Minimum Connected Dominating Set Using a Collaborative Cover Heuristic for Ad Hoc Sensor Networks

Rajiv Misra, *Member*, *IEEE*, and Chittaranjan Mandal, *Member*, *IEEE*

Abstract—A minimum connected dominating set (MCDS) is used as virtual backbone for efficient routing and broadcasting in ad hoc sensor networks. The minimum CDS problem is NP-complete even in unit disk graphs. Many heuristics-based distributed approximation algorithms for MCDS problems are reported and the best known performance ratio has $(4.8 + \ln 5)$. We propose a new heuristic called collaborative cover using two principles: 1) domatic number of a connected graph is at least two and 2) optimal substructure defined as subset of independent dominator preferably with a common connector. We obtain a partial Steiner tree during the construction of the independent set (dominators). A final postprocessing step identifies the Steiner nodes in the formation of Steiner tree for the independent set of G. We show that our collaborative cover heuristics are better than degree-based heuristics in identifying independent set and Steiner tree. While our distributed approximation CDS algorithm achieves the performance ratio of $(4.8 + \ln 5)\mathrm{opt} + 1.2$, where opt is the size of any optimal CDS, we also show that the collaborative cover heuristic is able to give a marginally better bound when the distribution of sensor nodes is uniform permitting identification of the optimal substructures. We show that the message complexity of our algorithm is $O(n\Delta^2)$, Δ being the maximum degree of a node in graph and the time complexity is $O(n)$.

Index Terms—Connected dominating set (CDS), Steiner tree, routing backbone, maximal independent set (MIS).

1 Introduction

Wireless ad hoc and sensor networks are popularly used for disaster control and geographical monitoring-related applications. Such ad hoc networks lack network infrastructure for connectivity and control operations. In remote data gathering applications, the sensor network often uses in-network data aggregation to optimize network communication [2]. In-network aggregation is an intermediate processing of global data gathered often reducing the routing load, thereby saving communication energy, and results in increasing network lifetime.

Lossless aggregation depends on coverage of aggregating nodes. The set of aggregating nodes forms a dominating set of the network graph. This subset of nodes selected as aggregation nodes is organized in a Steiner tree to form a data aggregation backbone. The effectiveness of the aggregation algorithm is achieved when the underlying CDS tree is minimized. Therefore, constructing an aggregation backbone is modeled as the minimum connected dominating set problem in graph theory. Besides aggregation, the smaller sizes of CDS also simplify network control operations confines routing operations to a few nodes set leading to advantages such as energy efficiency and low latency. Ad hoc networks use a CDS as a virtual backbone for efficient routing and broadcasting operations. In this work, we report an improved construction of a minimal CDS using effective coverage as a metric in collaborative cover heuristic and Steiner tree achieving the approximation factor $(4.8 + \ln 5)\mathrm{opt} + 1.2$, where opt is the size of any optimal CDS.

A connected dominating set CDS(G) of a graph $G = (V, E)$, is defined as a subset $\mathrm{CDS}(G) \subseteq \mathrm{V}(G)$ of $\mathrm{V}(G)$ such that each node in $V(G) - CDS(G)$ is adjacent to at least one node in CDS(G) and the graph induced by CDS(G) is a connected subgraph of G. The problem of finding the CDS with minimum cardinality called Minimum Connected Dominating Set (MCDS) problem, which is known to be NP-complete [6]. Therefore, polynomial-time approximation algorithms for small size CDS construction are of interest. Existing schemes for small size CDS have used degree-based heuristic [5] for optimization of independent set and connectors in CDS construction. In this paper, we argue that the degree-based heuristic looses the coverage information due to overlapping of coverage area, which is vital to further improve on the size of the CDS, leading to our new collaborative cover heuristic based on effective coverage. We describe a collaborative coverage heuristic to identify better coverage dominators based on their effective coverage. The effective coverage is ratio of coverage over the size of cover, i.e., $\frac{|coverage|}{|cover|}$, where coverage means set of nodes covered by dominators and cover is the set of dominator nodes. A set of nodes having the highest effective cover in its one-hop vicinity is considered greedily for selecting them as dominators, which reduces the size of the dominators. We provide a local mechanism to explore the cover with effective coverage in the distance-2 region,

- R. Misra is with the Department of Computer Science and Engineering, Indian Institute of Technology, Patna, India. E-mail: rajivm@iitp.ac.in.
- C. Mandal is with the Department of Computer Science and Engineering and the School of Information Technology, Indian Institute of Technology, Kharagpur, India. E-mail: chitta@iitkgp.ac.in.

Manuscript received 20 May 2008; revised 16 March 2009; accepted 4 May 2009; published online 11 May 2009.
Recommended for acceptance by P. Mohapatra.
For information on obtaining reprints of this article, please send e-mail to: tpds@computer.org, and reference IEEECS Log Number TPDS-2008-05-0197.
Digital Object Identifier no. 10.1109/TPDS.2009.78.

which is used in our distributed approximation algorithm to generate smaller size CDS.

Recent works have used a second phase in the MCDS for a Steiner tree construction to optimize the Steiner nodes to tap the independent nodes as terminals obtained in the first phase of construction to achieve an approximation factor of $(4.8 + \log 5)$. We have used the first phase of construction to generate a partial Steiner tree along with the independent set construction; this is achieved by shifting the independent set nodes to a proper placement to identify the Steiner nodes among the neighboring nodes. Thus, unlike most of the reported schemes that fix the independent nodes first and take second phase for Steiner tree construction, we shift the independent set (with better coverage) placement to identify most of the Steiner nodes in the first phase itself. The second phase of the algorithm then becomes a postprocessing step leading to a Steiner tree of no higher cost.

In the energy constrained ad hoc and sensor networks, such schemes help to extend the network lifetime due to its smaller size CDS compared to other CDS schemes, in terms of: 1) A smaller dominating set resulting in larger domatic partition giving better energy conservation and 2) Smaller size dominating set means large coverage giving high degree of data aggregation, thereby reducing the network traffic.

The described algorithm has $O(n\Delta^2)$ message complexity, Δ being the max degree of node in graph. The approximation factor of distributed algorithm for finding minimum connected dominating set is $(4.8 + \ln 5)\mathrm{opt} + 1.2$, where opt is the size of any optimal CDS.

The rest of paper is organized as follows: In Section 2, we discuss related works on CDS construction algorithms. Section 3 is on preliminaries giving definitions and a brief background necessary for our work. Section 4 states problem formulation and lists the contributions of this work. Section 5 explains the principles behind our collaborative cover heuristic. Steiner tree construction from a given set of dominators is explained in Section 6. In Section 7, we present our distributed algorithm for aggregation-CDS based on collaborative cover. Section 8 is on analysis of the algorithm. We give simulation results in Section 9. Finally, we conclude the paper in Section 10.

2 Related Work

In this section, we review the literature, which is divided into the following two sections.

2.1 In-Network Aggregation Problem

Several reported schemes on routing algorithms, such as Directed Diffusion [13], Pegasis [16], and GAF [24], have used in-network data aggregation, where a spanning tree performs aggregation function opportunistically along the internals of the tree, as data flows level by level from leaves to root. The opportunistic aggregation-based schemes are neither optimal nor giving approximation guarantees. The aggregation schemes are categorized into two types: 1) lossless aggregation and 2) lossy aggregation.

The lossy aggregation schemes are based on exploiting correlated data in tree construction. A connected correlation dominating set scheme reported in [10] constructs CDS for capturing correlation structure to provide lossy aggregation efficiently. We have not come across any significant reported matter on lossless aggregation.

2.2 Minimum Connected Dominating Set Problem

The use of the connected dominating set (CDS) as a virtual backbone was first proposed by Ephremides et al. in 1987 [8]. Since then, many algorithms that construct CDS have been reported and can be classified into the following four categories based on the network information they use:

1. centralized algorithms,
2. distributed algorithms using single leader,
3. distributed algorithm using multiple leaders, and
4. localized algorithms.

Guha et al. [26] first gave two centralized greedy algorithms for CDS construction in general graphs having approximation ratio $O(ln\Delta)$. Centralized CDS algorithm to be used as virtual backbone for routing application was first reported by Das et al. [7]. The centralized CDS algorithms require global information of the complete network. Hence, it is not suited for wireless sensor networks that do not have centralized control. Construction of CDS may be achieved through a distributed algorithm based on either a single leader or multiple leaders.

Distributed algorithms with multiple leader approach do not require an initial node to construct CDS. Alzoubi et al.'s technique [3] first constructs an MIS using a distributed approach without a leader or tree construction and then interconnects MIS nodes to get a CDS. Wu and Li [22] reported a CDS algorithm to identify the CDS using a marking approach to identify dominators with independent nodes and then prune the redundant nodes from the CDS using two sets of pruning rules to generate CDS. The multiple leader minimum CDS schemes approximate size of min-CDS to $192\mathrm{opt} + 48$, where opt is the size of optimal CDS [3]. Due to its large approximation factor, the multiple leader-based distributed CDS construction is not effective for exploiting lossless in-network aggregation. In a localized approach for CDS construction, Adjih et al. [1] presented an approach for constructing small size CDS based on multipoint relays (MPR), but no approximation analysis of algorithm is known yet. Based on the MPR approach, several extensions have been reported leading to localized MPR-based CDS construction. The localized without a approximation guarantees is again not competitive to efficiently exploit aggregation.

A single-leader distributed algorithm for CDS assumes an initial leader in place to provide initialization for the construction of distributed algorithm. A base station could be the initiator for construction of CDS in sensor networks. The distributed algorithm uses the idea of identifying a maximal independent set (MIS) and then identifies a set of connectors to connect the MIS is ascertained to form CDS. Wan et al. [21] presented an ID-based distributed algorithm to construct a CDS tree rooted at the leader. For UDGs, Wan et al.'s [21] approach guarantees the approximation factor on size of CDS at most $8|\mathrm{opt}| + 1$ has $O(n)$ time complexity and having $O(n \log n)$ of message complexity to construct CDS using a single initiator. The approximation factor on the size of CDS was later improved in another work reported by Cardei et al. [5] having an approximation factor of $8|\mathrm{opt}|$ for degree-based heuristic and degree-aware optimization for identifying Steiner nodes as the connectors in CDS construction. This distributed algorithm grows from a single leader and has $O(n)$ message complexity, $O(\Delta n)$ time complexity, using one-hop neighborhood information. Later, Li et al. [15] reported a better approximation factor of $4.8 + \log 5$ by constructing a Steiner tree when connecting all nodes in I, the independent dominating set.

3 Preliminaries

This section is divided into two parts: 1) dominating set and 2) network model.

3.1 Dominating Set

Wireless networks generally have omnidirectional antennae and nodes use transmission power to establish connection with all nodes in the transmission range. Assume that medium access control layer protocol deals with the intricacies of interference of radio signals, channel regulation, collision handling giving us way to model network as unit disk graph. A graph $\mathrm{G} = (\mathrm{V}, \mathrm{E})$ is a unit disk graph (UDG) if there exist $\Phi : V \mapsto \mathbb{R}^2$ satisfying $(i, j) \epsilon E$ iff $\| \Phi(i) - \Phi(j) \|_2$. Φ is called a realization of G. Thus, wireless network is modeled as UDG. In a given graph $G = (V, E), V' \subseteq V$, a subset is an MIS if no two vertices in V' are adjacent (independence) and that every $u \epsilon V - V'$ has a neighbor in V' (maximality). A dominating set D is a subset of V such that any node not in D has a neighbor in D. A maximal independent set is also a dominating set in the graph and every dominating set that is independent must be maximal independent, so maximal independent sets are also called independent dominating sets. If the induced subgraph of a dominating set D is connected, then D is the CDS. The relationship between size of an MIS of G and the minimum CDS of G plays an important role in establishing the approximation factor of approximation algorithm for minimum connected dominating set. Wan et al. [21] showed that in every UDG $G, |\mathrm{MIS}(G)| \leq 4|\mathrm{CDS}(G)| + 1$, which was improved by Wu et al. [23] to $|\mathrm{MIS}(G)| \leq 3.8|\mathrm{CDS}(G)| + 1.2$. We use the improved relationship of MIS and min-CDS for approximation analysis of our proposed algorithm.

3.2 Ad Hoc Network Model: Distances Are Unknown

We describe the network model used in this work. Assume that nodes do not have any geometric or topological information, thus, even the distances to neighbors are unknown to the nodes. The communication overhead due to interference is assumed to be negligible. The computation is partitioned into rounds. Assume that the nodes receive all messages sent in previous round, execute local computations, and send messages to neighbors in a round. A wireless ad hoc network is represented as a UDG. Nodes using exchange of hello messages can find its distance-1 neighbor nodes and ascertain its degree. Given $G(V, E), G^2$ has vertex set $V(G)$ and edge set $E^2 = \{\{u, v\} | u, v \in V(G) \wedge \text{shortest distance}(u, v) \leq 2\}$.

4 Problem Formulation and Contributions

Consider wireless sensor network consisting of a (large) number (n) of nodes deployed in a geographical region. Each node is mounted by an omnidirectional antenna with the transceivers having maximum transmission range of R. The ad hoc network is a unit disk graph $G = (V, E)$, where $|V| = n$ be all the nodes, E be the edges, and edge between any pair of nodes exists if the distance is at most R, taken at a unit radius. The problem is to find a minimum cardinality connected dominating set of G is NP-complete. Therefore, the aim of this work is the development of heuristic-based approach to construct a CDS with guaranteed approximation factor to the size of any optimal CDS. When a minimal CDS is used as aggregation backbone for lossless in-network aggregation problem, it saves the network traffic leading to increased lifetime of the energy constrained ad hoc and sensor networks.

4.1 Contributions

The contribution of this paper is summarized as follows:

1. A distributed approximation algorithm for minimum connected dominating set problem with a known initiator.
2. A new collaborative cover heuristic which helps in identifying smaller cardinality MIS of G as compared to ID-based or degree-based heuristics.
3. A Steiner tree construction process in two phases:
   a. Steiner nodes identified in the first phase to drive the MIS construction by shifting independent set nodes to locate the connectors in identifying Steiner nodes.
   b. The second phase becomes a postprocessing step of identifying the Steiner nodes to construct the CDS tree satisfying a standard bound.
   c. The approximation factor of our algorithm is $(4.8 + \ln 5)\mathrm{opt} + 1.2$, where opt is the size of any optimal CDS. The algorithm has time complexity of $O(n)$ and $O(D)$ rounds, where D is the network diameter. The algorithm requires at most $O(n\Delta^2)$ messages for its construction complexity, where Δ is the maximum node degree in G.

We have shown that our CDS approach, when used for in-network aggregation application, prolongs the network lifetime.

5 Collaborative Cover Heuristic

Reported works on distributed approximation algorithm for CDS construction using a single leader either use ID-based heuristic [21] or degree-based heuristic [5]. Cardei et al. [5] have shown that the degree-based heuristic is better as compared to a pure ID-based heuristic in identifying smaller size CDSs greedily. In identifying an MIS using degree-based heuristics, nodes with the highest degree in their neighborhood are selected greedily forming an MIS of the underlying graph.

An improvement over the existing degree-based heuristic is a new collaborative cover heuristic described in this paper. The collaborative cover heuristic is based on the idea of using the information of overlapping coverage of the nearby independent set of nodes. On considering the nearby independent nodes, we observe that the effective coverage is less when they are considered in isolation. In a degree-based heuristic, each node is considered in the isolation, thereby loosing important information to further optimize the size of the MIS and CDS. The loss of effective coverage is due to overlapping of coverage area of nearby independent nodes. Therefore, instead of effective degrees being considered in isolation, we propose a more encompassing heuristic which considers the coverage of nearby independent nodes while identifying effective coverage (or effective cover of network nodes). Thus, the collaborative cover heuristic is based on effective coverage information, which intuitively is better than effective degree. We now provide a formalized definition of the concept of collaborative cover.

Definition 1 (Node neighborhoods). *Consider a node u. Nodes covered by u are represented as $N(u)$, known as neighbors of u. The set $N[u]$ represents nodes covered by u including u. Let the nodes be called independent if they are not neighbors. Independent neighbor of u is a subset of $N(u)$ such that any pair of nodes in this subset are independent. $N_2(u)$ is a set of nodes that is at most at a distance-2 from u known as at most distance-2 neighbors of u. Let the distance-2 neighbors of u be represented as $\{N_2(u) - N(u)\}$.*

For any node, we now define a cover of its distance-2 neighbors such that any pair in the cover are independent.

Definition 2 (Distance-2 independent halo). *Let H be the independent cover of the distance-2 neighbor of u. If H is an independent cover, then $H \subseteq \{N_2(u) - N(u)\}$ and $\{N_2(u) - N(u)\} \subseteq N[H]$ and any pair of nodes in H are independent.*

Such a cover H of $\{N_2(u) - N(u)\}$, where any pair of nodes in H are independent, is obtained using either ID-based or a *degree*-based heuristic. Note that in either of heuristic, any pair of independent nodes in H that are distance-2 neighbors has ignored the estimate of coverage loss due to the overlapping in coverage. Further, these independent nodes later require additional Steiner nodes to form the connected substructure. With this background, we now argue a need of new heuristic, which accounts for effective coverage. We propose a collaborative cover heuristic to compute the effective coverage of independent distance-2 neighbor nodes collaboratively.

Definition 3 (Independent covers). *Let v_H be a node in H and $R_H = \{N(v_H) \cap \{N_2(u) - N(u)\}\}$ be the coverage of v_H for distance-2 region of u. Then $I(R_H)$ be any independent set of R_H that covers R_H. Thus, $R_H \subseteq N[I(R_H)]$. Therefore, node v_H and any independent set in its neighborhood $I(R_H)$ form the disjoint covers of R_H. Note that there may be multiple such instances of independent sets $I(R_H)$. Let S be the set all instances of independent sets of R_H, where each independent set I covers the region $R_H \subseteq N[I_i]$ for $1 \leq i \leq p$, so let $S = MIS(R_H) = \{I_1, I_2, \ldots, I_p\}$.*

Consider any node v_H and a subset of its neighborhood region R_H. We know that v_H covers the region R_H. There are many possible independent sets (IS) in region R_H each of which covers R_H. Let the set S denote a set of IS, which can cover R_H. We have to compute weights for each instance of IS on analyzing its coverage to ascertain its quality. Next, we define a measure to compute its effective coverage weight.

Definition 4 (Effective coverage). *The effective coverage weight of an independent set (I_i) with respect to a region ($\{N_2(u) - N(u)\}$) is the ratio of coverage for the region by the independent set over size of the independent set. Thus, effective coverage weight $= \frac{N[I_i] \cap \{N_2(u) - N(u)\}}{|I_i|}$.*

The effective coverage weight is computed for each independent set to identify an ordered pair of (I_i, wt_i). We can now identify a weighted independent set to cover a given region R_H.

Definition 5 (Weighted independent covers). *The weighted independent set (I_i, wt_i) (for $1 \leq i \leq p$) is an ordered pair of independent set and its effective coverage weight such that each independent set is a cover of the region $R_H = \{N[v_H] \cap \{N_2(u) - N(u)\}\}$. Thus, $R_H \subseteq N[I_i]$ for ($1 \leq i \leq p$). Let the region R_H has p number of covers with the weights represent the ratio of the effective coverage over the cardinality of cover. Thus, the weighted independent cover is given by $\{(I_1, wt_1), (I_2, wt_2), \ldots, (I_p, wt_p)\}$.*

In addition to associating the weights for effective coverage with independent sets, we look for those I in S which have a common neighbor node in $N(u)$. Thus, the condition for I that does the check is $\{N[I] \cap N(u)\} \neq 0$. The common neighbor node is called as connector because it can connect the node u and its distance-2 independent neighbors.

Definition 6 (IS with a common connector). *The independent set I_i with at least a common connector in $N(u)$ is stated as: $\exists w \in N(u)[I_i| \ w \text{ connects at least 2 nodes of } \mathrm{I_i}, \text{i.e } |N(w) \cap I_i| \geq 2]$.*

For any node v_H, the independent set I_i and its effective coverage weight wt_i associated with a connector w together form a tuple $t_H = (I_i, wt_i, w)$.

The collaborative cover heuristic proposed in this paper is based on the intuitive argument that the degree-based heuristic may result to a nonoptimal choice locally in the construction of CDS leading to a nonoptimal CDS eventually. The collaborative cover heuristic often replaces a nonoptimal choice of degree-based heuristic with the improved effective coverage using collaborative cover locally. The replacement of degree-based selection with collaborative cover-based selection suggests the existence of multiple cover locally. Since, the domatic number of any connected graph is at least 2 by Ore's theorem (in lemma 1); therefore, premise of multiple cover is validated to explore and prune the local best cover.

Result 1 (By Ore in 1962 [11], [18]). *For a connected graph G, the domatic number of $G \geq 2$.*

Thus, at every stage of connected graph, there exist at least two covers in graph and our approach aims to improve locally with the local best approximation to reduce

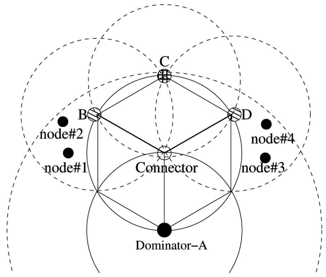

Fig. 1. Example for comparing collaborative cover and degree-based heuristics.

size of CDS eventually for minimum connected dominating set problem.

Definition 7 (Optimal substructure). *Let node w be called as connector if it is a common neighbor between dominators u and v, where v is the distance-2 neighbor of u.*

An optimal substructure which is a tuple (I_i, wt_i, w) in the neighborhood $N(v)$ of any node v is the highest weight independent set with a common connector w that can connect an IS to some node u and if the weight of the IS is greater than the coverage of the node v for a given region (i.e., effective coverage $wt_i >$ coverage of node $|R_H|$).

Example 1. A CDS construction stage of ad hoc network is shown in Fig. 1, which consists of a dominator A, three potential dominators (B, C, D), and six nodes (having two nodes as neighbor to each B, C, D). Let the dominator A need to select its distance-2 dominators out of the potential choices B, C, and D.

According to the degree-based heuristic, the potential dominator C covers four nodes compared to B and D at three each. Therefore, C becomes a dominator whereas B and D stay as its member nodes. The size of cover for C becomes 1 and coverage of C is 4. Further, in order to cover the nodes $\{1, 2, 3, 4\}$, at least two more dominators are needed. Thus, the cover size is at least 3 for coverage of four nodes (considering only two-hop cover of A). Thus, dominator C requires two more dominators, one from each set: $\{1, 2\}$ and $\{3, 4\}$, leading to the required three dominators based on degree information. Thus, the weight of the cover is given as:

$$weight = \frac{|coverage|}{|cover|} = \frac{4}{3} = 1.33.$$

Based on the collaborative cover heuristic, the potential dominators B, D are selected as dominators. The size of cover becomes as 2 and the coverage of dominating set $\{B, D\}$ is 5. The collaborative cover $\{B, D\}$ of size 2 has a coverage of 5. Thus, effective coverage of collaborative cover has the $weight = \frac{|coverage|}{|cover|} = \frac{5}{2} = 2.5$.

Higher weight indicating more coverage in collaborative cover heuristics as compared to the degree-based heuristic leads to smaller size of cover. Furthermore, the number of connector needed in collaborative adds to single number as compared to the degree-based heuristic of more than one.

Theorem 1 (Local identification of optimal substructure). *The optimal substructure is computed locally requiring only distance-2 local information.*

Proof. It is evident from example 1 that all covers in the neighborhood of a potential dominator are evaluated and the best is finally chosen. This entire process is carried out locally, around the potential dominator, requiring only distance-2 local information. □

In the next section, we describe the construction of Steiner tree carried out in over two phases of the CDS construction.

6 Steiner Tree Construction

A Steiner tree for a given subset of nodes (called as terminals) I in a graph G is a tree interconnecting (known as tapping) all the terminals I using a set of Steiner nodes in $\{V(G) - I\}$. We can connect maximal independent set I by using Steiner nodes forming a Steiner tree interconnecting all the nodes in I. The objective is to find a Steiner tree with minimum number of Steiner nodes to obtain a small size of CDS. We define the Steiner tree with minimal Steiner nodes as:

Definition 8 (Minimal Steiner nodes). *Let $I \subseteq V(G)$ be the maximal independent set I of G. Minimal Steiner nodes are subset $V(G) - I$, forming a Steiner tree to interconnect (or tap) the independent nodes I (or terminals).*

For unit disk graphs, the Steiner nodes have a property that any Steiner node can tap at most five independent nodes (or terminals). From the property of unit disk graph given in [17], we know that any node is adjacent to at most five independent nodes. Therefore, any Steiner node can interconnect at most five independent (terminal) nodes. Using this property, we define our scheme to identify the Steiner nodes in the following steps:

Step 1. All the dominatee nodes with five adjacent independent nodes from separate components are chosen become Steiner nodes and the set of adjacent independent nodes forms a connected component. Note that new component thus obtained by an association of Steiner node and its adjacent independent set nodes of different components reduces the number of components in the network, which needs to be updated to dominatee having the adjacent independent set in different components.

Step 2. For each dominatee, recompute the adjacent independent nodes in different components information.

Step 3. Repeat the above steps (1 and 2) for dominatees having four adjacent independent set nodes in different components.

Step 4. Repeat the above steps (1 and 2) for dominatees having three adjacent independent set nodes in different components.

Step 5. Repeat the above steps (1 and 2) for dominatees having two adjacent independent set nodes in different components.

Thus, the set of the Steiner nodes forming a single connected component of independent set nodes contributes to CDS. In the next section, we describe our CDS algorithm using heuristic based on collaborative cover.

7 CDS Using the Collaborative Cover Heuristic

Let every node know its distance-1 and distance-2 neighbors. Assume that every node also knows its MIS in the unit disk around it.

The CDS construction grows the CDS-tree incrementally in a BFS manner. Each node maintains the following state variables: 1) The pointer $parent$ is used for the parent link in CDS-tree, 2) The level variable l indicates the level of node from root ($l = 0$) of CDS-tree in BFS construction, and 3) The $color$ variable records the current status of node (initially all the nodes are white, dominators and connectors are colored black, potential dominator at distance-2 takes yellow color, whereas dominatees are gray).

Let u be a leader node, which initiates the construction of CDS algorithm. The algorithm has three main steps: 1) This step is to identify the independent set (cover) of the distance-2 neighbors using degree-based heuristic; 2) This step computes the collaborative cover for each node of a cover (identified in step 1) and a weight based on effective coverage; and 3) This step is to identify a connector, if any, for the highest weight independent set (identified in step 2) with u.

The algorithm starts at the leader node to identify dominators and connectors in CDS-tree constructing two levels at a time (level-l dominator to level-$(l+1)$ connector and level-$(l+1)$ connector to level-$(l+2)$ dominator) of the CDS-tree at each step until no idle nodes are left.

The set of yellow leaders forms an MIS of distance-2 region of u. The yellow leaders perform two tasks: 1) identify leaders of yellow leaders in its two-hop adjacent yellow leaders to form an MIS of yellow leaders induced by graph $G^2[yellow\ leaders]$ and 2) for each yellow leader, compute the MIS of yellow neighbors with common gray nodes.

The yellow leader computes the MIS with common gray neighbor and identifies the highest effective coverage MIS among them.

The yellow leader compares its coverage with the highest weight effective coverage of MIS with common adjacent gray nodes. The yellow leader becomes active if its effective coverage weight has larger coverage than its own coverage. Note that active yellow leader satisfies the following three properties represented by a tuple (I_i, wt_i, w_i), which triggers to explore alternate MIS with better coverage to elect leaders of yellow leaders in the entire yellow leaders of u:

1. Size of MIS I_i of node is at least two.
2. Independent nodes of MIS have a common connector w_i.
3. Effective coverage weight wt_i of MIS is greater than coverage of a node itself.

The active yellow leader sends effective coverage of MIS to its two-hop neighboring yellow leaders. $G^2[yellow\ leader]$ is the subgraph of G^2 induced by $yellow\ leaders$. Note that for any given $yellow\ leader$, the subgraph $G^2[yellow\ leader]$ identifies $yellow\ leaders$ in its distance-2 neighborhood. The leaders of yellow leaders are identified based on their effective coverage, which form MIS of graph in $G^2[yellow\ leaders]$ that is a subgraph of G^2 induced by yellow leaders. The yellow leaders are pruned locally to identify an improved MIS based on coverage heuristics in the following two phases: 1) In the first phase, the leaders of yellow leaders grow its highest effective coverage MIS with common gray to become as dominators. 2) In the second phase, the remaining yellow leaders use the dominators to form its MIS and then grow them to become dominator. Note that in the above two phases, the MIS of distance-2 neighbors of u is identified and updated as dominators. These dominators trigger selection of the adjacent gray nodes, which connect the highest number of dominators.

At this point, node u has identified distance-2 cover preferably as dominators with a connector. The size of cover is reduced heuristically for a larger coverage. Once the dominators (at level-$(l+2)$) and connectors (at level-$(l+1)$) are identified, the (level-$(l+2)$) dominators become leaders to repeat the steps to grow the CDS-tree further until no white nodes are left. After the end of the first phase, the algorithm has identified MIS and the connectors. These connectors, which form an initial Steiner tree, are discarded to identify new Steiner nodes in the second phase. In the second phase, iteratively the Steiner nodes are picked, which connects independent set nodes in different components. At the end of the second phase, the Steiner tree is formed out of Steiner nodes, thus, identified. It may be noted that the collaborative cover process involves an optimization to reduce the number of dominators. The computation is local, therefore, it is suitable for computing using a distributed approach.

Algorithm 1. CDS by collaborative cover heuristic

1: Initialize $\langle parent = \text{nil}\rangle, \text{level}\langle l = 0\rangle, \langle color = \text{white}\rangle$, $count = 0$ for each node.
2: Consider a leader node u initiating construction of the CDS. Leader node u, becomes a dominator and updates its state as $\langle color = \text{black}, parent = \text{ID}, l = 1\rangle$.
3: Node u sends message $m_1 = \langle u, l\rangle$ to its adjacent nodes.
4: Each adjacent node w on receiving $m_1 = \langle u, l\rangle$ from u becomes a dominatee and updates its variables as $\langle color = \text{gray}, parent = \text{u}, \text{level } l_w = l_u + 1\rangle$. Node w sends message $m_2 = \langle w, u, l_u + 1\rangle$ to identify the distance-2 nodes of u.
5: A white node v on receiving m_2 from w, becomes a distance-2 neighbor of u and updates its state variables as $\langle color = \text{yellow}, \text{level } l_v = l_u + 2\rangle$ and records its adjacent gray neighbors $N_{gray}(v) = \{w\}$, initializes adjacent yellow neighbors $N_{yellow} = nil$, updates effective degree nodes $N_{\text{eff}}(v) = N(v) - \{w\}$, where $N(v)$ is the nodes adjacent to v.
6: After a lapse of τ time, when all the m_2 messages are delivered to yellow nodes v, the yellow nodes v broadcast message $m_3 = \langle |N_{\text{eff}}(v)|\rangle$ containing its effective degree to its adjacent yellow nodes v.
7: Yellow nodes v of u on receiving m_3 from v' update its adjacent yellow neighbors $N_{yellow} = N_{yellow} \cup \{v'\}$, ranks its adjacent yellow nodes on the basis of their effective degree ($|N_{\text{eff}}|$, ID), where node ID is used for tie breaking. If node v has the highest effective degree node in its distance-1 vicinity, then v becomes a yellow leader. The yellow leader v broadcasts message $m_4 = \langle N_{yellow}(v)\rangle$ containing its coverage of yellow nodes to its adjacent yellow nodes.
8: Each yellow node v (of u) on receiving m_4 from yellow leader v', computes $I_{v'}(v) = N_{yellow}[v'] - N_{yellow}[v]$, the set of yellow nodes in the neighborhood of v' not

adjacent to v and broadcasts message $m_5 = \langle v, I_{v'}(v), N_{gray}(v), N_{\text{eff}}(v)\rangle$ to the yellow leader node v'.

9: Each yellow leader v (of u) on receiving m_4 from v' (of u), computes all MIS (yellow neighbors (v)) and then selects only those MISes whose $|MIS| > 1$ and have common gray neighbors as $D(v) = \{D_1, \ldots, D_k\}$ (possibly empty). Node v computes effective coverage of each $D_i, (\forall i \in 1..k)$. The effective coverage weight of $D_i(v)$ is given by:

$$weight_i = \frac{|N[D_i(v)] \cap (N_2(u) - N(u))|}{|D_i(v)|}.$$

This forms a tuple $D(v) = \{(D_1, wt_1, w_1), \ldots, (D_k, wt_k, w_k)\}$, where wt_i represents the coverage weight and w_k is common connector node at level-$(l+1)$. Each yellow leader node identifies on the basis of highest effective coverage weight, the MIS set D_h in its neighborhood (arbitrarily select one in case of tie). If the highest effective coverage weight, of the MIS set D_h is greater than the coverage of v itself, then yellow leader becomes *active*. Each active yellow leader v, sends message $m_5 = \langle \text{eff. coverage}(D_h), \text{ID}\rangle$ to its 2-hop neighboring yellow leaders of v. {Note that active yellow leader means it has an MIS which three properties 1) $|\text{MIS}| \geq 2$, 2) MIS has at least one common gray node and 3) effective coverage weight indicates that the effective coverage of this MIS is greater than coverage of yellow leader node itself. The active yellow leader triggers the pruning of MIS by activating all yellow leaders to elect a new set of MIS.}

10: Each active yellow leader v (of u) on receiving m_5 resolves the leaders of (active) yellow leader with highest effective coverage in its 2-hop region. The set of yellow leaders undergoes local pruning to identify local best coverage $MIS(N_2(u))$ (i.e an MIS of $N_2(u)$) in following two phases:
   1) In first phase each leader of yellow leaders in $(G^2[\text{yellow leaders}])$ is identified and the nodes its D_h become dominators and update $color = \text{black}$. Their common gray nodes becomes connectors by receipt of a message m_6.
   2) In second phase the remaining uncovered yellow nodes identify their MIS to become dominators (updating their color to black) to cover all the yellow nodes. The dominators of second phase sends message m_7 to select their connectors among the gray nodes (preferably which are already connectors of first phase).

11: Particular gray nodes at level $l+1$ on receiving m_6 or m_7 come to know whether they are connectors.

12: Note that the identification of connectors among the gray nodes completes the construction three levels $l, l+1, l+2$ of CDS construction. The connectors at level-$(l+1)$ are identified to connect level-l dominators with level-$(l+2)$ dominators by breadth first expansion of the CDS-tree in a distributed manner.

13: The algorithm phase-I terminates when no white nodes left unexplored.

{**Phase-II: Identifying Steiner nodes**}

{Phase-II discards the connectors and iteratively identifies Steiner nodes for connecting independent set nodes belonging to different components}

14: Each node in I broadcasts m_{10} message so that dominatees can know of adjacent independent set nodes in different components.

15: Initially all independent set nodes forms different components and the Steiner nodes list is empty. In the next step, dominatees having required number of adjacent independent set nodes in different components are identified as Steiner nodes iteratively.

16: **for** $i = 5, 4, 3, 2$ **do**

17:     **while** a gray node v exists having i-adjacent independent nodes of I in different components **do**

18:         Add node v into Steiner nodes list

19:     **end while**

20: **end for**{The identified Steiner nodes connect the dominator nodes to form a Steiner tree. Thus, independent set nodes and Steiner nodes forms the CDS of G}

8 Algorithm Analysis

In analysis of Algorithm 1, we provide the approximation factor of size of CDS and complexity analysis in following sections.

8.1 Approximation Analysis of CDS Algorithm

Lemma 1. *For Algorithm 1, the size of every maximal independent set computed in phase I is at most* $3.8\text{opt} + 1.2$, *where* opt *is the size of a minimum connected dominating set in the unit disk graph.*

Proof. From the result reported in [23]. □

Lemma 2. *The size of Steiner nodes obtained from Algorithm 1 is at most* $(1 + \ln 5)\text{opt}$, *where* opt *is the size of any optimal CDS.*

Proof. The proof follows directly from [15, theorem 2] because at step 15 of Algorithm 1, the set of connector nodes originally identified is discarded and a new set of Steiner nodes is identified in steps 16-20, also based on the Steiner node identification scheme reported in [15]. □

It may be noted that steps 16-20 for Algorithm 1 may optionally be skipped and the original set of connectors used in which case lemma 2 will no longer apply. However, in Section 9, we show that the original set of connectors that is identified compares well the connectors identified in steps 16-20.

Theorem 2. *For Algorithm 1, the size of the CDS is at most* $(4.8 + \ln 5)\text{opt} + 1.2$, *where* opt *is the size of any optimal CDS.*

Proof. From lemmas 1 and 2, we have:

$$\begin{aligned} |\text{CDS}| &= |I| + |\text{Steiner nodes}| \\ &= 3.8\text{opt} + 1.2 + (1 + \ln 5)\text{opt} \\ &= (4.8 + \ln 5)\text{opt} + 1.2. \end{aligned}$$

□

TABLE 1
Simulation Parameters

Parameter	Value	Summary
M	100×100	Deployment area.
r	25,50	Maximum transmission range
n	25-500	Network size
d	3-50	Network density, number of nodes per unit area

8.2 Complexity Analysis

Theorem 3. *The algorithm for Connected dominating set has time complexity $O(n)$ time and $O(D)$ rounds, where D is the network diameter and message complexity of $O(n\Delta^2)$, where Δ is the maximum degree of node in G.*

Proof. Assume that in a given unit disk, the size of an MIS is always less than maximum degree of a node in G, therefore, $|\text{MIS}| \leq \Delta$. Each node sends at most two messages to become gray (dominatee) and at most Δ messages per degree to update neighbor's information and Δ^2 to get neighbors of neighbor, to become dominator. Thus, message complexity is $O(n\Delta^2)$, where Δ is the maximum node degree.

While establishing the relationship between connectors and dominators, the message complexity is only size of CDS, which is at most $O(n)$. Thus, the message complexity of algorithm is $O(n\Delta^2)$. Each node is explored one by one, so the time complexity is $O(n)$. The number of synchronous rounds is $O(D)$, where D is the network diameter, which is bounded by the shortest distance of the farthest node from a given leader. □

9 Simulation Results

In this section, we present the simulation results to measure the performance of Algorithm 1. The first part of the section aims to analyze the performance of algorithm experimentally, whereas the second part measures the effectiveness of algorithm for a data aggregation application using an energy model. The simulation experiments considered for analyzing the performance are the following:

1. Performance comparison of Steiner nodes with independent set nodes.
2. Performance comparison of Steiner nodes against ignored connectors.
3. Performance comparison with the related techniques. The experiment for measuring the effectiveness on aggregation is given as
4. energy analysis of network for exploiting aggregation.

In the experimental setup, we model wireless ad hoc sensor network as a set of nodes deployed in a predetermined rectangular area of dimension 100×100 square units called as deployment area M. We use a uniform random number generator that chooses the x and y coordinates in deployment area M for sensor nodes. We assume that each node has the uniform transmission range r. The edge between any pair of nodes exists, if the distance between them is at most r. The induced graph of underlying network becomes a unit disk graph. In our simulation setup, we use the approximate governing relation for the transmission radius given by $r^2 = (d * M)/(\pi * n)$ [2]. The deployment area in our experimental setup is assumed as rectangular shape, which effects the nodes located at border as low degrees called as border effect. In our simulations, to offset border effect, we use a correction of higher transmission radius judiciously to nullify the border effect. The simulation parameters are summarized in Table 1. The Simulation is carried out in PROWLER/MATLAB, an event-driven simulator for Ad hoc Networks.

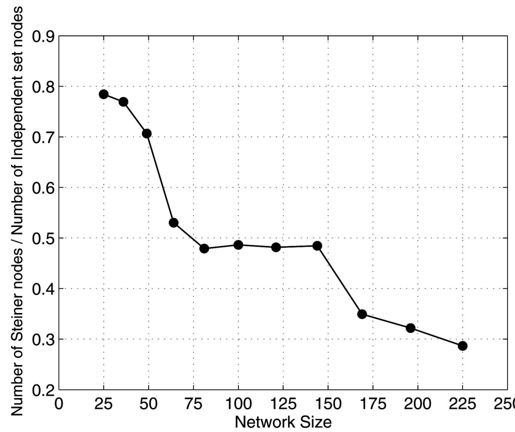

Fig. 2. Performance comparison of number of Steiner nodes and number of independent nodes.

In the first experiment, we compare the Steiner nodes required to connect the independent set nodes using a metric, which is the ratio of the number of Steiner nodes to the number of independent set nodes. Transmission range is chosen as 25 units. Network size is varied from 25 to 225 nodes. Note that we take connected graph into consideration. We run the algorithm 100 times on different sets of parameters. The averaged results are reported in Fig. 2. For large size networks, the ratio comes out to be lesser than 0.3 indicates that the Steiner nodes often connect more than three independent sets to achieve the results.

Next, we analyze through simulation the performance of Steiner nodes as compared to connectors identified while identifying independent set, which are ignored to identify optimal Steiner nodes as a postprocessing step. We give an account of how far we achieved in partial Steiner tree in our collaborative cover CDS algorithm.

The performance is shown in Fig. 3 of the 100 runs for the parameters n, r. The results show that our collaborative cover is quite close in identifying partial Steiner tree in its first phase of construction, and therefore, a postprocessing step only requires to identify some of the optimal Steiner nodes to achieve Steiner tree.

Note that besides this, our collaborative cover also gains in reducing independent set, which is discussed in later part of this section.

We also analyze the message exchanges for CDS construction in our algorithm. We run the algorithm 100 times on different sets of parameters varying network sizes from 100 to 500. The comparison shows that the number of messages in our CDS construction are closer to that of degree-CDS approach. Thus, our collaborative cover CDS is not sacrificing on the message overheads. The message complexity analysis of $O(n\Delta^2)$, where Δ is the maximum

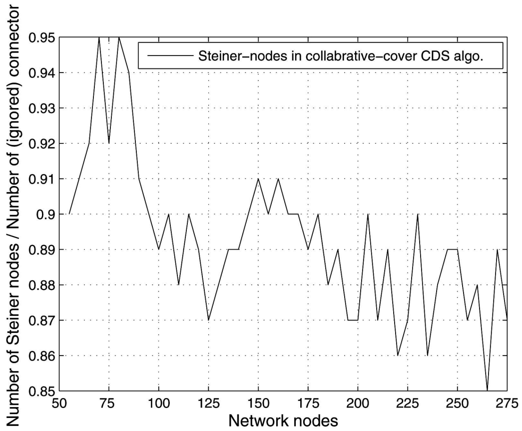

Fig. 3. Performance comparison of Steiner nodes with (ignored) connectors.

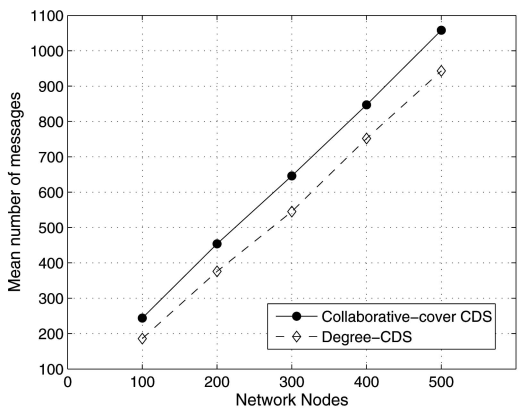

Fig. 4. Comparison of message exchanges in CDS construction.

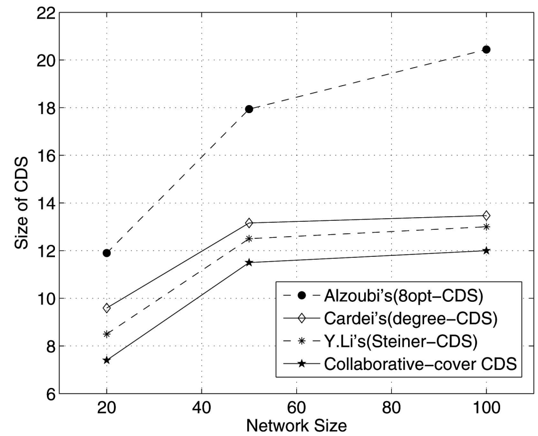

Fig. 5. Performance comparison with CDS algorithms ($\mathrm{R} = 25$).

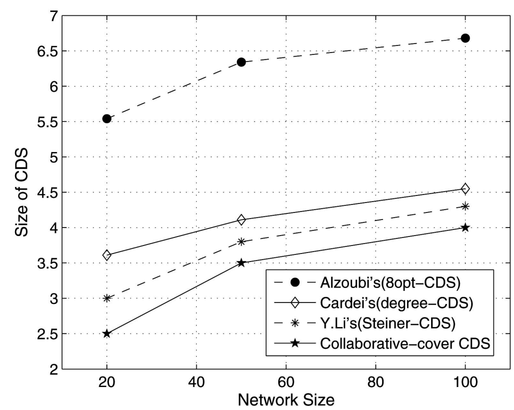

Fig. 6. Performance comparison with CDS algorithms ($\mathrm{R} = 50$).

degree of G, is also validated by comparing the simulation results (shown in Fig. 4) with degree-CDS scheme.

Finally, we compare the performance of our collaborative cover-based CDS algorithm with the CDS algorithm reported by Cardei et al. [5], Wan et al. [21], and Li et al. [15]. Assume the maximum transmission range values to be (25 or 50) units for the network with varying the node sizes as (20 or 50 or 100). We considered only the connected graph for our result analysis.

The performance comparison is shown in Fig. 5, for maximum transmission range $\mathrm{r} = 25$, whereas for $\mathrm{r} = 50$ is shown in Fig. 6 to demonstrate the comparison of the 100 runs for some parameter sets. The simulation results reveal that our collaborative cover-based CDS algorithm reduces the size of CDS by 15 percent compared to Cardei et al.'s [5] approach, whereas reduction of CDS size is 10 percent in Li et al.'s CDS [15] approach. From both the results, we observe that our proposed one is better than Wan et al.'s [21], Cardei et al.'s [5], and Li et al.'s [15] approach in identifying a smaller size of CDS.

9.1 Aggregation-Based Energy Model

In order to evaluate the energy profile for data aggregation in our aggregation-CDS algorithm, we considered an aggregation-based energy model. Let the energy dissipation for aggregation to be 5 nJ/bit. This value is drawn from realistic experimentation reported in the literature as energy dissipation for performing beamforming computations to aggregate data is 5 nJ/bit [12]. Table 2 summarizes the system parameter used for energy modeling in our simulation.

TABLE 2
Description of Parameters

Parameter	Value	Summary
E_l	50nJ/bit	Energy dissipated in transceiver for per bit operation.
E_{agg}	5nJ/bit	Energy dissipated in data aggregation per bit
α_{friss}	10pJ/bit/m^2	radio transmitter coefficient for short distances.
α_{2-ray}	0.0013pJ/bit/m^4	radio transmitter coefficient for longer distances.
M	100m^2	target area of 100x100m^2.
m	1000bit	frame size in bit per round of data gathering.

In order to evaluate the role of the number of dominators in energy dissipation, we need to compare energy dissipation in the entire network in aggregation CDS with degree CDS. Consider the energy dissipation of nodes in network represented as E_{dom} for nodes having dominator's role and $E_{non\text{-}dom}$ for the nondominators. The nondominators nodes spend energy $E_{non\text{-}dom}$ to communicate the sensed data to the nearest dominator at distance d within direct transmission radius r_{max}, and therefore, obey Friss free space propagation model having attenuation d^2 with coefficient (α_{friss}). Let E_l be the per bit energy dissipation of transceiver

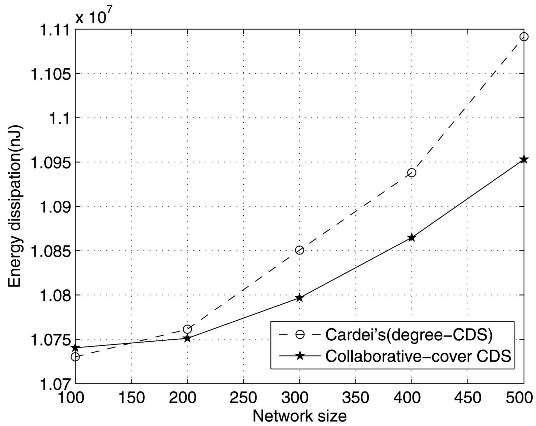

Fig. 7. Performance comparison of aggregation energy dissipation with degree-CDS algorithm.

electronics. In order to transmit a message of m-bits at a distance d, the nondominator expends energy:

$$E_{non\text{-}dom} = m.E_l + m.\alpha_{\text{friss}}.d^2. \quad (1)$$

Let the dominators dissipate energy E_{dom} in 1) receiving information from dominatees (E_l), 2) performing aggregation (E_{agg}), and 3) transmitting aggregate data to base station ($\alpha_{2\text{-}ray}.d^4$). It may be noted that the average distance d between dominator and base station is much greater than maximum transmission radius r_{max}. Thus, the network nodes have two modes of communication, i.e., higher range communication (beyond $d > r_{max}$) and multihop communication. Using opportunistic routing if multihop energy dissipation greater than higher range direct transmission energy, then the higher range transmission is used which follows 2-ray propagation model with attenuation d^4. Thus, the multihop communication energy is upper bounded by energy dissipation of 2-ray propagation model with attenuation d^4. Thus, to transmit m-bit message after aggregating data from its dominatees in its neighborhood say $|\text{Nbd}|$, the radio energy E_{dom} expends:

$$E_{dom} = m.E_l.|\text{Nbd}| + m.E_{agg}.|\text{Nbd}| + m.\alpha_{2\text{-}ray}.d^4. \quad (2)$$

Thus, energy dissipation of a dominator and its dominatee is given by

$$E_{total\text{-}dom} = E_{dom} + |\text{Nbd}|.E_{non\text{-}dom}. \quad (3)$$

Therefore, total energy dissipation of network with $|\text{CDS}| = k$ dominators is given by

$$E_{total} = k.E_{total\text{-}dom}. \quad (4)$$

Equation (4) provides the total energy dissipation of network in communicating the sensed data to base station while performing aggregation at the dominators of CDS. Using (4), we conducted an experiment to simulate our CDS algorithm for computing the network-wide energy dissipation and analyze the effect of smaller size of CDS on in-network aggregation in energy dissipation of network. We have taken a frame m of size 1,000 of sensing data generated from all nodes, which is communicated by our CDS-based aggregation backbone to the base station located centrally inside target area. The simulation results are captured for single round of data gathering application. We then compare the energy dissipation for single-round data communication for degree-based CDS [5]. The results in Fig. 7 show the crossover at the early network size of 100 nodes and beyond network size 200 onward in our aggregation-CDS reduces the dissipation energy substantially of sensed data communication even for a single round. The reduction in the network-wide energy dissipation using our aggregation-CDS results in increase of the network lifetime.

10 Summary

In this paper, we have described a distributed approximation algorithm for identifying a minimal size connected dominating set using the collaborative cover heuristic for which the approximation factor is at most $(4.8 + \ln 5)\text{opt} + 1.2$, where opt is the size of any optimal CDS. A postprocessing step identifies the Steiner nodes leading to a Steiner tree for independent set nodes. This improves upon the existing approximation for reported CDS algorithms. When our proposed CDS scheme is used for lossless in-network aggregation function, it shows a substantial improvement in reducing energy dissipation of network compared to the degree-based CDS. The message complexity of our algorithm is at most $O(n\Delta^2)$, where being the maximum degree of a node in graph and time complexity is $O(n)$.

References

[1] C. Adjih, P. Jacquet, and L. Viennot, "Computing Connected Dominated Sets with Multipoint Relays," *Ad Hoc & Sensor Wireless Networks*, vol. 1, nos. 1/2, pp. 27-39, 2005.
[2] I.F. Akyildiz, W. Su, Y. Sankarasubramaniam, and E. Cayirci, "A Survey on Sensor Networks," *IEEE Comm. Magazine*, vol. 40, no. 8, pp. 102-114, Aug. 2002.
[3] K.M. Alzoubi, P.-J. Wan, and O. Frieder, "Message-Optimal Connected Dominating Sets in Mobile Ad Hoc Networks," *Proc. ACM MobiHoc*, pp. 157-164, 2002.
[4] J. Blum, M. Ding, A. Thaeler, and X. Cheng, *Connected Dominating Set in Sensor Networks and MANETs*, pp. 329-369. Kluwer Academic, 2004.
[5] M. Cardei, M.X. Cheng, X. Cheng, and D.Z. Du, "Connected Dominating Set in Ad Hoc Wireless Networks," *Proc. Sixth Int'l Conf. Computer Science and Informatics (CS&I '02)*, 2002.
[6] B.N. Clark, C.J. Colbourn, and D.S. Johnson, "Unit Disk Graphs," *Discrete Math.*, vol. 86, nos. 1-3, pp. 165-177, Jan. 1990.
[7] B. Das, R. Sivakumar, and V. Bharghavan, "Routing in Ad Hoc Networks Using a Spine," *Proc. Sixth Int'l Conf. Computer Comm. and Networks (IC3N '97)*, p. 34, 1997.
[8] A. Ephremides, J. Wieselthier, and D. Baker, "A Design Concept for Reliable Mobile Radio Networks with Frequency Hopping Signaling," *Proc. IEEE*, vol. 75, no. 1, pp. 56-73, Jan. 1987.
[9] S. Funke, A. Kesselman, U. Meyer, and M. Segal, "A Simple Improved Distributed Algorithm for Minimum cds in Unit Disk Graphs," *ACM Trans. Sensor Networks*, vol. 2, no. 3, pp. 444-453, 2006.
[10] H. Gupta, V. Navda, S.R. Das, and V. Chowdhary, "Efficient Gathering of Correlated Data in Sensor Networks," *Proc. ACM MobiHoc*, pp. 402-413, 2005.
[11] T.W. Haynes, S.T. Hedetniemi, and P.J. Slater, *Fundamentals of Domination in Graphs*. CRC Press, 1998.
[12] W. Heinzelman, A. Chandrakasan, and H. Balakrishnan, "An Application-Specific Protocol Architecture for Wireless Microsensor Networks," *IEEE Trans. Wireless Comm.*, vol. 1, no. 4, pp. 660-670, Oct. 2002.
[13] C. Intanagonwiwat, R. Govindan, and D. Estrin, "Directed Diffusion: A Scalable and Robust Communication Paradigm for Sensor Networks," *Mobile Computing and Networking*, pp. 56-67, 2000.

[14] D. Kim, Y. Wu, Y. Li, F. Zou, and D.-Z. Du, "Constructing Minimum Connected Dominating Sets with Bounded Diameters in Wireless Networks," *IEEE Trans. Parallel and Distributed Systems,* vol. 20, no. 2, pp. 147-157, Feb. 2009.

[15] Y. Li, M.T. Thai, F. Wang, C.W. Yi, P.J. Wang, and D.Z. Du, "On Greedy Construction of Connected Dominating Sets in Wireless Networks," *Wireless Comm. and Mobile Computing (WCMC),* vol. 5, no. 8, pp. 927-932, Jan. 2005.

[16] S. Lindsey, C. Raghavendra, and K.M. Sivalingam, "Data Gathering Algorithms in Sensor Networks Using Energy Metrics," *IEEE Trans. Parallel and Distributed Systems,* vol. 13, no. 9, pp. 924-935, Sept. 2002.

[17] M.V. Marathe, H. Breu, H.B. Hunt, III, S.S. Ravi, and D.J. Rosenkrantz, "Simple Heuristics for Unit Disk Graphs," *Networks,* vol. 25, pp. 59-68, 1995.

[18] O. Ore, *Theory of Graphs,* vol. 38. Am. Math. Soc. Colloquium Publications, 1962.

[19] M.T. Thai, F. Wang, D. Liu, S. Zhu, and D.-Z. Du, "Connected Dominating Sets in Wireless Networks with Different Transmission Ranges," *IEEE Trans. Mobile Computing,* vol. 6, no. 7, pp. 721-730, July 2007.

[20] M.T. Thai, N. Zhang, R. Tiwari, and X. Xu, "On Approximation Algorithms of K-Connected M-Dominating Sets in Disk Graphs," *Theoretical Computer Science,* vol. 385, nos. 1-3, pp. 49-59, 2007.

[21] P.-J. Wan, K.M. Alzoubi, and O. Frieder, "Distributed Construction of Connected Dominating Set in Wireless Ad Hoc Networks," *Mobile Networks and Applications,* vol. 9, no. 2, pp. 141-149, 2004.

[22] J. Wu and H. Li, "On Calculating Connected Dominating Set for Efficient Routing in Ad Hoc Wireless Networks," *Proc. Third Int'l Workshop Discrete Algorithms and Methods for Mobile Computing and Comm. (DIALM '99),* pp. 7-14, 1999.

[23] W. Wu, H. Du, X. Jia, Y. Li, and S.C.H. Huang, "Minimum Connected Dominating Sets and Maximal Independent Sets in Unit Disk Graphs," *Theoretical Computer Science,* vol. 352, no. 1, pp. 1-7, 2006.

[24] Y. Xu, J.S. Heidemann, and D. Estrin, "Geography-Informed Energy Conservation for Ad Hoc Routing," *Proc. ACM MobiCom,* pp. 70-84, 2001.

[25] S. Yang, J. Wu, and F. Dai, "Efficient Backbone Construction Methods in Manets Using Directional Antennas," *Proc. 27th Int'l Conf. Distributed Computing Systems (ICDCS '07),* p. 45, 2007.

[26] S. Guha and S. Khuller, "Approximation Algorithms for Connected Dominating Sets," *Algorithmica,* vol. 20, no. 4, pp. 374-387, Apr. 1998.

Rajiv Misra received the MTech degree in CSE from the Indian Institute of Technology (IIT) Bombay in 1989 and the PhD degree from IIT Kharagpur in 2009. He is currently an assistant professor in the Department of Computer Science and Engineering at IIT Patna. He works in the area of mobile computing. His research interest includes the algorithms for ad hoc and sensor networks. He is a member of the IEEE.

Chittaranjan Mandal received the PhD degree from the Indian Institute of Technology (IIT) Kharagpur in 1997. He is currently an associate professor in the Department of Computer Science and Engineering and School of Information Technology at IIT Kharagpur. Prior to joining IIT, he served as a reader with Jadavpur University, Calcutta. His research interests include networked systems, formal modeling and design, and Web technologies. Since 2000, he has been an industrial fellow of Kingston University, London, United Kingdom. He was a recipient of the Royal Society Fellowship in 2006. He is a member of the IEEE.