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Wireless Sensor Network MCDS Construction Algorithms With Energy Consideration for Extreme Environments Healthcare

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ABSTRACT With the enhancement of people's health awareness, more and more users are willing to wear portable micro-health monitoring equipment and communicate with remote medicine center for real-time diagnosis. Although, under normal circumstances, users' health status can be detected at any time, in extreme circumstances, such as earthquakes, how to make the medical center monitor user data for a long time for rescue will be of great significance. In this paper, we will study the networking of portable wearable devices based on wireless sensor networks. We mainly use minimal connected dominating sets (MCDSs) to organize nodes in extreme environments effectively, form virtual backbone networks, send data to the rescue or medical personnel, and maximize network lifetime. Specifically, we propose an adverse dominator selection procedure (ADSP), where the dominators are selected by their children-independent nodes. The ADSP has two versions, which are Independent node degree-based Adverse Dominator Selection Procedure (IADSP) and residual Energy-based Adverse Dominator Selection Procedure (EADSP). Based on IADSP and EADSP, two approximation MCDS construction algorithms named Independent node degree based MCDS (IMCDS) and Energy-efficient Independent neighbor-based MCDS (EIMCDS) are proposed, respectively. Both of them have the message complexity as $O(N\Delta)$. The performance ratio of IMCDS has an upper bound as $O(\sqrt{N})$. The simulation results show that IMCDS and EIMCDS perform well in terms of CDS size, and the routing algorithm based on EIMCDS has better energy efficiency performance than that of IMCDS and classical routing protocol.

INDEX TERMS Adverse dominator selection procedure, extreme environment, healthcare, minimal connected dominating set, wireless sensor networks.

I. MOTIVATION

The progress of wireless sensor network technology and the continuous development of microelectronics technology have greatly promoted the development of health care [1]. With the improvement of people's health awareness, more and more people are willing to wear a device that can detect their own state at any time, and transmit health data to remote medical centers or community health centers for real-time comprehensive diagnosis. Users can walk around with their detection devices, which communicate with each other based on WSN technology. Through efficient networking technology and routing algorithm, users' health data can be transmitted to remote servers in real time. Recently, there are some related research results, such as IoT-aware smart hospital system (SHS) [2], break-the-glass access control (BTG-AC) model to address data availability issue and to detect the security policy violations [3], a home-based wireless ECG (Electronic Cardio Gram) monitoring system [4], and a fall detection system for elderly person monitoring [5].

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At present, health care-related systems mainly focus on four aspects [1]: Proactiveness, Transparency, Awareness, Trustworthiness. However, the above research results are mainly based on the normal environment, while in extreme environments, such as earthquakes, floods, fires and other scenarios the research results are still relatively few.

We can consider one of the following extreme scenarios, earthquake. When a major earthquake occurs, many users in a community are trapped in buildings. They wear portable health monitoring equipment, which has been networked and communicated through WSN technology. When an earthquake occurs, rescuing people will be the first important thing for rescue centers or medical centers. Rescue workers need to know not only the locations of the trapped users, but also the life statuses of the users. At this time, health monitoring equipment will play a key role. However, in extreme environments, the energy of devices is limited, and the failure of any device may lead to the loss of data [6], which may even result into information islands. Therefore, it is necessary to design and propose energy-efficient networking algorithms and routing protocols based on WSN, in order to maximize the energy supply time of all portable devices in WSN networks, and regularly send user status to the outside world to guide rescue.

At present, there are many research results related to wireless networks, and they cover all aspects of our lives. As wireless network technology has become more and more mature, mobile edge computing related topics have gradually become research hotspots in recent years. For example, in [7], the problem of indoor wireless network location in mobile edge computing environment was studied. However, WSN still carries out some research on its theoretical depth and application breadth, such as in [8], integrating energy harvesting technology for WSN. In [9], the coverage and connectivity technology of WSN network was studied. In [10], PSO (Particle Swarm Optimization)-based intelligent clustering technology of WSN was integrated. Besides, there are few studies on WSN energy-efficient networking algorithms for health care in extreme environments.

Topology control in WSN is an energy management networking technology and is an efficient way to manage the sensor nodes for saving energy, which optimizes the network's topology by removing redundant links. The topology control based routing protocol can improve bandwidth utilization, delivery ratio, extend network lifetime and reduce interference [11] as well as the packet retransmission [12].

The topology control has mainly two types [13]: power control and hierarchical topology control. The hierarchical topology aims to construct a connected dominating set (CDS), which is a subset of the fully connected network and covers all nodes in the network. Besides, any two nodes in CDS are connected with each other. A CDS serves as a virtual backbone for wireless sensor network, and the packets are forwarded through the CDS from the source node to the destination.

II. RELATED WORK

In order to improve the routing performance in wireless sensor network, such as reducing the interference and saving the energy as well as restraining flooding in the network, the size of CDS should be minimized. But constructing a minimal CDS (MCDS) is usually an NP-hard problem [14], and some research work has been done to construct an approximate MCDS.

Alzoubi *et al.* [15] proposed a two-phase algorithm. The first phase was constructing a MIS (Maximum Independent Set) based on the concept of complementary and the second phase was selecting the connectors and constructing a CDS. The most important contribution of this paper was bringing forward the performance ratio, which guaranteed to generate a CDS with an upper bounded size. Wan *et al.* [16] presented that the dominators of MIS were selected based on the lower level neighbors' states, while the connectors were selected based on the maximum dominator node degree. A greedy algorithm S-MIS was proposed by Li *et al.* [17], which had two phases. The first phase was the same as proposed in [16]. The black-blue component was proposed in the second phase and a greedy algorithm was proposed to determine the grey nodes. Thai *et al.* [18] put forwarded two algorithms named as TFA (The First Algorithm) and TSA (The Second Algorithm) respectively. TFA was the extension of S-MIS in the DGB (Disk Graphs with Bidirectional links), while TSA has two phases, and the first phase was constructing a MIS by choosing the nodes with the biggest radius as the dominators. The second phase of TSA was the same as that of the TFA.

The MCDS construction algorithms described above were MIS-based algorithms, where in the first stage, the MIS was constructed, and the connecters were selected in the second stage. In the procedure of constructing the MIS, the criterions of selecting the dominators were different in various algorithms. In general, the node degree, the energy and node id were used as the criterions more frequently.

In [19], the criterion of selecting the dominators in the first stage was the node degree of the unmarked neighbors, and in the second stage, the criterion of selecting the connectors was the number of unmarked nodes adjacent to the non-fragment nodes. In [20], the criterion of constructing a CDS was the timer, which was based on the transmission ranges of nodes. And in [21], the criterion was the weighted composed of the node degree and the battery power. The node id was used as the criterion in [22] and [23]. In [22], the node with the largest id was selected as the dominator, while in [23] the node with the smallest id was selected as the dominator.

Besides the MIS based algorithms, some non-MIS algorithms were also proposed. The non-MIS algorithms were classified into mainly two types: tree based algorithms (also named heuristic algorithms) and distributed algorithms.

Wu and Li [24] proposed a very simple marking process and all the marked nodes formed a CDS. In order to delete the redundant marked nodes, the pruning algorithms named as Rule-1 and Rule-2 were proposed. It was a very simple distributed algorithm, and the pruning algorithms had inspired a lot of research work. The algorithm proposed by Dai and Wu [25] extended the algorithm in [24] and the pruning process was extended to Rule-k. The authors had proved that Rule-k outperformed Rule-1 and Rule-2 especially in networks with relatively high vertex degree and high percentage of unidirectional links. Misra and Mandal [26] proposed an algorithm for constructing a MCDS by using the Steiner tree. The collaborative cover was used by including two principles, which were about the domatic number and optimal substructure. The collaborative cover heuristics outperformed the degree-based heuristics in identifying independent set and Steiner tree. Two versions of MCDS algorithms were proposed by Sakai *et al.* [27], which were SI (Single-Initiator) version and MI (Multi-Initiator) version. The SI version generated the smallest CDS with single initiator, and MI version generated the smallest CDS with multiple initiators. The algorithms were timer based, and the CDS were constructed from the initiators. The minimum localized information was required for handing the nodal mobility as well as the lengthy recovery of the corrupted CDS. There were also many other algorithms belonging to the non-MIS type, for example in [28], a routing cost (routing path length) constraint CDS construction algorithm was proposed by L. Ding *et al.*, and the routing path length can be adjusted. The node pair was used as the criterion to select the dominators. Both the CDS size and the routing path length outperformed other algorithms. Ren *et al.* [29] applied effective degree to find a prior CDS and then optimized the CDS by using Minimum-weight Spanning Tree (MST). Three-hop messages were needed to learn the path to the dominators. The algorithm performed well in terms of CDS size as well as Average Hop Distance (AHD). Tang *et al.* [30] proposed a MCDS construction algorithm based on the reduced neighbor set, which is a set consist of the unmarked neighbors. The constructed CDS has good performance in terms of CDS size.

III. OUR CONTRIBUTIONS

The non-MIS based algorithms are more flexible than the MIS based algorithms. In this paper, we propose two non-MIS based MCDS construction algorithms. The main contributions we have made are presented as follows.

- We research the energy-efficient topology control technology of WSN in extreme environment, and propose a WSN networking algorithm based on MCDS to prolong the network lifetime in extreme environment.
- We propose an adverse dominator selection procedure named ADSP, which has two versions. The first version is independent node degree based ADSP, named IADSP, which is used to select the dominators in the CDS construction process of IMCDS.
- We propose a residual energy based adverse dominator selection procedure, which is the second version of ADSP, named as EADSP, and used to select the dominators in the CDS construction process of EIMCDS.
- Based on IADSP and EADSP, two MCDS construction algorithms are proposed. The first algorithm IMCDS focuses on reducing the CDS size, and the second algorithm EIMCDS focuses on the energy efficiency improvement.
- The performance ratio of IMCDS is analyzed and the performance ratio of IMCDS has an upper bound as $O(\sqrt{N})$. Besides, the message complexity of IMCDS and EIMCDS is also analyzed, which is $O(N\Delta)$, where Δ is the maximum neighbor number of a node, and N is the node number.

The rest of this paper is organized as follows: in Section IV, the preliminary knowledge is introduced. In Section V, we present the IMCDS algorithm, the EIMCDS algorithm is proposed in Section VI. In Section VII, we analyze the performance of IMCDS, and in Section VIII, the performances of IMCDS and EIMCDS are simulated. Finally, this paper is summarized in Section IX.

IV. PRELIMINARY KNOWLEDGE

Before introducing the MCDS construction algorithms, the assumptions, preliminary knowledge and notations should be presented firstly, and then each algorithm will be described in detail.

TABLE 1. Notations.

Name	Meaning
N	Node number
r_i	Transmission range of node i
N_{bn}	Black neighbor number
N_{rn}	Red neighbor number
D_{in}	Independent node degree
T	Countdown timer
R_a	The radius of a circle network area
E_o	Initial energy of node
E_{elec}	Data receiving and transmission energy per bit
E_{fs}	Short distance transmission energy per bit
E_{mp}	Long distance transmission energy per bit
E_{da}	Data aggregation energy per bit
L_{dp}	Data package length
L_{cp}	Control package length
p	Optimal cluster head selection probability of Leach
M	Side length of a square network area
(x_{bs}, y_{bs})	The location of base station

A. NOTATIONS DEFINITION

In TABLE 1, the variables and notations are defined for better reading. The messages are defined in each algorithm for better understanding. Besides, the intermediate variables used in the performance analysis are not defined in this table. Besides the notations, the network conditions will be introduced in the next subsection.

B. NETWORK CONDITIONS

In this paper, we assume all the sensor nodes are randomly distributed in the two-dimensional network field and have different transmission ranges. The link between any pair of nodes is bidirectional and the neighbor of one node is defined in Definition 1 below.

Definition 1: If and only if $d(u, v) < min(r_u, r_v)$, node v is a neighbor of u, and node u is a neighbor of v. $d(u, v)$ denotes the distance between node u and v, r_u and r_v denote the transmission ranges of node u and v respectively. In this paper, we do not consider the case of unidirectional connectivity.

C. NODE COLOR

Definition 2: Dominator node is marked black, and dominated node also named dominatee is marked grey. If a node is neither a dominator nor a dominatee, it is an independent node and marked white. There are also other nodes named as candidate dominators marked red, which is a temporary status.

In this paper, node color is a marker that identifies the state of a node. When a node is marked with different colors, the state of the node is different. For example, when a node is black, the node is a dominant node or dominator. The function of the node is to receive the packets sent by its children and then forward them. When the state of a node is grey, the node is a dominated node or dominatee. It only sends its own data packet to the dominant node. White node and red node are the initial state and intermediate state respectively, not the final state when the CDS is constructed.

In the next sections, we use black node, grey node, white node and red node to represent the dominator, the dominatee, the independent node and the candidate dominator respectively for simplicity.

D. ADVERSE DOMINATOR SELECTION PROCEDURE

In this paper, the dominators are selected by their independent neighbors (white neighbors), which are the children nodes of these dominators. The dominators selection criterions can be calculated out or received by their independent neighbors before the selecting process beginning. We call this selection process as Adverse Dominator Selection Procedure (ADSP), which means the dominators are determined by their children nodes instead of their parent nodes. This dominator selection procedure can be defined as different versions according to the selection criterions.

In the next sections, we will use the independent node degree and residual energy of node to propose two versions of ADSP named as IADSP and EADSP respectively, and the principle of ADSP will be introduced in detail by the IADSP and EADSP.

V. IMCDS ALGORITHM

A. INDEPENDENT NODE DEGREE BASED ADSP

In IMCDS, the dominator selection criterion is the independent node degree, then we call this process as Independent node degree based Adverse Dominator Selection Procedure (IADSP). The IADSP is executed by the white node i.e. the independent node, and the algorithm is presented in **Algorithm 1**.

Algorithm 1 IADSP Executed by White Node

```
if black neighbor number N_bn > 0 then
  | do not select any red neighbor as dominator
end
if black neighbor number N_bn = 0 and red neighbor
number N_rn > 1 then
  | calculate the independent node degree of these red
  | neighbors;
  | select k red neighbors which have the maximum
  | independent node degree;
  | if k = 1 then
  |   | select the only one red neighbor as a dominator;
  | end
  | if k > 1 then
  |   | select the one red neighbor with the minimal
  |   | node id as a dominator;
  | end
end
```

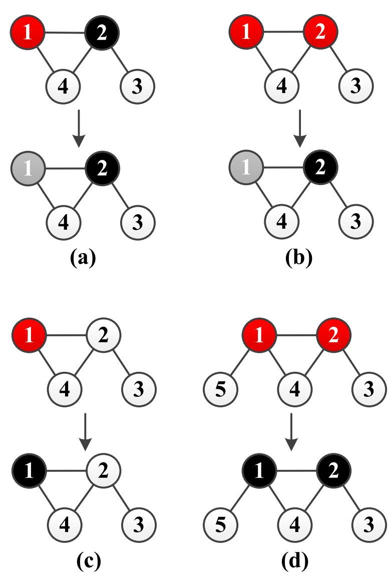

FIGURE 1. The sketch map of IADSP.

In order to introduce the principle of IADSP in detail, we give several possible cases in FIGURE 1, and analyze the results of IADSP selection in each case.

As we can see from the FIGURE 1, four possible situations are presented. In the FIGURE 1(a), node 4 cannot select red node 1 as a dominator since the dominator 2 is the neighbor of node 4. In the FIGURE 1(b), node 4 only selects red node 2 as a dominator, and red node 1 cannot be selected as a dominator, because the red node 2 has the maximum independent node degree compared with the red node 1.

As for node 3, it only selects red node 2 as a dominator. In the FIGURE 1(c), node 4 and node 2 select the red node 1 as a dominator, for there is only one red node. In FIGURE 1(d), node 5 selects the red node 1 as a dominator, and node 3 selects the red node 2 as a dominator. Node 4 will select the red node 1 as dominator, for the red node 1 has the smaller id compared with the red node 2, although they have the same independent node degree. Based on the IADSP, the CDS construction algorithm IMCDS is designed in the following subsection.

B. CDS CONSTRUCTION ALGORITHM OF IMCDS

Before the IMCDS construction algorithm is executed, the sensor nodes are static and have the knowledge of one-hop neighbor. In the beginning, all sensor nodes are marked white. In order to describe the IMCDS clearly, we define the following messages at first:

- **Req-IADSP**: A request message, sent by a red node, is used to request the white neighbors. The message contains the independent degree of the red node.
- **Rep-IADSP**: A response message, sent by a white node, is used to response to the Req-IADSP message. The message contains id of the selected red neighbor.
- **Black-Msg**: A broadcast message, sent by a black node, is used to broadcast its black status.
- **Grey-Msg**: A broadcast message, sent by a grey node, is used to broadcast its grey status.
- **Req-Blacks**: A request message, sent by a black node, is used to request the black neighbor information from its grey neighbors.
- **Rep-Blacks**: A response message, sent by a grey node, is used to response to the Req-Blacks message. The message contains the number of black neighbors.

In the next description, we introduce the algorithms executed by all types of nodes. The algorithms of IMCDS are BS (Base Station) algorithm, black node algorithm, white node algorithm, red node algorithm and grey node algorithm. Firstly, the BS algorithm executed by base station is presented in **Algorithm 2**, which selects an initial node to construct a MCDS.

Algorithm 2 BS Algorithm of IMCDS

```
Select the root node denoted by i which has the
maximum residual energy;
Broadcast its current time and root node i across the
network;
```

As for the black node, it updates its neighbor statuses and pruning the redundant black node to get the minimal CDS. The algorithm is presented in **Algorithm 3**.

As for the white node, it will call the IADSP to select the dominator, and also should update its neighbors' statuses. Its algorithm is shown in **Algorithm 4**.

In IMCDS, each red node calculates its independent node degree and broadcasts it to its neighbors, and then waits the Rep-IADSP messages or other messages from its neighbors. It may be selected as a dominator based on its independent node degree. The red node algorithm is introduced in **Algorithm 5**.

The grey sensor nodes in IMCDS should process three types of messages, which are Black-Msg, Req-Black messages received from its black neighbors and Grey-Msg from its grey neighbors. The algorithm of grey node is shown in **Algorithm 6**.

After the algorithms presented above are executed and all the nodes in the network have been marked black or grey, the CDS construction process is ended. But the CDS size is not the minimal, and the redundant dominators should be deleted by another algorithm to get the minimal CDS.

Algorithm 3 Black Node Algorithm of IMCDS

```
if a Grey-Msg from neighbor j is received then
    update its neighbors statuses
end
if a Black-Msg from neighbor k is received then
    update its neighbor statuses;
    put k into its children set of dominator
end
if all of its neighbors are marked grey or black then
    if its children set of dominator is empty then
        call the pruning process BDPP, and get the
        returned value m;
        if m > 1 then
            change its status into grey;
            broadcast a Grey-Msg to its neighbor
        end
    end
end
```

Algorithm 4 White Node Algorithm of IMCDS

```
set a timer T and wait all the Req-IADSP messages from
its red neighbors;
if all the Req-IADSP messages from red neighbors are
received or T expires then
    call the procedure IADSP in Algorithm 1;
    put the selected one red neighbor denoted by k into
    Rep-IADSP messages;
    send the Rep-IADSP message to the selected red
    neighbor k;
    delete the timer T
end
if a Grey-Msg from neighbor j is received then
    update status of neighbor j
end
if a Black-Msg from neighbor j is received then
    change its status into red;
    update the status of its neighbor j;
    set j as its parent node
end
```

Algorithm 5 Red Node Algorithm of IMCDS

calculate the independent node degree D_{in} according to its neighbors statuses;
broadcast a Req-IADSP containing the D_{in} to its white neighbors;
set a timer T and waits the Rep-IADSP messages from white neighbors;
if *the timer T is in validity* **then**
  if *a Rep-IADSP message from one of its white neighbor is received* **then**
    change its status into black;
    broadcast a Black-Msg to its neighbors;
    delete the timer T;
  end
  if *a Black-Msg or Grey-Msg from neighbor j is received* **then**
    update the status of its neighbors j;
  end
  if *a Req-IADSP message from its neighbor is received* **then**
    ignore it;
  end
end
if *the timer T expires* **then**
  change its status into grey;
  broadcast a Grey-Msg to its neighbors;
end

Algorithm 6 Grey Node Algorithm of IMCDS

if *a Req-IADSP message is received* **then**
  ignore it;
end
if *a Black-Msg or Grey-Msg from its neighbor j is received* **then**
  update the status of neighbor j;
end
if *a Req-Blacks message from a black neighbor b is received* **then**
  put the black neighbor number into Rep-Blacks message;
  send the Rep-Blacks message to b;
end

In this paper, the pruning process of IMCDS is named as Black node Degree based Pruning Process (BDPP). The algorithm is presented in **Algorithm 7**.

The 7 algorithms proposed above consists the IMCDS algorithm. Because the algorithms are scattered, it is difficult to understand the whole working process of IMCDS, so we continue to give an example diagram in FIGURE 2, which introduces the specific operation principle of IMCDS.

In FIGURE 2, node 1 is the root node and broadcasts a Black-Msg to its neighbors 2, 3, 4, 5, 6 and 7.

Algorithm 7 BDPP Algorithm of IMCDS Executed by Black Node

broadcast a req-Blacks messages to its grey neighbors;
set a timer T and wait messages;
if *T do not expire* **then**
  if *Rep-Blacks messages from all of its grey neighbors are received* **then**
    obtain the minimum black neighbor number m of its grey neighbors;
    if $m > 1$ **then**
      mark itself grey;
      broadcast a Grey-Msg to its neighbors
    end
    if $m = 1$ **then**
      ignore it
    end
  end
end

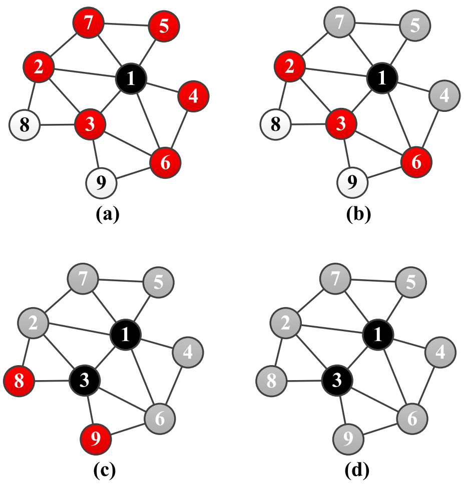

FIGURE 2. An example of IMCDS.

They will change their statuses into red, when they receive the Black-Msg, shown in FIGURE 2(a).

Node 5, 7 and 4 do not have any white neighbors, and thus if they broadcast the Req-IADSP messages, they will not receive the Rep-IADSP messages and change their statuses into grey, which is shown in FIGURE 2(b).

Node 2, 3 and 6 have the white neighbors, and if they broadcast the Req-IADSP messages to node 8 and 9, only node 3 receives the Rep-IADSP messages from node 8 and 9, since node 3 has the maximum independent node degree compared with that of node 2 and 6. The final topology is shown in FIGURE 2(d).

According to IMCDS, we know that node 1 is the parent node of node 3, and node 3 does not have the children node, which causes only node 3 calls **BDPP** algorithm to delete the redundant dominators. Because not all the grey neighbors of node 3 are covered by node 1, node 3 will not turn its status into grey.

VI. ENERGY EFFICIENT IMCDS ALGORITHM

The IMCDS algorithm is an approximation algorithm to construct a MCDS, which is based on the criterion of independent node degree, and the node energy is considered only in the **Algorithm 2** for the root node selection. In this section, we consider the residual energy as the dominator selection criterion.

A. CDS CONSTRUCTION ALGORITHM OF EIMCDS

Before introduce the EIMCDS, the messages of EIMCDS are defined as follows, where we only list the messages different from that of IMCDS. In IMCDS the two messages Req-IADSP and Rep-IADSP are replaced by the messages Req-EADSP and Rep-EADSP respectively.

- **Req-EADSP**: A request message, sent by a red node, is used to request the white neighbors. The message contains the residual energy of the red node.
- **Rep-EADSP**: A response message, sent by a white node, is used to response to the Req-EADSP message. The message contains id of the selected red neighbor.

In the EIMCDS, the algorithms executed by the white node, black node, grey node and red node are similar with that algorithms of IMCDS. The only different is the messages. Besides, we should replace the procedure IADSP in **Algorithm 4** with EADSP (residual Energy based Adverse Dominator Selection Procedure), which is described in **Algorithm 8** and executed by white node.

Algorithm 8 EADSP Executed by White Node

if *black neighbor number* $N_{bn} > 0$ **then**
  do not select any red neighbor as dominator
end
if *black neighbor number* $N_{bn} = 0$ *and red neighbor number* $N_{rn} > 1$ **then**
  get the residual energies of these red neighbors;
  select the k red neighbors which have the maximum residual energies;
  if $k = 1$ **then**
    select the only one red neighbor as a dominator;
  end
  if $k > 1$ **then**
    select the one red neighbor with the minimal node id as a dominator;
  end
end

According to these algorithms, it is still difficult to understand the working principle of EIMCDS, so we also give an example to illustrate the working procedure of EIMCDS as we introduce IMCDS. This example is shown in FIGURE 3.

In the FIGURE 3, we assume node 1 is the root node (a black node selected by the BS), and then node 2, 3, 4, 5, 6 and 7 turn themselves into red, shown in FIGURE 3(a). According to EIMCDS, node 4, 5 and 7 will not receive any Rep-EADSP message, because they do not have any white neighbors. Node 4, 5 and 7 will change their statuses into grey, shown in FIGURE 3(b). According to EADSP, node 8 selects node 2 as a dominator, because node 2 has more residual energy compared with node 3. Similarly, node 9 selects node 6 as a dominator. Because node 3 cannot receive any Rep-EADSP from node 8 and node 9, it turns itself into grey, shown in FIGURE 3(c).

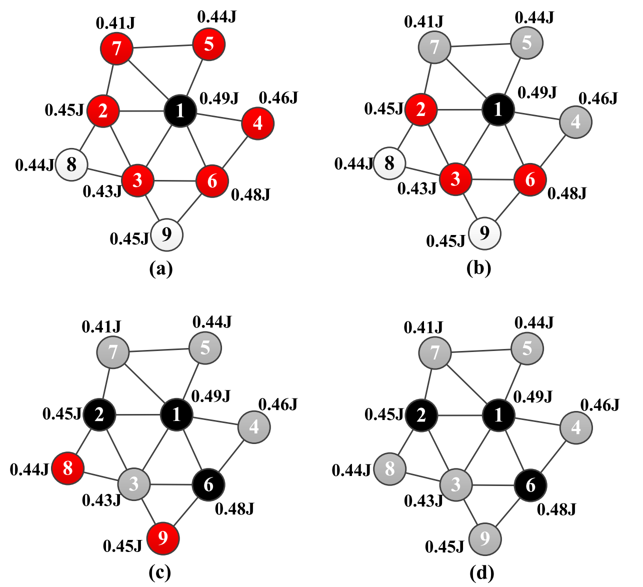

FIGURE 3. An example of EIMCDS.

When node 2 and node 6 change their statuses into black, node 8 and 9 receives the Black-Msg messages and turns their statuses into red. Because node 8 and 9 have no white neighbors, they finally turn into grey, shown in FIGURE 3(d).

In the process of EIMCDS, nodes 2 and 6 have the same parent node 1, and they have no children dominator according to EIMCDS. In the FIGURE 3, nodes 2 and 6 find that all of their neighbors are either black or grey. Thus node 2 and node 6 execute the BDPP procedure. Because not all of the grey neighbors of node 2 are covered by other dominators, node 2 will not turn its status into grey. Similarly, node 6 will not turn into grey for the same reason.

VII. PERFORMANCE ANALYSIS

In this section, we prove that the dominators construct a CDS firstly, and then analyze the performance ratio (PR) of the constructed MCDS.

A. CONNECTED DOMINATING SET PROPERTY

Theorem 1: The dominators selected by IMCDS or EIMCDS construct a Connected Dominating Set (CDS).

Proof: The difference between IADSP and EADSP is the selection criterion. The independent node degree is the selection criterion in IADSP, while the residual energy is in EADSP. Because the main principles of IMCDS and EIMCDS are the same, we prove that the black nodes selected according to the IMCDS construct a CDS for streamline. The same proof method can be used for EIMCDS.

According to the IMCDS, we find that any black node can communicate with the root node by sending messages to its parent node, which will forward the received messages to its parent node. According to this forwarding process, the messages can be forwarded to the root node. Besides the root node can communicate with any node by sending messages to children node, which will forward the received messages. Therefore, any two black nodes can communicate through at least one path containing the root node, which means the selected dominators by IMCDS construct a Connected Set (CS).

Assume there is a white node which is not dominated by any black node. Then the neighbors of the white node are all grey nodes. Take a grey neighbor k, which is the last node turns its status into grey, of the white node as an example. Before the node k mark itself grey, it is a red node. Because node k has a white neighbor, it will receive a Rep-IADSP from the white node and turns its status into black, which is contradict with the condition that it is a grey node. Therefore, there is no white node left, and the connected set constructed by the black nodes is also a Dominating Set (DS).

Therefore in summary, the dominators selected by IMCDS construct a CDS. The conclusion is also suitable for the EIMCDS.

B. PERFORMANCE RATIO

1) APPROXIMATION CDS SIZE OF IMCDS

In this subsection, we analyze the PR of IMCDS, since the algorithm IMCDS focuses on reducing the CDS size. We assume all the nodes have the same transmission range denoted by r for simplicity and are uniformly distributed in a circle area with the radius R_a.

The node number is N, and the average area size occupied by single node is:

$$S_n = \pi \left(R_n\right)^2 \tag{1}$$

Assume the node occupied area is a circle, and the area size is:

$$S_a = \pi \left(R_a\right)^2 \tag{2}$$

Because all the nodes have filled the network area, then we have:

$$S_a = N \cdot S_n \tag{3}$$

Thus, the occupied area radius of a node is:

$$R_n = \frac{R_a}{\sqrt{N}} \tag{4}$$

In order to insure the connection of the original network graph, the minimum transmission of a node is:

$$r_{\min} = 2R_n \tag{5}$$

Because all the nodes have the same transmission range and are uniformly distributed in the circle network area, we use the FIGURE 4 to illustrate the dominator selection based on the root node.

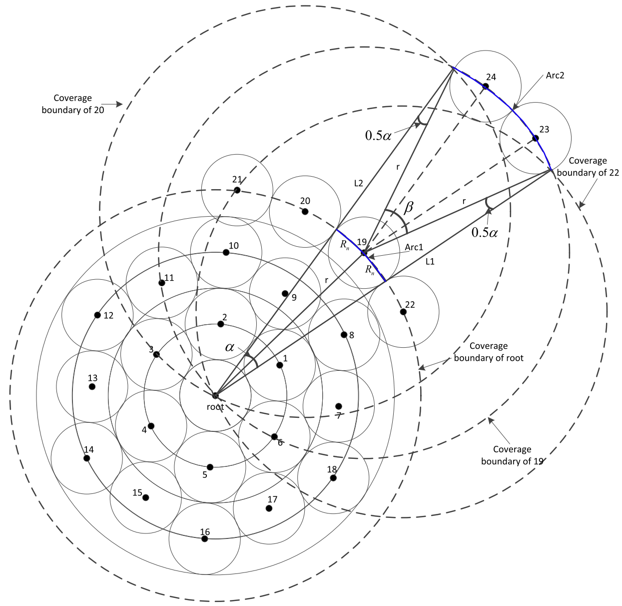

FIGURE 4. The geometric diagram about the dominators selection.

According to the IMCDS, the nodes on the boundaries of coverage of root node are selected as dominator nodes, since they have the maximum independent node degrees compared with the nodes within the coverage of the root node. Therefore, the nodes such as 19, 20, 21 and 22 in FIGURE 4 are selected as the dominators, and they have a common parent, the root node.

In order to analyze the MCDS size constructed by the IMCDS, we need to analyze the children dominators of node 19, since it represents the general situation. The MCDS size of IMCDS can be derived from the circumstances of node 19.

According to the FIGURE 4, the length of $Arc1$ is:

$$Arc1 = \alpha r \tag{6}$$

In FIGURE 4, the nodes on the boundaries of coverage of root node are selected as the dominators. We get the maximum number of the root's children dominator:

$$D_{max}^{root} = \frac{2\pi r}{Arc1} = \frac{2\pi}{\alpha} \tag{7}$$

Because node 19 has a circle covering area, which intersects with the covering area of node 20 and 22 and node 19 has an arc that is not covered by node 20 and node 22, then the nodes 23 and 24 on the boundaries of node 19 i.e $Arc2$ can be selected by their independent nodes as dominators.

In order to calculate the length of the $Arc2$, we mark an angle α in FIGURE 4. Because the R_n is very small compared with r, the following equation can be established:

$$\alpha \approx 2 \arcsin \left(\frac{R_n}{r}\right) \tag{8}$$

According to FIGURE 4, we get the angle β:

$$\beta = 2\pi - [(\pi - \alpha) + (\pi - \alpha)] = 2\alpha \tag{9}$$

The $Arc2$ is calculated by the following formulation:

$$Arc2 = \beta r \tag{10}$$

The maximum number of the children dominators of node 19 is:

$$D_{\max}^{nroot} = \frac{Arc2}{Arc1} = 2 \tag{11}$$

If the root node is level 0, then the level of dominators covered by root node is 1, and we assume there are at most L_{max} levels. According to the IMCDS, the maximum level L_{max} is approximately calculated by:

$$L_{max} = \left\lfloor \frac{R_a}{r} \right\rfloor \tag{12}$$

According to equation (10), (11) and (12), the total size of CDS constructed by IMCDS in uniform distribution is:

$$\begin{aligned} N_{imcds} &= 1 + D_{max}^{root} + D_{\max}^{nroot} D_{max}^{root} + \left(D_{\max}^{nroot}\right)^2 D_{max}^{root} \\ &\quad + \ldots + \left(D_{\max}^{nroot}\right)^{L_{\max}-1} D_{max}^{root} \\ &= 1 + \frac{2\pi}{\alpha}\left(2^{L_{\max}} - 1\right) \end{aligned} \tag{13}$$

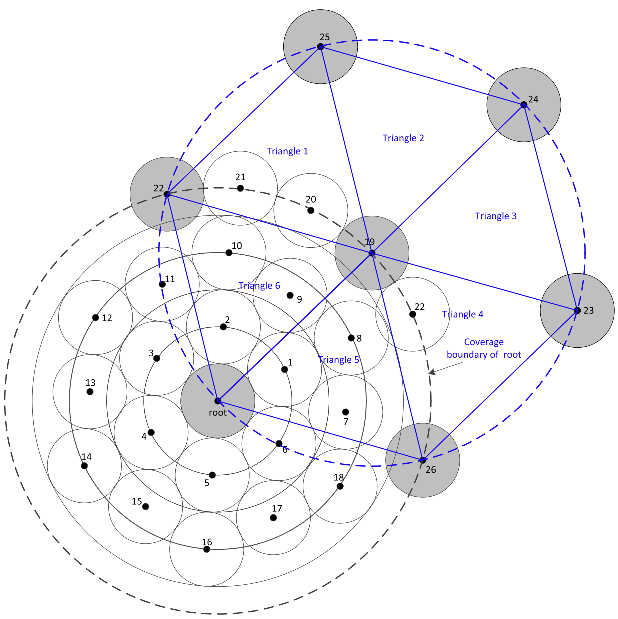

FIGURE 5. The hexagon critical coverage for the optimal CDS.

2) APPROXIMATION OPTIMAL CDS SIZE

In the circle area, because the nodes are uniformly distributed and the transmission radius of the nodes is the same, the hexagonal connected coverage set will be the critical coverage with the least number of nodes. Then we use FIGURE 5 to illustrate the optimal CDS size calculation. As we can see from the FIGURE 5, the network area can be covered by many hexagons, and each hexagon is consist of 6 triangles. Let's take triangle 1 as an example, which has the size as:

$$S_t = \frac{\sqrt{3}r^2}{4} \tag{14}$$

Since all nodes have the same transmission radius, the average coverage of each triangle vertex is:

$$S_v = \frac{\sqrt{3}r^2}{12} \tag{15}$$

Let's take node 19 as an example. It is a common vertex of six triangular shown in FIGURE 5, so its coverage size is:

$$S_{19} = \frac{\sqrt{3}r^2}{2} \tag{16}$$

Therefore, in the hexagonal connected dominant set, the average coverage of each dominant node is $\frac{\sqrt{3}r^2}{2}$. According to equation (2), we can calculate out the CDS size i.e the number of dominators for the optimal CDS:

$$N_{opt} = \frac{2\pi\,(R_a)^2}{\sqrt{3}r^2} \tag{17}$$

3) UPPER BOUND OF PERFORMANCE RATIO

When the CDS sizes of IMCDS and the hexagonal approximation optimal case are obtained, we can get the performance ratio for IMCDS:

$$\begin{aligned} PR = \frac{N_{imcds}}{N_{opt}} &= \frac{1 + \frac{2\pi}{\alpha}\left(2^{L_{\max}} - 1\right)}{\frac{2\pi\,(R_a)^2}{\sqrt{3}r^2}} \\ &= \frac{\sqrt{3}}{2}\left(\frac{r^2}{\pi\,(R_a)^2} + \frac{\left(2^{L_{\max}} - 1\right) r^2}{\arcsin\left(\frac{R_n}{r}\right)(R_a)^2}\right) \end{aligned} \tag{18}$$

According to (5), we know that R_n/r is less than 0.5 and bigger than 0, which means $\arcsin\left(\frac{R_n}{r}\right)$ is bigger than R_n/r, and if we put equation (4) into (18), then we have:

$$\begin{aligned} PR &\leq \frac{\sqrt{3}}{2}\left(\frac{r^2}{\pi\,(R_a)^2} + \frac{\left(2^{L_{\max}} - 1\right) r^2}{\frac{R_n}{r}(R_a)^2}\right) \\ &= \frac{\sqrt{3}}{2}\left(\frac{r^2}{\pi\,(R_a)^2} + \frac{\left(2^{L_{\max}} - 1\right) r^3\sqrt{N}}{(R_a)^3}\right) \end{aligned} \tag{19}$$

According to (19), we let $x = \frac{R_a}{r}$, then we have:

$$PR \leq \frac{\sqrt{3}}{2}\left(\frac{1}{\pi x^2} + \frac{(2^x - 1)\sqrt{N}}{x^3}\right) \tag{20}$$

where we assume x is a continuous variable, and then we can try to get the optimal value of x which makes the upper bound of PR minimized. Besides, we let:

$$f(x) = \frac{1}{\pi x^2} + \frac{(2^x - 1)\sqrt{N}}{x^3} \tag{21}$$

where we also let $x > 1$, which means the transmission range of node is less than the network area radius. After obtaining the second derivative of $f(x)$, we have:

$$f''(x) = \frac{6x}{\pi x^5} + \frac{12\pi\sqrt{N}(2^x - 1)}{\pi x^5} - \frac{6\pi x\sqrt{N} \cdot 2^x \cdot \log 2}{\pi x^5} + \frac{2^x \pi x^2 \sqrt{N}(\log 2)^2}{\pi x^5} = \frac{\left(\begin{array}{l} 6x - 12\pi\sqrt{N} + \\ 2^x\pi\sqrt{N}\left((x\log 2 - 3)^2 + 3\right) \end{array}\right)}{\pi x^5} \tag{22}$$

It is easy to find that the molecular part of the second derivative $f''(x)$ is a monotonic increasing function. We substitute $x = 1$ and calculate out the value of the molecular part is greater than 0, which means the molecular of $f''(x)$ is positive. Besides, the denominator of $f''(x)$ is also bigger than 0, then we have that the function $f(x)$ is a convex function, which has a minimum value [31].

Because the $f(x)$ is a convex function, then we can get the optimal value of it. But the form of function is so complex that it is impossible to get the analytic expression of its optimal value directly. A feasible method is to obtain its numerical solution by iteration method, which is introduced in the next.

4) NUMERICAL SOLUTION OF THE UPPER BOUND OF PR

In this part, we calculate the minimum upper bound of PR for different number of nodes. The sensor nodes varies from 100 to 300 with the step as 20. We set the initial point of x as 20, then by using the numerical function, we get the following results of the upper bound PR, shown in FIGURE 6.

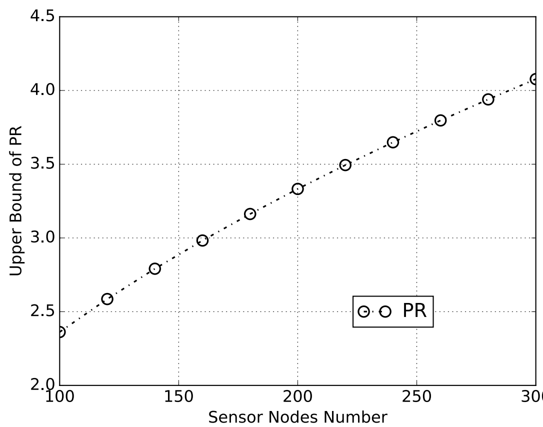

FIGURE 6. The upper bound of performance ratio.

As we can see from the FIGURE 6, the upper bound of PR increases as the sensor node number increases, and in the case of all nodes, the optimal value of x is 4. Besides, if we decrease the node number to 18, the upper bound of PR is approximately equal to 1, the reason is that the number of nodes is very small, which cannot reflect the characteristics of the two methods. Therefore, we set the node size to be more than 100. According to the results, we know that the upper bound of PR is $O(\sqrt{N})$, and as the number of nodes decreases, PR can be as low as 3 or less.

C. MESSAGE COMPLEXITY

For any node k in IMCDS, its initial status is white, and the maximum number of its neighbors is Δ.

In the CDS construction process, k receives at most Δ Req-IADSP messages from its neighbors. It also sends at most Δ Rep-IADSP messages to its neighbors. Besides, k receives at most Δ Black-Msg messages and Grey-Msg messages from its neighbors. It also at most receives Δ Req-Black messages from its black neighbors, and it sends at most Δ Rep-Black messages to its black neighbors.

Then, for node k, the total messages of the CDS construction process are 5Δ. Since there are N sensor nodes in the network, then the message complexity of IMCDS is $O(N\Delta)$, which is also the message complexity of EIMCDS, because it has the same message mechanism with that of IMCDS.

VIII. PERFORMANCE EVALUATION

In order to evaluate the performance of IMCDS and EIMCDS, we simulate the CDS size at first, and then evaluate the network lifetime to illustrate the energy efficiency of EIMCDS.

A. SIMULATION SETTINGS

In this paper, the simulation is performed in the MATLAB environment. The simulation contains mainly two parts, i.e. the CDS size simulation and energy efficiency (or network lifetime) simulation. Both in the two parts, all the sensor nodes are randomly distributed in a square network area. Each sensor node has the same initial energy, and have different transmission range. The commonly used parameter values are set in TABLE 2.

TABLE 2. Parameter values.

Name	Value
E_o	$0.5J$
E_{elec}	$50 \times 10^{-9}J$
E_{fs}	$10 \times 10^{-12}J$
E_{mp}	$13 \times 10^{-16}J$
E_{da}	$5 \times 10^{-9}J$
L_{dp}	$4000bits$
L_{cp}	$30bits$
p	0.05
M	$100m$
(x_{bs}, y_{bs})	$(50m, 175m)$

In the TABLE 2, the parameters are used in the network lifetime simulation part, and in the CDS size simulation, the parameters values used will be set in each simulation subsection.

In the TABLE 2, the parameter L_{cp} is the control package length, which is 200bits in leach routing protocol, while in our EIMCDS and IMCDS based routing protocol, each control package contains only flag or number information of neighbor nodes, then if we use 200bits for control package a lot of energy will be wasted. Besides, in Leach protocol, no control message contains a lot of information. So, we set the control message package as 30*bits*. As for the data package, which may contains a lot of data, such as video, picture or text information, then we set the data package length L_{dp} as 4000bits for general purpose.

There is a parameter p, which is the optimal cluster head selection probability of Leach. In the [32], there is a section to analyze the optimal number of clusters, and we have found that if the node number is 100, the most energy efficient case is that the cluster number is 5, so we get the optimal probability of been selected as a cluster head for a node is 0.05. Actually, in [32], there is an equation to calculate the optimal cluster head number, and according to this equation, we can calculate a range for the optimal cluster head number, and according to which we also get an optimal cluster head selection probability range. In this paper, we get the optimal cluster head selection probability from this range, and we fix it as 0.05 for simplicity.

In the CDS size simulation part, we compare the size of IMCDS as well as EIMCDS with that of other two classical algorithms, which are the second algorithm of Thai's denoted by TSA in [18] and the second algorithm of Xiang's denoted by XSA in [23].

In the network lifetime simulation part, we compare the network lifetime of the routing protocol based on EIMCDS with that of IMCDS and routing protocol Leach.

B. NODE NUMBER IMPACT ON THE CDS SIZE

The network area is a square area with the side length as 100 meters. The sensor node number varies from 10 to 100 with the step as 10. All nodes are randomly distributed in the network area. We consider two cases, the first is that all nodes have the same transmission radius, and the second is that all nodes have different transmission radius. In the first case, we set the transmission ranges $r_i(1 \leq i \leq N)$ as 30 meters. In the second case, we set the transmission ranges r_i of node as a random number belonging to the interval [20, 40]. The CDS size simulation results are shown in FIGURE 7.

According to FIGURE 7(a) and FIGURE 7(b), we find that IMCDS has the minimal CDS size compared with that of EIMCDS, XSA and TSA. EIMCDS has smaller CDS size compared with XSA and TSA. Because the selection of dominant nodes in IMCDS is based on the degree of independent nodes, and in EIMCDS, the selection of dominant nodes is the residual energy of nodes, so IMCDS has a smaller size of CDS than EIMCDS.

We also find that as the node number increases, the CDS size increases gradually. The reason is that as the node number increases, the occupied area size of nodes increases, which results in more dominators for totally covering the increased occupied area.

C. TRANSMISSION RANGE IMPACT ON THE CDS SIZE

As the transmission range of node increases, the node covers more nodes and larger area size, which decreases the CDS size. In this subsection, the network area has the side length as 200 meters. The node number is fixed as 100. Two situations are simulated, which are nodes with the same transmission range situation and nodes with different transmission range situation. We set the transmission ranges $r_i(1 \leq i \leq N)$ of nodes as a fixed element in a vector V and as a random number belonging to one interval of an interval set S to represent two cases of equal and unequal transmission ranges. The two sets are defined as follows:

$$V = \{30, 35, 40, 45, 50, 55, 60, 65\} \tag{23}$$

$$S = \left\{ \begin{array}{l} [20, 40], [25, 45], [30, 50], [35, 55], \\ [40, 60], [45, 65], [50, 70], [55, 75], \\ [60, 80], [65, 85] \end{array} \right\} \tag{24}$$

The CDS size simulation curves are presented in FIGURE 8.

As shown in FIGURE 8(a) and FIGURE 8(b), we find that as the transmission ranges of nodes increase, the CDS size decreases. The reason is that the nodes with the big transmission ranges can cover more network area compared with the case where nodes have smaller transmission ranges. Besides, the CDS size of IMCDS is the minimum compared with other algorithms. The CDS size of EIMCDS is smaller than that of XSA and TSA.

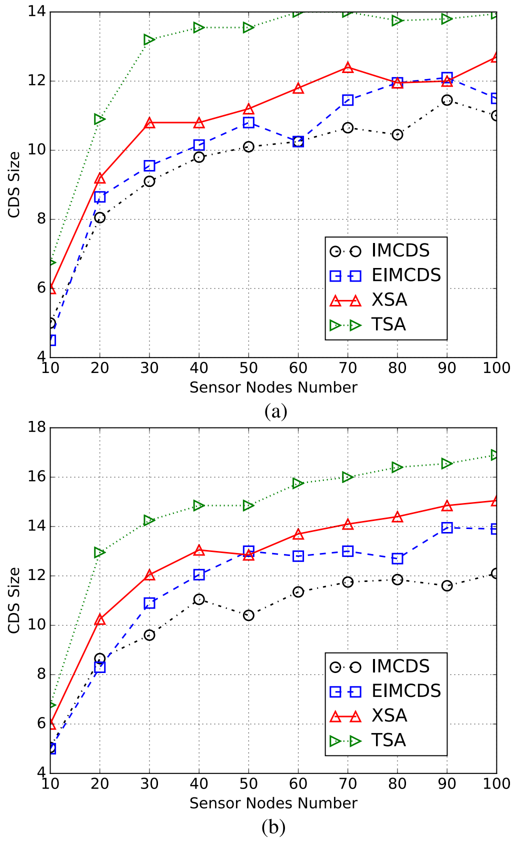

FIGURE 7. The node number impact on the CDS size. (a) $r_i = 30$. (b) $20 \leq r_i \leq 40$.

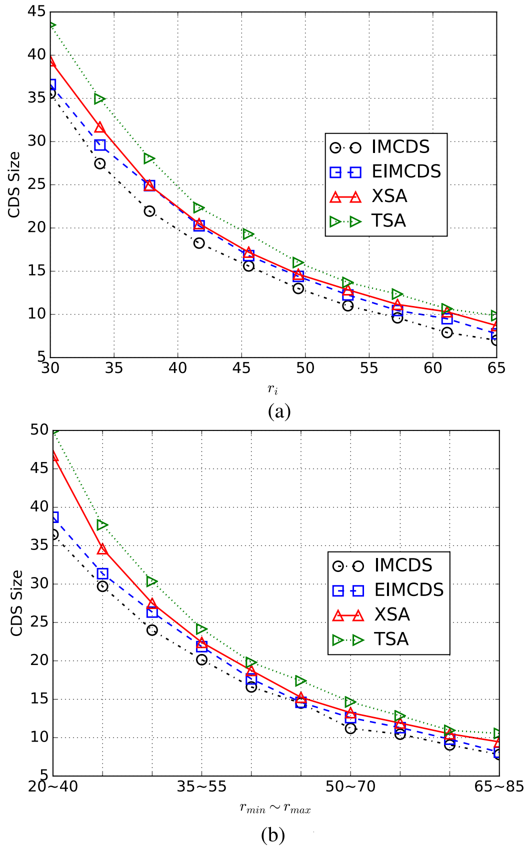

FIGURE 8. **The transmission range impact on the CDS size. (a) $r_i \in V$. (b) $r_i \in S$.**

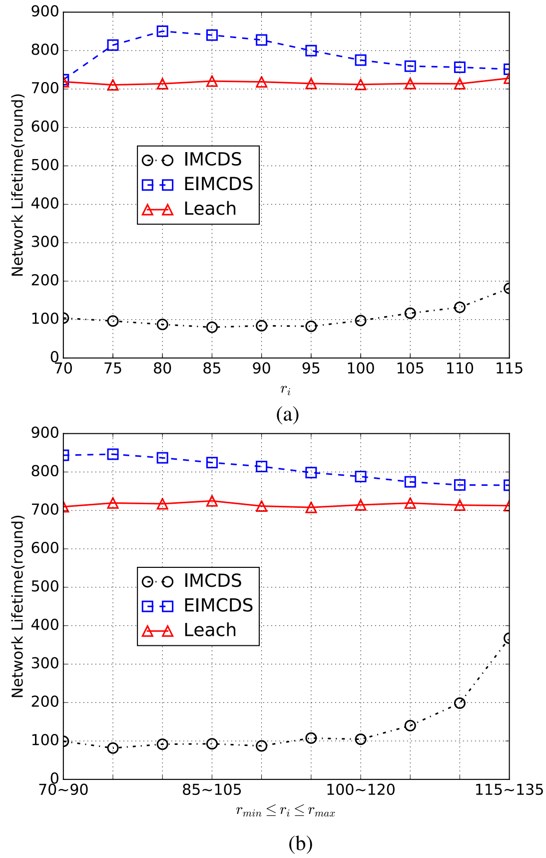

FIGURE 9. **The transmission range impact on the network lifetime. (a) *The first scenario*. (b) *The second scenario*.**

D. THE ENERGY EFFICIENCY OF EIMCDS

In order to evaluate the energy efficient of EIMCDS, we compare the routing algorithms based on EIMCDS with that of IMCDS and the classical routing protocol Leach in terms of network lifetime.

When the CDS of IMCDS or EIMCDS is constructed each sensor node sends one data package to its parent sensor node. When the BS receives the data package from the root node, this round is end, and then the network should reconstruct a new CDS for the routing of next round. The network and communication parameters are set in the TABLE 2.

In the next simulation, we simulate the network lifetime of Leach, IMCDS based routing (denoted by IMCDS for simplicity) and EIMCDS based routing (denoted by EIMCDS for simplicity) respectively. We will evaluate the transmission range, sensor nodes number and network area size impact on the network lifetime respectively.

1) TRANSMISSION RANGE IMPACT ON THE NETWORK LIFETIME

In this subsection, the network field is a 100m × 100m square area. We have simulated two scenarios, where in the first scenario all the sensor nodes have the same transmission range varying from 70m to 115m with the step as 5m, while in the second scenario all the sensor nodes have different transmission ranges belonging to the interval $[r_{min}, r_{max}]$. The r_{min} varies from 70m to 115m and r_{max} varies from 90m to 135m, and all the steps are 5m. The sensor nodes number is 100. The simulation results are presented in FIGURE 9. As for the Leach protocol, its transmission range is defined in [32], we only change the transmission ranges of IMCDS and EIMCDS.

As we can see from the FIGURE 9(a) and FIGURE 9(b), EIMCDS performs the best in both scenarios, and the IMCDS performs the worst. The main reason is that in the IMCDS, the black nodes are selected according to the independent node degree, which means if the nodes with the big white node degrees, they have the higher probabilities to be selected as black nodes, then their energy will soon be consumed, which results the worst network lifetime.

In the FIGURE 9(a) and FIGURE 9(b), we find that the network lifetimes of Leach at different transmission ranges are almost the same, which is because in the two scenarios the network parameters of Leach are the same. As for the EIMCDS, the changes of its network lifetimes at different transmission ranges are not big, since when the transmission ranges of nodes increases, the CDS size will decrease, which will decrease the number of black nodes and the energy consumption balance performance among nodes can be improved. If the transmission ranges become big, nodes will consume more energy to construct the CDS compared with the case nodes with smaller transmission range, then if the transmission ranges increase the network lifetime will decrease slightly.

As for the IMCDS in the FIGURE 9(a) and FIGURE 9(b), if the transmission ranges increase, the network lifetime increases significantly, which is because the dominators of IMCDS are selected based on the independent node degrees, and as the transmission range increases, the CDS size will decrease. Besides, the root node is selected according to the residual energy of the node, so the smaller size of CDS can better balance the residual energy of the root node, thereby improving the network lifetime.

2) SENSOR NODES NUMBER IMPACT ON THE NETWORK LIFETIME

In this subsection, we will change the node number from 50 to 100 with the step as 5 nodes. The network area size is 100m × 100m, and the transmission ranges are set as the same in the first scenario and different in the second scenario. In the first scenario, all the transmission ranges are 80m, and in the second scenario, all the transmission ranges are randomly determined in the interval [70, 90]. The simulation results are shown in FIGURE 10.

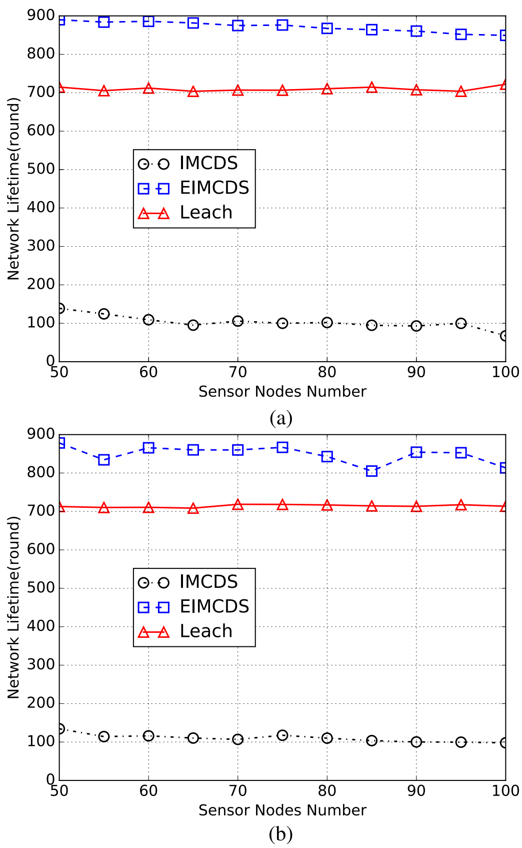

FIGURE 10. The node number impact on the network lifetime. (a) *The first scenario*. (b) *The second scenario*.

As we can see from the FIGURE 10(a) and FIGURE 10(b), we find that all the three routing algorithms hardly change their network lifetime. Firstly, let's analyze the EIMCDS, which selects the black nodes based on the energies of black nodes. Besides, the black nodes are selected according to the red nodes which have the white neighbor nodes, which means if a red node far away from its parent black node it definitely will be selected as a black node. Then if the transmission range is big, the CDS size will not be influenced significantly by the node number, which results the approximately same network lifetime at different node numbers. Besides, if the node number increases, the black nodes will dominate more grey nodes, which cause more energy consumption for black nodes, but as the node number increases, the energy consumption balance among the nodes can be improved, which may offset the consumed energy of the node number increasing. The reason is also suitable for IMCDS.

As for the Leach, because it optimal probability for cluster head selection is set as 0.05, then for different node numbers, the cluster head numbers are different. As the node number increases, the cluster heads increase, and cluster member numbers of each cluster are not influenced by the node number, which results the approximately the same network lifetime at different node numbers.

3) NETWORK AREA SIZE IMPACT ON THE NETWORK LIFETIME

In this part, we change the side length of the square network area, which varies from 210m to 300m with the step as 10m. The sensor node number is 100. Similarly, we still simulate the results in two scenarios. In scenario 1, all nodes have the same transmission radius and are equal to 80 meters. In scenario 2, all nodes have different transmission radius, which is a random number in the range [70], [90]. The simulation results are shown in FIGURE 11.

According to FIGURE 11, with the increase of network area, the network lifetime of EIMCDS and Leach decreases gradually. This is because with the increase of network area size, the CDS of EIMCDS increases and the communication distance between nodes in Leach increases. Because EIMCDS takes energy balance into account, increasing CDS will increase the number of dominators in each round of EIMCDS. In addition, due to limited energy, the network lifetime of EIMCDS will be reduced. For Leach protocol, the increase of network area size will lead to the increase of communication distance between nodes, which will increase communication energy consumption and reduce network lifetime.

For IMCDS, the network lifetime does not change significantly with the increase of network area size. The reason is analyzed as follows. Because IMCDS does not consider the characteristics of energy consumption, the increase of CDS will lead to the decrease of the dominatee number of each dominator, which is conducive to improving the energy balance between nodes. In addition, the increase of network area and CDS will lead to the increase of communication distance, thus improving energy consumption. However, due to the improvement of energy consumption balance, the two will offset each other, thus presenting the result that the network lifetime does not change much.

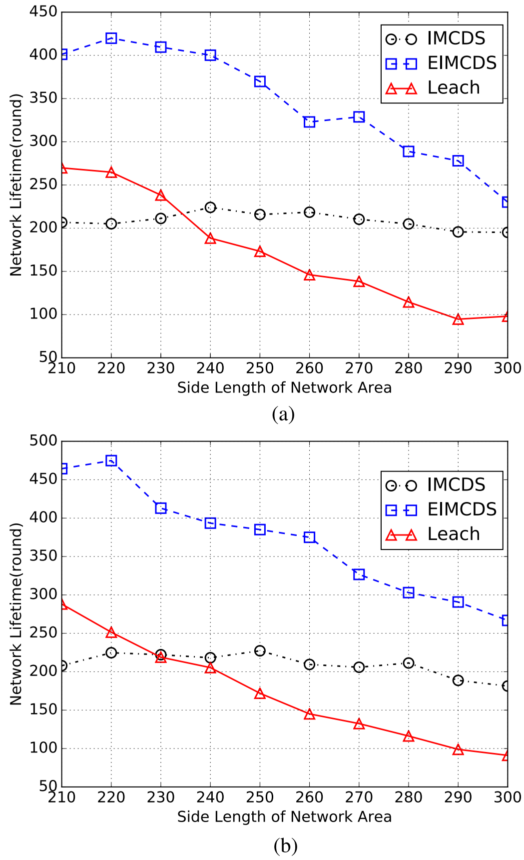

FIGURE 11. **The network area size impact on the network lifetime. (a) *The first scenario*. (b) *The second scenario*.**

According to FIGURE 11, we can find that EIMCDS is the best in terms of network lifetime, IMCDS is the second best, Leach is the worst.

IX. CONCLUSION

In this paper, we research the healthcare related issue in extreme environments, and focus on the WSN-based topology control networking algorithm as well as its routing algorithm. Specifically, we propose two approximate MCDS construction algorithms, IMCDS and EIMCDS, for wireless sensor networks. In IMCDS, dominator nodes are selected according to the degree of independent nodes, while in EIMCDS, dominator nodes are selected according to the residual energy of nodes. The dominator node is chosen by its independent neighbor node, which is a reverse selection process, that is, the child node selects its own parent node as the dominator node. IMCDS and EIMCDS only need one hop neighbor information. Their message complexity is $O(N\Delta)$. In uniformly distributed network scenarios, their upper bound performance ratio is $O(\sqrt{N})$.

We simulate the size of the CDS constructed by MCDS algorithms proposed by us and the network lifetime of the routing protocol based on the MCDS algorithms. Compared with classical algorithms, it is found that the CDS constructed by IMCDS and EIMCDS has the smallest number of dominator nodes. Compared with classical routing protocols, the routing protocol based on EIMCDS has the largest lifetime considering the impact of transmission radius of nodes, the size of network area and the number of network nodes.

Although the IMCDS and EIMCDS have good performance in terms of CDS size and energy efficiency, the mobility of sensor nodes is not considered, and the dynamic maintenance mechanism used to solve the mobility of nodes will be our future work.

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