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Location-free Coverage Maintenance in Wireless Sensor Networks

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Sensing coverage maintenance is concerned with providing coverage to a targeted region with prolonged system lifetime by utilizing redundant deployment of sensor nodes. Most existing approaches to coverage maintenance require knowledge of accurate location information. In this paper, we propose a novel location-free coverage maintenance scheme in wireless sensor networks that exploits power control and radio connectivity information in constructing sparse structures in wireless sensor networks. Our solution is based on the solid theoretical basis of the coverage property of minimal dominating sets derived in this paper. Extensive simulation studies show that the proposed location-free coverage maintenance protocol can indeed provide comparable coverage with similar or even less working nodes as compared to location-based solutions. Meanwhile, it is robust to non-uniform node density, inaccuracies in transmission range control and heterogeneity in sensing ranges.

Index Terms

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I. Introduction

Recent technological advances have led to the emergence of small, low-power devices that integrate sensors and actuators with limited on-board processing and wireless communication capabilities. Pervasive networks of such sensors and actuators open new vistas for many potential applications, such as battlefield surveillance, environment monitoring and biological detection. One critical measure of the quality of sensing (QoS) of a wireless sensor network (WSN) is its coverage, i.e., "how well do the sensors observe the physical space". As pointed out in [14], the definition of coverage is application-dependent. In this paper, we are particularly interested in maintaining the coverage of a target region, termed *area coverage*.

Due to the unreliability and limited battery power of wireless sensor nodes, it is often desirable to deploy them in massive quantity to ensure good coverage. Furthermore, due to the limited accessibility of the target region it is sometimes difficult or impossible to place sensors at ideal locations. This makes coverage maintenance, i.e., judiciously selecting a subset of functioning nodes (also called *working set*) to monitor the environment (and powering off the rest), a critical problem in prolonging the network lifetime of WSNs. Existing algorithms [3], [20], [22], [23], [25], [26] in maintaining area coverage usually rely on the availability of accurate location information. Such information is often difficult to obtain in low-end systems. For example, the accuracy of low-end solutions such as commercial GPS systems is on the order of 3m while high-end solutions such as those using ultra-wide band radio cost over $10,000 [21] even in small-scale deployment.

In this paper, we pose a seemingly improbable question, i.e., "*Can we maintain sensing coverage without knowledge of node location?*" We show through rigorous analysis and experimental study that the answer is positive. The novelty of our solution lies in the exploitation of power control and radio connectivity information in constructing sparse structures in wireless sensor networks. Though wireless connectivity has been considered in literature to construct logical or absolute coordination space based on hop count distances to anchor nodes with known locations [2], [4], accuracy of the proposed localization methods is often low and insufficient for

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coverage maintenance purposes: i) distance measurement using radio connectivity is in general coarse-grained and ii) geometric embedding of relative distance graph is often not unique [16].

One extensively investigated sparse structure in multihop wireless networks is (connected) dominating set ((C)DS). Much work has been done to devise distributed algorithms [1], [12] to construct minimal (connected) dominating set with different objective functions. Our solution to location-free coverage maintenance is based on the observation that minimal dominating sets provide coverage of points in an area (termed *point coverage*) when the sensing range equals the transmission range. However, point coverage is in general not equivalent to area coverage. Through rigorous analysis, we derive lower bound of the coverage of minimal dominating sets for arbitrary combination of sensing and transmission ranges. Furthermore, for random geometric graphs, we establish sufficient and necessary conditions that point coverage is equivalent to area coverage. Based on the theoretical results, we propose a coverage maintenance protocol that incorporates existing minimum dominating set (MDS) selection algorithms to determine the set of functioning nodes and demonstrate its effectiveness through extensive simulations. Our simulation study shows that the proposed location-free coverage maintenance protocol can indeed provide comparable coverage with similar or even less working nodes as compared to location-based solutions. Furthermore, the proposed protocols are shown to be robust to non-uniform node density, inaccuracies in transmission range control, and heterogeneity in sensing ranges.

Our contributions in this paper can be summarized as:

- We provide a rigorous analysis of the coverage property of minimal dominating set. To the best of our knowledge, this is the first work that establishes the connection between point coverage and area coverage in geometric graphs.
- We propose a location-free coverage maintenance protocol using the concept of dominating sets. When incorporated with different DS selection algorithms, the proposed protocol can be potentially tailored to achieve different optimization goals in coverage maintenance.

The rest of the paper is organized as follows. In Section II, we present a review of related work in coverage maintenance. We establish the analytical results on coverage property of minimal dominating sets in Section III. A location-free coverage maintenance protocol is proposed and evaluated in Section IV and Section V, respectively. Finally, we conclude the paper with a list of future work.

II. Related Work

Based on coverage requirements, existing coverage algorithms can be categorized as those which provide area coverage, point coverage and barrier coverage [5]. As their names suggest, the objective of area coverage and point coverage is to cover a region (area) and points in a region, respectively. Barrier coverage, on the other hand, targets to minimize the probability of undetected penetration through the barrier [13]–[15]. For example, Meguerdichian *et al* [14] have considered the problem of determining a maximal breach path and the maximal support path of the agent. In what follows, we will focus on area coverage algorithms that are most pertaining to our work.

Location-dependent coverage maintenance approaches: Slijepcevic *et al.* [19] address the problem of finding the maximal number of covers in a sensor network, where a cover is defined as a set of nodes that can completely cover the monitored area. They prove the NP completeness of this problem, and provide a centralized heuristic solution. They show that the proposed algorithm approaches the upper bound of the solution under most cases. It is, however, not clear how to implement the solution algorithm in a distributed manner. Berman *et al.* [3] consider the problems of power efficient monitoring in sensor networks. They devise an efficient data structure to represent the monitored area with at most n^2 points guaranteeing the full coverage which is superior to approaches based on grid points. An efficient provably good centralized algorithms for sensor monitoring schedule is proposed which maximizes the total lifetime including a $(1 + ln(1 + q)^{-1})$-approximation algorithm for the case when a q-portion of the monitored area is required to cover.

Tian *et al.* [20] propose an algorithm that provides complete coverage using the concept of sponsored area. In this algorithm, whenever a sensor node receives a packet from one of its working neighbors, it calculates its sponsored area (defined as the maximal sector covered by the neighbor). If the union of all the sponsored areas of the sensor node covers the whole disk covered by itself, the node turns itself off.

In the rest of this paper, we use *coverage* to denote *area coverage* unless otherwise noted.

Zhang *et al.* [26] study the relationship between sensing coverage and connectivity. They prove that if the communication range is at least twice the sensing range, a complete coverage of a convex area implies connectivity of the working nodes. Furthermore, the authors propose a distributed, localized algorithm called optimal geographical density control (OGDC) to determine the set of nodes who should be active for sensing tasks. In OGDC, a node can be in one of three states: UNDECIDED, ON and OFF. The algorithm runs in rounds, and at the beginning of each round a set of one or more starting nodes are selected as working nodes. After a back-off time, a starting node broadcasts a power-on message and changes its state to ON. When a node receives a power-on message, it checks whether its neighbors cover its sensing area, and if so, it will change to OFF state. A node decides to change into the ON state if it is the closest node to the optimal location of an ideal working node selected to cover the crossing points of the coverage areas of two working neighbors.

All the above algorithms require location information. They mainly differ in the algorithm complexity and size of the resulting working set.

Location-free coverage maintenance attempts: Ye *et al.* [25] present PEAS, a distributed, probing based density control algorithm for robust sensing coverage. In this work, a subset of nodes operate in the active mode to maintain coverage while others are put into sleep. A sleeping node wakes up occasionally to check if there exist working nodes in its vicinity. If no working nodes are within its probing range, it starts to operate in the active mode; otherwise, it sleeps again. At any time instance, the working nodes form a dominating set of a graph where an edge exists between two nodes if their distance is less than the probing range. The probing range can be adjusted to achieve different levels of coverage redundancy. The algorithm guarantees that the distance between any pair of working nodes is at least the probing range, but does not ensure that the coverage area of a sleeping node is completely covered by other nodes.

The problem of finding dominating sets in a graph has been extensively studied in literature [7], [12] and applied in the context of ad hoc routing and connectivity management [1], [8], [18]. It has been suggested in [5] that CDS can be used *directly* as an approximation for area coverage. However, it is unclear how good such an approximation is and how to decide protocols that provide full coverage using CDS. We will show in Section V that using CDS for coverage maintenance is not energy-efficient and does not have significant gain in coverage.

III. Coverage Property of Minimal Dominating Set

In this section, we derive the coverage property of minimal dominating sets and compare it with the coverage of the original set of nodes. It is worth noting that the analytical results obtained here are general to all *MDS* selection algorithms.

A. Preliminaries

Consider n nodes on a 2-D plane $\mathbb{R}^2$ represented by a undirected geometric graph $G(V, E)$, where V is the vertex set and E is the edge set. If a node u is within the maximum transmission range t_{max} (associated with the maximum transmission power) of another node v, then an edge (u, v) is in E. The neighboring set of a node v is denoted by $N(v)$. We call a subgraph $G_{\mathcal{P}}$ a realization of $G(V, E)$ for a transmission power matrix $\mathcal{P}$. $\mathcal{P}$ is an $n \times n$ symmetric matrix. $p_{uv} = p_{vu} \leq P_{max}$ is the transmission power between nodes u and v. Symmetry is required to ensure bidirectionality of the links. In the analysis, we consider the special case that $p_{uv} = p_{vu} = const$, $\forall u, v \in V$. Thus, the $G_{\mathcal{P}}$ is determined by a single value, i.e. the transmission range radius t, simplified as G_t. Clearly, if $t_2 > t_1$, $G_{t_1} \subseteq G_{t_2}$.

A dominating set of an undirected graph G is a subset S of the vertex set V such that every vertex in $V - S$ is adjacent to a vertex in S [11]. A minimal dominating set of a graph G is a dominating set which ceases to be a dominating set if any vertex is removed from it. We assume the sensing range of a sensor node is modeled by a disk of radius s (called *disk model*). Under the disk model, a point p on the plane is covered if and only if there exists at least one node in V within its s radius. The sensing range s of a sensor is in general determined by the sensitivity of its sensing component, geometric and surface property of the environment, and nature of the event sources. For the ease of analysis, we assume isotropic sensors, i.e., the sensing range is a constant among all nodes. However, the location-free coverage maintenance protocol we propose in later section does not require such a restrictive condition.

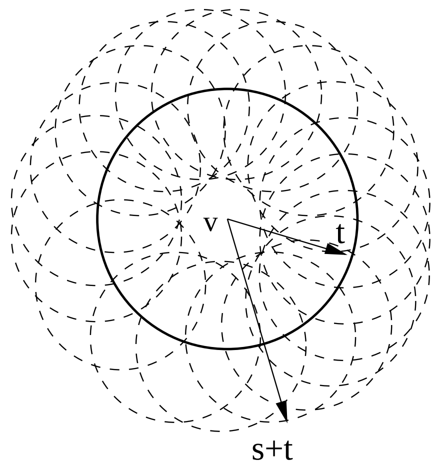


Fig. 1. Tightness of the lower bound of MDS coverage. There are infinite number of nodes on and inside the ring centered at v and with radius of t. Node v is chosen as the dominator.

B. A Lower Bound of Coverage on General Geometric Graphs

In this section, we first give a lower bound of coverage by minimal dominating sets in a general geometric graph. Given sensing range s, let $\mathcal{A}_V(s)$ be the geometric area covered by all nodes in V and $\mathcal{A}_{MDS}(s)$ be the geometric area covered by a minimal dominating set MDS. We use $A_V(s)$ and $A_{MDS}(s)$ to denote the corresponding size of the geometric areas respectively (termed *numeric areas*).

The key result is as follows.

Theorem 1: Let the transmission range and sensing range be t and s respectively.

$$\frac{A_{MDS}(s)}{A_V(s)} \geq \frac{s^2}{(s+t)^2} \quad . \tag{1}$$

Before delving to the proof, we first show this lower bound is tight for sparse graphs. An example is given in (Fig. 1) with node v and infinite number of nodes on and inside the circle centered at v of radius t. Node v is chosen as the dominator. The ring between two co-centric circles of radius t and $t+s$ is not covered by v. Consequently, the equality in Eq. (1) holds.

Although the lower bound appears to be somewhat intuitive, the proof is a little involved. It is motivated by the work by Cheng and Edelsbrunner [6] on the area and perimeter derivatives of a union of disks. We first introduce a few notations and lemmas.

Let B_i be a disk centered at a point $z_i \in \mathbb{R}^2$ with radius r_i, $i = 1, \ldots, n$. The power distance of a point $x \in \mathbb{R}^2$ from B_i is defined as $\pi_i(x) = ||x - z_i||^2 - r_i^2$. Thus, the bounding circle P_i consists of all points with zero power distance from B_i. The bisector of two disks is the line of points with equal power distance to both. Define $B_i^j = \{x \in \mathbb{R}^2 | \pi_j(x) \leq \pi_i(x) \leq 0\}$, which is the portion of B_i on B_j's side of the bisector. Let P_i^j and P_i^{jk} be the lengths of the circle arcs in the boundaries of B_i^j and $B_i^j \bigcap B_i^k$ (as illustrated in Figure 2).

Let $\mathbf{r} = [r_1, r_2, \ldots, r_n]$ and $\mathbf{z} = [z_1, z_2, \ldots, z_n]$ denote vectors of disk radii and positions of centers, respectively. The numeric area of the union of n disks $A_{\mathbf{r}}$ is a function of the placement of the disks as well as their radii. The area derivative of the union of disks characterizes the variation of the numeric area with respect to *motion* (changes in $\mathbf{z}$) and *growth* (changes in $\mathbf{r}$). The following result is a simplified version of the area derivative theorem by Cheng and Edelsbrunner [6] when only growth of the radii is considered.

Theorem 2 (Area Derivative Theorem): Assume disks are at general positions, i.e., none of four centers co-circle. The derivative of the (numeric) area of a union of n disks with radius vector $\mathbf{r}$ is $DA_{\mathbf{r}} = 2\pi\sigma$, where $\sigma_i = 1 - (\sum_j P_i^j - \sum_{j,k} P_i^{jk})/2\pi r_i$, $i = 1, 2, \ldots, n$.

In Theorem2, σ_i characterizes the contribution of disk B_i's boundary to the perimeter of $A_{\mathbf{r}}$. In particular, if a disk does not share boundary with $A_{\mathbf{r}}$ (i.e., is fully contained inside $A_{\mathbf{r}}$), then $\sigma_i = 0$.

Fact 1: For a differentiable map $f : R^m \to R$, the derivative at a point $\overline{x} = \{x_1, x_2, \ldots, x_m\} \in R^m$ is a linear map $Df_m : R^m \to R$. Let $g(x) = f(\overline{x})$ and $x_i = x, i = 1, 2, \ldots, m$. Then, $\frac{dg(x)}{dx} = \sum_i \frac{\partial f}{\partial x_i}|_{x_i = x}$.

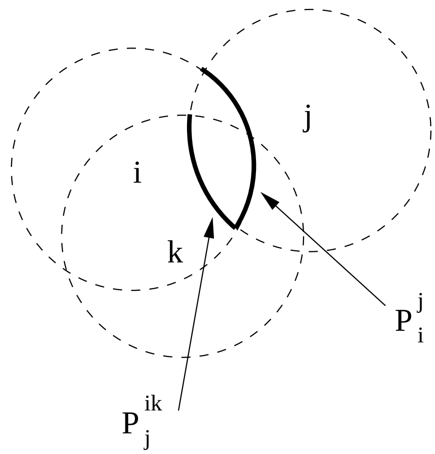


Fig. 2. Union of disks. P_i^j and P_j^{ik} are the lengths of the circle arc in the boundaries of B_i of B_j's side of the bisection and the arc on B_j segmented by the bounding circle of B_i and B_k.

Combining Theorem 2 and Fact 1, when $r_i = r$, $i = 1, \ldots, n$, we have the following lemma.

Lemma 1: Let A_r be the numeric area of the union of n disks with common radius r on a plane. Its derivative with respect to r is given by $A'_r = \sum_i 2\pi r\sigma_i$, where $\sigma_i = 1 - (\sum_j P_i^j - \sum_{j,k} P_i^{jk})/2\pi r$.

Lemma 2: For a differentiable function $g : R^+ \to R^+$, if $g'(x) \leq \frac{2g(x)}{x}$, $\forall x \in R^+$, then

$$\frac{g(x_1)}{g(x_2)} \leq \frac{x_1^2}{x_2^2}, \;\; 0 < x_2 \leq x_1 \in R^+. \tag{2}$$

Proof: Since $g'(x) \leq \frac{2g(x)}{x}$ and $g(x)$ is positive for $x > 0$, we have

$$\frac{g'(x)}{g(x)} = (ln(g(x)))'_x \leq \frac{2}{x}.$$

Integrate both sides of above equation from x_2 to x_1, we have

$$ln(\frac{g(x_1)}{g(x_2)}) \leq 2ln(\frac{x_1}{x_2}),$$

therefore, $\frac{g(x_1)}{g(x_2)} \leq \frac{x_1^2}{x_2^2}$, $0 < x_2 \leq x_1 \in R^+$.

■

Lemma 3: Consider two disks B_i and B_j of radius r_i and r_j centered as z_i and z_j respectively. Let S_i (S_j) be the sector defined by the arc $P_i - P_i^j$ ($P_j - P_j^i$) and the line segments that join the two end points of the arc and its center. Then

$$Area(S_i \cap S_j) = 0.$$

Proof: If $B_i \cap B_j = \emptyset$ ($\emptyset$ is an empty set), $P_i^j = P_j^i = \emptyset$ and thus $S_i = B_i$, $S_j = B_j$. Clearly the result holds.

If $B_i \cap B_j \neq \emptyset$, the bisector separates $B_i \cup B_j$ into two parts, i.e., $B_i - B_i^j$ and $B_j - B_j^i$ which intersect at the bisector. Since $S_i \subseteq B_i - B_i^j$ and $S_j \subseteq B_j - B_j^i$, S_i and S_j only intersect at the bisector. The result holds.

■

Now we are in the position to prove Theorem 1.

Proof: (Theorem 1) Consider a dominator node u. The numeric area covered by u is πs^2. Let D_u be the set of nodes that are dominated by u including u itself. A point p is covered by nodes in D_u only if p is within $s + t$ from u (note that the reverse does not always hold). Therefore, the maximum possible geometric area covered by D_u is a disk centered at u of radius $s + t$. Therefore, the ratio between the numeric areas covered by u and D_u is at most $\frac{s^2}{(s+t)^2}$.

By definition of the dominating set, we have $\bigcup\limits_{u \in MDS} D_u = V$.

There are two cases:

Case 1: None of the coverage area of the nodes in MDS overlap. Summing up coverage area of all the dominators, we have

$$A_{MDS} = Area\left(\bigcup_{u\in MDS} B_u(s)\right) = |MDS|\cdot \pi s^2. \tag{3}$$

On the other hand,

$$A_V \leq Area\left(\bigcup_{u\in MDS} B_u(s+t)\right) \leq |MDS|\cdot \pi (s+t)^2. \tag{4}$$

Combining Eq. (3) and (4), we get

$$\frac{A_{MDS}}{A_V} \geq \frac{s^2}{(s+t)^2} \ .$$

Case 2: The coverage area of some nodes in MDS overlap. Let the cardinality of MDS, $|MDS| \triangleq m$. Let v_i and B_i, $i=1,\dots,m$ be the nodes in MDS and disks centered at v_i with radius s. Then, $A_{MDS}(s) = Area(\mathcal{A}_{MDS}(s)) \triangleq A_s$ while $A_V \leq Area(\mathcal{A}_{MDS}(s+t)) \triangleq A_{s+t}$. Therefore, to prove $\frac{A_{MDS}}{A} \geq \frac{s^2}{(s+t)^2}$, it is sufficient to show $\frac{A_s}{A_{s+t}} \geq \frac{s^2}{(s+t)^2}$.

Instead of deriving the relationship between A_s and A_{s+t} directly, we study the growth of $A_r \triangleq |\bigcup_{i=1}^{i=m} B_i(r)|$ with respect to r, i.e., the total area occupied by disks B_i of radius r, $i=1,\dots,m$. Our goal is to prove that $\forall$ $r_1 > r_2$, $\frac{A_{r_1}}{A_{r_2}} \leq \frac{r_1^2}{r_2^2}$. By Lemma 2, it is sufficient to show that the derivative A_r' is no bigger than $\frac{2A_r}{r}$, $\forall r>0$.

From Lemma 1, we have

$$A_r' = 2\pi r\sum_i \left(1-(\sum_j P_i^j - \sum_{j,k} P_i^{jk})/2\pi r\right). \tag{5}$$

The term $\sigma_i = 1-(\sum_j P_i^j - \sum_{j,k} P_i^{jk})/2\pi r$ gives the portion of the perimeter of B_i that is at the boundary of $\mathcal{A}_r$. Let $S_{i,l}$, $l=1,\dots,m_i$ be the set of sectors defined by the arc segments of P_i at the boundary of $\mathcal{A}_r$ and the line segments that join the end points of the arc segments and their centers. Therefore,

$$\pi r^2\sigma_i = \sum_{l=1}^{m_i} Area(S_{i,l}) = Area(\bigcup_{l=1}^{m_i} S_{i,l}).$$

From Lemma 3, $\forall i,j,l,l'$, $Area(S_{i,l}\cap S_{j,l'}) = 0$ or equivalently, $Area(S_{i,l}) + Area(S_{j,l'}) = Area(S_{i,l}\cup S_{j,l'})$ (since $S_{i,l}\subseteq S_i$). Therefore,

$$\begin{aligned} & A_r'\cdot r/2 \\ = & \sum_{i=1}^{m} \pi r^2 \sigma_i \\ = & \sum_{i=1}^{m}\sum_{l=1}^{m_i} Area(S_{i,l}) \\ = & Area(\bigcup_{i=1}^{n}\bigcup_{l=1}^{m_i} S_{i,l}) \\ \leq & A_r. \end{aligned}$$

The last inequality is due to $\bigcup_{i=1}^{n}\bigcup_{l=1}^{m_i} S_{i,l} \subseteq \bigcup_{i=1}^{n} B_i$. Thus, $A_r' \leq \frac{2A_r}{r}$. ■

From Theorem 1, we can see as long as t is significantly small, MDS can provide comparable coverage as that of V. This is intuitively true. In general, as t goes smaller, the adjacent matrix becomes sparser (recall that if $t_1 < t_2$, $G_{t_1} \subseteq G_{t_2}$). The size of the dominating set of G_t tends to increase and so does its coverage. As an example, consider the case when $t=\xi$, where ξ is an arbitrarily small positive number. The off-diagonal entries of the adjacent matrix of G_t are all zero, i.e., $|E|=0$. Therefore, $MDS(G_t) = V$ and $A_{MDS} = A$ entails.

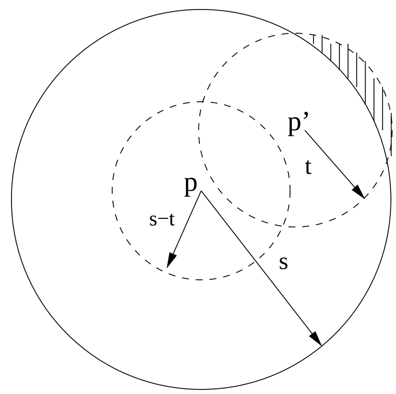


Fig. 3. Considerations to tighten the sufficient condition. If there is no node in the shaded area, p is covered.

C. Random Geometric Graph

Note that the above lower bound can be mainly attributed to the boundary effect in a sparse graph. In particular, unless nodes at the boundary are selected in MDS, MDS can never provide the same coverage as the original set. To remove the artifact at the boundary, we consider nodes are distributed in a square region R of edge length l following the torus convention, i.e., each disk that protrudes one side of the region R enters R again from the opposite side.

Sufficient Condition: First, we investigate a sufficient condition for MDS to achieve good sensing coverage. Intuitively, the denser the nodes are, the better coverage the minimal dominating set can provide. This is because MDS needs to dominate all the nodes. If the nodes are densely distributed, almost all points in the plane are within the transmission range of at least one node in MDS.

Theorem 3: Suppose nodes v, $\{v \in V\}$ follow Poisson point process of density (rate) ρ in R. For $\forall \epsilon > 0$ and a point $p \in A_V$, where A_V is the area covered by all nodes in V with sensing range s. Then, there $\exists r$ s.t. $P\{\exists u \in MDS \text{ and } d_{u,p} \leq r + t\} \geq 1 - \epsilon$.

Proof: Consider an arbitrary point p. A sufficient condition that p is within $r + t$ distance from a dominator is that there is a node u within r distance from p. Otherwise, u is not dominated. Since nodes follow a Poisson point process with density ρ, the following equality holds,

$$P\{\exists u \text{ s.t. } d(p,u) \leq r | p \in A\} = \begin{cases} 1 & \text{if } r \geq s \\ \frac{1-e^{-\pi\rho r^2}}{1-e^{-\pi\rho s^2}} & \text{if } r < s \end{cases}$$

From the sufficient condition,

$$\begin{aligned} & P\{\exists v \in MDS \text{ s.t. } d_{v,p} \leq r + t | p \in A\} \\ \geq \quad & P\{\exists u \in V \text{ s.t. } d_{u,p} < r | p \in A\} \\ = \quad & \begin{cases} 1 & \text{if } r \geq s \\ \frac{1-e^{-\pi\rho r^2}}{1-e^{-\pi\rho s^2}} & \text{if } r < s \end{cases} \end{aligned} \tag{6}$$

Therefore, $\forall \epsilon$, let $r = min(s, \sqrt{\frac{-log(\epsilon + e^{-\pi\rho s^2} - \epsilon e^{-\pi\rho s^2})}{\pi\rho}})$ and the above inequality holds as $\rho \to \infty$, $r \to 0$. ■

Immediately from Theorem 3, we have the following result.

Corollary 1: Suppose nodes $v, \{v \in V\}$ follow Poisson point process of rate ρ in R. $\forall \epsilon$, let

$$t = s - min(s, \sqrt{\frac{-log(\epsilon + e^{-\pi\rho s^2} - \epsilon e^{-\pi\rho s^2})}{\pi\rho}}, \tag{7}$$

any minimal dominating set of G_t (recall that G is a subgraph of G induced by transmission range t) provides the same coverage as that of V with probability *at least* $1 - \epsilon$.

Corollary 1 can be directly applied to select dominating sets with probabilistic coverage guarantee. However, we find through the experiments in Section V that the estimation of transmission ranges given by Eq. (7) is often too

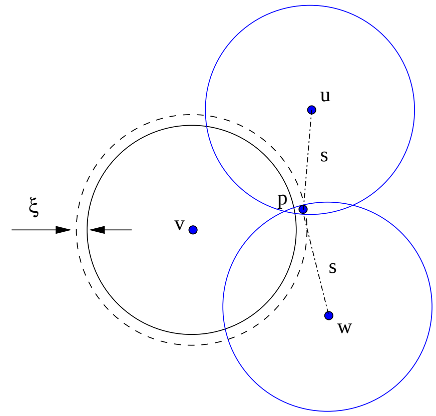


Fig. 4. Illustration of the necessary condition.

conservative. This is due to the sufficient condition we use is loose. There are two main factors that contribute to the looseness of the results:

- The above proof only utilizes the general property of dominating sets and does not account for the specifics of individual dominating set algorithms. Considerations of specific dominating set algorithms would sacrifice the extensibility to other algorithms that are available or will become available over time.
- Transmission range in Eq. (7) can be further increased by taking into account of the geometry of node distribution but the computation is far more cumbersome and does not have close-form solution. For example, in Figure 3, there exists a node p' outside the disk centered at p with radius $s-t$. Then, a sufficient condition for $p \in \mathcal{A}_{MDS}(s)$ is that the shaded area is void (and thus p' itself is a dominator or dominated by some nodes inside the disk with radius s). Deriving numerical approximation to tighten the sufficient condition will be part of our future work.

Necessary Condition: Now, we derive a necessary condition that the transmission range needs to satisfy in order for the resulting dominating set to provide the same coverage of original node set V. Essentially, we try to answer the question, "*can t be arbitrarily large?*"

We first make the observation that if the node density is arbitrarily small, MDS of G_t may include all nodes in V even for large t's. Therefore, constraints on the node density are necessary in imposing an upper bound on t. For randomly placed nodes following Poisson point process of rate ρ in a square region R of edge length l, it is well-known [10] that there exists a threshold ρ_c such that if $\rho > \rho_c$, all points in R are covered with high probability. In fact, $\rho_c = log(l^2) + 2loglog(l^2) + c(l)$, where $c(l) \to \infty$ as $l \to \infty$.

Theorem 4: Given sensing range s, if all points in R are covered, then there exists a point p not covered by MDS of G_t for $t > 2s$.

Proof: We use a proof by contradiction. Suppose every point in R is covered by the MDS of G_t for $t > 2s$. Without loss of generality, let us consider one node $v \in MDS$. Let S_v be the set of nodes in MDS that are centered on the boundary or inside of the disk B_v with radius t excluding v. We see $S_v \neq \emptyset$ for $t > 2s$. This is because if $S_v = \emptyset$, the points with distance of $\frac{t}{2}$ from v are not covered by either v (since $\frac{t}{2} > s$) or $MDS \backslash S_v$ (since these points are at least $\frac{t}{2}$ away from nodes in $MDS - \{v\}$). Hence these points are not covered by the MDS, which contradicts every point in $\mathbb{R}^2$ is covered by the MDS.

Since $S_v \neq \emptyset$, v is dominated by S_v. There are two cases, *Case 1:* All nodes D_v dominated by v are in S_v, i.e., $(V - S_v \cup v) \cap D_v = \emptyset$. We can remove v from MDS and the resulting set is still a dominating set. This contradicts with the definition of MDS.

Case 2: There exists a node $u \in (V - S_v \cup v) \cap D_v$. Define $\xi \triangleq \frac{t-2s}{2} > 0$. Let p be a point at the intersection of u's perimeter P_u and the ring bounded by two concentric circles centered at v with radius s and $s + \xi$ (see Figure 4). First, p cannot be covered by v since its distance from v is larger than s. Second, p cannot be covered by $MDS - S_v$ either. This is because the distance from any point x in $MDS - S_v$, $x \neq v$ to point p is larger than $t - (s + (t - 2s)/2) = t/2 > s$. Therefore, p must be covered by at least one node $w \in S_v$ or equivalently, $\exists w$ s.t. $d(p, w) \leq s$. Otherwise, p is not covered by MDS. Now, we have $d_{u,w} \leq d_{u,p} + d_{p,w} \leq 2s < t$, or in another word, u is dominated by w. The first inequality is due to the triangle inequality. This implies any node u dominated by v can be dominated by another node w, which is in S_v. Therefore, v can be removed from $S_v \cup v$ while satisfying the dominating property. This is in contradiction with the definition of minimal dominating set.

By case 1 and case 2, theorem 4 holds.

■

The necessary condition only utilizes the "minimal" property of MDS and thus is general to all MDS selection algorithms.

IV. Construction of Dominating Set for Coverage Maintainable

In this section, we propose a coverage maintenance protocol that provides good sensing coverage using dominating set.

We assume nodes can adjust their transmission range by changing the transmission power level. The relationship between transmission range and power level is usually dependent on the radio characteristics and environment. Measurement-based propagation models and fine-grained channel modeling techniques can be used to predict the attenuation of signals over distance. For example, studies [17] indicate that average received signal power decreases logarithmically with distance in both outdoor and indoor environment, i.e., $\overline{PL}(d) \propto (\frac{d}{d_0})^n$, where d_0 is the close-in reference distance, d is the transmitter-receiver separation distance and n is the path loss exponents. The typical value of n ranges from 2.7 to 3.5 for urban area cellular radio, from 1.6 to 1.8 for in building line-of-sight, 4 to 6 in presence of obstruction in building.

Our proposed coverage maintenance protocol is shown in Figure 5. It takes sensing range, maximum transmission power and a DS selection algorithm as inputs, and outputs the working set. Based on the DS selection algorithm, we can devise a suite of protocols with different objective functions (e.g., power balanced, maximal life time, k-coverage etc.). To be general, we assume the DS selection algorithm requires K-hop neighborhood information, $K = 1, 2, \ldots$.

The algorithm consists of three steps. First, (from line 1-7 in Figure 5), each node determines a local node density by counting the number of nodes in its ttl-hop neighborhood using the maximum transmission range. Suppose the number of ttl-hop neighbors of node v is cnt_v. Then, the local node density can be approximated as $\rho_v = \frac{cnt_v+1}{\pi t_{max}^2 ttl^2}$ (recall that t_{max} is the maximum transmission range). ttl reflects the trade-off between robustness of the estimation and adaptability to variations of node density. This process can be carried out periodically at large intervals. A node v then sets its transmission range as follows:

$$t_v = s - min(s, \sqrt{\frac{-log\epsilon_0}{\pi\rho_v}}) \tag{8}$$

Beacon messages are transmitted using this range (ϵ_0 to be determined later). Beacon messages are used to construct $1-hop$ neighbor list corresponding to t_v.

In the second step (from line 8-13 in Figure 5), neighboring nodes exchange their 1-hop neighbor lists. Line 11 is needed to ensure bidirectionality. To this end, the adjacency matrix of the subgraph induced by t_v, $v \in V$ is determined. Line 14-22 is needed *only* for DS selection algorithms that require K-hop neighborhood information ($K > 1$). Lastly (line 23), we can apply a DS selection algorithm to the resulting subgraph to obtain the cover set.

It should be noted that t_v, $v \in V$ is only used to determining the working set. All subsequent message and data exchange still use the maximum transmission range (power level).

V. Performance Evaluation

In this section, we investigate through extensive simulations the performance of the proposed location-free coverage maintenance protocol. We will also study the robustness of the protocol to the variation of node density, inaccuracies in transmission range control and the presence of heterogeneous sensing ranges.

Input: $ALG_{DS}(K)$, sensing rang s,
maximum transmission range t_{max}
Output: Working set
for $v \in V$
  $cnt_v \leftarrow COUNT(v, t_{max}, ttl)$
  $\rho_v \leftarrow \frac{cnt_v + 1}{\pi t_{max}^2 ttl^2}$
  $t_v \leftarrow s - min(s, \sqrt{\frac{-log(\epsilon_0)}{\pi \rho_v}})$
  node v broadcast a beacon message with range t_v.

/* *Upon receiving a beacon message from node u* */
  $N(v) \leftarrow u \cup N(v)$
end

for $v \in V$
  broadcast its neighbor list $N(v)$ using t_{max}

/* *Upon receiving node u's neighbor list*/
  if $v \in N(u)$ **and** $u \overline{\in} N(v)$
    $N(v) \leftarrow u \cup N(v)$
  endif
end

$k \leftarrow K$
while $k > 1$
  for $v \in V$
    Transmit $(K - k)$-hop neighbor list $N_k(v)$ with P_{max}.

/* *Upon receiving $N_k(u)$ from node u*
    Merge $N_k(u)$ with $N_{k-1}(v)$.
  end
  $k \leftarrow k - 1$
end /* *construct K-hop neighbor list* */

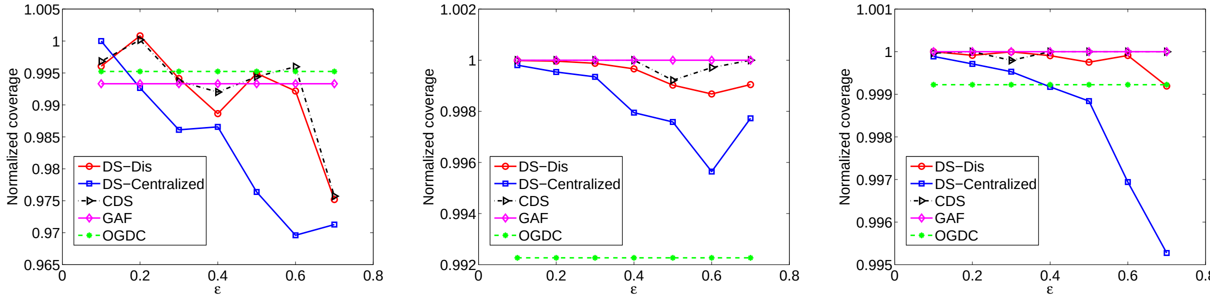
Apply $ALG_{DS}(K)$
return the working set.

Fig. 5. **Location-free sensor coverage maintenance algorithm**

A. Simulation Setup

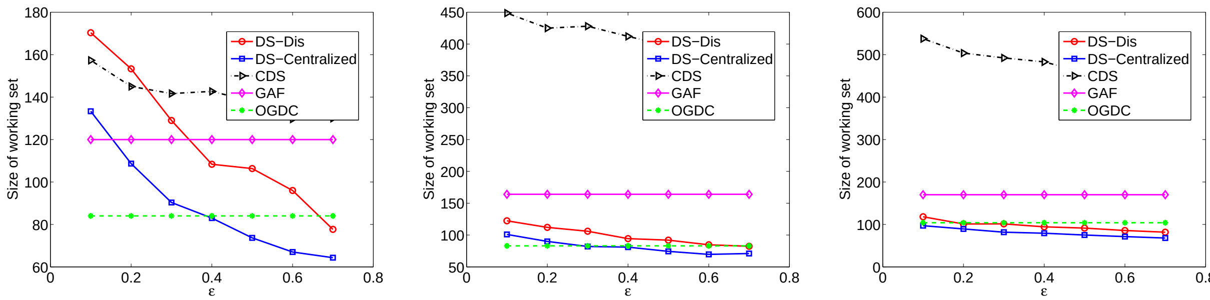
In evaluating the proposed protocol, we implement several dominating set selection algorithms that are each representative in its category (i.e., centralized, distributed, connected dominating set etc.)

- Greedy algorithm for selecting dominating set (short as *DS-Centralized*): In the centralized greedy algorithm, at each step, a node that dominates the most number of un-dominated nodes is added until all nodes are dominated.This centralized algorithm can achieved H_Δ approximation, where Δ is the maximum degree of a node, and H_i is the ith harmonic number. It is proven that such approximation ratio is best possible unless NP has $n^{O(loglogn)}$-time deterministic algorithm [9].
- Kuhn and Wattenhofer's constant time distributed dominating set approximation (short as *DS-Dis*): In [12], Kuhn and Wattenhofer propose a fully distributed approximation algorithm based on LP relaxation techniques. The idea is to first approximate the LP relaxation of (0,1) integer programming for minimum dominating set problem and assign the resulting solution as weight to each node. A node with a larger weight has a higher likelihood to become a dominator. The algorithm can compute a dominating set of expected size $O(k\Delta^{2/k}log(\Delta|DS_{opt}|)$ in $O(k^2)$ rounds where each node sends $O(k^2\Delta)$ messages of size $O(log(\Delta))$.
- Aloubi *et al*'s ID-based approach [1] (short as *CDS*): The algorithm consists of three steps: leader election, maximal independent set (MIS) selection and dominating tree construction. Leader election elects the node with smallest ID as the leader. The leader node broadcasts its identity to all nodes. Upon receiving the identity of the leader, nodes start the MIS procedure using ID-based rank assignment. Finally, nodes in MIS build the dominating tree using scoped broadcasts with time-to-live (TTL) set to 3.



(a) N=200 (b) N=800 (c) N=1200

Fig. 6. Coverage as a function of ϵ_0. Sensors are uniformly distributed in a $40m \times 40m$ square region. $t_{max} = 8m$ and $s = 4m$.



(a) N=200 (b) N=800 (c) N=1200

Fig. 7. Size of working set as a function of ϵ_0. Sensors are uniformly distributed in a $40m \times 40m$ square region. $t_{max} = 8$ and $s = 4$.

Among all three algorithms, DS-Centralized tends to generate the smallest DS while the CDS generates the largest. The reason we include a CDS algorithm is to study whether "connectivity" among the DS can improve the coverage as suggested in [5].

In addition to the proposed location-free coverage maintenance protocol, we also evaluate as a baseline the performance of OGDC and a hexagon-based GAF-like algorithm considered in [26]. The later algorithm is built upon GAF [24] and operates as follows. The entire area is divided into hexagonal grids of side length $s/2$ and one node is selected to provide coverage in each grid. Both OGDC and hexagon-GAF algorithms require knowledge of node location.

B. Performance Metrics

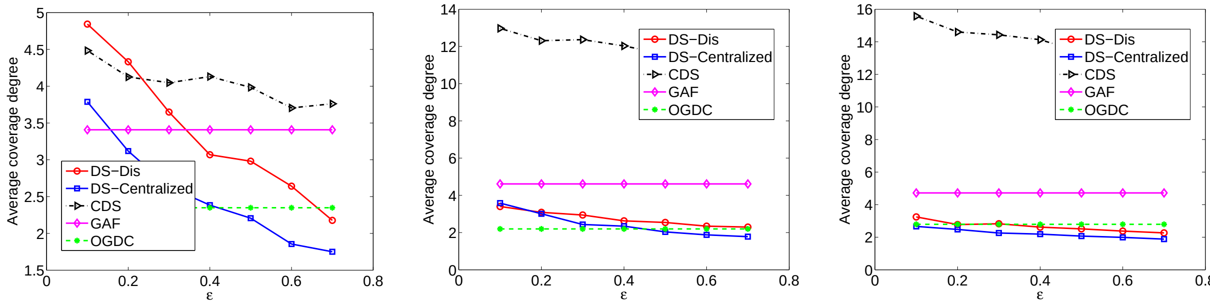
The performance metrics of interest are (i) the normalized coverage, i.e., the ratio of covered area of the selected dominating set to the total area covered by all nodes, (ii) the size of the resulting dominating set (or working nodes), (iii) average coverage degree of all points in the interested area. A point is said to be k-covered if it is covered by k nodes but not $k + 1$ in the working set. Average coverage degree is thus an average of the degree of coverage across all nodes. It reflects the redundancy of the coverage algorithm.

C. Simulation Results

The simulation study is conducted in a $40m \times 40m$ square area. Coverage is computed by dividing the area into 40×40 square grids of $1m \times 1m$. A grid is considered covered if the center of the grid is covered. The ttl for the density estimation is set to 1.

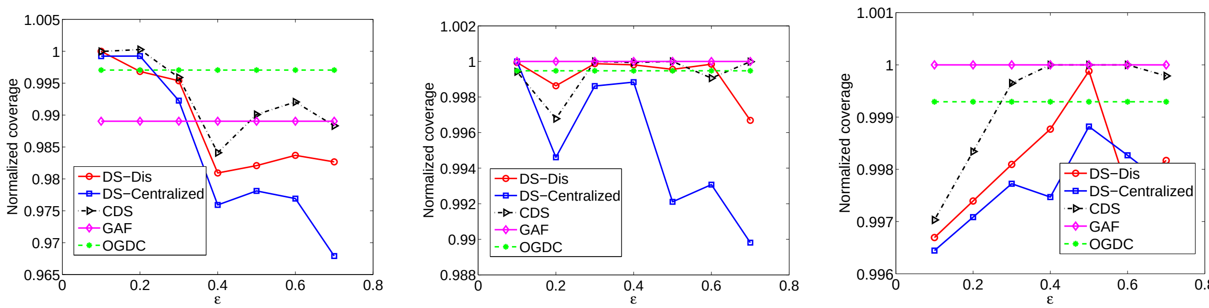
Choice of ϵ_0: In this set of experiments, we vary ϵ_0 in the proposed coverage maintenance protocol (Fig. 5) from 0.1 to 0.7 and investigate its impact on the coverage of the resulting working set. Three scenarios are considered with

When the transmission range t is small, the graph can be disconnected. In this case, a CDS algorithm finds one connected dominating set for each connected component in the graph.



(a) N=200 (b) N=800 (c) N=1200

Fig. 8. Average coverage degree as a function of ϵ_0. Sensors are uniformly distributed in a $40m \times 40m$ square region. $t_{max} = 8$ and $s = 4$.



(a) N=200 (b) N=800 (c) N=1200

Fig. 9. Coverage as a function of ϵ. Sensors are non-uniformly distributed in a $40m \times 40m$ square region. $t_{max} = 8m$ and $s = 4m$.

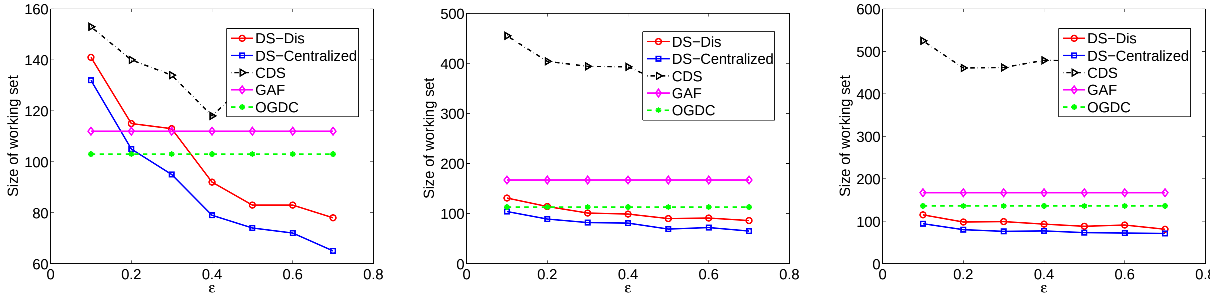
$N = 200, 800, 1200$ sensors uniformly distributed in the $40m \times 40m$ area, respectively. The maximum transmission range and sensing range are set to be $t_{max} = 8m$ and $s = 4m$ such that full coverage implies connectivity [26]. The results are shown in Fig. 6-8.

From Fig. 6 and Fig. 7, we observe that as ϵ_0 goes larger, the coverage and size of the resulting working set reduces. This is because a larger transmission range is used in constructing the dominating set. The relationship between coverage and ϵ_0 (or subsequently, transmission range) is not strictly monotonic as the coverage is not only affected by the size of the working set but also its distribution. Compared to DS-Dis and DS-Centralized, CDS has large redundancy as demonstrated from the average coverage degree (Fig. 8). Even for dense graphs (i.e., $N = 400, 800$), close to half of the nodes are selected achieving an average coverage degree over 10 (i.e., each point in the area is on average covered by more than 10 nodes in the working set). Clearly, CDS is not a very good choice for energy conservation purpose and provides no significant gain in coverage.

For $\epsilon_0 \in [0.1, 0.7]$, compared with OGDC, the coverage of the proposed protocol in conjunction with DS-Dis, DS-Centralized, CDS are at most three percentile less for sparse graphs ($N = 200$) and one percentile less for dense graphs ($N = 400, 800$). An interesting cross-over point occurs when ϵ_0 is around 0.6 for $N = 200, 800$ and 0.2 for $N = 1200$, the size of working set of our proposed algorithm is smaller than that of OGDC. This is a very encouraging result as our protocol do not assume knowledge of node's location while location information is required in both OGDC and GAF.

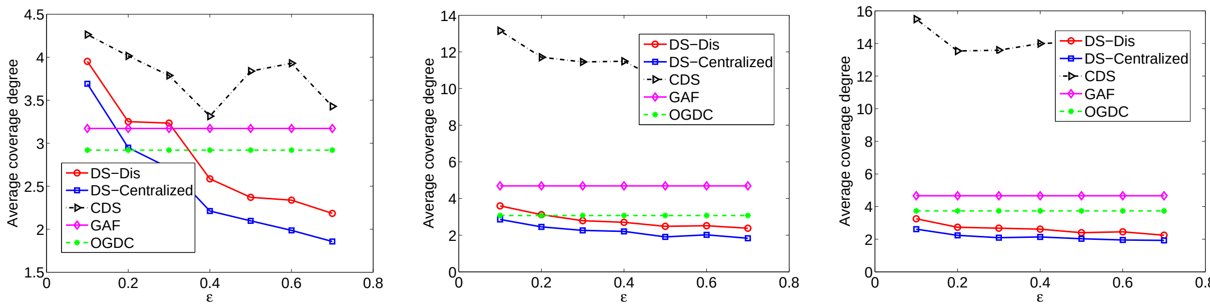
Non-uniform node distribution: To further confirm the above observations, we experiment with non-uniform node distribution. The entire area is divided into 16 identical blocks. The node density in each block is randomly chosen among $[0.5\lambda, 1.5\lambda]$, where $\lambda = \frac{N}{1600}$ is the average density of the entire area. Again, ϵ_0 varies from 0.1 to 0.7 and the number of nodes N changes from N=200 to 800. The results are shown in Fig. 9-11.

We can see the trend remains the same for non-uniform distribution. When comparing Fig. 6-8 with Fig. 9-11 back-to-back, we see that the coverage of our proposed scheme is *slightly* worse in the non-uniform case while the number of resulting working set is *slightly* larger. This can be attributed to the density estimation procedure (Fig 5, line 3), which is based on the number of nodes within the maximum transmission radius and thus is coarse-grained.



(a) N=200 (b) N=800 (c) N=1200

Fig. 10. Size of working set as a function of ϵ. Sensors are non-uniformly distributed in a $40m \times 40m$ square region. $t_{max} = 8m$ and $s = 4m$.



(a) N=200 (b) N=800 (c) N=1200

Fig. 11. Average coverage degree as a function of ϵ. Sensors are non-uniformly distributed in a $40m \times 40m$ square region. $t_{max} = 8m$ and $s = 4m$.

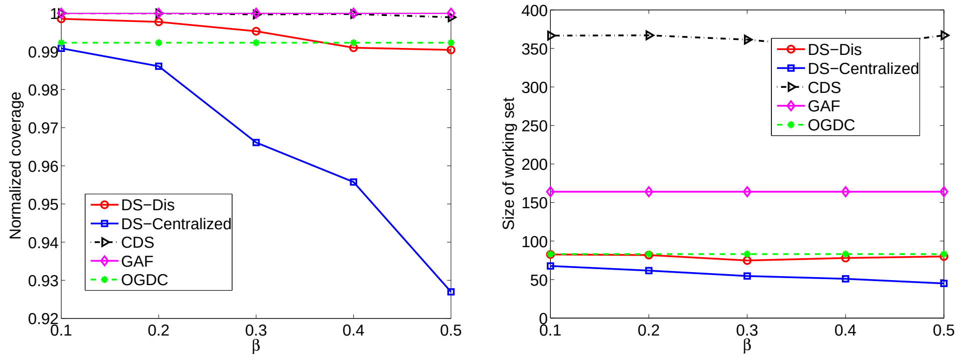
From these results, we conclude that our proposed algorithm can provide comparable coverage using similar or even less working nodes as compared to OGDC in both uniform and non-uniform field of nodes with various density. In the following experiments, we fix ϵ_0 to be 0.6.

Sensitivity analysis of transmission range control: As described in Section IV, our location-free coverage maintenance protocol requires the ability to control the transmission range by adjusting transmission power. The two are highly correlated and in fact can be characterized using parametric models or channel modeling techniques. However, due to the randomness in the environment, it is likely that the actual transmission range used may differ from the targeted value.

In this set of experiments, we evaluate the tolerance of errors between the targeted and actual transmission range values in our proposed protocol. Let t_v be the targeted transmission range of node v determined by Eq. (8). The actual transmission range t_v^{actual} of a node is uniformly chosen from $[(1-\beta)t_v, (1+\beta)t_v]$ independent from its neighbors. Following the procedure in Fig. 5, the neighbor list is determined using t_v^{actual}, $v \in V$. Therefore, the induced subgraph may differ from the one determined by t_v, $v \in V$. Fig. 12 shows the results for $\beta \in [0.1, 0.5]$, $N = 800$ and $\epsilon = 0.6$. Except for DS-Centralized, β has little impact on the coverage and size of the resulting working set. With large β (or a large variation in the actual transmission range), DS-Centralized selects less nodes to provide coverage. The reason is as follows. As shown in Line 10-12 in Fig. 5, an edge is added in the reverse direction if an directed edge is detected. With t_{actual} uniformly chosen from $[(1+\beta)t, (1-\beta)t]$, edge addition is likely to occur which in effect makes the induced graph denser. This is in part an artifact of the independence assumption we make in computing t_v^{actual} in this set of experiments. In reality, actual transmission range tends to be location-dependent. The effect of locality in transmission range control will be considered in our future work.

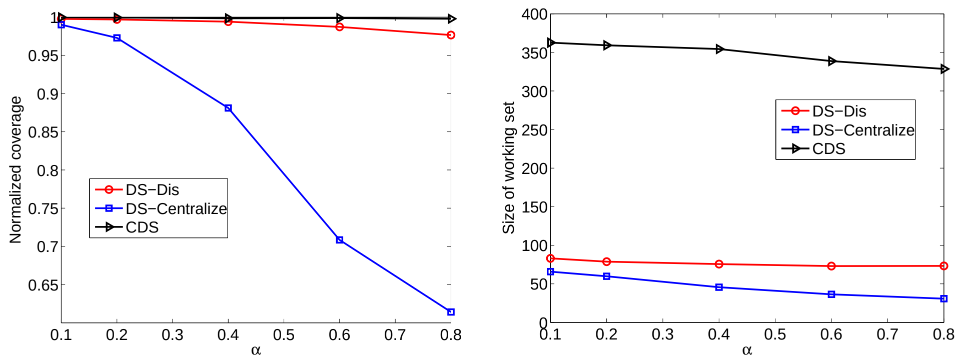
Isotropic sensors: Due to hardware heterogeneity, sensors may have different sensing ranges. In this set of experiments, each sensor's sensing range s is known to itself but randomly chosen between $[(1-\alpha)\overline{s}, (1+\alpha)\overline{s}]$, where $\overline{s} = 4m$ and α varies from 0.1 from 0.8.

Note both OGDC and GAF are not designed to handle heterogeneous sensing ranges. In GAF, the target area is



(a) Normalized coverage (b) Size of working set

Fig. 12. Coverage and size of DS as functions of variation in transmission power control parameter β with $N = 800$ sensors are uniformly distributed in a $40m \times 40m$ square region. $t_{max} = 8m$, $\epsilon_0 = 0.6$ and $s = 4m$.



(a) Normalized coverage (b) Size of working set

Fig. 13. Isotropic sensors: coverage and size of DS as functions of α with $N = 800$ sensors uniformly distributed in a $40m \times 40m$ square region. $\epsilon_0 = 0.6$, $t_{max} = 8m$ and $\overline{s} = 4m$.

partition into identical hexagonal grids of side length $\overline{s}/2$. In OGDC, the initial set of working nodes are chosen to be those close to the intersection points of homogeneous hexagonal grids. Therefore, we choose not to include these two schemes in our comparison.

As shown in Fig. 13, coverage maintenance using DS-Dis and CDS perform very well even with large variation of sensing ranges. The coverage of DS-Centralized, however, degrades significantly as α grows larger. Again, this can be attributed to the way asymmetric links are resolved in our protocol (Fig. 5, Line 10-12).

In summary, among the set of dominating set selection algorithms and parameter settings considered, *we recommend the use of Kuhn and Wattenhofer's algorithm with ϵ_0 set to 0.6.*

VI. Conclusion and Future Work

In this paper, we have studied the coverage property of dominating set and established the connection between area coverage and point coverage through rigorous analysis. The analytical results make possible the design of a suite of location-free coverage maintenance protocols utilizing transmission range control and the knowledge of wireless connectivity. Our experiment studies show that the proposed location-free coverage maintenance protocol can indeed provide comparable coverage using similar or even less working nodes as compared to other location-based solutions. The proposed protocols are shown to be robust to non-uniform node density, inaccuracies in transmission range control and heterogeneity in sensing ranges.

As part of our ongoing work, we plan to tighten the necessary and sufficient conditions of MDS coverage, and evaluate the performance of energy-balanced and k-cover MDS algorithms in conjunction with our location-free coverage maintenance protocol.

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