Hindawi Publishing Corporation
EURASIP Journal on Wireless Communications and Networking
Volume 2007, Article ID 40154, 15 pages
doi:10.1155/2007/40154

Research Article

Constructing Battery-Aware Virtual Backbones in Wireless Sensor Networks

Chi Ma,[1] Yuanyuan Yang,[2] and Zhenghao Zhang[3]

[1] *Department of Computer Science, Stony Brook University, Stony Brook, NY 11794, USA*
[2] *Department of Electrical and Computer Engineering, Stony Brook University, Stony Brook, NY 11794, USA*
[3] *Department of Computer Science, Carnegie Mellon University, 5000 Forbes Avenue, Pittsburgh, PA 15213-3891, USA*

Received 14 October 2006; Accepted 13 March 2007

Recommended by Lionel M. Ni

A critical issue in battery-powered sensor networks is to construct energy efficient virtual backbones for network routing. Recent study in battery technology reveals that batteries tend to discharge more power than needed and reimburse the over-discharged power if they are recovered. In this paper we first provide a mathematical battery model suitable for implementation in sensor networks. We then introduce the concept of battery-aware connected dominating set (BACDS) and show that in general the minimum BACDS (MBACDS) can achieve longer lifetime than the previous backbone structures. Then we show that finding a MBACDS is NP-hard and give a distributed approximation algorithm to construct the BACDS. The resulting BACDS constructed by our algorithm is at most $(8 + \Delta)$opt size, where Δ is the maximum node degree and opt is the size of an optimal BACDS. Simulation results show that the BACDS can save a significant amount of energy and achieve up to 30% longer network lifetime than previous schemes.

1. INTRODUCTION

A sensor network is a distributed wireless network which is composed of a large number of self-organized unattended sensor nodes [1–3]. Sensor nodes, which are small in size and communicate untethered in short distance, consist of sensing, data processing, and communication components with limited battery supply. Applications of sensor networks range from outer-space exploration, medical treatment, emergency response, battlefield monitoring to habitat, and seismic activity monitoring. A typical function of sensor networks is to collect data in a sensing environment. Usually the sensed data in such an environment is routed to a sink, which is the central unit of the network [4–6]. Although a sensor network does not have a physical infrastructure, a virtual backbone can be formed by constructing a *connected dominating set* (CDS) [7–9] in the network for efficient packet routing, broadcasting, and data propagating.

In general, a sensor network can be modeled as a graph $G = (V, E)$, where V and E are the sets of nodes and edges in G, respectively. A CDS is a connected subgraph of G where all nodes in G are at most one hop away from some node in the subgraph. Figure 1 shows a CDS for a given sensor network. In this example, packets can be routed from the source (node I) to a neighbor in the CDS (node G), along the CDS backbone to a dominating set member (node D), which is closest to the destination (node B), and then finally to the destination. A node in the CDS is referred to as a *dominator*, and a node not in the CDS is referred to as a *dominatee*. There has been a lot of work that dedicates to construct a *minimum connected dominating set* (MCDS) which is a CDS with a minimum number of dominators. Unfortunately, finding such an MCDS in a general graph was proven to be NP-hard [10, 11]. So was in a *unit disk graph* (UDG) [12], where nodes have connections only within unit distance. Approximation algorithms were proposed to construct CDS, see, for example, [13–15]. The CDS computed by these algorithms has at most $8\,\text{opt}_{\text{MCDS}}$ size, where opt_{MCDS} is the size of the MCDS.

Although previous CDS construction algorithms achieve good results in terms of the size of the CDS, a minimum size CDS does not necessarily guarantee the optimal network performance from an energy efficient point of view. The MCDS model assumes that the battery discharging of a sensor node is linear, in other words, the energy consumed from a battery is equivalent to the energy dissipated in the device. However, research has found that this is a rather rough assumption on

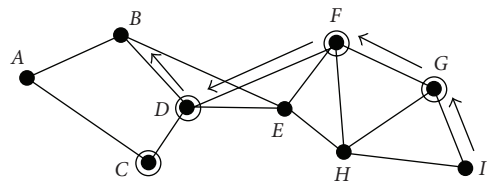


Figure 1: The minimum connected dominating set (MCDS) $\{C, D, F, G\}$ forms a backbone for the sensor network. A packet is forwarded from node I to node B by the backbone.

the real sensor batteries [16–19]. Recent study on battery behavior reveals that, unlike what we used to believe, batteries tend to discharge more power than needed, and reimburse the over-discharged power later if they have appropriate rests [16–18]. The process of this reimbursement is referred to as *battery recovery*. In this paper, we will present a mathematical battery discharging model, which is independent of battery chemistry. This model can accurately model the battery discharging/recovery behavior with online computable functions for implementing in wireless ad hoc networks. Based on this model, we will introduce *battery-aware connected dominating set* (BACDS) and show that the BACDS can achieve better network performance than the MCDS.

The rest of the paper is organized as follows. In Section 2, we discuss some background and related work to place our work in context. We study the mathematical battery model in detail and present a simplified model suitable for sensor network applications in Section 3. Section 4 first gives the BACDS model along with its performance comparison with the MCDS model, then presents a distributed approximation algorithm to construct the BACDS. We also analyze the performance of the algorithm and give an upper bound on the size of the BACDS obtained in this section. Finally, we give simulation results in Section 5 and concluding remarks in Section 6.

2. BACKGROUND AND RELATED WORK

Before constructing the battery-aware CDS, in this section, we provide some background on battery models and existing CDS construction algorithms.

2.1. Modeling battery discharge behavior

The most commonly used batteries in wireless devices and sensors are nickel-cadmium and lithium-ion batteries. In general, a battery consists of cells arranged in series, parallel, or a combination of both. Two electrodes: an anode and a cathode, separated by an electrolyte, constitute the active material of each cell. When the cell is connected to a load, a reduction-oxidation reaction transfers electrons from the anode to the cathode. To illustrate this phenomenon, Figure 2 shows a simplified symmetric electrochemical cell. In a fully charged cell (Figure 2(a)), the electrode surface contains the maximum concentration of active species. When the cell is connected to a load, an electrical current flows through the external circuit. Active species are consumed at the electrode surface and replenished by diffusion from the bulk of the electrolyte. However, this diffusion process cannot keep up with the consumption, and a concentration gradient builds up across the electrolyte (Figure 2(b)). A higher load electrical current I results in a higher concentration gradient and thus a lower concentration of active species at the electrode surface [20]. When this concentration falls below a certain threshold, the electrochemical reaction can no longer be sustained at the electrode surface and the charge is unavailable at the electrode surface (Figure 2(e)). However, the unused charge is not physically "over-consumed," but simply unavailable due to the lag between the reaction and the diffusion rates. If the battery current I is reduced to zero or a very small value, the concentration gradient flattens out after a sufficiently long time, reaching equilibrium again (Figure 2(c)). The concentration of active species near the electrode surface following this recovery period makes unused charge available again for extraction (Figure 2(d)). We refer to the unused charge as *discharging loss*. Effectively recovering the battery can reduce the concentration gradient and recover discharging loss, hence, prolong the lifetime of battery (Figure 2(f)). Experiments on nickel-cadmium battery and lithium-ion battery show that the discharging loss might take up to 30% of the total battery capacity [19]. Hence, precisely modeling battery behavior is essential for optimizing system performance in sensor networks.

Researchers have developed high-level mathematical models that capture the battery behavior and are independent of battery chemistry [17–19]. An analytical battery model was proposed in [19], however, this model requires long computing time and large precomputed look up tables. We therefore provided a discrete time battery model in [17, 18] with online computable functions. This model splits the time into discrete time slots with a fixed slot length and is suitable for packetized ad hoc networks. We will discuss this model in more detail in Section 3.

2.2. Distributed algorithms for MCDS construction

As we discussed in Section 1, CDS is the virtual backbone of a wireless sensor network. Packets route through CDS to the sink or to other sensors. A non-CDS network is a network that does not adopt CDS as backbone, which would reduce its overall performance as indicated in previous research [9, 21]. Algorithms for constructing CDS in wireless sensor networks have been studied by several researchers [21, 22]. The first algorithm reported in [22] is a greedy heuristic algorithm with bounded performance guarantees. In this algorithm, initially all nodes are colored white. The CDS is grown from one node outward by coloring black those nodes that have maximum number of white neighbors. This algorithm yields a CDS of size at most $2(1 + H(\Delta))\,\mathrm{opt}_{\mathrm{MCDS}}$, where H is the harmonic function and Δ is the maximum node degree. Das, et al. proposed an algorithm based on [22] by selecting a node with the maximum degree as the root of a spanning tree T, then repeatedly running the coloring procedure to form the spanning tree [9]. This algorithm has an approximation

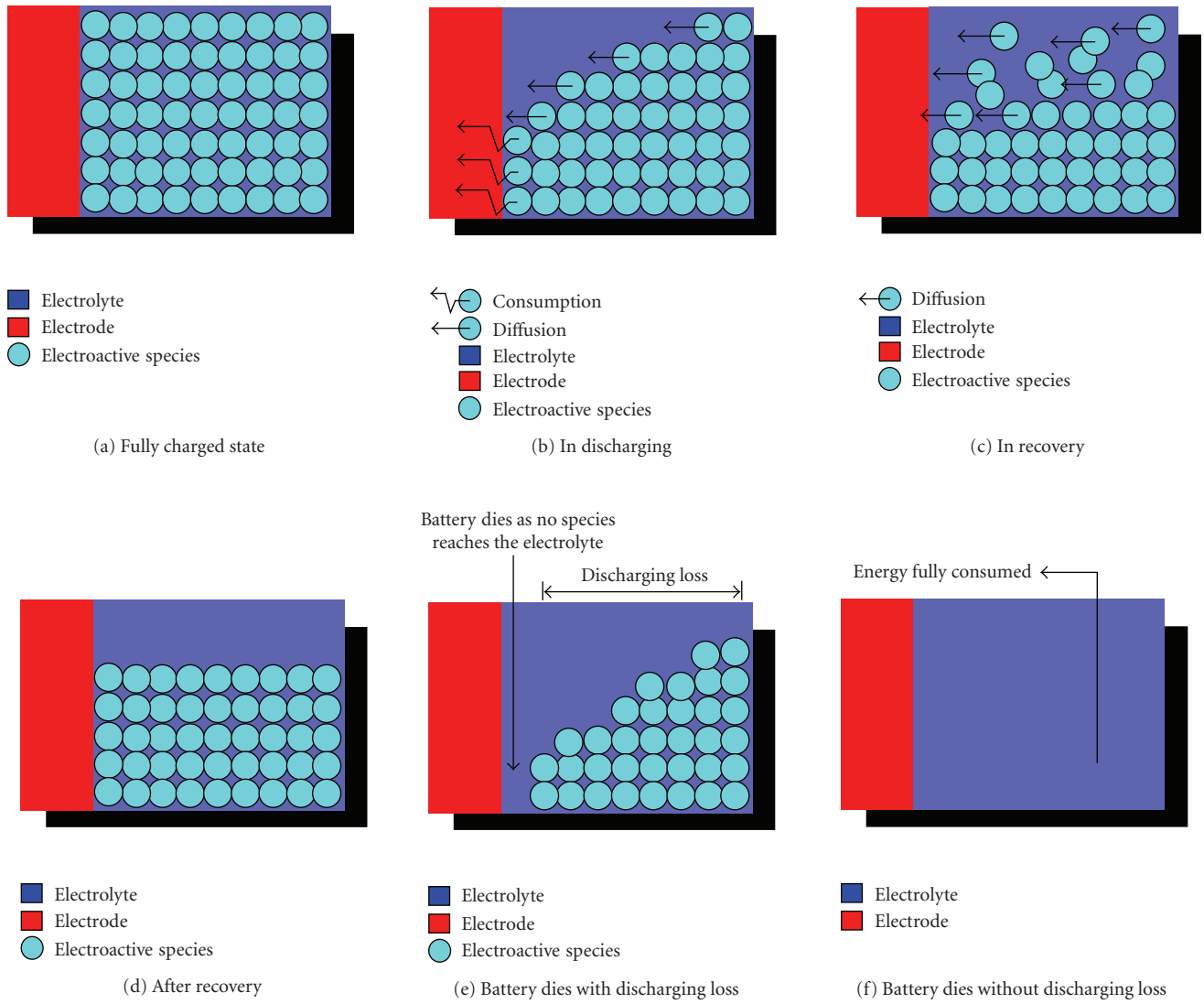


Figure 2: Battery operation at different states.

ratio of $O(\log \Delta)$ for a general graph. However, these algorithms are centralized algorithms, which makes their applications quite limited.

Distributed algorithms for CDS constructions have been proposed in recently years. They can be categorized as WCDS-based, Pruning-based and MIS-based, approaches. In these distributed algorithms, each node in the network is assigned a unique ID. The *weakly connected dominating set* (WCDS) is a dominating set of graph G such that WCDS and its neighbors induce a connected subgraph of G. In a WCDS, the nodes are partitioned into a set of cluster heads and cluster members, such that each cluster member is within the radio range of at least one cluster head. In the algorithm proposed in [23], nodes elect their neighbor with the lowest ID as their cluster head. Whenever a node with a lower ID moves into the range of a cluster head, it becomes the new cluster head. A problem of this algorithm is that the cluster structure is very unstable: when a lower ID node moves in, a cluster may break into many subclusters. Apparently, this reorganization is unnecessary in many situations.

Pruning-based approaches construct a CDS first and then prune the redundant nodes from this CDS [9]. In a pruning-based algorithm, any node having two disconnected neighbors is marked as a dominator. The redundant dominator set is post-processed by pruning nodes out of the CDS. The closed neighbor set of node u is defined as the set of u's neighbors plus u itself. A node u is pruned out if there exists a node v with higher ID such that the closed neighbor set of u is a subset of the closed neighbor set of v. Unfortunately, the theoretical bound on the resulting CDS obtained by this algorithm remains unspecified.

Minimum independent set (MIS) is an independent set such that adding any new node to the set breaks the independence property of the set. Thus, every node in the graph is adjacent to some node in the MIS. MIS-based algorithms construct a CDS by finding an MIS and then connect it.

References [13, 15] gave an algorithm for unit disk graphs with performance bounds. It first constructs a rooted spanning tree in G, then a labeling process begins from the root to the leaves by broadcasting "Dominator/Dominatee" messages to form the MIS. The final phase connects the nodes in the MIS to form a CDS. The algorithm has time and message complexities of $O(n)$ and $O(n \log n)$, respectively, for an n-node graph. The resulting CDS has a size of at most $8\,\mathrm{opt}_{\mathrm{MCDS}}$. Reference [14] presented a multileader MIS-based algorithm by rooting the CDS in multiple sources. Its performance ratio is $192|\,\mathrm{opt}_{\mathrm{MCDS}}\,| + 8$.

All the existing MCDS algorithms assume that the battery discharging of a sensor node is linear. This is a rough assumption as shown in Section 2.1, and it does not necessarily guarantee the optimal network performance from an energy efficient point of view. In the following sections we will introduce an accurate battery model to describe the battery discharging behavior. Then we will use this battery model to construct energy efficient virtual backbones in wireless sensor networks.

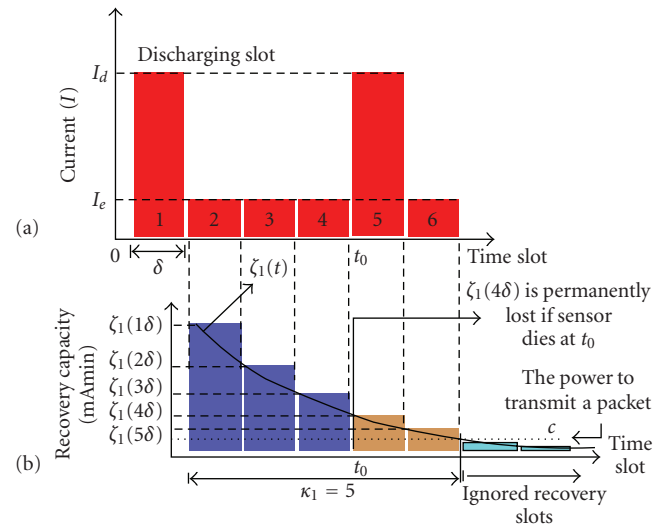
3. BATTERY DISCHARGING MODELS

The battery discharging model presented in [17, 18] is an online computable model for general ad hoc wireless networks. In this section, we further reduce the computational complexity to make it implementable in sensor networks. We assume that a battery is in discharging during time $[t_{\mathrm{begin}}, t_{\mathrm{end}}]$ with current I. The consumed power α is calculated in [17, 18] as

$$\alpha = I \times (t_{\mathrm{end}} - t_{\mathrm{begin}}) + I \times \frac{\pi^2}{3\beta^2} \times \left(e^{-\beta^2(t-t_{\mathrm{end}})} - e^{-\beta^2(t-t_{\mathrm{begin}})}\right), \tag{1}$$

where t is the current time and β is a constant parameter. The right-hand side of (1) contains two components. The first term, $I \times (t_{\mathrm{end}} - t_{\mathrm{begin}})$, is simply the energy consumed in device during $[t_{\mathrm{begin}}, t_{\mathrm{end}}]$. The second term is the discharging loss in $[t_{\mathrm{begin}}, t_{\mathrm{end}}]$ and it decreases as t increases. The constant β (> 0) is an experimental chemical parameter which may be different from battery to battery. In general, the larger the β, the faster the battery diffusion rate, hence, the less the discharging loss.

In ad hoc networks, current I is a continuous variable for various applications such as operating systems, multimedia transmission, word processing, and interactive games. However, in sensor networks, the simple sensing and data propagating activities of sensor nodes may only require several constant currents [24]. We define the constant currents of dominator nodes and dominatee nodes as I_d and I_e, respectively. A dominator needs to keep active and listen to all channels at all times. Compared with I_d, the I_e of a dominatee is very low. We divide the sensor lifetime into discrete time slots with slot length δ. In each time slot, the battery of a node is either as a dominator ($I = I_d$) or a dominatee ($I = I_e$). Figure 3(a) shows the discrete time activities on a



$m = 4, i = 2, \kappa_2 < (m - i)$
Entry 2 should be removed

Time slot (i)	κ_i	Current (I)
1	5	1
2	1	0
3	1	0

(c) Recovery table

FIGURE 3: The discharging of a sensor battery. (a) The node is a dominator in slots 1 and 5 and dominatee in slots 2, 3, 4, and 6. (b) The capacity $\zeta_1(t)$ is discharged in slot 1 and recovered gradually in the following slots. $\zeta_1(t)$ after slot 6 is ignored. If this battery dies in slot 5, $\zeta_1(4\delta)$ is permanently lost. (c) The recovery table records the recovery status κ_i at $m = 4$. The 0 and 1 in the current column stand for I_d and I_e, respectively.

sensor node, where $\zeta_n(t)$ is the discharging loss in the nth time slot $[(n-1)\delta, n\delta]$, $n \geq 1$. From (1), we have

$$\zeta_n(t) = I_n \times \frac{\pi^2}{3\beta^2}\left(e^{-\beta^2(t-n\delta)} - e^{-\beta^2(t-(n-1)\delta)}\right), \tag{2}$$

where I_n is either I_d or I_e, and t is the current time.

We can see that $\zeta_n(t)$ is recovered gradually in the following $(n+1)$th, $(n+2)$th, ... slots until t. It should be mentioned that discharging loss $\zeta_n(t)$ is only a potentially recoverable energy. In Figure 3, if the battery dies at the 5th slot, the energy $\zeta_1(4\delta), \ldots, \zeta_4(4\delta)$ do not have a chance to be recovered. Thus, the battery permanently loses them. At time t, the gross discharging loss energy of this battery is

$$\zeta(t) = \sum_{i=1}^{m} \zeta_i(t), \tag{3}$$

where $m = \lfloor t/\delta \rfloor$. The lower the $\zeta(t)is$, the better the battery is recovered. To be aware of the battery recovery status, $\zeta(t)$ needs to be calculated at each slot. However, the computation can be simplified by observing that $\zeta_i(t)$ decreases exponentially as t increases. Naturally, $\zeta_i(t)$ can be ignored if $\zeta_i(t)$ is less than a small amount of power c, where c is the power to transmit a single packet. We introduce κ_i such as

Table 1: The maximum size of the recovery table ($\beta = 0.4$).

c/I_d	1200 mA	800 mA	400 mA	100 mA
200 mAmin	1	2	3	4
400 mAmin	2	3	3	5
600 mAmin	3	3	4	6
800 mAmin	3	4	5	6

$\zeta_i(\kappa_i\delta) < c < \zeta_i((\kappa_i - 1)\delta)$, that is, after $t = \kappa_i\delta$, $\zeta_i(t)$ is ignored. We have

$$\kappa_i = \left\lceil \frac{1}{\beta^2\delta} \log \frac{\pi^2(1 - e^{-\beta^2\delta})}{3\beta^2 c/I_i} \right\rceil, \tag{4}$$

where $I_i = I_d$ or I_e. We maintain κ_i in a recovery table. At the mth slot, if $\kappa_i < (m - i)$, which indicates that $\zeta_i(m\delta) < c$, then this entry i is removed from the table. An example is given in Figure 3(c) where the second entry is about to be removed.

Introducing this recovery table has several advantages and is also feasible for sensor networks. First, we can reduce the computational complexity of battery-awareness. Only the remained entries in the table are used for computing $\zeta(t)$. Now (3) can be rewritten as

$$\zeta(t) = \sum_j \zeta_j(t), \tag{5}$$

where entry j is the entry remained in the recovery table. Second, we can reduce the complexity of table maintenance. In order to check whether an entry needs to be removed, rather than calculating $\zeta_i(t)$ for every i at each time, we only need to read κ_i from the table and compare it with m. Because κ_i is computed once, maintaining the recovery table is simple. Third, the size of the table is feasible for sensor memory. According to (4) and (5), the total entries in the recovery table are no more than $\lceil (1/\beta^2\delta) \log(\pi^2(1 - e^{-\beta^2\delta})/3\beta^2 c/I_d) \rceil$. For various possible values of I_d and c of sensors, Table 1 shows the maximum number of entries in a recovery table ($\beta = 0.4$). Considering that the memory capacity of today's sensor node is typically larger than 512 KB [25, 26], it is acceptable to store and maintain such a recovery table in sensor memory. Thus, we can reduce the computational complexity by maintaining a recovery table on a sensor node with a feasible table size.

In summary, in this section we use the battery model to achieve battery-awareness by capturing its recovery $\zeta(t)$. The lower the $\zeta(t)$, the better the sensor node is recovered at time t. We introduce the recovery table to reduce the computational complexity. We also show that maintaining such a table is feasible for today's sensor nodes. Next we apply this battery model to construct the BACDS to prolong network lifetime.

4. BATTERY-AWARE CONNECTED DOMINATING SET

In this section, we first introduce the concept of battery-aware connected dominating set (BACDS), and show that the BACDS can achieve better network performance. Then we provide a distributed algorithm to construct BACDS in sensor networks.

MCDS algorithm:
Repeat
Every node i with $P_{\text{residual}}(i) \geq P_{\text{threshold}}$ is marked as *qualified*;
All other nodes are marked as *unqualified*;
Call *MCDS construction algorithm* for all *qualified* nodes;
If successful, use the MCDS constructed as the backbone;
Otherwise report "no backbone can be formed" and exit;
Until Some dominator j has $P_{\text{residual}}(j) < P_{\text{threshold}}$;

BACDS algorithm:
Repeat
Every node i with $P_{\text{residual}}(i) \geq P_{\text{threshold}}$ is marked as *qualified*;
All other nodes are marked as *unqualified*;
Call *BACDS construction algorithm* for all *qualified* nodes;
If successful, use the BACDS constructed as the backbone;
Otherwise report "no backbone can be formed" and exit;
Until δ time has elapsed or some dominator j has
$P_{\text{residual}}(j) < P_{\text{threshold}}$;

Algorithm 1: Outline of MCDS and BACDS algorithms for forming a virtual backbone.

4.1. Battery-aware dominating

Let the sensor network be represented by a graph $G = (V, E)$ where $|V| = n$. For each pair of nodes $u, v \in V$, $(u, v) \in E$ if and only if nodes u and v can communicate in one hop. The maximum node degree in G is Δ. Each node v is assigned a unique ID_v. $P_{\text{residual}}(v)$ is v's residual battery power. $P_{\text{threshold}}$ is the threshold power adopted in CDS construction algorithms. $\zeta^v(t)$ is the discharging loss of v at time t. For any subset $U \subseteq V$, we define $\zeta^U_{\max} = \max\{\zeta^v(t) \mid v \in U\}$.

Next we explain how to use the battery model to construct an energy-efficient dominating set in a sensor network. Intuitively, longer network lifetime can be achieved by always choosing the "most fully recovered" sensor nodes as dominators. For a graph $G = (V, E)$ at time t, we define a BACDS as a set $S_B (\subseteq V)$ such that

$$S_B \text{ is a CDS of } G, \qquad \zeta^{S_B}_{\max} = \min\{\zeta^S_{\max} \mid S \text{ is a CDS of } G\}. \tag{6}$$

An optimal BACDS is a BACDS with a minimum number of nodes and is denoted as MBACDS. For notational convenience, we let

$$\zeta^{\text{BACDS}} \equiv \min\{\zeta^S_{\max} \mid S \text{ is a CDS of } G\}. \tag{7}$$

BACDS can achieve better performance than MCDS since it balances the power consumption among sensor nodes. Algorithm 1 gives the outline of the MCDS and BACDS

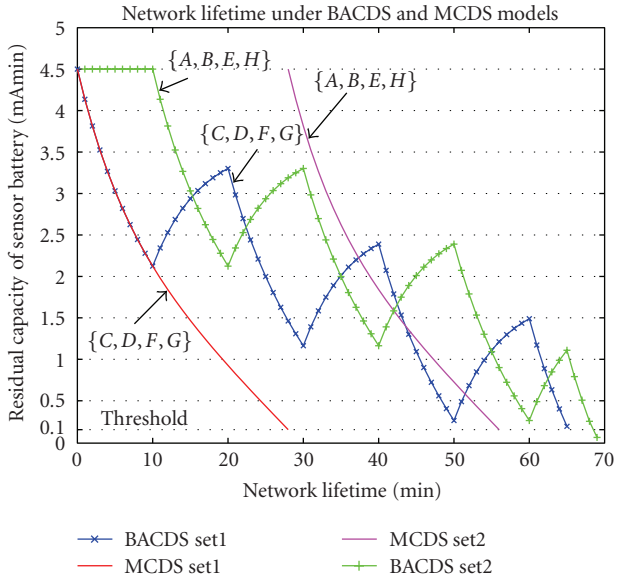
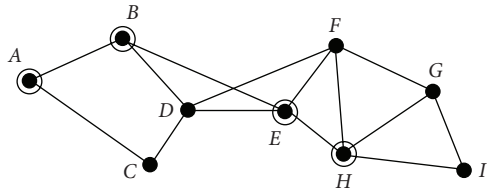


Figure 4: The sensor network in Figure 1 achieves longer lifetime using the BACDS model than the MCDS model. The results were simulated with the battery discharging model. In this case, the network lifetime is prolonged by 23.2% in the BACDS model.



$\{A, B, E, H, I\}$: $\zeta = 0$
$\{C, D, F, G\}$: $\zeta = 2.1 \times 10^4$ mAmin

Figure 5: The battery-aware connected dominating set (BACDS) for the network in Figure 1 at $t = 10$ minutes. The $\zeta^i(t)$ for each node i is listed above.

algorithms for forming a virtual backbone in a sensor network, where node i is qualified to be selected as a dominator as long as its residual battery power $P_{\text{residual}}(i)$ is no less than the threshold power $P_{\text{threshold}}$.

We conducted simulations to compare the two algorithms. Figure 4 shows the simulated lifetime under BACDS and MCDS models for the network in Figure 1. At the beginning, all nodes are identical with battery capacity $C = 4.5 \times 10^4$ mAmin and $\beta = 0.4$. The discharging currents are $I_d = 900$ mA and $I_e = 10$ mA. An MCDS is chosen as $\text{Set}_1 = \{C, D, F, G\}$ (Figure 1). Since MCDS does not consider the battery behavior, Set_1 remains as the dominator until the power of all nodes in Set_1 drops to a threshold 0.1×10^4 mAmin. After that, another MCDS is chosen as $\text{Set}_2 = \{A, B, E, H\}$. After Set_2 uses up its power, no node in the network is qualified as a dominator. The total network lifetime is 56 min (Figure 4).

On the other hand, in the BACDS model a CDS is formed by the nodes with minimum $\zeta(t)$s. The network reorganizes

(1) Find a subset SET^+ in G;
(2) Construct a subset COV in SET^+;
/*COV covers the nodes in $V - \text{SET}^+$*/
(3) Construct a subset CDS^+ in SET^+;
/* CDS^+ is the CDS of SET^+*/
$\text{SET}^0 = \text{COV} \cup \text{CDS}^+$ is a BACDS;

Algorithm 2: The outline of the BACDS construction.

the BACDS for every δ time. Suppose at the beginning the BACDS is still $\text{Set}_1' = \{C, D, F, G\}$. After $\delta = 10$ min, the power of nodes in Set_1' is reduced to 2.1×10^4 mAmin. At this time, a new BACDS is chosen as $\text{Set}_2' = \{A, B, E, H\}$ (Figure 5). During the next 10 minutes, Set_2' dissipates the power to 2.1×10^4 mAmin while Set_1 recoveries its nodes' power from 2.1×10^4 mAmin to 3.35×10^4 mAmin. Then the BACDS is organized again. As shown in Figure 4, the total network lifetime in the BACDS model is 69 minutes, which is 23.2% longer than the MCDS model.

We have seen that BACDS can achieve longer lifetime than MCDS. Next we will consider the BACDS construction algorithm.

4.2. Formalization of BACDS construction problem

The BACDS construction problem can be formalized as follows: given a graph $G = (V, E)$ and $\zeta^i(t)$ for each node i in G, find an MBACDS. For simplicity, we use ζ to denote $\zeta(t)$ in the rest of the paper. First, we have a theorem regarding the NP-hardness of the problem.

Theorem 1. *Finding an MBACDS in G is NP-hard.*

Proof. Consider a special case that all nodes in G have the same ζ values. In this case, finding an MBACDS in G is equivalent to finding an MCDS in G. Since the MCDS problem is NP-hard, the MBACDS problem is also NP-hard. □

Now since the MBACDS construction is NP-hard, we will construct a BACDS by an approximation algorithm. By definition, the BACDS to be constructed, S_B, must satisfy the following two conditions: (i) $\zeta_{\max}^{S_B} = \zeta^{\text{BACDS}}$; (ii) S_B is a CDS of G. Also, the size of S_B should be as small as possible.

Our algorithm is designed to find a set to satisfy these conditions. To satisfy condition (i), the algorithm finds a subset SET^+ in G, such that for any subset $S'(\subseteq \text{SET}^+)$, $\zeta_{\max}^{S'} \leq \zeta^{\text{BACDS}}$. We will prove that, as long as a set $S'(\subseteq \text{SET}^+)$ is a CDS of G, we can guarantee that $\zeta_{\max}^{S'} = \zeta^{\text{BACDS}}$.

To satisfy condition (ii), the algorithm will find two sets: CDS^+ and COV, both in SET^+. $\text{CDS}^+(\subseteq \text{SET}^+)$ is an MCDS of SET^+. $\text{COV}(\subseteq \text{SET}^+)$ is a cover of $V - \text{SET}^+$, which dominates all the nodes in $V - \text{SET}^+$. We will prove that $\text{SET}^0 = \text{COV} \cup \text{CDS}^+$ is the BACDS we want. The detailed algorithm will be presented in Section 4.3. Algorithm 2 gives an outline of the BACDS construction algorithm.

We now show that $\text{SET}^0 = \text{COV} \cup \text{CDS}^+$ is indeed a BACDS.

Theorem 2. *$SET^0 = COV \cup CDS^+$ is a BACDS.*

Proof. We first define SET^+ as

$$\text{SET}^+ = \{v \in V \mid \zeta^v \leq \zeta^{\text{BACDS}}\}. \quad (8)$$

We know that CDS^+ is a CDS of SET^+ and COV dominates the nodes in $V - \text{SET}^+$. To prove $\text{SET}^0 = \text{COV} \cup \text{CDS}^+$ is a BACDS, we need to show that set SET^0 is a connected dominating set of G, and $\zeta_{\max}^{\text{SET}^0}$ is minimized.

First, we show that SET^0 is connected. Because $\text{COV} \subseteq \text{SET}^+$, every node in COV is at most one hop away from CDS^+. Also, since CDS^+ is connected, $\text{SET}^0 = \text{COV} \cup \text{CDS}^+$ is connected.

Second, we prove that SET^0 is a dominating set of G. Since CDS^+ is a CDS of SET^+, all nodes in SET^+ are dominated by CDS^+. Also, since all nodes in $V - \text{SET}^+$ are covered by COV, $\text{SET}^0 = \text{COV} \cup \text{CDS}^+$ is a dominating set of G.

Finally, we show that $\zeta_{\max}^{\text{SET}^0}$ is minimized, that is, $\zeta_{\max}^{\text{SET}^0} = \zeta^{\text{BACDS}}$.Since $\text{SET}^0 \subseteq \text{SET}^+ = \{v \in V \mid \zeta^v \leq \zeta^{\text{BACDS}}\}$, we have $\zeta_{\max}^{\text{SET}^0} \leq \zeta^{\text{BACDS}}$. However, SET^0 is also a CDS of G. Thus, $\zeta_{\max}^{\text{SET}^0} \geq \zeta^{\text{BACDS}}$. Therefore, $\zeta_{\max}^{\text{SET}^0} = \zeta^{\text{BACDS}}$, and we have proved that $\text{SET}^0 = \text{COV} \cup \text{CDS}^+$ is a BACDS. □

In summary, in this subsection we have shown that we can construct a BACDS by finding three subsets SET^+, COV, and CDS^+ step by step. Then $\text{SET}^0 = \text{COV} \cup \text{CDS}^+$ is a BACDS. Next we will give the algorithms to construct SET^+, COV, and CDS^+.

4.3. A distributed algorithm for BACDS construction

Our algorithm for BACDS construction consists of three procedures for constructing SET^+ and COV in G. In the algorithm, we use $N(v)$ to denote the set of neighbor nodes of v. each node is colored in one of the three colors: black, white, and gray. $N_{\text{black}}(v), N_{\text{white}}(v)$, and $N_{\text{gray}}(v)$ are the sets of black, white, and gray neighbors of v, respectively. Also we use sets $\text{list}_{\text{gray}}(i)$ and $\text{list}(i)$ to store the neighbor information for node i.

First we consider the construction of SET^+. To find SET^+, we do the following: the ζ^i of each node i in G is collected in the sink; then the sink calculates $\zeta_{\max}^{\text{SET}^+}$ and broadcasts it in a beacon; on receiving the beacon, all nodes with $\zeta^i \leq \zeta_{\max}^{\text{SET}^+}$ form set SET^+. The procedure is described in Algorithm 3. Initially, all nodes in G are colored gray. Then the algorithm colors some gray nodes black. In the end, the set of black nodes is SET^+.

Note that in SET^+ finding procedure, the sink collects information from sensors only once, and broadcasts the $\zeta_{\max}^{\text{SET}^+}$ in a single beacon. The overhead of information collecting and broadcasting is minimum.

Now we consider the construction of COV. This problem of constructing a minimum size COV can be formulated as the following given two graphs $\overline{G}_1$ and $\overline{G}_2$. Nodes in $\overline{G}_1$ and $\overline{G}_2$ are interconnected with edges. A minimum size COV is to be found in $\overline{G}_1$ such that $\overline{G}_2 \subseteq N(\overline{G}_1)$. We show that finding a minimum size COV is NP-hard even in an UDG graph. If we can show that this problem is NP-hard in an UDG, it is clear that this problem is also NP-hard in a general graph. We have the following theorem regarding its NP-hardness.

```
(1)   All nodes in G are colored gray;
(2)   Each gray node i in the network does the following:
(3)    begin
(4)      Broadcast a packet which includes its ID_i;
(5)      Receive neighbors' IDs;
(6)      Calculate ζ^i;
(7)      Route a packet with (ID_i, ID_N(i), ζ^i) to the sink;
(8)      Listen to the beacon for ζ_max^SET+;
(9)      if ζ^i ≤ ζ_max^SET+ then node i is colored black;
(10)   end;

(11)  The sink does the following:
(12)     begin /* Calculate ζ_max^SET+ */
(13)       Collect packets from sensor nodes;
(14)       S_0 := {ζ^i | i = 1, 2, ..., n};
(15)       S_1 := ∅;
(16)       repeat
(17)         S_2 := {those nodes with the smallest ζ in S_0};
(18)         S_0 := S_0 − S_2;
(19)         S_1 := S_1 ∪ S_2;
(20)       until S_1 is a CDS or S_0 = ∅;
(21)       if S_1 is a CDS then
(22)         ζ_max^SET+ := ζ_max^S1;
(23)         Broadcast ζ_max^SET+ in a beacon;
(24)       end if;
(25)       else report "no CDS can be found"
(26)     end;
   SET+ := {black nodes };
```

Algorithm 3: SET^+ finding procedure.

Theorem 3. *Finding a minimum COV in an UDG is NP-hard.*

Proof. To see this, we use the fact that it is NP-hard to find a minimum dominating set in an UDG. Given any UDG instance, say, $\overline{G}$, which has vertex set $\overline{V} = \{v_1, v_2, \ldots, v_n\}$, we construct another UDG $\overline{G}'$, which has vertex set $\overline{V}' = \{v_1, v_2, \ldots, v_n, v_1', v_2', \ldots, v_n'\}$. $\overline{G}'$ is actually constructed by adding n new vertices $v_1', v_2', \ldots, v_n'$ to $\overline{G}$, where v_i' and v_i are geographically close enough such that v_i' has the same set of neighbors as v_i. Then let $\overline{G}_1 = \{v_1, v_2, \ldots, v_n\}$ and $\overline{G}_2 = \{v_1', v_2', \ldots, v_n'\}$. We will find the COV in $\overline{G}_1$, where $\overline{G}_2$ is the set of vertices to be covered. It is not hard to see that the optimal solution to the COV problem in the new UDG is also a minimum dominating set in the original UDG. Because constructing a minimum dominating set in UDG is an NP-hard problem [15], the problem of finding COV is therefore NP-hard. □

An approximation algorithm to construct a COV has been given in [27]. Initially, $S_1 = \text{SET}^-$ and $S_2 = V - \text{SET}^+$. This algorithm greedily selects node i in S_1 such that $|N(i) \cap S_2|$ is maximized. Then node i is moved to COV and $N(i) \cap S_2$

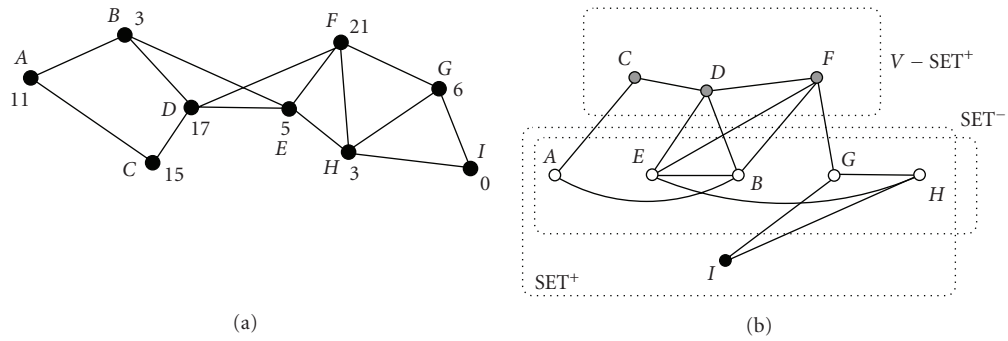


Figure 6: Constructing SET^+ and SET^- in graph G. (a) Nodes are associated with their ζ values. (b) SET^+ and SET^- in (a).

(1) $\text{SET}^- := \emptyset$;
(2) Each node $i \in \text{SET}^+$ does the following:
(3) *begin*
(4) *if* $\exists j \in N(i)$ and $j \in (V - \text{SET}^+)$ *then*
(5) $\text{SET}^- := \text{SET}^- \cup \{i\}$;
(6) *end*;

Algorithm 4: SET^- finding procedure.

are removed from S_2, respectively. This algorithm can finally obtain a COV with $|\text{COV}| \leq \log(|\text{SET}^-|)$. However, this approximation algorithm is difficult to be implemented in our scenario, because it is a centralized algorithm. At each step, this algorithm has to select a node with a maximum number of neighbors, which requires the collection and analysis of global information. Next we will present a distributed algorithm to construct a COV. In our algorithm, nodes only need to know neighbors at most 2 hops away.

Since $\text{COV}(\subseteq \text{SET}^+)$ is a cover of $V - \text{SET}^+$, to find COV, we only need to consider the nodes which are one hop away from $V - \text{SET}^+$. We use SET^- to denote these nodes. SET^- is defined as

$$\text{SET}^- = \{v \in \text{SET}^+ \mid \exists u \in (V - \text{SET}^+),\ (u, v) \in E\}. \quad (9)$$

Figure 6 gives the SET^+ and SET^- for a given sensor network with their associated ζ values. SET^- can be found by the procedure described in Algorithm 4.

Now we construct COV from SET^-. COV can be obtained as follows. Initially, $\text{COV} = \emptyset$, $S_1 = (V - \text{SET}^+)$. Then, for node $v \in S_1$ with the lowest ID number, add all nodes $u \in \text{SET}^-$ to COV, where u and v are one hop neighbors. Then we remove $N(u) \cap S_1$ from S_1. Repeatedly doing so until S_1 is empty. Then we obtain set COV. The localized procedure for finding COV from SET^- is described in Algorithm 5. There are three colors used to color a node: white, black, and gray. Initially, nodes in SET^- are colored white and nodes in $V - \text{SET}^+$ are colored gray. Then the procedure colors some white nodes black. In the end, the set of black nodes is the COV. Four messages are used: *addblack*, *black*, *remove*, and *update*.

(1) Each nodes in $\text{SET}^- \cup (V - \text{SET}^+)$ does the following:
(2) *begin*
(3) Nodes in SET^- are colored white;
(4) Nodes in $V - \text{SET}^+$ are colored gray;
(5) $\text{COV} := \emptyset$;
(6) Each gray node i broadcasts ID_i to its white neighbors $N_{\text{white}}(i)$;
(7) Each white node j adds the received IDs to a set $\text{list}_{\text{gray}}(j)$ and broadcasts $\text{list}_{\text{gray}}(j)$ to its gray neighbors $N_{\text{gray}}(j)$;
(8) Each gray node i does the following:
(9) *begin*
(10) Receive all $\text{list}_{\text{gray}}(N_{\text{white}}(i))$;
(11) $\text{list}(i) := \cup \text{list}_{\text{gray}}(N_{\text{white}}(i))$;
(12) *while* $\text{list}(i) \neq \emptyset$ *do*
(13) *if* $\text{ID}_i = \min\{\text{id} \mid \text{id} \in \text{list}(i)\}$ *then*
(14) Broadcast *addblack* to $N_{\text{white}}(i)$;
(15) $\text{list}(i) := \emptyset$;
(16) *else if black* message is received *then*
(17) broadcast *remove* to $N_{white}(i)$;
(18) $\text{list}(i) := \emptyset$;
(19) *else if update*(k) message is received *then*
(20) $\text{list}(i) := \text{list}(i) - \{k\}$;
(21) *end while*;
(22) *end*;
(23) Each white node j does the following:
(24) *begin*
(25) *while* $\text{list}_{\text{gray}}(j) \neq \emptyset$ *do*
(26) *if addblack* message is received *then*
(27) Color itself black;
(28) $\text{list}_{\text{gray}}(j) := \emptyset$;
(29) Broadcast *black* to $N_{\text{gray}}(j)$;
(30) *else if remove* message is received from k *then*
(31) Broadcast *update*(k) to $N_{\text{gray}}(j)$;
(32) $\text{list}_{\text{gray}}(j) := \text{list}_{\text{gray}}(j) - \{k\}$;
(33) *end while*;
(34) *end*;
(35) *end;*
COV := {black nodes};

Algorithm 5: COV finding procedure.

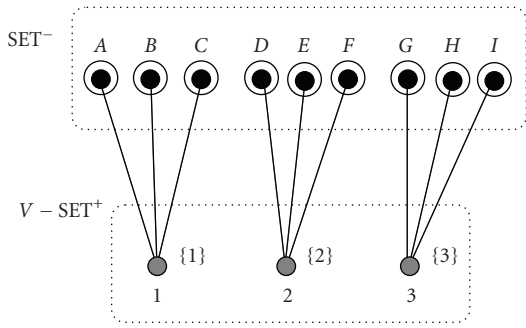


FIGURE 7: The size of finding COV is at most $\Delta \operatorname{opt}_c$. opt_c is the size of an optimal cover.

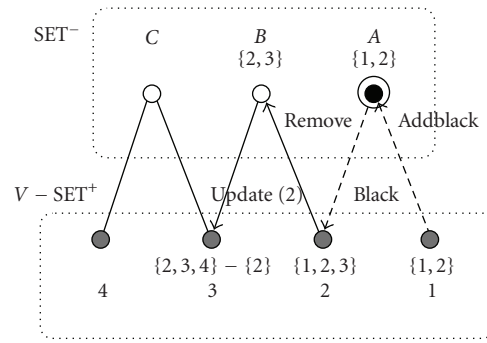


FIGURE 8: In the worst case, the complexity of finding COV is $O(n - |\text{SET}^+| + |\text{SET}^-|)$. It processes one node in each step.

Our algorithm only requires at most 2-hop information to construct the COV. We now prove the correctness of the *COV Finding Procedure*. We will show that the COV found by this procedure is a cover of $V - \text{SET}^+$. We will also give an upper bound on the size of set COV.

Lemma 1. *Set COV found by COV finding procedure covers $V - SET^+$. Its size $|COV|$ is at most $\Delta \operatorname{opt}_c$, where Δ is the maximum node degree of G and opt_c is the size of an optimal cover.*

Proof. By contradiction. Suppose when the *COV finding procedure* terminates, there exists a gray node i which is not covered by COV. It indicates that $N(i) \cap \text{COV} = \emptyset$, which means $N(i) \cap \text{SET}^-$ is not colored black. Since $N(i) \cap \text{SET}^-$ is not colored black, all nodes in $N(i) \cap \text{SET}^-$ should receive *remove* messages from i, otherwise their $\text{list}_{\text{gray}} \neq \emptyset$ and the procedure does not terminate. However, i broadcasts *remove* message if and only if one of its white neighbors is colored black. Thus, $N(i) \cap \text{COV} \neq \emptyset$, which is a contradiction. Hence, COV is a cover.

Now we consider the size of COV. Initially COV is empty, and we add some nodes to it in later steps. We will show that (i) at each step, at least one node, which belongs to the optimal cover, is added to COV; and (ii) at each step, at most $\Delta - 1$ extra nodes, which do not belong to the optimal cover, are added to the COV. By combining (i) and (ii), we obtain that $|\text{COV}|$ is at most $\Delta \operatorname{opt}_c$, where opt_c is the size of an optimal cover.

We first consider (i). According to the algorithm, at each step, node i sends *addblack* messages to $N_{\text{white}}(i)$. Therefore, there are at most Δ nodes added to COV in each step. Among the Δ nodes there must exist at least one node which is in the optimal cover, because an optimal cover has to cover node i. Next we consider (ii). Since among the Δ nodes added to COV there are at least one node belonging to the optimal cover, each time we add at most $\Delta - 1$ extra nodes not belonging to the optimal cover to COV. Thus, $|\text{COV}|$ is at most $\Delta \operatorname{opt}_c$. □

The worst case occurs when nodes in $V - \text{SET}^+$ are not connected by nodes in SET^-. Figure 7 gives an example of $|\text{COV}| = \Delta \operatorname{opt}_c$. Because node 1 has the lowest ID in $\text{list}(i) = \{1\}$, 1 broadcasts *addblack* message to its neighbors: A, B, C; and adds them to COV set. The same thing happens for nodes 2 and 3. Clearly $\operatorname{opt}_c = 3$. Thus, we have $|\text{COV}| = \Delta \operatorname{opt}_c = 9$, where $\Delta = 3$ is the maximum degree of nodes in $V - \text{SET}^+$.

Now we prove that the *COV Finding Procedure* can finally terminates, that is, all $\text{list}_{\text{gray}}(j)$ and $\text{list}(i)$ will finally be empty. We also give the time complexity of *COV Finding Procedure*.

Lemma 2. *All $list_{gray}(j)$ and $list(i)$ will finally be empty. COV finding procedure has time complexity of $O(n - |SET^+| + |SET^-|)$.*

Proof. First, we show that $\text{list}_{\text{gray}}(j)$ will finally be empty. Suppose there is a white node j where $\text{list}_{\text{gray}}(j) \neq \emptyset$. Without loss of generality, we have a node $u_1 \in \text{list}_{\text{gray}}(j)$ with the lowest ID. In this procedure, u_1 is the node that colors j black. If u_1 does not send *addblack* to j, there must be a node $u_2 \in \text{list}(u_1)$ such that $\text{ID}(u_1) > \text{ID}(u_2)$. Then if u_2 does not broadcast *addblack*, there must be a node $u_3 \in \text{list}(u_2)$ such that $\text{ID}(u_2) > \text{ID}(u_3)$, and so on. Then we have $\text{ID}(u_1) > \text{ID}(u_2) > \text{ID}(u_3) > \cdots$. Since there are a finite number of nodes, there must exist a node, u_k, such that $\text{ID}(u_k) = \min\{\text{id} \mid \text{id} \in \text{list}(u_k)\}$. The node u_k should send *addblack*, which indicates that finally $\text{list}_{\text{gray}}(j)$ should be empty.

Second, we show that $\text{list}(i)$ will finally be empty. By Lemma 1, each gray node i is finally covered by some black node, which indicates that all gray nodes received *black* messages. Therefore, finally $\text{list}(i)$ will be $\emptyset$. In this procedure, because it colors at least one node black in each step, the time complexity is $O(n - |\text{SET}^+| + |\text{SET}^-|)$. □

Figure 8 shows the worst case of the *COV Finding Procedure*. With the lowest ID in list(1), node 1 broadcasts *addblack* message. Node A is colored black and informs node 2 by broadcasting *black* message. From the right to the left, the procedure adds one node to COV at each step.

Now we consider the CDS^+ construction. We can adopt any existing MCDS construction algorithm for this purpose. Since the MIS-based algorithm in [13, 15] achieves the best performance in terms of its set size and time and message complexities, we adopt this algorithm here. This algorithm is

(1) *begin*
(2) call SET^+ *finding procedure* for G;
(3) call SET^- *finding procedure* for SET^+;
(4) call *COV finding procedure* for SET^-;
(5) call CDS^+ *finding algorithm for* SET^+;
(6) $SET^0 := COV \cup CDS^+$;
(7) *end*;

Algorithm 6: The algorithm for finding a BACDS in graph G.

a UDG-based algorithm. However, our BACDS constructing algorithm is not restricted to a UDG. In fact, we can employ any other general graph-based MCDS algorithm to construct CDS^+. The complete algorithm for finding a BACDS is given in Algorithm 6.

Figure 9 gives an example of finding a BACDS. First, SET^+ and SET^- are found (Figure 9(a)); then COV is constructed by the algorithm (Figures 9(b)–9(e)); finally, CDS^+ is found and SET^0 is formed (Figure 9(g)). In this example, compared with the MBACDS (Figure 9(h)), SET^0 contains one more dominator.

In the next subsection, we will analyze the performance of our BACDS construction algorithm and give an upper bound on the size of SET^0.

4.4. Complexity analysis of the algorithm

In this subsection, we analyze the approximation ratio, the time complexity, and the message complexity of the algorithm. We also consider mobility issues for this algorithm. We use opt, opt_{MCDS}, opt_c, and $\text{opt}_{\text{MCDS}}^{\text{SET}^+}$ to denote the sizes of MBACDS in G, MCDS in G, the minimum cover in SET^-, and the minimum CDS^+ in SET^+, respectively.

Theorem 4. *The size of* SET^0 *is at most* $(8+\Delta)\,\text{opt}$. *The time complexity and the message complexity of the algorithm is* $O(n)$ *and* $O(n(\sqrt{n}+\log n+\Delta))$, *respectively, where* n *is the number of nodes in* G.

Proof. First, we consider the size of SET^0. Note that MBACDS $\cap$ SET^- is a cover and $|\text{MBACDS}| = \text{opt}$. It indicates that

$$\text{opt}_c \le |\text{MBACDS} \cap \text{SET}^-| \le \text{opt}. \tag{10}$$

Since we have proved in Lemma 1 that $|\text{COV}| \le \Delta\,\text{opt}_c$, we have

$$|\text{COV}| \le \Delta\,\text{opt}. \tag{11}$$

We employ the MIS-based CDS finding algorithm for CDS^+ construction. It can obtain a CDS^+ with a size of at most $8\,\text{opt}_{\text{MCDS}}^{\text{SET}^+}$. Thus,

$$|\text{CDS}^+| \le 8\,\text{opt}_{\text{MCDS}}^{\text{SET}^+}. \tag{12}$$

Because constructing an MBACDS needs to consider the extra battery parameter, the size of the MBACDS is no less than opt_{MCDS}. Thus, we have

$$\text{opt}_{\text{MCDS}} \le \text{opt}. \tag{13}$$

Clearly, the size of a minimum CDS^+ in SET^+ is at most opt_{MCDS} because it needs to consider extra nodes in $V - SET^+$. Thus,

$$\text{opt}_{\text{MCDS}}^{\text{SET}^+} \le \text{opt}_{\text{MCDS}}. \tag{14}$$

By (12), (14), and (13) we obtain

$$|\text{CDS}^+| \le 8\,\text{opt}. \tag{15}$$

Therefore, from (11) and (15) we have

$$|\text{SET}^0| = |\text{COV} \cup \text{CDS}^+| \le (8+\Delta)\,\text{opt}. \tag{16}$$

Now we analyze the complexity of the algorithm. Our algorithm consists of three phases: SET^+ and SET^- constructions, COV construction, and CDS^+ construction. In the first phase, to find SET^+ and SET^-, each node only needs to propagate their messages to the sink and wait for a beacon. A node needs at most $\sqrt{n}$ hops to relay a message to the sink. Hence, the time complexities for sending the message and receiving a beacon are $O(\sqrt{n})$ and $O(1)$, respectively. The time complexity of the second phase is $O(n - |\text{SET}^+| + |\text{SET}^-|)$ as Lemma 2 shows. The complexity of the third phase is $O(|\text{SET}^+|)$. Therefore, the total time complexity of the algorithm is $O(n)$.

Now we consider the number of messages transmitted. In the first phase, the total number of messages relayed in the network is at most $O(n\sqrt{n})$. The beacon has $O(1)$ message complexity. At the beginning of the second phase, to set up the lists, all white nodes and gray nodes need to send $|\text{SET}^-|$ and $n - |\text{SET}^+|$ messages, respectively. After that, all the gray nodes send at most $|\text{SET}^-|$ *addblack* messages and $\Delta|\text{SET}^-|$ *remove* messages. All the white nodes send at most $\Delta(n - |\text{SET}^+|)$ *update* messages, and all the black nodes send no more than $|\text{SET}^-|$ *black* messages. Thus, in the second phase, there are totally at most $O(n\Delta)$ messages. If we employ the algorithm in [13], the message complexity in the third phase is $O(n + n\log n)$. Hence, the total message complexity of our algorithm is $O(n(\sqrt{n}+\log n+\Delta))$. □

In our BACDS construction algorithm, the network is required to be reorganized every δ period by selecting those most fully recovered nodes. This periodical organization seems an extra overhead. However, we observe that as long as we employ a CDS infrastructure in a sensor network, there is always such overhead and the overhead in the MCDS model might be even higher than that in the BACDS model. This is because that a CDS has to be reorganized whenever a dominator dies. The overheads might be even higher in the MCDS case because MCDS algorithms select those nodes with a maximum node degree, lowest ID, or shortest distance to neighbors as dominators. These nodes, which we referred to as burden nodes, remain as the dominators all the time

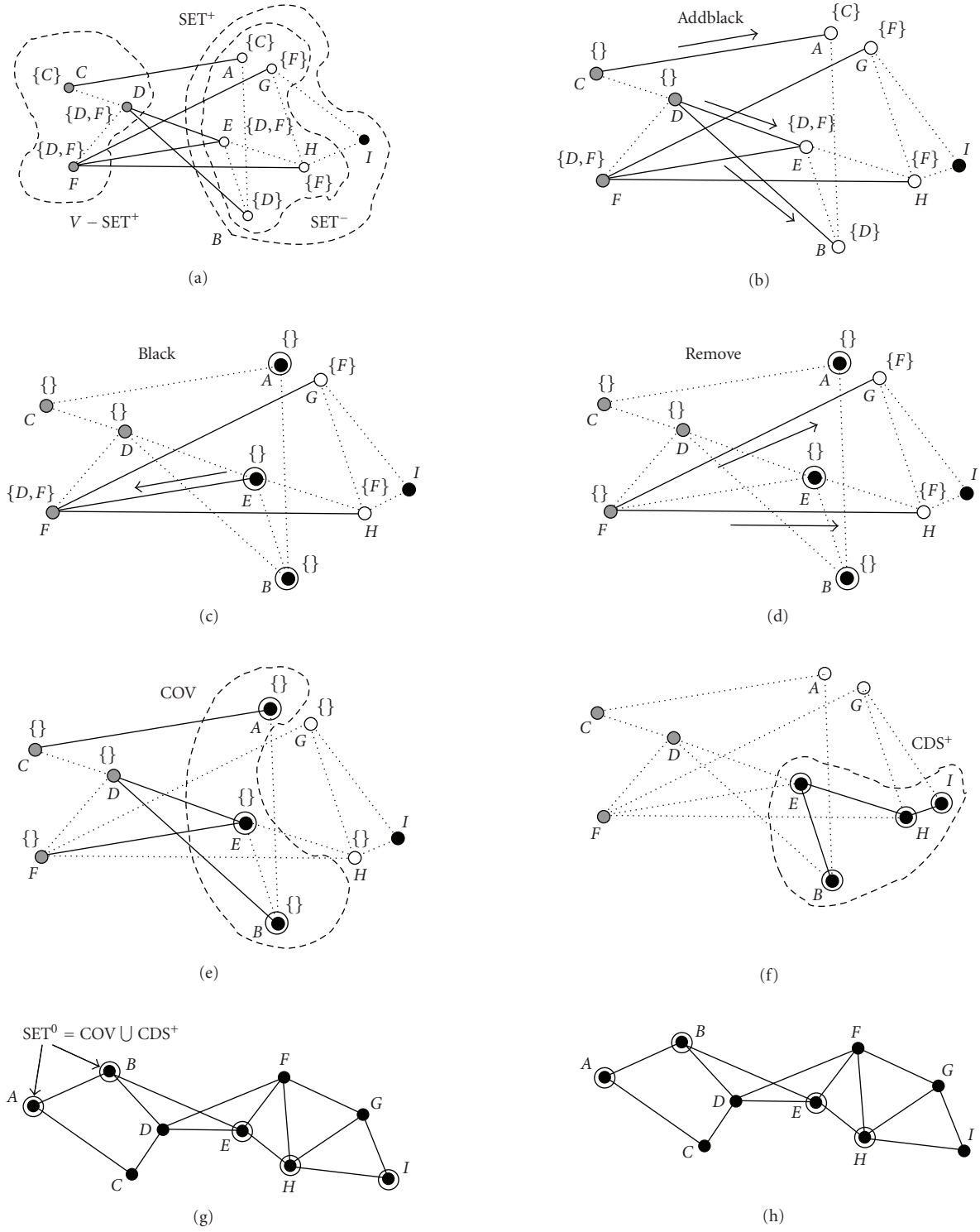


FIGURE 9: Finding a BACDS in the network in Figure 6(a). (a) SET^+ and SET^- in G, set list(i) or $list_{gray}(i)$ of each node i are listed above. (b)–(e) Finding COV in SET^-. (f) Finding CDS^+ in SET^+. (g) SET^0 is the resulting BACDS. (h) The optimal BACDS of this network.

and have larger ζ and lower available power. An MCDS containing such burden nodes is more likely to be reorganized from time to time whenever any burden node uses up its power. While the metric of our BACDS construction algorithm is to balance the power consumption among sensor nodes, in other words, to avoid the burden nodes. Therefore, it is not surprising to see that the reorganization overhead in the BACDS model may be lower than that in the MCDS model. The simulation results in Section 5 verify our observations.

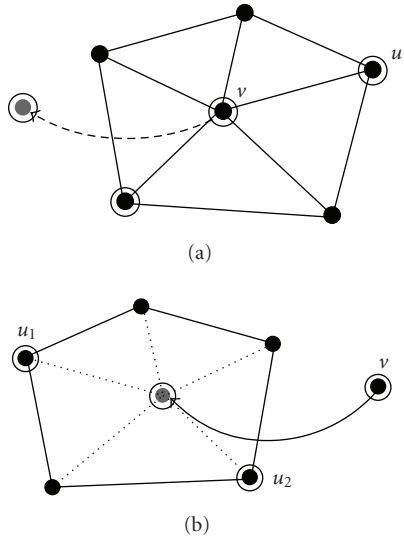


Figure 10: Mobility issue of BACDS. (a) A dominator moves away. (b) A new dominator is selected.

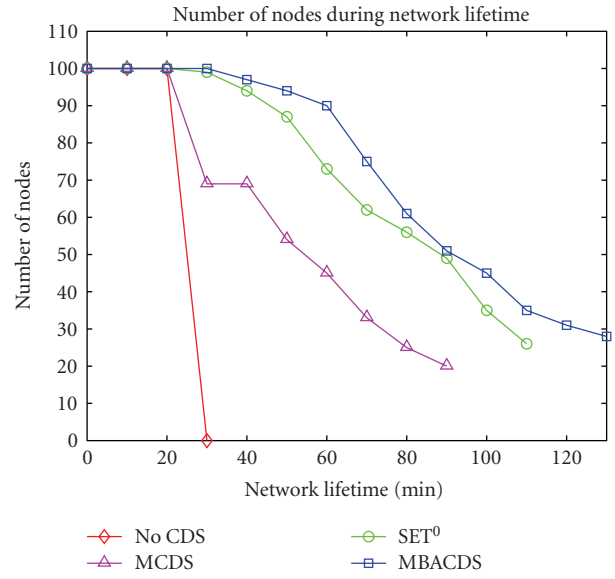


Figure 11: Comparing the network lifetime under different models.

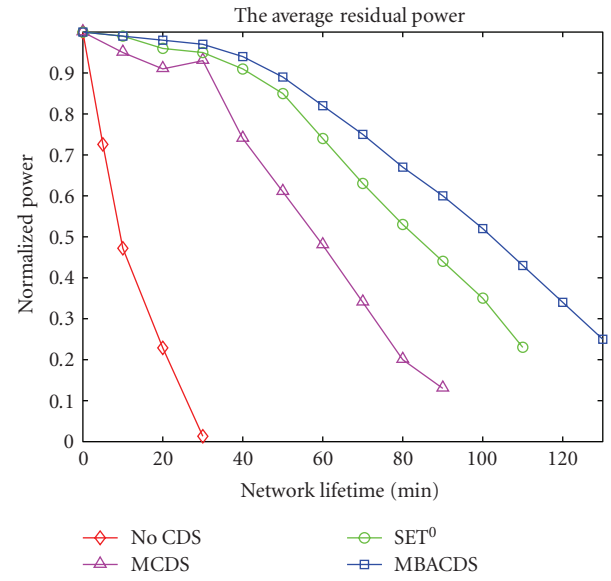


Figure 12: The average power per node in the network.

Furthermore, compared with MCDS construction algorithms, the BACDS algorithm has less overhead even during the construction. Naturally, the BACDS partitions the network into different sets: SET^+, SET^-, COV, and so forth. In each step of the construction, only the sensors in a specified set work on constructing the BACDS, and other sensors turn them into sleep or low-power state to save power. For instance, when constructing COV in SET^-, the sensors in $\text{SET}^+ - \text{SET}^-$ turn to sleep; and when constructing the CDS^+, the sensors in $V - \text{SET}^+$ turn to sleep. Thus, power dissipation is reduced. However, when constructing an MCDS, all sensor nodes have to keep active and listen to their channels all the time, even at the time they do not contribute to the MCDS construction. Consequently, more power is dissipated than the BACDS algorithm.

Our BACDS construction algorithm also considers the mobility issue. By monitoring the sensor mobility and their battery status, it can dynamically adjust the BACDS locally. There are three changes that should be handled to maintain the BACDS: (1) A dominator $v \in \text{SET}^0$ moves away from $N(v)$; (2) A new node v moves in; (3) A dominator finds out that one of its dominatees v has $\zeta^v \leq \zeta^{\text{SET}^+}$. Figure 10 illustrates the situation. In case (1), a new dominator must be selected. Since there must exist another dominator node u in $N(v)$ to connect the original dominating set, a spanning tree rooted at u can be formed among the nodes in $N(v)$. Nodes in this spanning tree become the new dominators. In both cases (2) and (3), node v needs to check if making itself as a new dominator can reduce the size of the BACDS. In our algorithm, v collects all $N(u_i)$ information from its dominator neighbor nodes u_i, $i = 1, 2, \ldots$. Node v is selected as a new dominator if and only if there are more than one u_i such that $N(u_i) \subset N(v)$. After v is selected as the new dominator, u_i are turned to dominatees. Therefore, all nodes in this network are still dominated by at least one dominator while the size of the BACDS is reduced.

5. SIMULATION RESULTS

We conducted extensive simulations to evaluate the network performances under the BACDS model and MCDS model, in terms of network lifetime, power dissipation and set size. We generated a sensor network with $n = 100$ randomly deployed nodes. The communication radius is $r = 1$. Any pair of nodes are connected if and only if their distance is shorter than r. We let $d = 6$ be the average degree of nodes, where d indicates the density of the network. To simulate the traffic model that each sensor is automatically collecting and propagating data to the sink, we let sensors randomly generate 1–5 packets every minute and send them to backbone nodes. Each sensor node i is associated with a discharging loss value ζ^i ($i \leq n$). ζ^i

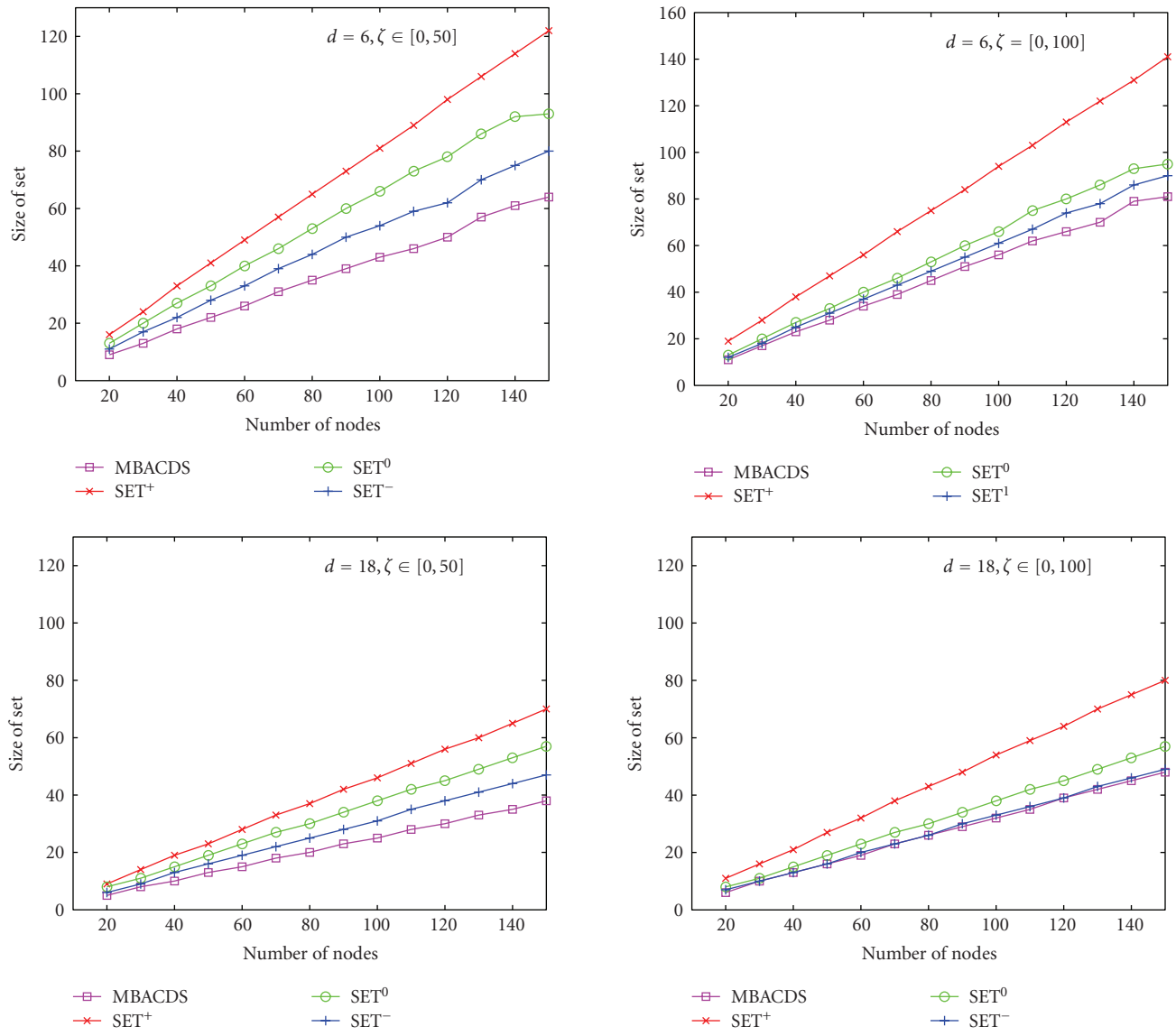


Figure 13: The size of constructed sets with different ζ and d.

is uniformly randomly distributed in $[0, 2 \times 10^4]$ (mAmin). For simplicity, we assume that initially the available power of node i is $C_i = 4.5 \times 10^4$ mAmin and $\beta_i = 0.4$ as in the example of Figure 4. The discharging currents are $I_d = 900$ mA and $I_e = 10$ mA, respectively. We simulated the network lifetime under different models. Our simulation results show that the BACDS achieves longer network lifetime. Their reorganization overheads are also compared. By implementing our BACDS construction algorithm, we also compare the set sizes of SET^0 with MBACDS, where the MBACDS of a network is computed offline. The simulation results verify the upper bound of SET^0 in Theorem 4.

Network lifetime

We first compare the network lifetime achieved by MCDS and BACDS. Figure 11 shows the number of nodes decreases with respect to the lifetime. Four models: no-CDS, MCDS, MBACDS, and SET^0 are implemented. A network without a CDS infrastructure terminates at 30 minutes as all its nodes use up their power. MCDS achieves about 83 minutes total lifetime. MBACDS organizes its dominators every 10 minutes. The lifetime is prolonged by up to 52% in MBACDS model. SET^0 is the BACDS constructed by our algorithm. It obtains a lifetime prolonged up to 30%. We also note that MBACDS terminates with more nodes remained in the network. This is because MBACDS balances the power consumption of each nodes, thus, more nodes are preserved in the network.

Power dissipation

We compare the available power per sensor node under different models in Figure 12. In this comparison, the average

power is the total available power of the network over the number of active nodes. The average power is normalized. MBACDS achieves higher average power during the lifetime. It should be mentioned that at 30 minutes, the average power of MCDS suddenly increases. This is because many of its dominators suddenly die at that time. Consequently, the average power increases as the total number of nodes decreases.

Set size

We implemented our BACDS construction algorithm to verify the upper bound on the set size. The size of the generated network is $n = 20, \ldots, 140$. Four sets are compared: SET^+, SET^-, SET^0, and MBACDS. Figure 13 compares the sizes of these sets with a different node degree d and discharging loss ζ. It shows that as d increases, the sizes of MBACDS and SET^0 are reduced. This is due to the larger degree of the dominators. While as ζ increases its distribution space from $[0, 50]$ to $[0, 100]$, the sizes of MBACDS and SET^0 increase. The results verify the upper bound of SET^0 in Theorem 4.

6. CONCLUSIONS

In this paper, we have considered constructing battery-aware energy efficient backbones in sensor networks to improve the network performance. We first gave a simplified battery model in order to accurately describe the battery behavior online and reduce the computational complexity on a sensor node. Then by using the battery model, we have showed that an MCDS does not necessarily achieve maximum lifetime in a sensor network. We introduced the BACDS model and proved that the minimum BACDS can achieve longer lifetime than the MCDS. We showed that the MBACDS construction is NP-hard and provided a distributed approximation algorithm to construct a BACDS in general graphs. We also analyzed the size of the resulting BACDS as well as its time and message complexities. We proved that the resulting BACDS is at most $(8 + \Delta)$ opt size, where Δ is the maximum node degree and opt is the size of the MBACDS. The time and message complexity of our algorithm are $O(n)$ and $O(n(\sqrt{n} + \log n + \Delta))$, respectively. Our BACDS construction algorithm also considers the mobility issues to dynamically maintain the BACDS backbone. The simulation results show that the BACDS model can save a significant amount of energy and achieve up to 30% longer network lifetime than the MCDS in sensor networks.

ACKNOWLEDGMENTS

This research work was supported in part by the US National Science Foundation under Grant number ECS-0427345 and by the US Army Research Office under Grant number W911NF-04-1-0439.

REFERENCES

[1] I. F. Akyildiz, W. Su, Y. Sankarasubramaniam, and E. Cayirci, "A survey on sensor networks," *IEEE Communications Magazine*, vol. 40, no. 8, pp. 102–114, 2002.

[2] C. Ma, M. Ma, and Y. Yang, "Data-centric energy efficient scheduling for densely deployed sensor networks," in *Proceedings of IEEE International Conference on Communications (ICC '04)*, vol. 6, pp. 3652–3656, Paris, France, June 2004.

[3] G. J. Pottie and W. J. Kaiser, "Wireless integrated network sensors," *Communications of the ACM*, vol. 43, no. 5, pp. 51–58, 2000.

[4] Z. Zhang, M. Ma, and Y. Yang, "Energy efficient multi-hop polling in clusters of two-layered heterogeneous sensor networks," in *Proceedings of the 19th IEEE International Parallel and Distributed Processing Symposium (IPDPS '05)*, p. 81b, Denver, Colo, USA, April 2005.

[5] K. Sohrabi, J. Gao, V. Ailawadhi, and G. J. Pottie, "Protocols for self-organization of a wireless sensor network," *IEEE Personal Communications*, vol. 7, no. 5, pp. 16–27, 2000.

[6] S. Tilak, N. B. Abu-Ghazaleh, and W. Heinzelman, "Infrastructure tradeoffs for sensor networks," in *Proceedings of the 1st ACM International Workshop on Wireless Sensor Networks and Applications (WSNA '02)*, pp. 49–58, Atlanta, Ga, USA, September 2002.

[7] S. Butenko, X. Cheng, D.-Z. Du, and P. Pardalos, "On the construction of virtual backbone for ad hoc wireless networks," in *Cooperative Control: Models, Applications and Algorithms*, pp. 43–54, Kluwer Academic Publishers, Dordrecht, The Netherlands, 2003.

[8] T. W. Haynes, S. Hedetniemi, and P. Slater, *Fundamentals of Domination in Graphs*, Marcel Dekker, New York, NY, USA, 1998.

[9] J. Blum, M. Ding, A. Thaeler, and X. Cheng, "Connected dominating set in sensor networks and MANETs," in *Handbook of Combinatorial Optimization*, pp. 329–369, Kluwer Academic Publishers, Dordrecht, The Netherlands, 2004.

[10] B. S. Baker, "Approximation algorithms for NP-complete problems on planar graphs," *Journal of the ACM*, vol. 41, no. 1, pp. 153–180, 1994.

[11] T. S. Rappaport, *Wireless Communications*, Prentice Hall, Upper Saddle River, NJ, USA, 1996.

[12] B. N. Clark, C. J. Colbourn, and D. S. Johnson, "Unit disk graphs," *Discrete Mathematics*, vol. 86, no. 1–3, pp. 165–177, 1990.

[13] K. M. Alzoubi, P.-J. Wan, and O. Frieder, "Distributed heuristics for connected dominating sets in wireless ad hoc networks," *Journal of Communications and Networks*, vol. 4, no. 1, pp. 22–29, 2002.

[14] K. M. Alzoubi, P.-J. Wan, and O. Frieder, "Message-optimal connected dominating sets in mobile ad hoc networks," in *Proceedings of the 3rd ACM International Symposium on Mobile Ad Hoc Networking and Computing (MobiHoc '02)*, pp. 157–164, Lausanne, Switzerland, June 2002.

[15] P.-J. Wan, K. M. Alzoubi, and O. Frieder, "Distributed construction of connected dominating set in wireless ad hoc networks," in *Proceedings of the 21st Annual Joint Conference of the IEEE Computer and Communications Societies (INFOCOM '02)*, vol. 3, pp. 1597–1604, New York, NY, USA, June 2002.

[16] C. Ma, Y. Yang, and Z. Zhang, "Constructing battery-aware virtual backbones in sensor networks," in *Proceedings of the International Conference on Parallel Processing (ICPP '05)*, pp. 203–210, Oslo, Norway, June 2005.

[17] Y. Yang and C. Ma, "Battery-aware routing in wireless ad hoc networks—part I: energy model," in *Proceedings of the 19th International Teletraffic Congress (ITC '05)*, pp. 293–302, Beijing, China, September 2005.

[18] C. Ma and Y. Yang, "Battery-aware routing in wireless ad hoc networks—part II: battery-aware routing," in *Proceedings of the 19th International Teletraffic Congress (ITC '05)*, pp. 303–312, Beijing, China, September 2005.

[19] D. Rakhmatov and S. Vrudhula, "Energy management for battery-powered embedded systems," *ACM Transactions on Embedded Computing Systems*, vol. 2, no. 3, pp. 277–324, 2003.

[20] M. Doyle, T. F. Fuller, and J. Newman, "Modeling of galvanostatic charge and discharge of the lithium/polymer/insertion cell," *Journal of the Electrochemical Society*, vol. 140, no. 6, pp. 1526–1533, 1993.

[21] B. Chen, K. Jamieson, H. Balakrishnan, and R. Morris, "Span: an energy-efficient coordination algorithm for topology maintenance in ad hoc wireless networks," in *Proceedings of the 7th Annual International Conference on Mobile Computing and Networking (MOBICOM '01)*, pp. 85–96, Rome, Italy, July 2001.

[22] S. Guha and S. Khuller, "Approximation algorithms for connected dominating sets," *Algorithmica*, vol. 20, no. 4, pp. 374–387, 1998.

[23] A. Ephremides, J. E. Wieselthier, and D. J. Baker, "A design concept for reliable mobile radio networks with frequency hopping signaling," *Proceedings of the IEEE*, vol. 75, no. 1, pp. 56–73, 1987.

[24] V. Raghunathan, C. Schurgers, S. Park, and M. B. Srivastava, "Energy-aware wireless microsensor networks," *IEEE Signal Processing Magazine*, vol. 19, no. 2, pp. 40–50, 2002.

[25] A. Mainwaring, J. Polastre, R. Szewczyk, D. Culler, and J. Anderson, "Wireless sensor networks for habitat monitoring," in *Proceedings of the 1st ACM International Workshop on Wireless Sensor Networks and Applications (WSNA '02)*, pp. 88–97, Atlanta, Ga, USA, September 2002.

[26] Telos Sensor Mote, http://www.moteiv.com/products/tmotesky.php.

[27] R. Raz and S. Safra, "A sub-constant error-probability low-degree test, and a sub-constant error-probability PCP characterization of NP," in *Proceedings of the 29th Annual ACM Symposium on Theory of Computing (STOC '97)*, pp. 475–484, El Paso, Tex, USA, May 1997.