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Full Length Research Paper

Energy-aware distributed algorithm for virtual backbone in wireless sensor networks with bidirectional links

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An important characteristic that distinguishes wireless sensor networks (WSNs) from other distributed systems is their need for energy efficiency because sensors have finite energy reserve. Since there is no fixed infrastructure or centralized management in WSN, a connected dominating set (CDS) has been proposed as a virtual backbone. The CDS plays a major role in routing, broadcasting, coverage and activity scheduling. To reduce the traffic during communication and prolong network lifetime, it is desirable to construct a minimum CDS (MCDS). The MCDS problem has been studied intensively in unit disk graph (UDG), in which the nodes have the same transmission range. In real world, this kind of networks is not necessarily containing nodes with equal transmission range. In this paper, a new timer-based energy-aware distributed algorithm for MCDS problem in disk graph with bidirectional links (DGB), in which nodes have different transmission ranges, is introduced which has outstanding time and message complexity of $O(n)$ and constant approximation ratio. Theoretical analysis and simulation results are also presented to verify our approach's efficiency.

Key words: Disk graphs, energy-aware, minimum connected dominating set, virtual backbone, wireless sensor network.

INTRODUCTION

Wireless sensor networks (WSNs) have attracted a great deal of research attention due to their wide range of potential applications. In WSN, there is no fixed or pre-defined infrastructure. The nodes in a WSN generally communicate with each other, either through a single hop or multiple hops. Although there is no physical backbone infrastructure, a virtual backbone can be formed by constructing a connected dominating set (CDS).

Energy efficiency is an important issue in WSN, because battery resources are limited. From the analysis of the energy consumption of a sensor node, it has been found that a great amount of energy is consumed for communications. Mechanisms that reduce the communication cost and conserve energy resources are highly desirable, as they have a direct impact on network lifetime. In order to prolong the lifetime of each node and, hence, the network, power consumption should be minimized and balanced among nodes.

A dominating set (DS) of a graph is a subset of nodes such that each node in the graph is either in the subset or adjacent to at least one node in that subset. A CDS is a DS, which induces a connected sub graph. In other words, assume an undirected graph $G(V,E)$, a subset $V' \subseteq V$ is a CDS of G if for each node $u \ \varepsilon \ V$, u is either in V' or there exists a node $v \ \varepsilon \ V'$ such that $uv \ \varepsilon \ E$ and the sub graph induced by V', that is, $G(V')$, is connected. A CDS is a good candidate of a virtual backbone for wireless networks, because any non-CDS node in the network has 1-hop distance from a CDS node. With the help of the CDS, routing is easier and can adapt quickly to network topology changes (Wu et al., 1999). Since, Only the CDS nodes are responsible for relaying messages for the network, the non-CDS nodes

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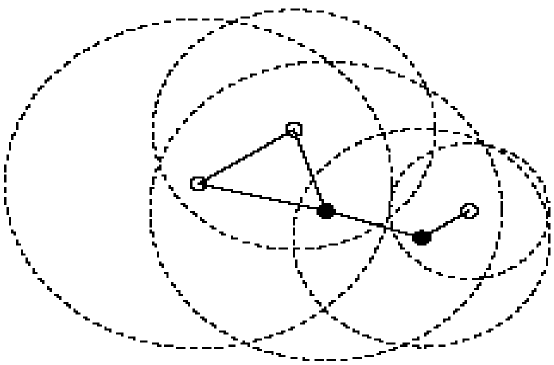

Figure 1. Disk graph with bidirectional links (DGB).

can thus turn off their communication module to save energy when they have no data to be transmitted out. Also, the efficiency of multicast or broadcast routing can also be improved through the utilization of CDS (Wu et al., 2003). To reduce the traffic during communication and prolong network lifetime and simplify the connectivity management, it is desirable to construct a minimum CDS (MCDS).

The MCDS problem has been studied intensively in unit disk graph (UDG), in which each node has the same transmission range. Unfortunately, computing a MCDS of a UDG graph has been proved to be NP-hard (Clark et al., 1990). An approximation algorithm for the minimization problem is an algorithm which guarantees the approximation ratio $\frac{D_{a\lg}}{D_{opt}}$, where $D_{a\lg}$ is the size of the solution of the approximation algorithm in the worst case and D_{opt} is the size of the optimal solution.

To build a MCDS, we compute a maximal independent set (MIS) of the network graph. An independent set (IS) of an undirected graph $G(V,E)$, is a subset of V that no two nodes in the subset have an edge. In other words, if I is a IS and $u \varepsilon I$, $v \varepsilon I$ then $uv \notin E$. An MIS of a graph is an IS that cannot include any more nodes within V. Thus an MIS is a DS of an undirected graph.

However, in practice, the transmission ranges of all nodes are not necessary equal. In this case, a WSN can be modeled using a directed graph $G(V,E)$. The nodes in V are located in a Euclidean plane and each node $v_i \varepsilon V$ has a transmission range $r_i \varepsilon [r_{\min}, r_{\max}]$. A directed edge $(v_i, v_j) \varepsilon E$ if and only if $d(v_i, v_j) \le r_i$ where $d(v_i, v_j)$ denotes the Euclidean distance between v_i and v_j. Such graphs are called disk graphs. An edge (v_i, v_j) is bidirectional if both (v_i, v_j) and (v_j, v_i) are in *E*, that is, $d(v_i, v_j) \le \min\{r_i, r_j\}$.

In this paper, we study the MCDS problem in disk graphs where all the edges in the network are bidirectional, called disk graphs with bidirectional links (DGB). Here, G is undirected. Figure 1 gives an example of DGB representing a network (Thai et al., 2007).

In Figure 1, the dotted circles represent the transmission ranges and the black nodes represent a CDS. The MCDS problem in DGB is NP-hard since the MCDS problem in UDG is NP-hard and UDG is a special case of DGB. It is clear that when nodes can use the arbitrary values for their transmission ranges like DGB, a special case of this model is a state in which all nodes have same transmission ranges like UDG.

Since the backbone nodes should be responsible for forwarding packets of other node in addition to its own packets, their energy consumption is high. So it is desirable in selection node for CDS, we consider residual energy in the node. Our algorithm has two phases; in the first phase we compute a MIS and in the second phase we choose the minimal number of the nodes (called connectors) to make the CDS. In the first phase, we use a weight that it combination of remaining energy, and transmission range, also in the second phase, we use a weight that it combination of remaining energy, and effective degree, to prolong network lifetime and reduce size of CDS. In each round, we compute a new backbone (the nodes are different from selected previous nodes as backbone) to achieve energy balancing, which extends the lifetime of the network.

Thai et al. (2007) proposed the first distributed algorithm for MCDS in DGB with the constant approximation ratio and the time and message complexity of $O(n^2)$, which is dominated by MIS phase. Their algorithms in this phase using SORT list for finding node with largest transmission range among its neighbors. In this paper, this selection has been achieved without sort list. Instead, a timer is used at each node which enables a node with largest weight to be identified. By this approach, the time and message complexity are reduced to $O(n)$. However, we provide a new timer-based energy-aware distributed algorithm for finding MCDS in DGB with constant approximation ratio and the time and message complexity of $O(n)$.

The main contributions of this paper are as follow:

1. The algorithm is energy-aware and energy balancing, that they are highly desirable for WSN.
2. The algorithm is fully distributed, which can be easily implemented in WSN.
3. The algorithm has constant approximation ratio in DGB, which reduces the overhead of maintaining the backbone and the cost in communication.
4. The algorithm has the time and message complexity of $O(n)$ that it is the very better than (Thai et al., 2007).
5. We conduct theoretical analysis and simulation results

to evaluate average performance of our approach.

RELATED WORKS

The MCDS problem in UDG in wireless networks has been studied extensively. Current MCDS approximation algorithms include centralized and distributed algorithms. Following the increased interest in wireless sensor networks, many distributed approaches have been proposed for the reason that there is no need for global network topology knowledge. These algorithms contain two types. One type is to form a maximal independent set (MIS) initially, and then find some connectors to make the independent nodes connected together. Wan et al. (2004) proposes a distributed algorithm based on quasi-global information (Spanning tree) with approximation ratio of 8 and $O(n)$ time complexity and $O(n\log n)$ message complexity, where n is number of nodes. Cheng et al. (2004) propose a degree-aware distributed algorithm with approximation ratio of 8 and $O(n)$ time complexity and $O(n\log n)$ message complexity. Min et al. (2006) propose an improved algorithm by employing a Steiner tree in the second phase to connect the nodes in the MIS with approximation ratio of 6.8.

The other type is to find an initial CDS and then prune some redundant nodes to attain MCDS. Wu et al. (1999) and Dai and Wu (2004) proposed a distributed algorithm with $\theta(m)$ message complexity and $O(\Delta^3)$ time complexity and the approximation ratio at most $O(n)$ where, Δ and m are the maximum degree in graph and number of edges respectively. Butenko et al. (2004) constructs a CDS starting with a feasible solution, and recursively removes nodes from the solution until a MCDS is found. This algorithm has time complexity of $O(nm)$. It does not have a performance analysis. Recently Adjih et al. (2005) propose a localized heuristic to generate a CDS multipoint relying (MPR). Each node initially computes a multipoint relay set, a subset of 1-hop neighbors that can cover all the 2-hop neighbors. This algorithm has $O(\Delta^3)$ time complexity and $\theta(m)$ message complexity. Wu et al. (2006) provides several extensions to generate smaller CDS using complete 2-hop information to cover each node's 2-hop neighbor set. They extend the notion of coverage in the original MPR (Adjih et al., 2005).

Basagni et al. (2004) compare some of these methods and show that approaches with nice theoretical features, such as Wan et al. (2004), may hardly be applicable in practice due to the complexity of their operations. Simple solutions such as Wu et al. (1999) and Dai and Wu (2004) can be good starting points to develop a light and effective solution for sensor networks. However, the aforementioned solutions have mostly been utilized within UDG in which the nodes have same transmission range, and for the other models such as DGB in which the nodes have different transmission range there are very few publications. In other words, only it can be referred to the solution offered by Thai et al. (2007), Du et al. (2006), and Park et al. (2007) where the nodes contain different transmission range. In Du et al. (2006) and Park et al. (2007), the network has been modeled by disk graphs with unidirectional links (DGU), and their algorithms have constant approximation ratio. In (Thai et al., 2007), the network has been modeled by DGB. This modeling approach employs constant approximation ratio which has time and message complexity of $O(n^2)$. Time and message complexity of this algorithm relates to the first phase of this algorithm which is building MIS. To build the MIS, each node of network uses a sort list to sort the transmission range of neighbors' nodes in order to select nodes with the largest transmission range as a member of MIS. Raei et al. (2008) propose a new distributed algorithm for MCDS problem in DGB that has constant approximation ratio and time complexity of $O(n)$ and message complexity of $O(n\log n)$ without sort list. Also, recently Raei et al. (2009) presented a new distributed algorithm for MCDS problem in DGB with time and message complexity of $O(n)$.

Recently, there is a great increasing focus on low cost and low energy consumption in wireless networks. Wu et al. (2003) present an algorithm for power aware connected dominating set based on (Wu et al., 1999). Zhou et al. (2005) proposed a distributed heuristic scheme for construction of energy-aware virtual backbone tree for WSN. Acharya et al. (2007) present a power aware MCDS construction when introducing a concept of threshold energy level for dominating nodes based on Butenko et al. (2004). Yuanyuan et al. (2006) present an energy efficient MCDS construction by using a weight and consider the balance of energy. Raei et al. (2008) altered (Yuanyuan et al., 2006) by an efficient timer and by this way improved message overhead.

However, all of the aforementioned energy aware solutions have been utilized within UDG. In this paper, a timer factor is used at each node which enables a node with largest weight to be identified. By this approach, the time and message complexity are reduced to $O(n)$. Therefore, our algorithm is the first energy-aware distributed algorithm for the MCDS in DGB; also it has constant approximation ratio and $O(n)$ time and message complexity.

DISTRIBUTED ALGORITHM FOR MCDS IN DGB

We assume that all nodes in WSN are distributed in a two-dimensional plane and the nodes have different transmission ranges. The network topology is modeled as a disk graph with bidirectional links, DGB in short. We use $G(V,E)$ to represent such networks, where V is the set of sensor nodes and E is the set of edges.

The aim of our algorithm is to compute a sub-optimal MCDS as a backbone for wireless sensor networks. Our algorithm consists of two phases. In the first phase, we compute a maximal independent set (MIS) of the network graph. The second phase of the algorithm is to choose the minimal number of the nodes (called connectors) to make the DS connected, that is, CDS.

Each node v_i has a unique id (ID_i), a state (S_i), a transmission range (R_i), an effective degree (D_i) and remaining battery power (E_i) also, we assume that each node v_i has a weight W_i of being in the backbone.

In the first phase, we set the W_i by following formula:

$$W_i = \sqrt{R_i} \times E_i \quad (1)$$

And for the second phase we set the W_i by following formula:

$$W_i = \sqrt{D_i} \times E_i \quad (2)$$

We have used from E_i in the both formula because constructed backbone has became energy efficient, and we have used R_i in (1) for MIS phase and D_i in (2) for the second phase because they will reduce size of CDS. Thus, each time the constructed CDS could have higher energy level and smaller size under the condition of energy balance.

In each phase, we select nodes with the largest weight among its neighbors by timer factor (ΔT_i). In each node v_i, ΔT_i set by the following formula:

$$\Delta T_i = \frac{1}{W_i} \times T_{MAX} \quad (3)$$

where T_{MAX} is maximum time for each timer, then each node with largest weight (W_i) terminate the timer faster than its neighbors. T_{MAX} is an optional value, but according to our experiences in different simulation, 1000 ms plays an acceptable role in the algorithm.

Phase 1: MIS construction

The algorithm always starts from a node that initiates the execution. We call this node initiator. We use colors to indicate if a node is in MIS or not, that is, use black to indicate the nodes in MIS and grey to indicate non-MIS nodes.

In this phase, each node is in one of the four states: white, black, grey and green. Initially, all nodes are in white, and at the completion of the algorithm all nodes in the network must be either in black (MIS nodes) or in grey (non-MIS nodes). The green is an intermediate state.

In this phase, there are two types of messages: (1) BLACK message sent out when a node becomes a black node; (2) GREY message, sent out when a node becomes grey node; Each message contains node state and id, that is, S_i and ID_i.

At the start of the algorithm, all nodes are in white. Then the initiator turns itself to black. A node that has turned itself in to black color will broadcast a BLACK message to its neighbors immediately to indicate itself as an MIS node. A white neighbor that receives the BLACK message becomes a grey node (that is, a non-MIS node), and broadcasts a GREY message to indicate its neighbors simultaneously. A white node that receives a GREY message is a neighbor of the non-MIS node; it needs to compete to become a black node. Upon receiving a GREY message, the white node mark itself green and set a timer (ΔT_i) based on (3), in which W_i set based on (1). It will stay in the green state until timer expires. During the timeout, it may receive a BLACK or GREY message. If receives a BLACK message, it implies that the competition fails, and other node has been selected as a MIS node already, then the node becomes grey and broadcast a GREY message. If receives a GREY messages do nothing and stays in the green. When timeout is due, it implies that the competition succeeds and this node can to be a MIS node, then the node will enter black state and broadcast BLACK message. During the coloring process, each grey node will keep a list of all the adjacent black (MIS) nodes to set D_i for next phase. The same operation continues from node to node as the BLACK or GREY messages propagate, until nodes have entered the state of either black or grey. The main idea of the algorithm is shown in Table 1.

The initiator starts the construction of a new CDS by execution the following procedure:

Initiator () {It colors itself black and broadcast a BLACK message}

Each node v_i, performs the function as shown in Table 1:

Upon the expiration of timer for green state, it executes the following procedure:

Timer-green () { It colors itself black and broadcast a BLACK message}

Theorem 1

The set of black nodes that is computed by the first

Table 1. Algorithm.

	MIS construction
1	Upon receiving a BLACK message, a white node marks itself grey and broadcast the GREY message
2	Upon receiving a GREY message, a white node marks itself green and set a timer (ΔT_i) based on (3), in which W_i set based on (1)
3	Upon receiving a BLACK message, a green node mark itself grey and terminate the timer and broadcast a GREY message
4	Upon receiving a GREY message, a green node, do nothing and stays in the green
5	Ignore the all messages if node is grey or black

phase forms a MIS of the network graph.

Proof

We donate the set of black nodes that computed by the first phase as B. The MIS algorithm colors the nodes of the graph layer by layer, and propagates out from the initiator to reach all nodes in the network, with one layer of black and the next layer as grey. At each layer (except initiator), black nodes are selected by grey nodes of previous layer and are marked black. The construction incrementally enlarges the black node set by adding black nodes 2-hops away from the previous black nodes set. Also the newly colored black nodes could not be adjacent to each other, for the interleaving coloring layer of black and grey nodes. Hence every black node is disjoint from other black nodes. This implies that B forms an IS. Further, the algorithm will end up with black or grey nodes only. Each grey node must have at least one black neighbor, so if coloring any grey node black, B will not be disjoint anymore. Thus, *B* is the MIS Υ.

Phase 2: CDS construction

Since a MIS in DGB is a DS, a CDS can be constructed by making the DS connected together, that is, by connecting the nodes in an MIS through some nodes (called connectors) not in the MIS. A localized approximation of minimum spanning tree may perform well enough. We call it dominating tree. So we take a greedy approximation algorithm that selects every non-MIS node with the maximum number black neighbors (D_i) which interconnect two or more MIS nodes, as a connector.

An MIS node can be in one of the two states: Black and blue. Non-MIS node can be in one of the three states: Grey, green and blue. When the algorithm is complete, all the nodes in the network graph are in the final state of either blue or grey. And all the blue nodes are the CDS nodes. There is one type of message: (1) BLUE message, sent out when a node becomes a CDS node. Each BLUE message contains S_i and ID_i .

After finishing phase 1, a node in the network graph is either in black (that is, an MIS node) or in grey state (that is, a non-MIS node), and each grey node keep a list of its black neighbors. Then the node will check to see whether it could begin the second phase of CDS algorithm. If all its neighbors become grey or black (that is, all its neighbors terminate phase 1 and become MIS or non-MIS nodes), the node will begin phase 2. In this phase, each node v_i has effective degree (D_i) that represents the number of MIS neighbors. Hence D_i is initiated with number of black neighbors. Apparently, the CDS algorithm starts from MIS initiator too because of message propagation order, so it is the root of dominating tree. At this point, the initiator can start phase 2 by coloring itself in blue (that is, becoming a CDS node) as the following: Initiator () {It colors itself blue and broadcast a BLUE message}

A node that colors itself in blue will broadcast a BLUE message to indicate itself as a CDS node. We assume that all messages are delivered in order. When a non-MIS node in grey begins phase 2, it responds to the messages receives. A grey node that receives a BLUE message (sent out by a neighbor of CDS node) if $D_i \neq 0$ then will enters the green state and set a timer (ΔT_i) based on (3), in which W_i set based on (2), else ignores the message. Only non-MIS nodes with at least one blue neighbor are effective, and this could guarantee the constructed dominating tree is connected. The intuition of green state for a non-MIS node is to probe the network and compete to see if it is suitable to behave as a connector. The node in green state may receive only one type of message: BLUE message. If a node in green state receives a BLUE message, it ignores the message. When green timer expires, if $D_i \neq 0$, it implies that the competition succeeds and this node can to be a connector, then the node will enter blue state and broadcast BLUE message. When a MIS node (black node) begins phase 2, it responds to the messages receives. A black node that receives a BLUE message (sent out by a connector) will enter blue state directly to become a CDS node and it broadcasts a BLUE message.

Table 2. Algorithm.

	CDS construction
1	Upon receiving a BLUE message, a grey node, if $D_i \neq 0$, it marks itself green and set a timer (ΔT_i) based on (3), in which W_i set based on (2), else ignore the message.
2	Upon receiving a BLUE message, a black node mark itself blue and broadcast a BLUE message contained S_i , ID_i .
3	Upon receiving a BLUE message, a green node, Ignore the message.
4	Ignore the all messages if node is blue.

The CDS construction algorithm continues until: 1) Any MIS node colored blue (i.e., becoming CDS node) terminates the algorithm. 2) Any non-MIS node terminates when it satisfies either of the following two conditions terminate the algorithm: it is colored blue (i.e., chosen as a connector) or all its neighbors are colored blue and grey (i.e., all its neighbors are in the final state). The phase 2 algorithm after initiator sending out BLUE message can be presented as in (Table 2). Each node v_i , performs the function in Table 2 based on its local information, in responses to the messages it receives:

Upon the expiration of timer for green state, it executes the following procedure:

Timer-green () {It colors itself blue and broadcast a BLUE message}

Theorem 2

Each MIS in our algorithm has a non-MIS neighbor that connects it to at least another MIS node.

Proof

Considering the propagation layer of our MIS algorithm, let B_i and G_i be the set of MIS and non-MIS nodes at i^{th} layer. For any node $g \ \varepsilon \ G_i$ is a non-MIS node formed at the i^{th} layer. In the phase 1, it is marked grey (non-MIS node) from white state on receiving a BLACK message from its black neighbor (MIS node) in B_i . Next, after determining its state, the grey node g sends out a GREY message to all its neighbors in the $i+1^{th}$ layer. The neighbor set a timer based on (3). When timeout is due, the neighbor will become a black node in B_{i+1} . This implies that there always exists a non-MIS neighbor node $g \ \varepsilon \ G_i$ has at least two MIS neighbor nodes in B_i and B_{i+1} respectively. So for an MIS node in B_i , there always exists that it has a neighbor in G_i connecting at least another MIS node in B_{i+1} .ϒ.

Theorem 3

The set of blue nodes computed by the second phase is a CDS of the network graph.

Proof

The set of blue nodes include MIS nodes and connectors. MIS is a DS, so we only need to proof the connectivity. Let $\{b_0, b_1, ... b_n\}$ be the independent set, which elements are arranged one by one in the construction order. Let H_i be the graph over $\{b_0, b_1, ... b_i\}$, $(1 \leq i < n)$ in which pairs of nodes are interconnected by connectors. We prove connectivity by induction on j that H_j is connected. Since H_1 consists of a single node, it is connected trivially. Assume that H_{j-1} is connected for some $j \geq 2$. Considering message propagation layer in the first phase, let B_{i-1} and G_{i-1} be the set of MIS and non-MIS nodes at the $i-1^{th}$ layer, respectively. The non-MIS node in G_{i-1} with maximal weight (2) is selected as connecters in phase 2. According to Theorem 2, it is enough to find non-MIS nodes, which interconnect B_{i-1} nodes at $i-1^{th}$ layer with B_i nodes in the i^{th} layer. As H_{j-1} is connected, so must be H_j . Therefore the set of blue nodes computed by the second phase is a CDS.

Theoretical analysis

The following two important properties are listed in (Thai et al., 2007) for CDS in DGB:

Lemma 1

In a DGB, every node is adjacent to at most five independent nodes.

Proof

If a node has six MIS nodes in its neighborhood, the angle between them in best condition is 60, so the distance between these MIS nodes is less than their transmission range; in other words, these MIS nodes are neighborhood of each other that this consequence has conflict with definition of the MIS which presented in the introduction.

Lemma 2

$|D_{opt}|$ is the size of optimal CDS (D_{opt}). In a DGB, the size of any MIS is upper bounded by $K|D_{opt}|$ where,

$$K = \begin{cases} 5 & if \quad R = 1 \\ 10 \left\lfloor \dfrac{\ln R}{\ln(2\cos(\pi/5))} \right\rfloor & Otherwise \end{cases}$$

and $R = \dfrac{r_{MAX}}{r_{MIN}}$.

Theorem 4

In the phase 2, the number of the blue nodes (connectors) will not exceed K$|D_{opt}|$, where K achieved from lemma 2.

Proof

Let *B* be the independent set and *S* be the connector set of a graph. From lemma 2, $|B| \le K|D_{opt}|$. From Theorem 1 and lemma 1, it can be deduced that the number of MIS neighbors for a connector is ranged from 2 to 5. Let *T* be the dominating tree spanning blue nodes found by our algorithm. The worst case for size of *T* occurs when all nodes are distributed in a line. By analyzing the utmost situation, the number of connectors must be less than the number of MIS nodes, that is, $|S| \le |B| - 1$, and from lemma 2, $|B| \le K|D_{opt}|$ then $|S| \le K|D_{opt}| - 1$. So the number of output connecting nodes will not exceed K$|D_{opt}|$.Υ.

Theorem 5

Our distributed algorithm has a constant approximation factor.

Proof

Our distributed algorithm includes two phases. Phase 1 is MIS construction, and phase 2 is CDS construction. From Lemma 2, the performance ratio in the first phase is K$|D_{opt}|$. From Theorem 4, the performance ratio is bounded K$|D_{opt}|$ in the second phase, so the resulting CDS will have size bounded by 2K$|D_{opt}|$. Then our algorithm has a constant approximation ratio of the optimal CDS.Υ.

Theorem 6

Our distributed algorithm has $O(n)$ time complexity, and $O(n)$ message complexity.

Proof

In first phase, for BLACK and GREY message, each node at most sends out once this kind of messages. Thus, the total number of these messages is $O(n)$.In second phase; for BLUE messages, since each blue node sends only once this message, the message complexity in the worst case is $O(n)$. The worst case occurs when all nodes are distributed in a line and in either ascending or descending order of their transmission ranges, then all the nodes send out the BLUE message finally. It is clear that the time complexity of first phase and also second phase is $O(n)$, because our algorithms in both phases for each node has time complexity $O(1)$ (the each node receive a message and may set a timer, not sort and not search) and since all the nodes run the algorithms, then time complexity is $O(n)$. Hence the message complexity of our distributed algorithm is $O(n)$ and its time complexity is $O(n)$.Υ.

SIMULATION RESULTS

Here, we verify our algorithm by evaluate its performance on random networks in terms of CDS size, message overhead (in Bytes), average energy consumption per node in CDS construction and the number of the rounds that the network survives until can not construct a

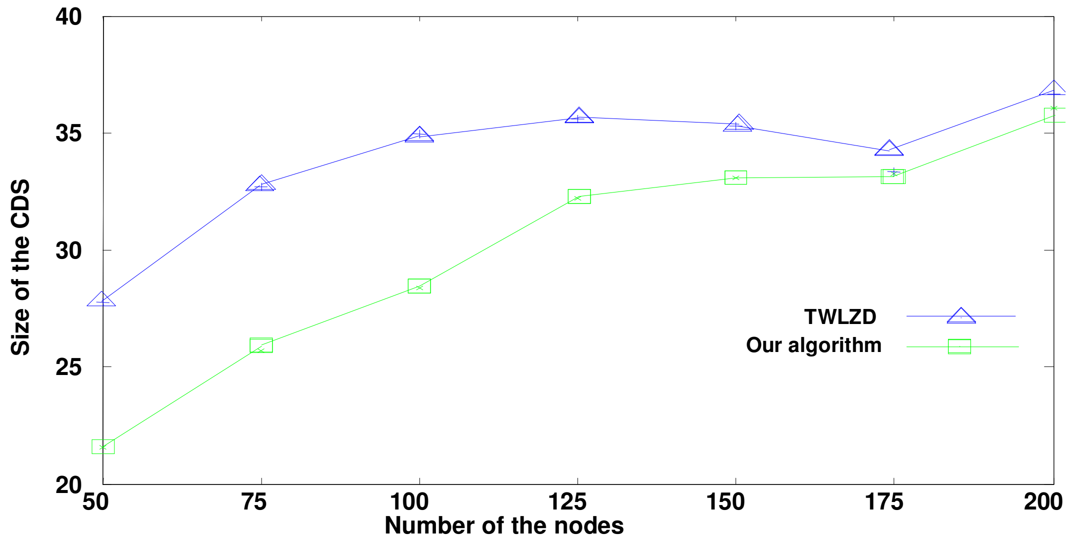

Figure 2. The CDS size.

backbone for the network (network lifetime). And we make comparison with only algorithm in DGB, Thai's algorithm in Thai et el. (2007) (TWLZD). The simulation network size is 50 to 200 numbers of nodes in increments of 25 nodes respectively, which are randomly placed in a 100 × 100 m square area to generate connected graphs. Each node randomly chooses its transmission range from the range of (10 and 30 m). The simulation makes average solutions over 20 iterations of random generating scenes.

We use the energy consumption model is presented in (Heinzelman et al., 2000). To send an *l*-bit data to a distance *d*, the radio expands:

$$E_{Sx}(l,d) = E_{Sx-elec}(l) + E_{Sx-amp}(l,d) = \begin{cases} l\,E_{elec} + l\,\varepsilon fs\,d^2 & d < d_0 \\ l\,E_{elec} + l\,\varepsilon mp\,d^4 & d \geq d_0 \end{cases} \quad (4)$$

The first item presents the energy consumption of radio dissipation, while the second presents the energy consumption for amplifying radio. When receiving this data, the radio expends:

$$E_{Rx}(l,d) = E_{Rx-elec}(l) = lE_{elec} \quad (5)$$

Here, $E_{elec} = 50nJ/bit$, $\varepsilon fs = 10pJ/bit/m^2$ and $\varepsilon mp = 0.0013pJ/bit/m^4$

In our simulation, we assume the broadcast packet size is 200 bit and the update packet size is used in (Thai et al., 2007) (TWLZD) for the black-blue component ID, is 50 bit long and T_{MAX} = 1000 ms. Each node is assigned initial energy level 0.1 J. In each round, 100 data packets randomly are generated in network and send to destination node by using the constructed backbone. So energy consumption is different for different nodes and may be changed.

Figure 2, shows the size of the CDS with the increasing number of nodes in the network. A smaller backbone improves network performance not just with respect to routing overhead but also with respect to maximizing network lifetime. Our algorithm has a good performance with smaller CDS size when comparing with TWLZD because, TWLZD in second phase use an inefficient Steiner tree.

As a measure of the message complexity (overhead) of backbone formation protocols, we have counted the average number of bytes transmitted by nodes in the network. As shown in Figure 3, our algorithm has a good performance in comparison with TWLZD. For example, when n = 125 the message overhead propagated by our algorithm is 5.7 times less than that of TWLZD.

As a measure of the energy efficiency of backbone formation protocols, we have computed the average energy consumption per node in the CDS construction. As shown in Figure 4, our algorithm has a good performance in comparison with TWLZD (Results are expressed in Joule). As expected, the energy consumption curves follow the trend observed for the message overhead (Figure 3) closely, given the dependency of energy consumption on the number of bytes transmitted and received by each node. For example, when n = 125 the average energy consumed by our algorithm is 5.1 times less than that of TWLZD. As a

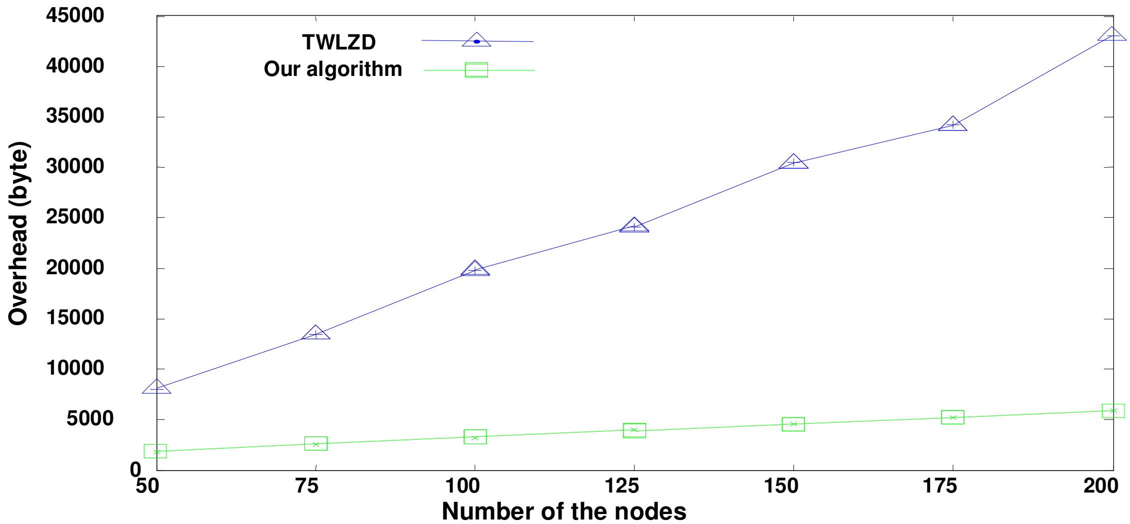

Figure 3. The message overhead (Number of Bytes).

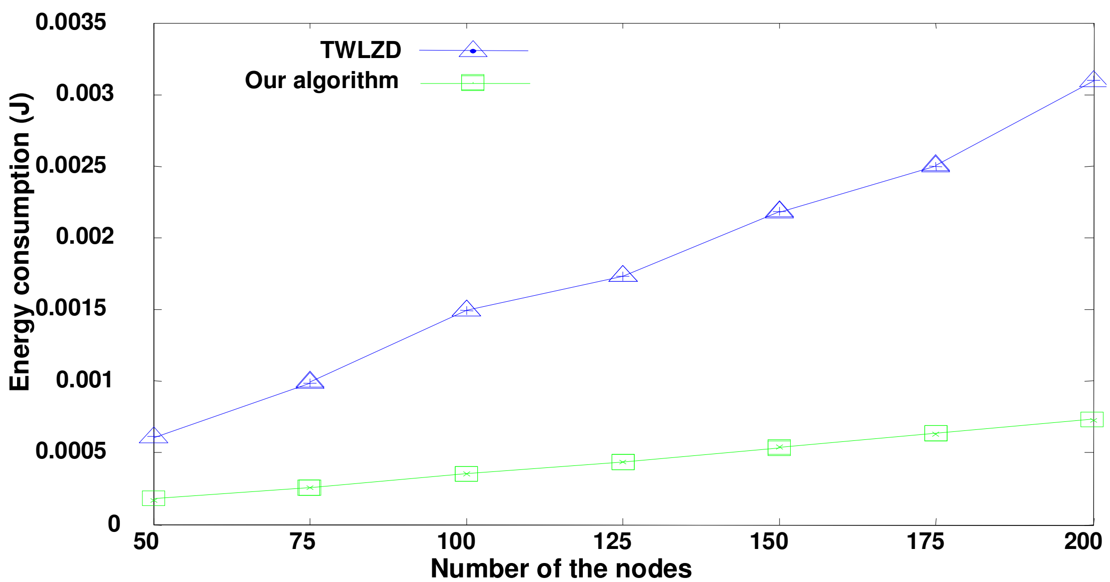

Figure 4. Average energy consumption per node in CDS construction.

measure of the energy balancing and network lifetime of backbone formation protocols, we have computed the average number of the rounds that the network survives until can not construct a backbone for the network. Figure 5, show the average number of the rounds that the network survives (network lifetime) with the increasing number of nodes in the network. Our algorithm is very better than TWLZD. This result is expected because; our algorithm is an energy efficient algorithm (Figure 4) and through (1) and (2) choose different node as backbone in different rounds, to achieve energy balancing. For example, when n = 125, the network lifetime by our algorithm is 2 times more than that of TWLZD.

CONCLUSION AND FUTURE WORKS

In this paper, we have proposed a new timer-based energy-aware distributed algorithm for the minimum connected dominating set (MCDS) problem in disk graphs with bidirectional links (DGB), in which the nodes have different transmission range. The main approach in our algorithms is to construct a maximal independent set (MIS) and then connect them. Through the theoretical analysis, we have shown that our algorithm has constant approximation ratio, and $O(n)$ the time and message complexity. The simulation results show that the algorithm can efficiently prolong network lifetime and

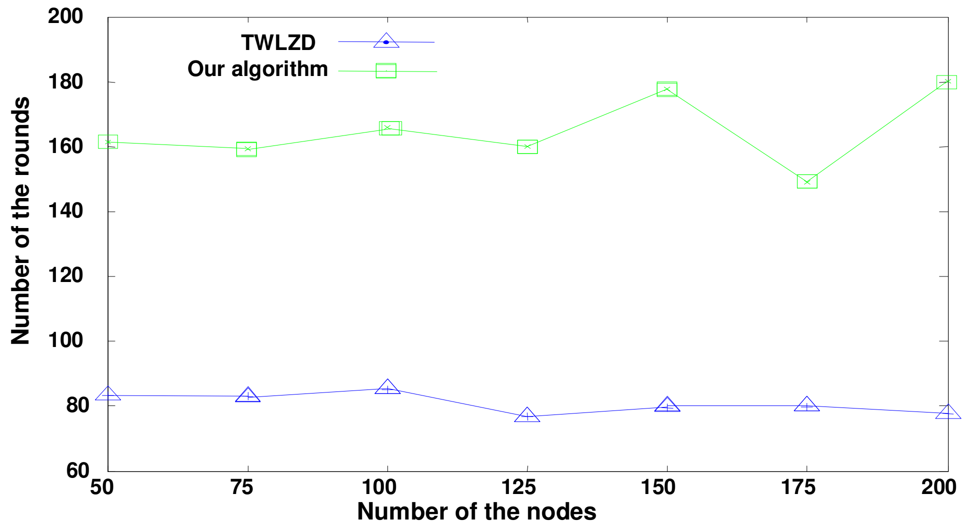

Figure 5. Network lifetime.

balance node energy consumption with a smaller backbone size, comparing with the only existing DGB algorithm. The future work it will be focused on a new distributed MCDS algorithm in disk graphs with unidirectional links (DGU), in which the graph is directed. Furthermore, the three dimensional space has positive points for employing the CDS in order to achieve the real world

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