control scheme described in section IV works under the assumption that all sensors share the same maximum transmission range in the sensor network and that the range is independent of direction. This does not hold in reality because of irregularity in the radio propagation environment and impracticality of a perfectly omnidirectional antenna, etc. However, note that in this topology control scheme, what is necessary for each sensor to make decision is only the knowledge of the existing bidirectional links within its l-hop neighborhood. This knowledge can be obtained by asking each sensor to broadcast its actual communication neighbor information within its l-hops neighborhood. It is trivial to see that theorem 3 still holds true under this situation, because the assumption of omnidirectional transmission range is not there. In order for k-RNG to preserve k-connectivity, we need to update the definition of k-RNG below.

Definition 12: (k^{th} Relative Neighbor Graph (k-RNG)) Given n nodes in a 2D plane, the k^{th} *relative neighbor graph* is the graph where an edge exists between any two nodes u, v, *iff* the communication link between u and v exists, and there exist less than k nodes, w, satisfying 1) $d(u,w) < d(u,v)$ and $d(v,w) < d(u,v)$; 2) the communication links (u,w) and (v,w) exist. □

With this updated definition of k-RNG, the proof of theorem 1 can then be used. Thus, this updated k-RNG subgraph preserves k-connectivity of the original graph.

Error Free Transmissions. To ensure correctness with unreliable communication models, some measures need to be taken in the Voronoi-based approach. We do not go into details as a similar discussion has been presented in [3] for the variable radii 1-connected 1-coverage problem. The basic idea is, 1) require positive confirmation before a node enters sleeping mode; 2) underestimate $N(I,l)$ in V-R assignment, and making sleeping decision.

B. Comparison with Other Approaches with a Performance Bound

The Voronoi-based approach is localized and distributed; but it presents a heuristics. An approximation algorithm for the VRKCKC problem remains an open problem. However, it is possible to generalize the centralized greedy algorithm in [3] to construct a variable radii 1-connected k-cover sensor set within $O(r \log hn)$ factor of the optimal energy cost, where r is the link radius (the maximum communication distance between any two sensors whose sensing regions intersect) of the network, h is the total number of sensing radius choices available to a sensor node. An extended version of this paper [35] includes the necessary arguments. This algorithm can be distributed. Still, performance comparisons in [35] shows that the Voronoi-based approach compares favorably for this 1-connected k-cover case.

VI. Performance Evaluation

We built a specific simulator for the distributed algorithms, and carried out experiments to evaluate the performance of the proposed algorithms. The simulator randomly places sensors within a given region. The simulator does not model any link layer protocol or wireless channel characteristics. Thus, all messages in the simulator are transmitted in an error-free manner. While such a simulator models an idealized communication subsystem, it is sufficient for our purpose of comparing the performance of our proposed algorithms.

Cost Model. The sensing energy cost function depends on the specific sensor type and environment, but is usually of the form $S(I)^x$, where $S(I)$ is the assigned sensing radius and x is a constant [36]. Similarly, the transmission energy cost function is of the form $T(I)^y$, where $T(I)$ is the assigned transmission radius and y is a constant between 2 to 4 [16]. For our experiments, we chose $x = y = 4$. We assume that total energy cost incurred (sensing and transmission) in keeping a sensor node active for a unit time is:

$$E(I) = \alpha S(I)^4 + (1-\alpha)T(I)^4 + C,$$

where α is a parameter that signifies relative weight of sensing and transmission energies, and C is a constant signifying a constant cost of keeping the sensor node active. In our experiments, we use three different values of α viz. 0.1, 0.5, and 0.9 to simulate different sensor types. For example, when α is 0.1, the energy consumption due to sensing is relatively much less than the energy consumption due to transmission. We measure the performance of our algorithms for all these three energy cost models.

Network and Battery Parameter Values. We run our experiments with the following choice of parameter values. The maximum sensing radius S^* as well as the maximum transmission radius T^* for each sensor node is chosen to be 10. Each sensor can choose from 5 different sensing and transmission radii: 2, 4, 6, 8, or 10. We randomly distribute a certain number of sensor nodes in a query region of size 50×50. The total size n of sensor network is varied between 150 to 600, representing sensor networks of varying sparsity, from very sparse (barely connected) to very dense. In our experiments, we set each sensor node's battery power as 12,000,000 units, and the constant C in the energy cost function is set at 2,000 units. If the sensing and transmission radii of a sensor node are set to the maximum (10), the total energy cost incurred in keeping the node active for a unit time is 12,000 units. In a naive approach wherein all sensor nodes are kept active with maximum sensing and transmission radii, the sensor network will last for 1,000 time slots, for any value of α. During the construction phase , the energy cost incurred in transmitting a message is proportional to the size of the message. We assume that an active sensor transmits 100 bytes of data in unit time; thus, the energy cost incurred in transmitting a message of size ℓ bytes during the construction phase is $(1-\alpha)10^4\ell/100$ (note that during the construction process, maximum transmission range is used). This indicates that even for the same construction process, more energy is consumed on sensor networks with smaller value α.

We measure the effectiveness of the Voronoi-based approach by comparing it with three other heuristics.

1) COMPLETE_KCONE – This is a straightforward method to address this problem. All sensors keep active. V-R assignment in Section V is used to assign sensing radii; Cone based topology control [18] is used to assign transmission radii.
2) COMPLETE_KRNG – All sensors keep active. V-R assignment in Section V is used to assign sensing radii; k-RNG is used to assign transmission radii. By comparing COMPLETE_KRNG with COMPLETE_KCONE, we show the effectiveness of k-RNG over CBTC.
3) SLEEPING_FIXED – In this method, the sleeping benefits are calculated and nodes are turned inactive in the same way as in the Voronoi-based approach. The only difference is that the radii are fixed. All combinations of possible sensing and transmission radii are tried in this experiment, while the best result among them is picked.

In the Voronoi-based approach, to save communication costs, we estimate sleeping benefit $B(I)$ of a node I using only the local k^{th} voronoi diagram of I (i.e., we assume that I has the same k^{th} local voronoi diagrams as its local voronoi neighbors).

We have conducted two sets of experiments. The first set of experiments is to compare the performance of the various algorithms in terms of the total energy cost of the 3-connected 2-cover sensor set delivered by the algorithms. The experiment results are presented in Figure 5. In the second set of experiments, we compare the performance of these algorithms in terms of their effectiveness in prolonging the sensor network lifetime.

Energy Cost of the Sensor Cover. In Figure 5, we present the energy cost of the 3-connected 2-cover returned by the algorithms for varying network density. Naive scheme of keeping all the sensors active using maximum transmission and sensing power is not presented in these figures. As we pointed out, the cost of this naive scheme is simply $12000 * n$, a much larger number than any of the shcemes we present here. We can see that the Voronoi-based approach delivers the most energy-efficient solution as expected.

COMPLETE_KCONE and COMPLETE_KRNG keep all sensors active, so their solutions incur more energy cost than Voronoi-based approach. This is particularly true, when the network density is high. Between these two non-sleeping schemes, COMPLETE_KRNG is consistently more energy efficient than COMPLETE_KCONE. Because they both keep all the sensors active while employing the same scheme in assigning sensing radii, this saving in energy cost for COMPLETE_KRNG over COMPLETE_KCONE is purely from transmission power control, resulting from Theorem 2. We can see that as the relative weight of transmission cost increases (α decreases), the difference between COMPLETE_KRNG and COMPLETE_KCONE grows rapidly.

SLEEPING_FIXED performs better than COMPLETE_KRNG when the network density is relatively high, in which case, a significant part of sensors can be put to sleeping and thus energy cost can be saved. While this saving is less obvious when the network density is low. When the network density is low, a much less percentage of sensors can satisfy the sleeping condition. As a result, both COMPLETE_KRNG and SLEEPING_FIXED have similar number of active sensors. In this situation, COMPLETE_KRNG shows superior performance over SLEEPING_FIXED because of the elaborate power control scheme it employed. This explains the crossover of the performance trends of the two schemes in the figures.

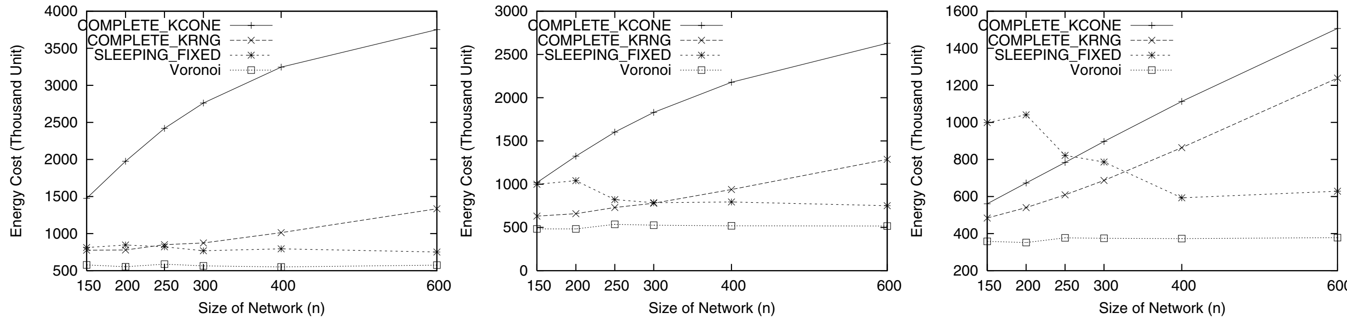
Note that the results shown here for SLEEPING_FIXED are the best one picked from all combinations of available transmission and sensing radii levels. Still, our Voronoi-based approach still consistently beats these best fixed radii results. This demonstrates the need for adaptive ability to control transmission and sensing ranges for energy conservation.

Network Lifetime: We run these algorithms to generate a 3-connected 2-cover, which remain active until some sensor dies. Then in COMPLETE_KCONE and COMPLETE_KRNG, the neighboring nodes reassign their sensing and transmission ranges to compensate for this; while in Voronoi-based approach and SLEEPING_FIXED, the dying sensor awakens its neighboring sleeping sensors to sustain the 3-connected 2-cover. The awakening of the sleeping sensors can be done in a local manner, which is similar to [3]. As mentioned before, employing the naive method, the network can last 1000 units of time under our settings. In Figure 6, we see that the energy efficiency exhibited in the connected sensor cover set really leads to a prolonged network lifetime. Again, Voronoi-based approach prolongs the network lifetime more effectively than all the others. COMPLETE_KCONE exhibits worst network lifetime than the others, which can be explained by the fact that its generated sensor cover incurs signifcantly more energy cost than the others. Again, COMPLETE_KRNG and SLEEPING_FIXED show a similar trend as in the previous set of experiments on energy cost. When the network is sparse, COMPLETE_KRNG is better; while when the network is dense, SLEEPING_FIXED shows better performance. Also, we can see Voronoi-based approach performs well in exploiting the network redundancy. It greatly improves the network lifetime as the network size (redundancy) grows.

VII. Conclusions

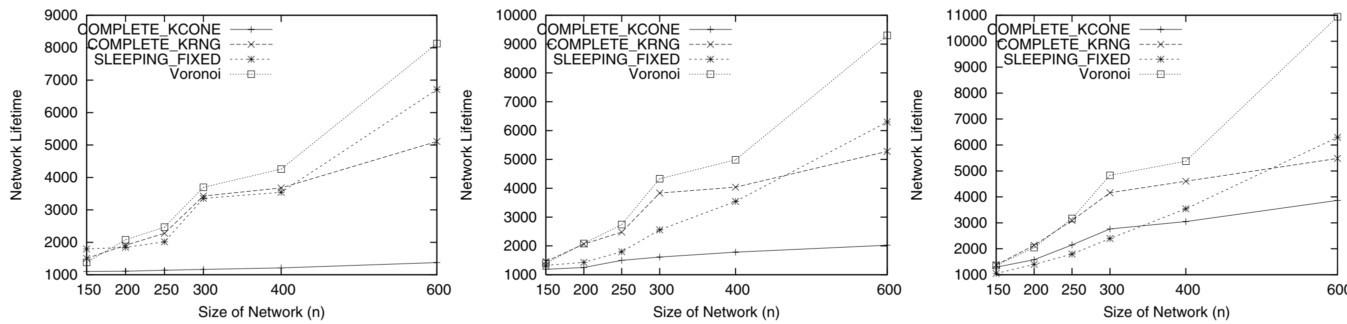
In this paper, we have addressed the problem of building a minimum-energy fault-tolerant connected sensor cover in a sensor network in the most general form. The cover is formed by choosing a subset of sensor nodes to keep active and also adjusting their transmission and sensing ranges to an appropriate value. The goal is to form a k_1-connected network of sensor nodes that is also able to provide a k_2 coverage, and does this with a minimum energy. The energy model assumes that the energy expended by each sensor node is sum of three components: a constant component modeling the cost of keeping the sensor node alive, a transmission power component that is a non-decreasing function of the transmission range, and a similar sensing power component. This very general modeling of a sensor network's coverage and connectivity is a contribution in this paper.

We propose a distributed and localized Voronoi-based algorithm to solve the above variable radii k_1-connected, k_2-coverage problem. The approach derives leverage from the new notion of the k-RNG structure that is a generalization of the well-known RNG structure. A distributed technique is used to inactivate desirable nodes while preserving k-connectivity of the remaining nodes. A set of simulations on random sensor networks demonstrates the superiority of this technique relative to other, simpler techniques for energy conservation, including a technique that uses fixed transmission and sensing ranges, but considers the best among all possible assignments. While the evaluations have been done in a set of idealized conditions, we present arguments that our technique applies to environments where sensing and transmission ranges are irregular and communication model is not error-free.



(a) $\alpha = 0.1$ (b) $\alpha = 0.5$ (c) $\alpha = 0.9$

Fig. 5. Total energy cost of 3-connected sensor 2-cover delivered by various algorithms for various network size.



(a) $\alpha = 0.1$ (b) $\alpha = 0.5$ (c) $\alpha = 0.9$

Fig. 6. Sensor network lifetime (3-connected 2-cover) for various distributed algorithms.

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