Distributed energy efficient backbone construction utilizing particle swarm optimization algorithm in wireless sensor networks with bidirectional links

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***Abstract*— Connected dominating set (CDS) problem is the most widely used method for backbone formation in wireless sensor networks. To date, numerous algorithms have been proposed for backbone construction on minimum CDS (MCDS) problem in unit disk graphs (UDG); however, only a few algorithms have been proposed on MCDS problem in disk graphs with bidirectional links (DGB) and on degree-constrained minimum-weight CDS (DC-MWCDS) problem in UDG. To the best of our knowledge, no work has been done on DC-MWCDS problem in DGB. In this paper, we present the OEDC-MWCDS problem (optimal energy and degree constrained minimum-weight connected dominating set) for energy efficient backbone construction in wireless sensor networks. Then, we model a wireless sensor network as a disk graph with bidirectional links and propose a backbone construction algorithm called EBC-PSO (energy efficient backbone construction utilizing particle swarm optimization algorithm) to obtain a CDS with the minimum weight subject to the optimal energy and degree constraints. The main objective of the proposed algorithm is to find the optimal values of energy and degree constraint to maximize network lifetime. In the proposed algorithm, optimal coefficients of minimum remaining energy and maximum degree of nodes are determined utilizing PSO algorithm. Then, in the selection of DS nodes, these coefficients are used. Simulation results verify the performance of the proposed algorithm in terms of network lifetime and backbone size.**

Index Terms*— *CDS problem, WSN, network backbone, graphs with bidirectional links, PSO Algorithm.

I. INTRODUCTION

WIRELESS sensor networks (WSN) have emerged as the-state-of-the-art-technology in gathering data from remote locations by interacting with physical phenomena [1–3]. A wireless sensor network is composed of hundreds or thousands of sensor nodes deployed in an environment to collect information and transmit reported messages to a sink node [2–6]. Since sensor networks have limited energy resources, energy conservation and maximization of the network lifetime are important issues in the design and implementation of them [7,8]. To extend the lifetime of wireless sensor networks, backbone construction has been extensively studied in these networks [8–22]. Connected dominating set (CDS) plays an important role in the construction of backbone in wireless sensor networks which has received much attentions in the past decade [7–10,13,15,18,23–26] A CDS with at least possible nodes in the network and minimum weight is called minimum connected dominating set (MCDS) and minimum weight CDS (MWCDS), respectively.

Two common types of CDS construction algorithms are 1) Unit Disk graphs (UDG), in which all nodes have the same transmission ranges and 2) Disk Graphs with Bidirectional links (DGB), in which nodes have different transmission ranges [20]. Fig. 1 gives an example of DGB representing a network. In Fig. 1, the dotted circles represent the transmission ranges and the black nodes represent a CDS.

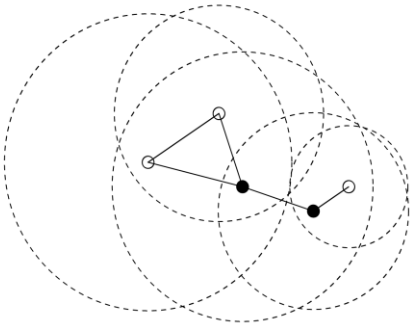

Fig. 1: A Disk graph with bidirectional links (DGB) [26]

Most of the CDS construction algorithms have been presented on unit disk graphs (UDG) [8–24] and few studies have been carried out on disk graphs with bidirectional links (DGB) [25–28]. In practice, the communication ranges of nodes in a network are not necessarily equal. Therefore, in this paper, disk graphs in heterogeneous networks in which nodes have different transmission ranges have been considered.

Several algorithms [8–10,15,17,20,23,24,28] showed that an energy efficient backbone formation significantly improves the performance of wireless sensor networks. The aim of most CDS formation algorithms is to minimize the size of the network backbone. The small size CDS significantly reduces the hop-count and message overhead [10,11,13,15,25,27–29]. The main problem of CDS with minimum size is that with the reduction in the CDS size, the degree of the backbone nodes increases. This places a heavy

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burden on the backbone nodes and causes high energy consumption by sensor nodes. In wireless sensor networks, where the nodes are generally limited in power, this reduces the backbone duration [9,12,14]. Therefore, determination of the optimal value of degree of constraint guarantees a good trade-off between CDS size and the degree of its nodes.

In this paper, an optimal energy and degree constrained extension of the MWCDS problem called OEDC-MWCDS (Optimal energy and degree constrained minimum-weight connected dominating set) is presented for energy efficient backbone construction. A CDS is energy and degree constrained if the degree of its nodes are smaller than the degree constraint (D_{cons}) and the energy of all nodes are higher than the energy constraint (E_{cons}). OEDC-MWCDS seeks for the CDS with the minimum weight, subject to the optimal energy and degree constraints E_{cons}, D_{cons}. Then, we propose an optimal algorithm (ECB-PSO) to construct a backbone utilizing PSO algorithm in disk graphs where all the edges in the network are bidirectional. Simulation results demonstrate that ECB-PSO outperforms the proposed algorithm in [28] in terms of network lifetime and backbone size.

The rest of the paper is organized as follows. In Section 2, related work in UDG and DGB is presented. Section 3 briefly reviews the dominating set and particle swarm optimization (PSO) algorithm. The proposed ECB-PSO algorithm is presented in Section 4. Section 5 presents theoretical analysis of the proposed algorithm and the simulation results are presented in Section 6. Section 7 concludes this paper.

RELATED WORK

CDS based methods have been extensively studied in UDG, in which all nodes have the same transmission ranges.

Raei et al. [24] presented an energy-aware distributed algorithm for MCDS problem in UDG in which all the nodes had the same transmission ranges. This algorithm includes two phases; maximal independent set (MIS) construction phase and CDS construction phase. A distributed algorithm was proposed by Zeng et al. [13] for energy efficient connectivity and coverage maintenance in wireless sensor networks. The algorithm computes a sub-optimal MCDS in polynomial time. The constructed CDS by that algorithm is small in size, which reduces the overhead of maintaining the backbone and the cost in communication. Chaung et al. [17] proposed a heuristic-based backbone algorithm called SmartBone to choose proper backbone nodes from a network. SmartBone consists of four phases. The first phase is the neighborhood information collection. The second phase is the Flow-Bottleneck Preprocessing (FlowBP), The third phase is the Backbone selecting procedure. Backbone selecting procedure selects coordinators according to the priority determined by linear combination of remaining energy and coverage. In the fourth phase, the dynamic density cutback procedure is performed to remove redundant nodes based on a cutback threshold. Furthermore, some input constraints on control input are proposed to improve the performance of the controller. The main key ideas of this paper can be enumerated as follows: A heuristic method was proposed by Dai and Wu [30] for backbone formation in wireless ad hoc networks. They proposed a CDS-based backbone formation algorithm in which the backbone was initially set to network hosts having two unconnected neighbors. Then, the backbone is pruned by removing the hosts whose neighbors are the neighbors of the other hosts of the initial backbone too. Li et al. [32] proposed a MIS-based greedy algorithm for finding the connected dominating set (CDS) in wireless networks. This algorithm includes two phases. In the first phase, MIS of the network is constructed. In the second phase, MIS nodes are constructed using a Steiner tree. A CDS-based intelligent backbone formation algorithm was proposed by Akbari Torkestani [29] for wireless ad hoc networks. At each iteration of this algorithm, a CDS of the network is constructed and the size of the CDS is compared with a dynamic threshold. Poostfroushan et al. [8] presented an energy efficient backbone formation algorithm on MCDS in UDG using PSO algorithm. The algorithm uses an optimal weight based on the minimum residual energy and maximum effective degree of nodes for backbone formation to prolong the network lifetime. Akbari Torkestani [12] introduced a degree-constrained extension of the CDS problem called OMCDS. OMCDS is a multi-objective problem aiming at both minimizing the weight of the CDS and finding the optimal degree of constraint simultaneously. This algorithm constructs the network backbone by finding a near optimal solution to the proxy equivalent to OMCDS problem. Akbari Torkestani [14] presented a degree-constrained minimum weight CDS (DC-MWCDS) problem for modeling the energy efficient backbone formation problem in wireless sensor networks. He proposed a distributed algorithm based on learning automata called DEEB. The performance of DEEB is dependent on the degree of constraint. To make a good trade-off between the transmission delay and the backbone lifetime, degree of constraint must be properly chosen. For this reason, he constructed a simulation experiment to measure the transmission delay and the backbone lifetime where degree of constraint changes from 2 to 15 and the number of nodes are 100.

To date, few algorithms have been proposed for CDS construction in DBG in which nodes have different transmission ranges.

Thai et al [26] presented three constant approximation algorithms for the CDS problem in DGB. The main approach in their algorithms is to construct a maximal independent set and then connect them together. For reducing the size of the CDS, they used a Steiner tree with a minimum number of Steiner nodes to interconnect the maximal independent set. A distributed algorithm was proposed by Raei et. al [25] for MCDS problem in DGB that has constant approximation ratio and time complexity of O(n) and message complexity of O($nlogn$) without a sort list. Raei et al. [28] proposed a timer-based energy-aware distributing algorithm for MCDS problem in DGB that has constant approximation ratio and time and message complexity of O(n). This algorithm consists of two phases. The first phase consists of computing a MIS of the network graph and the second one consists of choosing the minimal number of nodes to make the DS connection.

II. PRELIMINARIES

This section describes the variations of the unit disk graphs, disk graphs with bidirectional links and dominating set problems and also introduces the optimal energy and degree of constrained minimum-weight connected dominating set problem. This section also reviews PSO algorithm to provide a background for understanding the basics of the proposed backbone construction algorithm.

A. *UDG and DGB*

UDG: Let G = (V, E) be a graph to represent a wireless sensor network, where V denotes the set of nodes in the network and E denotes the set of edges that shows all links in the network. If all nodes of the network have the same transmission ranges, graph G will be known as a UDG [10,26,28].

DGB: In practice, the transmission ranges of all nodes are not necessary equal. In this case, a wireless sensor network can be modeled using a directed graph G=(V, E). The nodes in V are located in a Euclidean plane and each node vi ∈ V has a transmission range ri ∈ [rmin, rmax]. A directed edge (vi,vj) ∈ E if and only if d(vi,vj) ≤ ri where d(vi,vj) denotes the Euclidean distance between vi and vj. Such graphs are called disk graphs. An edge (vi,vj) is bidirectional if both (vi,vj) and (vj,vi) are in E, i.e., d(vi,vj) ≤ min{ri,rj} [26,28]. Disk graphs where all the edges in the network are bidirectional, called DGB. In this case, G is undirected.

B. *Dominating Set*

Dominating set: Given an undirected graph G = (V, E). V denotes the set of nodes and E denotes the set of edges. Dominating set (DS) of graph G 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 the subset [28].

Connected DS: If the induced sub-graph by the nodes in a DS is connected, dominating set is called a connected dominating set (CDS). The CDS of the network topology graph can be used as a virtual backbone to help each node transfer its data to the sink [7,19]. With the help of the CDS, the burden of average messages of a WSN could be reduced, so that routing becomes much easier and can quickly adapt to network topology changes [19,28]. Since only the CDS nodes are responsible for relaying messages of the network, the non-CDS nodes can thus turn off their communication module to save energy when they have no data to be transmitted out [13,28].

Minimum CDS: Minimum connected dominating set (MCDS) is a CDS with at least possible nodes in the network. MCDS problem has been shown to be NP-Hard [31].

Degree-constrained CDS: Let G = (V, E) be a connected and undirected graph, where V denotes the set of nodes and E denotes the set of edges. Di is the degree of vertex vi ∈ V. The number of vertices adjacent to the vertex vi (or the number of edges incident at vertex vi) is defined as the degree of this vertex. A degree-constrained CDS (DC-CDS) of graph G is a CDS of G subject to Di ≤ Dcons, for all vi ∈ V, where Dcons is a positive integer number denoting degree constraint [12,14].

Degree-constrained MCDS: The DC-CDS with at least possible nodes in the network is called the degree-constrained MCDS (DC-MCDS) [12,14]. Each backbone node has a weight in the network. The weight can be defined in terms of energy, time, band width and etc. Obviously, by reducing the number of backbone nodes, backbone weight also decreases. Therefore, in a realistic scenario where each node has a different weight, if the CDS has the minimum weight rather than the minimum cardinality, the MCDS (or DC-MCDS) based backbone is cost-effective [14].

Minimum weight CDS: Given an undirected and node-weighted graph G=(V,E,W). V denotes the set of nodes, E denotes the set of edges and W denotes the set of weights associated with the graph nodes. The minimum weight CDS (MWCDS) of the graph G is the CDS of G having the minimum weight. It is shown that the MWCDS is an NP-hard problem [32].

Degree-constrained MWCDS: Let G=(V,E,W) be a connected, undirected, and node-weighted graph. The degree-constrained minimum weight CDS (DC-MWCDS) of graph G is the CDS with the minimum weight subject to a degree constraint Dcons [12,14].

Optimal degree-constrained MWCDS: Let G=(V,E,W) be a connected, undirected, and node-weighted graph. The optimal degree-constrained minimum weight CDS (ODC-MWCDS) of graph G is the CDS with the minimum weight subject to an optimal degree constraint Dcons. On the other hand, ODC-MWCDS is an optimization problem that seeks for the CDS having the minimum weight subject to an optimal degree.

Energy and degree constrained MWCDS: Given a connected, undirected and node-weighted graph G=(V,E,W). The energy and degree constrained minimum-weight CDS (EDC-MWCDS) of graph G is the CDS with the minimum weight subject to the energy and degree constraints.

Optimal energy and degree constrained MWCDS: Given a connected, undirected and node-weighted graph G=(V,E,W). The optimal energy and degree constrained minimum-weight CDS (OEDC-MWCDS) of graph G is the CDS with the minimum weight subject to the optimal energy and degree constraints. OEDC-MWCDS is an optimization problem that seeks for the CDS having the minimum weight subject to the optimal energy and degree constraints. In this paper, coefficients of optimal energy and degree are determined utilizing PSO algorithm. In the next section, we use the OEDC-MWCDS problem for energy efficient backbone construction in disk graphs with bidirectional links.

Independent set: Given an undirected graph G = (V, E). An Independent set (IS) of graph G is a subset of vertices that no two nodes in the subset have an edge [19,28].

Maximal independent Set: Maximal independent set (MIS) is an independent set that cannot accept any more nodes in V. Thus an MIS is a DS of a graph. Note that this DS (obtained as the MIS) may not be connected [19,28].

C. *PSO Algorithm*

PSO is an evolutionary computation technique inspired by the social behavior of bird flocks and has been applied to solve large-scale nonlinear optimization problems [33]. It utilizes a “population” of particles that fly through the problem hyperspace with given velocities [34]. Performance of each particle is measured according to an objective function, which is problem-dependent.

An individual particle i is composed of three vectors: its position in the D-dimensional search space x^i, the best position that it has individually found $x^{i,best}$ computed as Eq. 1, and its velocity v^i.

$$x^{i,best}[t] = argmin_{\tau\leq t} f(x^i[\tau]) = argmin\{f(x^i[t], f(x^{i,best}[t-1])\} \tag{1}$$

f^i is the value of the objective function at x^i and $f^{i,best}$ is the value of the objective function at $x^{i,best}$ which is defined as Eq. 2.

$$f^{i,best}[t] = f(x^{i,best}[t]) = min_{\tau\leq t} f^i([\tau]) = min\{f^i[t], f^{i,best}[t-1])\} \tag{2}$$

x^g best computed as Eq. 3 is the best position amongst all particles from the first iteration to the t^th iteration.

$$x^{gbest}[t] = argminf_{i=1,\ldots,n}(x^{i,best}[t]) \tag{3}$$

f^g best is the value of the objective function at x^{gbest} defined as Eq. 4.

$$f^{gbest}[t] = f(x^{gbest}[t]) = minf_{i=1,\ldots,n^{i,best}}[t] \quad (4)$$

Particles were originally initialized in a uniform random manner throughout the search space. These particles then move throughout the search space by a fairly simple set of update equations. The algorithm updates the entire swarm at each time by updating the velocity and position of each particle in every dimension.

The scheme for updating the velocity vector of each particle depends on the particular PSO algorithm under consideration. A commonly used scheme was introduced by Shi and Eberhart [35], as shown in Eq. 5.

$$v^i[t+1] = wv^i[t] + c_1r_1\big(x^{i,best}[t] - x_j^i x^i[t]\big) + c_2r_2(x^{gbest}[t] - x^i[t]) \quad (5)$$

Once the velocity for each particle is calculated, each particle's position is updated by applying the new velocity to the particle's previous position as shown in Eq. 6.

$$x^i[t+1] = x^i[t] + v^i[t+1] \quad (6)$$

Where v^i [t] is the velocity of particle i at time t and x^i [t] is the position of particle i at time t. c1 and c2 are two positive constants, called the cognitive and social parameter, respectively; In many algorithms, these values are selected so that c_1+c_2≤4. r_1 and r_2 are random numbers uniformly distributed within the range [0,1]. W is inertia weight which its role is considered important for the PSO's convergence behavior. The bigger w is, the bigger the PSO's searching ability for the whole is, and the smaller w is, the bigger the PSO's searching ability for the partial. In common PSO algorithms, w is confined from 0.9 to 0.4 according to the linear decrease as Eq. 7.

$$\mathrm{w} = \mathrm{w}_{\max} - \frac{\mathrm{w}_{\max} - \mathrm{w}_{\min}}{\mathrm{iter}_{\max}} * \mathrm{iter} \quad (7)$$

III. MAIN RESULTS

A. Proposed EBC-PSO algorithm

To date, numerous algorithms have been proposed for backbone construction on MCDS problem in UDG and few studies have been conducted on MCDS problem in DGB and on DC-MWCDS problem in UDG. To the best of our knowledge, no work has been carried out on DC-MWCDS problem in DGB. Since energy efficiency and backbone size are important issues in backbone formation of wireless sensor networks, determination of the optimal values of energy and degree constraints are very importance that are optimally computed in this paper utilizing PSO algorithm. In our previous work [8], we assumed that all sensors in the network have the same transmission range and presented an energy efficient backbone formation algorithm on MCDS in UDG using PSO algorithm.

The first aim of this paper is to model the energy efficient backbone construction problem in wireless sensor networks with bidirectional links as the OEDC-MWCDS problem. Then an optimal algorithm called EBC-PSO was proposed to form a virtual backbone utilizing PSO algorithm in wireless sensor networks with bidirectional links.

Let G = (V, E) denotes the topology graph of the network, where V denotes the set of nodes and E denotes the set of edges. We assume that all nodes in WSN are dispersed randomly following a uniform distribution in a 2-dimensional plane and the nodes have different transmission ranges. The network topology is modeled as a disk graph with bidirectional links (DGB). Each node v_i has a unique id (ID_i), a state (S_i), a transmission range (R_i), an effective degree (De_i), remaining energy (E_i), and a weight (W_i) of being in the backbone.

In this paper, we determine the values of optimal variables utilizing PSO algorithm. Then, at the selection of DS nodes, these values are used. The optimal variables are defined as follows:

- Coefficient of minimum remaining energy of nodes: This parameter is the coefficient of average energy of live nodes.
- Coefficient of maximum degree of nodes: This parameter is the coefficient of maximum degree of live nodes.

Determination of the optimal coefficients utilizing PSO algorithm is done based on the proposed algorithm as shown in Fig.2. At the beginning of the network setup, proposed method for determination of optimal coefficients utilizing PSO algorithm is run only once, and the optimal coefficients of minimum remaining energy and maximum degree of nodes are determined with the aim of maximizing the network lifetime.

The operation of EBC-PSO is organized as rounds. Each round of this algorithm consists of two phases. MIS construction phase and CDS construction phase. In the first phase, an optimal maximal independent set (MIS) of the network graph is computed. The second phase is to choose the minimum number of nodes in order to make the connected DS. For selection of MIS nodes in MIS construction phase, we change the MIS construction phase of the proposed algorithm in [28] and consider optimal energy and degree constraints. In MIS construction phase of EBC-PSO, if the degree of each node is more than determined optimal degree constraint D_{cons} or the energy of each node is less than the determined optimal energy constraint E_{cons}, the node won't be selected as the MIS node. CDS construction phase of EBC-PSO is the same as the CDS construction phase of the proposed algorithm in [28].

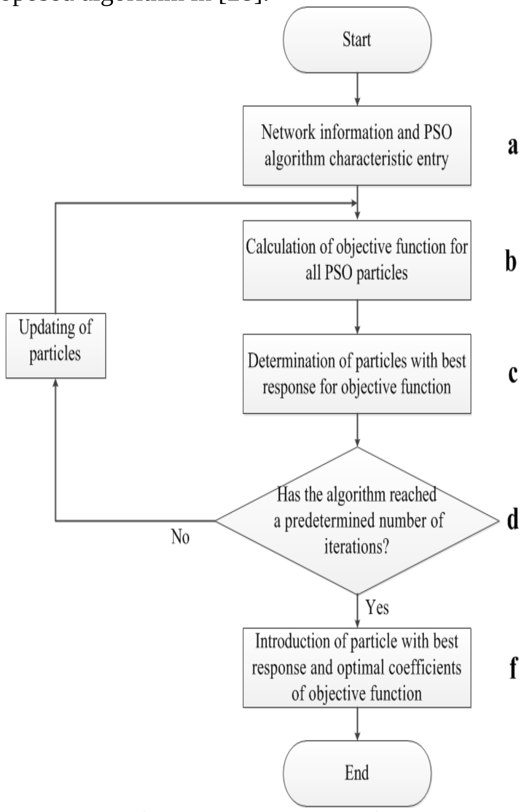


fig.2: Flowchart of the proposed algorithm for determination of optimal coefficients

The stages of the proposed algorithm for determination of the optimal coefficients are as follows:

a) In this stage, the network information is given as input data to the program. The information includes network size, the number of nodes, the position of each node, the transmission rang of each node, the initial energy of each node, the number of transmitted data packets, TMAX and PSO algorithm information such as the number of particles, the number of desired iterations and the values of c1 and c2.

b) In this stage, objective function is calculated for all PSO particles. In this paper, the objective function is to maximize the network lifetime.

c) In this stage, the particles with the best response are determined.

d) In this block, it is considered whether the algorithm has reached a predetermined number of iterations. If yes, the algorithm goes to step f otherwise goes to step e.

e) In this stage, the particle updates are done based on the objective function.

f) In this stage, the particle with the best response is introduced and the optimal coefficients of the objective functions are presented.

After determination of the optimal variables, average remaining energy of the live nodes and maximum degree of nodes are announced to the sink node in each round. The sink node computes the degree and energy constraints according to Eq.8 and Eq.9 and sends these values to the sensor nodes in the network. Then, in the MIS construction phase, if the degree of each node is more than the degree constraint D_{cons} or energy of each node is less than the energy constraint E_{cons}, the node won't be selected as the MIS node.

$$E_{cons} = E_{PSO} \times E_{avg} \tag{8}$$

Where E_{cons} is the energy constraint, E_{pso} is optimal coefficient of minimum remaining energy of the nodes determined by PSO algorithm and E_{avg} is the average energy of the network nodes.

$$D_{cons} = D_{PSO} \times D_{max} \tag{9}$$

where D_{cons} is the degree constraint, D_{pso} is the optimal coefficient of the maximum degree of the nodes determined by PSO algorithm and D_{max} is the maximum degree of the network nodes.

In the proposed algorithm, energy constraint is computed dynamically in each round. For announcing average remaining energy and maximum degree of nodes to the sink node, no additional messages are sent in the network. This work is done through marking certain bits in data packet by the nodes in the sending path. In fact, it is assumed that the sender node adds 20-bit header to the beginning of the message. The first 10 bits in the header indicates the remaining energy and the second one indicates the maximum degree of the node.

B. *MIS construction phase*

This phase starts from a node as an initiator that initiates the execution. We consider the sink node as the initiator. The colors are used to indicate whether a node is in MIS or not. Black color is used to indicate MIS nodes and gray color is used to indicate non-MIS nodes. In this phase, each node can be in one of four states: white, black, gray and transition. At the beginning, all nodes are in the initial state with white color and at the end of the phase, all nodes in the network are in black state (MIS nodes) or gray state (non-MIS nodes). The transition is an intermediate state.

Two types of messages exist in this phase: (1) BLACK message: sent out when a node becomes a black node; (2) GRAY message: sent out when a node becomes a gray node. Each message contains ID_i and state Si. State transition diagram of MIS construction has been shown in Fig.3.

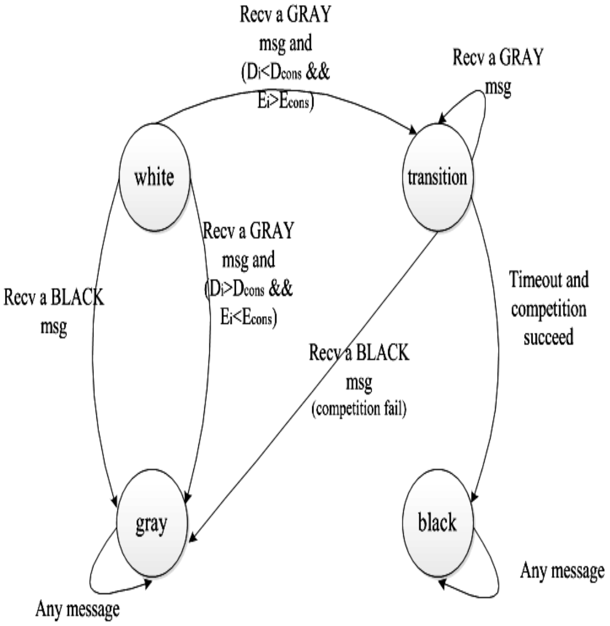


Fig.3: State transition diagram of MIS construction

The initiator (sink node) starts the construction of a CDS by coloring itself black. The node broadcasts a BLACK message to its neighbors to indicate itself as an MIS node. A white node that receives a BLACK message becomes a gray node and broadcasts a GRAY message.

A white node that receives a GRAY message, compares its degree and remaining energy with degree and energy constraints. If the degree of each node is more than degree constraint ($D_i>D_{cons}$) or energy of each node is less than energy constraint ($E_i< E_{cons}$), the node cannot be competed to become an MIS node and enters gray state. Then it broadcasts a GRAY message to its neighbors to indicate itself as a non-MIS node. Otherwise, it needs to compete to become a black node and enters transition state and sets a timer (ΔTi) based on Eq.10.

Eq.10, Eq.11 and Eq.12 are presented by Raei et al. [28].

$$\Delta T_i = \frac{1}{W_i} \times T_{MAX} \tag{10}$$

Where, TMAX is the maximum time for each timer which is an optional value. In each phase, a node with the highest weight (W_i) among its neighbors is selected by the timer factor (ΔT_i).

In MIS construction phase, W_i is set based on Eq.11.

$$W_i = \sqrt{R_i} \times E_i \tag{11}$$

The node will stay in the transition state until timer expires. During the timeout, it may receive a BLACK or GRAY message. If it receives a GRAY message, the node ignores it and stays in the transition state. If it receives a BLACK message, the node enters gray state and broadcasts a GRAY message. When timeout is due, it implies that the competition succeeds and this node can be an MIS node, then the node enters black state and broadcasts BLACK message. During the coloring process, each gray node will keep a list of all the adjacent black (MIS) nodes to set Dei for the next phase. The same operation continues from node to node until all nodes are placed in the state of either black or gray. Pseudo code of MIS construction phase is shown in Fig.4.

```
Each node i is white
Initiator (sink node) colors itself black and broadcasts a BLACK msg;
Each node i  receive a message
{
  If state(i)=black/gray
    Ignore the message and return;
  If state(i)=white
  {
    If msg-type=BLACK{
      state(i) ← gray;
      Broadcast a GRAY msg;}
    If msg-type=GRAY
    {
      If ($D_i > D_{cons}$ or  $E_i < E_{cons}$ ){
        state(i) ← gray;
        Broadcast a GRAY msg;}
      Else {
        state(i) ← transition;
        Set a timer ($\Delta Ti$ );}
    }
  }
  If state(i)= transition
  {
    If msg-type=BLACK{
      state(i) ← gray;
      terminate the timer;
      Broadcast a GRAY msg;}
    If msg-type=GRAY
      Ignore the msg;
    If the timer expires{
      state(i) ← black;
      Broadcast a BLACK msg;}
  }
}
```

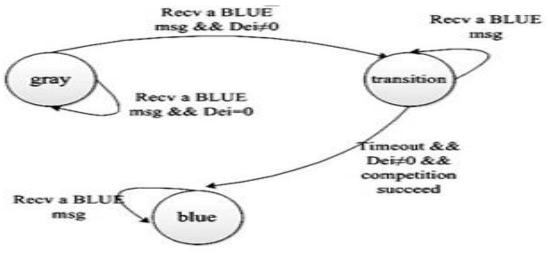
Fig.4: Pseudo code of MIS construction phase

C. CDS construction

A MIS in DGB is a dominating set and a CDS can be constructed by making the DS connected together. A localized approximation of the minimum spanning tree may perform well enough. A greedy approximation algorithm is used to select every non-MIS node with the maximum number of black neighbors (Di) which interconnect two or more MIS nodes, as a connector.

Fig.5 shows the state transition diagram of CDS construction. During the process, an MIS node is in one of two states: Black or blue. A Non-MIS node is in one of three states: Gray, blue or transition.

(a) State transition diagram for MIS nodes



(b) State transition diagram for non-MIS nodes

Fig.5: State transition diagram of CDS construction

At the end of the CDS construction phase, all nodes in the network are gray or blue. CDS nodes are in blue states. There is one type of message: BLUE message, sent out when a node becomes a CDS node. Each BLUE message contains Si and ID_i.

After the completion of MIS construction phase, a node in the network graph is either in black (that is, an MIS node) or in gray state (that is, a non-MIS node), and each gray node keeps a list of its black neighbors. If all neighbors of a node become gray or black (that is, all neighbors of a node terminate MIS construction phase and become MIS or non-MIS nodes), the node will begin the CDS construction phase. In the CDS construction phase, each node v_i has an effective degree (Dei) that indicates the number of MIS neighbors.

The initiator of MIS construction phase (sink node) starts CDS construction. It colors itself blue and broadcast a BLUE message to its neighbors to indicate itself as a CDS node. All messages are delivered in order. If the effective degree of a gray node that receives a BLUE message is not zero ($Dei \neq 0$), then it enters the transition state and sets a timer (ΔTi) based on Eq. 10, in which W_i is set according to the Eq.12, otherwise it ignores the message.

$$W_i = \sqrt{D_i} \times E_i \qquad (12)$$

If a node in the transition state receives a BLUE message, it ignores the message. When transition timer expires, if the effective degree of the gray node is not zero ($Di \neq 0$), it means that the competition succeeds and the node can be a connector. Therefore the node enters blue state and broadcast BLUE message.

A black node that receives a BLUE message will directly enter blue state to become a CDS node that broadcasts a BLUE message. The CDS construction phase continues until: 1) Any MIS node colored blue terminates the phase. 2) Any non-MIS node terminates when it is colored blue (i.e., chosen as a connector) or all its neighbors are colored blue and gray (i.e., all its neighbors are in the final state).Fig.6 shows pseudo code of CDS construction phase.

```
Each node i is gray or black
Initiator (sink node) colors itself blue and broadcasts a BLUE msg;
Each node i receive a message
{
  If state(i)=gray
  {
    If msg-type =BLUE{
      If $D_i \neq 0${
        state(i) ← transition;
        Set a timer ($\Delta Ti$ );}
      Else
        Ignore the msg;}
  }
  If state(i)=transition
  {
    If msg-type =BLUE
      Ignore the message;
    If the timer expires
    {
      If $D_i \neq 0${
        state(i) ← blue;
        Broadcast a BLUE msg;}
    }
  }
  If state(i)= black
  {
    If msg-type =BLUE {
      state(i) ← blue;
      Broadcast a BLUE msg;}
  }
  If state(i)= blue
    Ignore the message and return;
}
```

Fig.6: Pseudo code of CDS construction phase

D. *Theoretical analysis of the proposed algorithm*

The following two theorems and their proofs are similar to the theorems listed in [28].

Theorem 1: The set of black nodes computed by the MIS construction phase forms an MIS of the network graph.

Proof: The set of black nodes computed by the MIS construction phase is denoted as B. In this phase, the nodes of the graph is colored 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), grey nodes of the previous layer select black nodes. The construction incrementally enlarges the black node set by adding black nodes 2 hops away from the previous black nodes set. 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 independent set. 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 gray node black, B will not be disjoint anymore. Thus, B is the maximal independent set.

Theorem 2: The set of blue nodes computed by the CDS construction phase is a CDS of the network graph.

Proof: The set of blue nodes include MIS nodes and connectors. Since MIS is a DS, therefore only need to prove the connectivity. B= {b0,b1, . . . , bn} is the independent set, which elements are arranged one by one in the construction order. Hi is the graph over {b0,b1, . . . ,bi }, (1 ≤ i < n) in which the pairs of nodes are interconnected by connectors. Connectivity is proven by induction on j that Hj is connected. Since H1 consists of a single node, it is connected trivially. Assume that Hj−1 is connected for some j ≥ 2. Considering message propagation layer in MIS construction phase, let Bi−1 and Gi−1 be the set of MIS and non-MIS nodes at the (i − 1)th layer, respectively. The non-MIS node in Gi−1 with maximal weight (according to Eq. 12) is selected as connectors in CDS construction phase. According to the property that each MIS node calculated by the proposed algorithm has a non-MIS neighbor that connects it to at least another MIS node, it's enough to find non-MIS nodes, which interconnect Bi−1 nodes at (i − 1)th layer with Bi nodes in the ith layer. As Hj−1 is connected, so must be Hj. Therefore the set of blue nodes computed by CDS construction phase is a CDS.

The following important properties have listed in [29] for CDS in DGB:

Lemma 1: In a disk graph with bidirectional links (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 that the distance between these MIS nodes is less than their transmission range; in other words, these MIS nodes are in neighborhoods of each other so that this consequence is in conflict with definition of the MIS presented in section 3.

Theorem 3: Proposed algorithm (EBC-PSO) has O(n) time and message complexity.

Proof: In MIS construction phase, each node at most sends out once BLACK or GRAY message. Thus, the total number of these messages is O(n). In CDS construction phase; since each blue node sends only one BLUE message, the message complexity in the worst case is O(n). It is clear that the time complexity of MIS construction phase and CDS construction phase is O(n), because EBC-PSO in both phases for each node has the time complexity O(1) (each node receives a message and may set a timer, it doesn't perform sorting and search operations) and since all the nodes run the algorithm, then the time complexity is O(n).Also, in EBC-PSO, for sending the average remaining energy and maximum degree of nodes to the sink node, no additional messages are sent in the network. This work is done through marking certain bits in data packet by the nodes in the sending path. Thus, the time and message complexity of EBC-PSO is O(n).

IV. SIMULATION RESULTS AND DISCUSSIONS

In this section, two sets of simulation experiments are conducted in MATLAB. The first set of experiments are conducted to show the efficiency of EBC-PSO compared with the proposed algorithm in [28] in terms of backbone size, network lifetime, energy consumption in CDS construction and message overhead. Also, the performance of the proposed method using PSO algorithm is compare with that using genetic algorithm (GA) in terms of backbone size and network life. In the second set of experiments, different scenarios are defined to compare the performance of EBC-PSO in these scenarios with the proposed algorithm in [28].

The simulations are carried out by a random network topology with sensor nodes randomly distributed in the monitoring area. The simulation network size is 100-250 numbers of nodes in increments of 50 nodes respectively. The transmission range of each sensor node is set randomly from 20m to 30m. The simulation parameters are shown in Table.I.

TABLE I
SIMULATION PARAMETER

Parameter	Value
Network size	$100m \times 100m$
The initial energy of each node	$0.1J$
data packet size	2000 bits
broadcast packet size	250 bits
T_{MAX}	$100ms$
The number of particle of PSO algorithm	20
The number of iterations of PSO algorithm	20
c_1 parameter of PSO algorithm	1.5
c_2 parameter of PSO algorithm	2.5
E_{elec}	50 nJ/ bit
ε_{fs}	10 pJ/ bit/ m^2
ε_{amp}	0.0013 pJ/ bit/ m^4

For estimating the amount of energy consumption, the energy model presented in [36] is used. Eq. 13 is used to calculate the transmission energy, denoted as $E_{Tx}(k,d)$ required for a "k" bits message over a distance of "d".

$$E_{Tx}(k,d) = \begin{cases} kE_{elec} + k\varepsilon_{fs}d^2, & d < d_0 \\ kE_{elec} + k\varepsilon_{amp}d^4, & d \geq d_0 \end{cases} \tag{13}$$

To receive a "k" bits message, the required energy is calculated by Eq.14.

$$E_{Rx}(k) = k \times E_{elec} \tag{14}$$

The electronics energy E_{elec} is the energy required to run the transmitter or the receiver circuit, εfsd2 and εampd4 are the energies required to run the amplifier during transmission.

A. *Simulation results of experiment I*

Backbone size

Backbone size is the number of network nodes included in the backbone. Backbone size is inversely proportional to the radio transmission range. Communication cost is directly proportional to the backbone size [14]. Fig.7 shows the changes in backbone size of EBC-PSO in comparison with the method using GA and the proposed algorithm in [28]. To show the impact of network size on the backbone size, the number of nodes was changed from 100 to 250. It is obvious from Fig.7 that EBC-PSO has smaller backbone size compared with the method using GA and the proposed algorithm in [28].

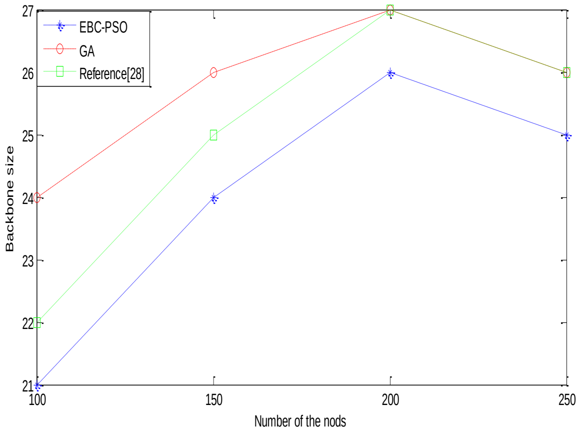


Fig.7: Backbone size versus the number of nodes

Network lifetime

Network lifetime is defined as the duration of network until the first node depletes its energy. So, the network lifetime effectively ends with the first node death (FND) [7]. Fig.9 shows the network lifetime of EBC-PSO, the method using GA and the proposed algorithm in [28] in terms of the first node death (FND) as the number of nodes changes from 100 to 250. As shown in Fig.8, EBC-PSO has better performance than the method using GA and the proposed algorithm in [28] in terms of network lifetime.

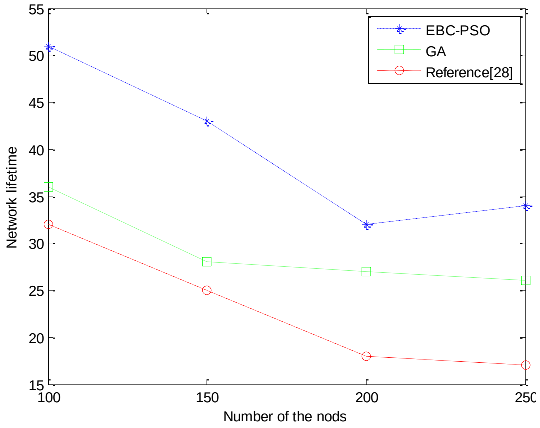


Fig.8: The network lifetime versus the network size

Message overhead

The average number of bytes transmitted by the nodes in the network is defined as the message complexity (overhead) of backbone formation algorithm. Fig.9 shows the message overhead of EBC-PSO and proposed algorithm in [28]. As mentioned earlier, in EBC-PSO, for sending average remaining energy and node degree to the sink node, no additional messages are sent in the network. This work is done through marking certain bits in the data packet by the nodes in the sending path. Thus, the message complexity (overhead) of EBC-PSO is approximately the same as that of proposed algorithm in [28]. Fig.9 also shows that message overhead of backbone formation algorithm increases as the network size increases.

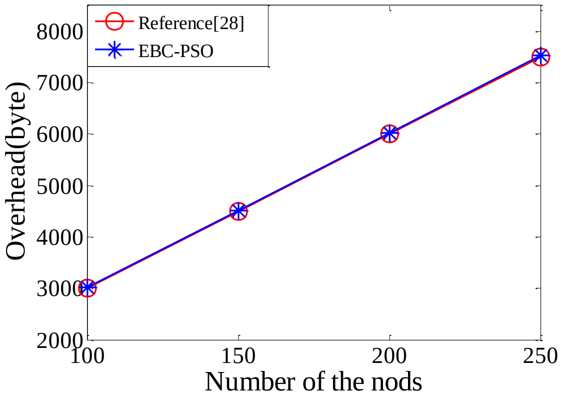


Fig.9: The message overhead (Number of Bytes) versus the network size

Energy Consumption in CDS construction

In order to compare the energy efficiency of EBC-PSO and proposed algorithm in [28], we have computed the average energy consumption per node in the CDS construction. Fig.10 shows the average energy consumed by each node in CDS construction. Consumed energy in CDS construction depends on the number of messages received and transmitted by each node. Since in EBC-PSO, for sending average remaining energy and maximum degree of nodes to the sink node, no additional messages are sent, consumed energy in CDS construction of EBC-PSO and proposed algorithm in [28] is approximately the same.

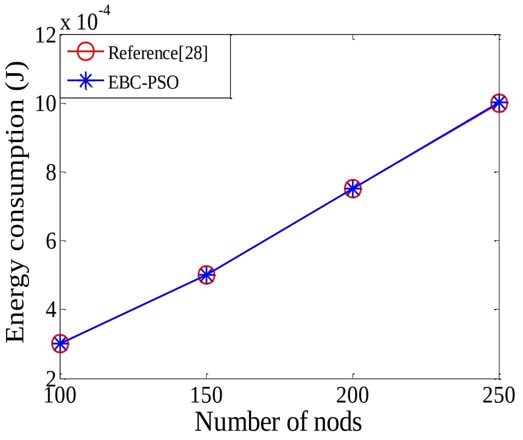


Fig. 10: Average energy consumption per node in CDS construction.

Fig.11 shows PSO algorithm convergence process for one of the 20 sample networks.

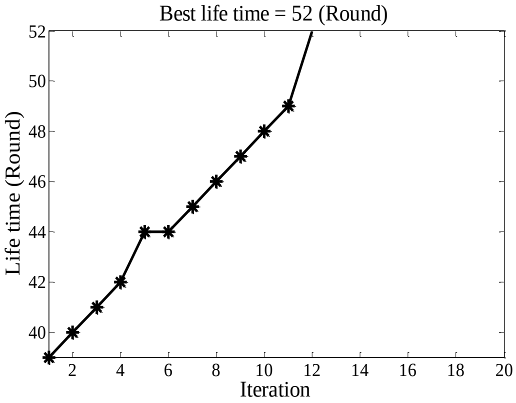


Fig.11: Convergence process of PSO algorithm for one of the 20 sample networks

The convergence time in a system with processor-Intel core i5, 4GB of physical memory and windows 7 is as follows:

TABLE II
CONVERGENCE TIME OF PSO ALGORITHM

Number of nodes	100	150	200	250
Convergence time in second	5	8	12	15

B. Definition of different scenarios

According to the application of network, we define different scenarios to describe the network lifetime and determine energy and degree constraints. Then, we compare the performance of EBC-PSO in these scenarios with that of the proposed algorithm in [28].

Scenario (1): In some applications of sensor networks, leaving a single node may lead to the lack of desired service and disrupt network performance. In these situations, in each round, the backbone nodes should be determined so that the first node death (FND) is delayed as much as possible. So in this case, our aim is to determine backbone nodes which its first node death (FND) occurs after the maximum possible time.

Scenario (2): In some applications of sensor networks, the maximum number of nodes in each round may be desirable. In these conditions, the backbone nodes are selected so that the maximum number of nodes remains alive in each round. So the objective function is defined as the total number of live nodes in each round.

Scenario (3): In some applications, the sensor network can continue its operations until the sensor nodes are alive. In these conditions, the sensor nodes should be selected so that the last node death is delayed as much as possible. So in this case, the aim is to determine backbone nodes so that the last node death occurs after the maximum possible time.

C. Simulation results of experiment II

The experiments are assumed to be performed in a square field of 100m×100m, in which nodes are randomly dispersed as shown in Fig.12. The parameters used in these simulations are the same as parameters of experiment I.

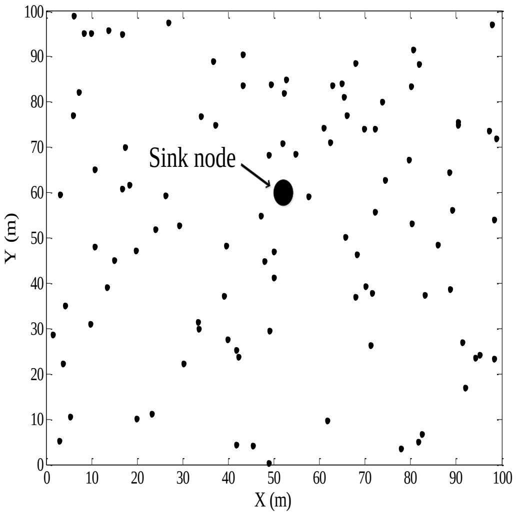


Fig.12: Nodes deployment in the network

Table 3 shows the results gained from simulations of EBC-PSO in different scenarios and the proposed algorithm in [28]. It also shows the optimal values of coefficients of minimum remaining energy and maximum degree of nodes. It is obvious from Table. III that in different scenarios, EBC-PSO has better performance than the proposed algorithm in [28]. EBC-PSO increases the network lifetime approximately 40% to 90%.

TABLE III
SIMULATON RESULT OF EXPERIMENT II

Algorithm	Coefficient of minimum remaining energy	Coefficient of maximum degree	First Node Dies	Last Node Dies	Total number of live nodes
Proposed algorithm in [28]	-	-	37	142	10583
Scenario 1	0.1066	0.6117	50	175	10549
Scenario 2	0.0363	0.7268	43	161	10792
Scenario 3	0.0422	0.8001	40	219	9010

Fig.13 and Fig. 14 indicates the performance comparison of EBC-PSO and the proposed algorithm in [28] using FND metric in scenario 1 and LND metric in scenario 3, respectively. .As shown in Table. III, Fig.13 and Fig.14, in scenario 1 that objective function has been intended First Node Dies (FND) and in scenario 3 that objective function has been intended Last Node Dies (LND), EBC-PSO has better performance than the proposed algorithm in [28].

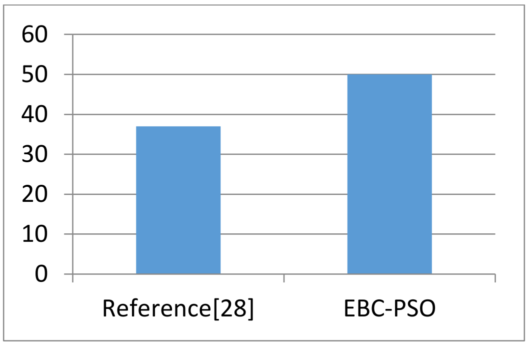


Fig. 13: Performance comparison of the network lifetime using FND metric (scenario 1)

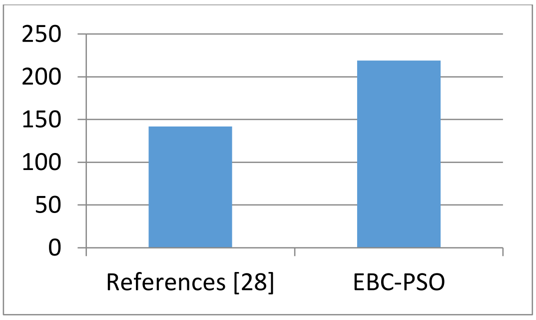


Fig.14: Performance comparison of the network lifetime using LND metric (scenario 3)

Fig.15 shows the total number of sensor nodes that remain alive over the simulation runs (scenario 2). It is clear from Fig.16 and Table 3 that in scenario 2, EBC-PSO has better performance than the proposed algorithm in [28] in terms of the total number of live nodes in each round.

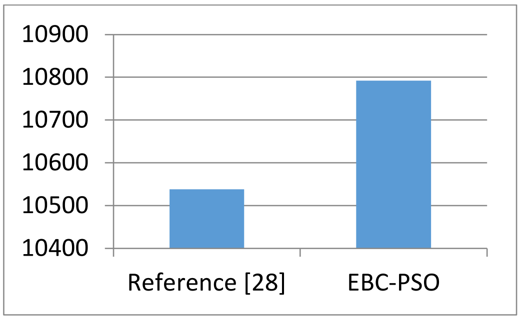


Fig.15: Performance comparison of the network lifetime in scenario 2

The total number of live nodes of EBC-PSO in different scenarios and the proposed algorithm in [28] over the simulation runs are shown in Fig.16.

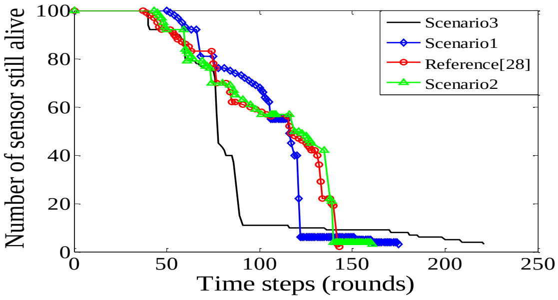


Fig.16: Number of live nodes per round

V. CONCLUSIONS

In this paper, an extension of the CDS problem called OEDC-MWCDS was presented to model the energy efficient backbone construction problem in wireless sensor networks. Then we proposed an optimal energy efficient backbone construction algorithm called EBC-PSO in disk graphs with bidirectional links (DGB) utilizing PSO algorithm. Proposed method aims at determination of energy and degree constraints of dominating set (DS) nodes to extend the network lifetime. For this reason, the optimal coefficients of maximum degree and minimum remaining energy of nodes are computed utilizing PSO algorithm. The obtained results demonstrated that EBC-PSO outperforms the method using genetic algorithm and the proposed algorithm in [28] in terms of backbone size and network lifetime. Then, we defined different scenarios for evaluation of the proposed algorithm in different conditions. Simulation results showed that EBC-PSO has a better performance than the proposed in [28] in the mentioned scenarios.

REFERENCES

[1] N. Aslam, W. Phillips, W. Robertson, S. Sivakumar, A multi-criterion optimization technique for energy efficient cluster formation in wireless sensor networks, Inf. Fusion. 12 (2011) 202–212.

[2] T. Dong, D. Zhang, Y. Shen, M. Guo, Energy efficient transmission distance adjustment under non-uniform distributed wireless sensor networks, in: Commun. Mob. Comput. (CMC), 2010 Int. Conf., IEEE, 2010: pp. 490–495.

[3] R. Sheikhpour, S. Jabbehdari, An energy efficient chain-based routing protocol for wireless sensor networks, KSII Trans. Internet Inf. Syst. 7 (2013) 1357–1378. doi:10.3837/tiis.2013.06.001.

[4] Y. Jin, L. Wang, Y. Kim, X. Yang, EEMC: An energy-efficient multi-level clustering algorithm for large-scale wireless sensor networks, Comput. Networks. 52 (2008) 542–562.

[5] P.-J. Chuang, S.-H. Yang, C.-S. Lin, Energy-efficient clustering in wireless sensor networks, in: Int. Conf. Algorithms Archit. Parallel Process., Springer, 2009: pp. 112–120.

[6] P. Saini, A.K. Sharma, Energy efficient scheme for clustering protocol prolonging the lifetime of heterogeneous wireless sensor networks, Natl. Inst. Technol. Jalandhar, Dep. Comput. Sci. Eng. Int. J. Comput. Appl. 6 (2010).

[7] X. Kui, Y. Sheng, H. Du, J. Liang, Constructing a CDS-based network backbone for data collection in wireless sensor networks, Int. J. Distrib. Sens. Networks. 9 (2013) 258081.

[8] S. Poostfroushan, M.A. Sarram, R. Sheikhpour, Energy efficient backbone formation using particle swarm optimization algorithm in wireless sensor networks, Int. J. Grid Distrib. Comput. 7 (2014) 123–134.

[9] J.A. Torkestani, Energy-efficient backbone formation in wireless sensor networks, Comput. Electr. Eng. 39 (2013) 1800–1811.

[10] Z. Rezaei, J.A. Torkestani, An energy-efficient MCDS-based routing algorithm for wireless sensor networks: Learning automata approach, Prz. Elektrotechniczny (Electrical Rev. 11 (2012) 147–151.

[11] Y. Zhao, J. Wu, F. Li, S. Lu, On maximizing the lifetime of wireless sensor networks using virtual backbone scheduling, IEEE Trans. Parallel Distrib. Syst. 23 (2012) 1528–1535.

[12] J.A. Torkestani, An adaptive backbone formation algorithm for wireless sensor networks, Comput. Commun. 35 (2012) 1333–1344.

[13] Y. Zeng, C.J. Sreenan, N. Xiong, L.T. Yang, J.H. Park, Connectivity and coverage maintenance in wireless sensor networks, J. Supercomput. 52 (2010) 23–46.

[14] J.A. Torkestani, Backbone formation in wireless sensor networks, Sensors Actuators A Phys. 185 (2012) 117–126.

[15] Z. Yuanyuan, X. Jia, H. Yanxiang, Energy efficient distributed connected dominating sets construction in wireless sensor networks, in: Proc. 2006 Int. Conf. Wirel. Commun. Mob. Comput., ACM, 2006: pp. 797–802.

[16] X.H. Yaqian Li, Rongrong Yin, Haoran Liu, A Reliable connected dominating set algorithm in wireless sensor networks, J. Comput. Inf. Syst. 8 (2012) 2583–2592.

[17] S.-Y. Chuang, C. Chen, SmartBone: an energy-efficient smart backbone construction in wireless sensor networks, in: Wirel. Commun. Netw. Conf. 2007. WCNC 2007. IEEE, IEEE, 2007: pp. 3394–3399.

[18] T. Moulahi, H. Guyennet, S. Nasri, R. Hajlaoui, On the construction of load-balanced (k, r-hop)-connected dominating set for WSNs, in: Adv. Networks Telecommuncations Syst. (ANTS), 2012 IEEE Int. Conf., IEEE, 2012: pp. 76–80.

[19] J. He, S. Ji, M. Yan, Y. Pan, Y. Li, Genetic-algorithm-based construction of load-balanced CDSs in wireless sensor networks, in: Mil. Commun. Conf. 2011-MILCOM 2011, IEEE, 2011: pp. 667–672.

[20] B.N. Umesh, G. Vasanth, Energy Efficient Routing of Wireless Sensor Networks Using Virtual Backbone and life time Maximization of Nodes, Int. J. Wirel. Mob. Networks. 5 (2013) 107–118.

[21] S. Hussain, M.I. Shafique, L.T. Yang, Constructing a cds-based network backbone for energy efficiency in industrial wireless sensor networks, in: High Perform. Comput. Commun. (HPCC), 2010 12th IEEE Int. Conf., IEEE, 2010: pp. 322–328.

[22] J. He, S. Ji, P. Fan, Y. Pan, Y. Li, Constructing a load-balanced virtual backbone in wireless sensor networks, in: Comput. Netw. Commun. (ICNC), 2012 Int. Conf., IEEE, 2012: pp. 959–963.

[23] A.A. Aziz, Y.A. Şekercioğlu, A distributed energy aware connected dominating set technique for wireless sensor networks, in: Intell. Adv. Syst. (ICIAS), 2012 4th Int. Conf., IEEE, 2012: pp. 241–246.

[24] H. Raei, M. Sarram, B. Salimi, F. Adibniya, Energy-aware distributed algorithm for virtual backbone in wireless sensor networks, in: Innov. Inf. Technol. 2008. IIT 2008. Int. Conf., IEEE, 2008: pp. 435–439.

[25] H. Raei, M. Sarram, F. Adibniya, Distributed algorithm for connected dominating sets in wireless sensor networks with different transmission ranges, in: Telecommun. 2008. IST 2008. Int. Symp., IEEE, 2008: pp. 337–342.

[26] M.T. Thai, F. Wang, D. Liu, S. Zhu, D.-Z. Du, Connected dominating sets in wireless networks with different transmission ranges, IEEE Trans. Mob. Comput. 6 (2007) 721–730.

[27] H. Raei, M.A. Fathi, A. Akhlaghi, B. Ahmadipoor, A new distributed algorithm for virtual backbone in wireless sensor networks with different transmission ranges, in: Comput. Syst. Appl. 2009. AICCSA 2009. IEEE/ACS Int. Conf., IEEE, 2009: pp. 983–988.

[28] H. Raei, M. Sarram, M. Ghasemzadeh, Energy-aware distributed algorithm for virtual backbone in wireless sensor networks with bidirectional links, Sci. Res. Essays. 6 (2011) 2154–2163.

[29] J.A. Torkestani, M.R. Meybodi, An intelligent backbone formation algorithm for wireless ad hoc networks based on distributed learning automata, Comput. Networks. 54 (2010) 826–843.

[30] F. Dai, J. Wu, An extended localized algorithm for connected dominating set formation in ad hoc wireless networks, IEEE Trans. Parallel Distrib. Syst. 15 (2004) 908–920.

[31] B.N. Clark, C.J. Colbourn, D.S. Johnson, Unit disk graphs, Discrete Math. 86 (1990) 165–177.

[32] F. Zou, Y. Wang, X.-H. Xu, X. Li, H. Du, P. Wan, et al., New approximations for minimum-weighted dominating sets and minimum-weighted connected dominating sets on unit disk graphs, Theor. Comput. Sci. 412 (2011) 198–208.

[33] C.-J. Ting, K.-C. Wu, H. Chou, Particle swarm optimization algorithm for the berth allocation problem, Expert Syst. Appl. 41 (2014) 1543–1550.

[34] Y. Del Valle, G.K. Venayagamoorthy, S. Mohagheghi, J.-C. Hernandez, R.G. Harley, Particle swarm optimization: basic concepts, variants and applications in power systems, IEEE Trans. Evol. Comput. 12 (2008) 171–195.

[35] Y. Shi, R. Eberhart, A modified particle swarm optimizer, in: Evol. Comput. Proceedings, 1998. IEEE World Congr. Comput. Intell. 1998 IEEE Int. Conf., IEEE, 1998: pp. 69–73.

[36] W.R. Heinzelman, A. Chandrakasan, H. Balakrishnan, Energy-efficient communication protocol for wireless microsensor networks, in: Syst. Sci. 2000. Proc. 33rd Annu. Hawaii Int. Conf., IEEE, 2000: p. 10–pp.