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Research Article

Energy Efficient Fault Tolerant Coverage in Wireless Sensor Networks

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Energy efficiency and fault tolerance are two of the major concerns in wireless sensor networks (WSNs) for the target coverage. Design of target coverage algorithms for a large scale WSNs should incorporate both the energy efficiency and fault tolerance. In this paper, we study the coverage problem where the main objective is to construct two disjoint cover sets in randomly deployed WSNs based on relay energy (E_{relay}). Further, we present an approximation algorithm called Energy Efficient Maximum Disjoint Coverage (EMDC) with provable approximation ratios. We analyze the performance of EMDC theoretically and also perform extensive simulations to demonstrate the effectiveness of EMDC in terms of fault tolerance and energy efficiency.

1. Introduction

WSN is a random or deterministic deployment of massive number of sensor nodes in a monitored area. WSNs have extensive applications, including military surveillance [1], target tracking, wild life monitoring, fire prevention, rescue operations, and air quality monitoring [2–4]. The primary goal of sensor nodes is to sense and collect raw data by monitoring particular environment, target, and barrier, and report that event to some sink node after some local processing or aggregation [5, 6].

Target coverage and network life time are two of the recent research trends in WSNs. Deployment of a set of sensors to cover a particular area, targets, or barrier is called coverage problem [7]. The main purpose of target coverage [8] is to continuously monitor a set of targets by using a subset of sensors. These sensor nodes are subject to failures due to various reasons. One of the common reasons is battery failure. Other reasons may include radio interference, software or hardware faults, and environmental changes. Sensor node failures may affect the coverage and connectivity adversely which in turn degrades the sensor network performance with higher network delays and higher energy consumption [9].

Sensor nodes are equipped with limited capacity batteries. Recently, it has been investigated whether it is possible to conserve energy by using duty cycle protocols, where nodes switch their radio on and off periodically prolonging the life time of a WSN. Due to one time battery life and difficulty of replacing it, sensor nodes are densely deployed to increase connectivity and target coverage. However, if all the nodes are constantly on, it may quickly deplete their battery and may affect the network life time. Therefore it is important to tune these sensors to duty-cycled mode where they alternate between the active and sleep periods. Further, sensor hardware or software may fail due to weather or other physical conditions in a WSN affecting coverage of target nodes. If coverage of the target nodes is achieved by a single set of covering nodes, they may soon deplete their energy affecting the network life time. Therefore, it is important for WSNs to use redundant or disjoint covering sensors to cover particular area, targets, or barriers to construct a fault tolerant network which may still cover the targets, area, or barrier despite the failure of some covering sensors.

In order to effectively utilize the sensor nodes, some studies have selected a number of cover sets to provide coverage to some target sets. These studies organize the cover sets [7, 10] into disjoint or nondisjoint cover sets [11, 12]. The selection of such disjoint or nondisjoint cover sets is proved to be NP-complete problem [9, 11]. Disjoint or nondisjoint cover sets monitor the targets in a cooperative way. Compared to nondisjoint cover sets, disjoint cover sets are better at fault tolerance because all the cover sets have exclusive sensor nodes among their sets. Each cover set can alternatively work to maximize the network lifetime.

A number of studies have addressed the issue of target coverage; however, only fewer of them considered the disjoint target coverage based on minimum relay energy. In this article, our key focus is on the fault tolerant target coverage problem with minimum relay energy. We formulate the disjoint target coverage problem based on E_{relay} energy. This problem differs from the target coverage which is based on disjoint covering sets, since coverage ensures that the E_{relay} energy of each sensor from each of the disjoint sets is kept at minimum. We aim to select two disjoint covering sets with minimum E_{relay} to cover the targets; that is, each sensor has minimum E_{relay} energy. It is crucial to select sensor nodes which consume minimum energy to report an event to the sink node. Therefore, our primary objective is to maximize the network lifetime by selecting two disjoint covering sets with minimum overall E_{relay} energy. In order to fulfil both the fault tolerance and energy efficiency requirements, we propose an efficient approximation algorithm, Energy Efficient Maximum Disjoint Coverage (EMDC), with provable approximation bound. Our key contributions in this paper are summarized as follows:

(i) We present a comprehensive comparison of well known target coverage, area coverage, and barrier coverage schemes.

(ii) We formulate disjoint coverage problem with minimum E_{relay} energy.

(iii) We propose an efficient bounded approximation algorithm, the EMDC, to the minimum E_{relay} energy coverage problem and present an appropriate theoretical analysis of the EMDC approximation ratio.

(iv) We perform simulations under different scenarios to establish the effectiveness of EMDC.

The remaining article is organized as follows: Section 2 gives a comprehensive background of the coverage and presents a comparison of different coverage schemes in WSNs. Section 3 summarizes the related work followed by the formulation of minimum energy disjoint coverage problem in Section 4. Section 5 presents EMDC algorithm design. Section 6 presents the theoretical analysis of EMDC. Section 7 presents the EMDC simulation results, and, finally, Section 8 concludes the paper.

2. Coverage in WSNs

A sensor is a device with the capability of responding to different physical stimuli including sound, heat, smoke, pressure, and any other event and transforming it into corresponding electrical or mechanical signal [13]. These signals are mapped to sensor information. A sensor node consists of one or more sensing units, battery, memory, data processing unit, and data transmission unit. A WSN consists of different sensing nodes placed in an area to detect or monitor certain activity. One of the most recent trends in WSNs research is the coverage question which reflects how well a particular area, target, or barrier is monitored. Coverage problems in WSNs can arise during the network design, deployment, or operation [14]. During the design of the network, coverage questions can be addressed by deciding the number of sensors to cover a particular area. In WSN deployment, sensors are deployed to achieve the coverage of desired targets, barriers, or areas in a geographical region. During the operational phase of a sensor network, a schedule is decided to conserve energy and increase network life time. Sensor coverage problems can be divided into three categories:

(i) *Area coverage*: [15–18], where the primary objective is to continuously observe or cover some particular area or whole sensor field.

(ii) *Target coverage*: [19], where the key objective is to monitor some particular points also termed as targets.

(iii) *Barrier coverage*: [20], a barrier coverage is a circular area where the presence of any intruder can be detected by a set of sensor deployed in this area.

Table 1 summarizes different coverage approaches with type of coverage and objectives in WSNs. Our work in this paper focuses on targeting coverage only.

2.1. Target Coverage Problems. In target coverage, the primary objective is to cover some particular set of points or targets deployed in a sensor field, for example, missile launchers in a battlefield. These targets can be covered by using a random or deterministic placement of sensors.

Optimal Placement of Sensors. In the deterministic approach to node placement, nodes are placed at predetermined locations to cover targets. The deterministic approach to node placement is convenient to use for reachable and friendly sensor fields. The main objective of this approach is to cover optimal locations by using a minimum number of covering nodes. In this technique, it is assumed that the locations of targets to be monitored are fixed, known, and are limited. In some cases, coverage of all the targets is not necessary, when the number of covering sensors is limited or it is expensive to cover them. Most of the problems related to sensor placement are optimization problems, and it is possible to formulate them as mathematical programming problems. However, greedy solutions may not produce the best possible placement. The problem to construct minimum number of disjoint sensors to cover targets is a well-known set cover problem [37]. Covering sensors can be represented as set covers used to cover particular deployed targets or area. To place a covering sensor, it must be placed on a location to cover at least one target, and it is possible to cover all the targets if the covering sensors are deployed on all the available locations. Different variants of the greedy approach for set cover are well documented in literature to solve various problems related to optimal node placement [38–41]. Apart

Table 1: Coverage approaches used in WSNs.

Method	Type of coverage	Main objectives
Disjoint dominating sets [21]	Area coverage	Maximize lifetime and energy of a WSN
Coverage configuration protocol (CCP) [15]	Area coverage	Improve connectivity and energy efficiency
Coverage based on CDS [22]	Area coverage	Enhance network lifetime and energy of a WSN
Placement algorithm for nodes [19]	Area coverage and Target coverage	Coverage and connectivity
Disjoint set cover algorithm [23]	Target coverage	Energy efficient strong coverage
Density control algorithm based on probing [24]	Area coverage	Energy efficient strong coverage
Optimal geographical density control (OGDC) algorithm [25]	Area coverage	Energy efficient strong coverage
Self-scheduling algorithm for nodes [16]	Area coverage	Energy efficient strong coverage
OSRCEA Algorithm [26]	Area coverage	Improved coverage and connectivity
Voronoi-based coverage improvement approach [27]	Area coverage	Improved coverage ratio
Localized algorithm for hole detection and healing [28]	Area coverage	Coverage hole detection and healing
Optimal angular coverage in video sensor networks [29]	Area coverage	Improved angular area coverage
Approximation algorithm for surface coverage [30]	Surface coverage	Improved surface coverage
Particle swarm optimization (PI-BPSO) algorithm [31]	Camera coverage	Improved homogeneous camera network coverage
Delaunay-based coordinate-free mechanism (DECM) [32]	Area coverage	Coverage hole detection and healing
Full-view coverage detection [33]	Area coverage	Full view coverage detection
Detection accuracy algorithm [34]	Target coverage	Achieve detection accuracy
Minimum weight barrier algorithm (MWBA) [26]	Barrier coverage	Increase detection probability of barriers
Strong barrier coverag algorithm [35]	Barrier coverage	Strong barrier coverage with minimum directional sensors
A greedy solution for k-barrier coverage [36]	Barrier coverage	To construct minimum size k-barrier coverage

from greedy algorithms, several approximation solutions have also been proposed for node placement [42, 43].

Coverage Lifetime Maximization. In a random placement, sensors are randomly scattered to cover targets. In a random deployment, a single sensor node may cover multiple fixed targets, and a fixed target may be covered by multiple deployed sensors. Deployment of sensors in a random placement may be dense. The coverage lifetime maximization problem which is a distinct version of the target coverage problem is to partition the sensors into more than one set covers subject to certain coverage requirements and to activate these set covers alternately to increase the network lifetime. An example of random deployment of target coverage is illustrated in Figure 1(a), where 6 sensing devices are deployed to cover 4 targets in a random setting. In Figure 1(a) the T_2 and T_4 targets are covered by two sensors, and T_1 and T_3 are covered by three sensor nodes. The coverage relationship between the sensors and targets can be depicted by a bipartite graph as illustrated in Figure 1(b).

To achieve target coverage, all the sensors can be activated which is not very energy efficient and may reduce the network lifetime. However alternatively activating the sensors may prolong the network lifetime. Assume that if all the sensors are activated for one unit of time, it will consume one unit of network lifetime. In Figure 1, we have two disjoint set covers $S_1 = \{s_1, s_3, s_6\}$ and $S_2 = \{s_2, s_4, s_5\}$ to cover all the targets. For one time unit set S_1 can cover targets, and, for the other S_2, increase the network lifetime to two time units. Using an optimal number of set covers and alternatively activating them may increase the network lifetime.

Another version of the target coverage is Maximum Set Cover (MSC), in which the primary objective is to cover all the specified targets all the time. The MSC problem is known to be $\mathcal{NP}$-complete [44]. Target coverage at all times is a strict requirement for the coverage. The k-set cover for minimum coverage breach problem allows coverage breach and relaxes the strict coverage requirement [45]. A breached target is not covered by any sensor, or in other words breach coverage requires partial target coverage only. In this

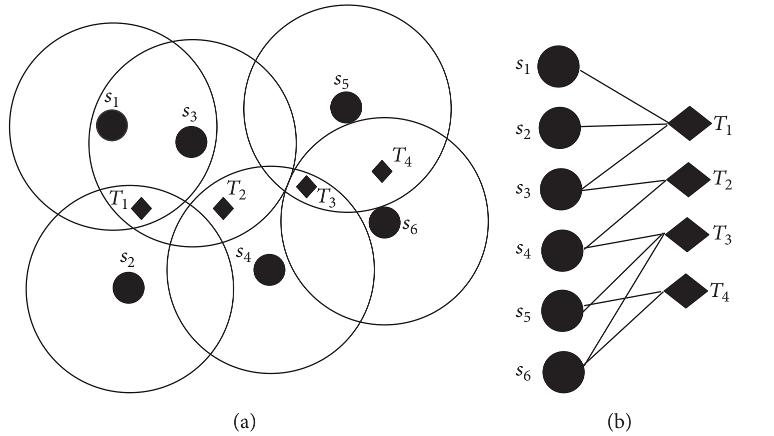

Figure 1: (a) Random deployment of sensor nodes. (b) Corresponding bipartite graph for (a).

problem, set covers are computed to cover only a fraction of fixed targets and are activated alternatively for short duration. The main objective of the k-set cover problem is to increase the lifetime of a WSN by constructing maximum k set covers [45–47]. In [45], a problem called disjoint set covers (DSC) has been proposed for complete target coverage which is similar to the MSC problem with disjointness constraints. Energy efficiency using disjoint set covers to alternatively perform the coverage task has been discussed in [18, 44].

Slijepcevic and Potkonjak [18] proposed a centralized solution for the k-coverage problem, where points enclosed in a particular area called fields are monitored by k set of sensors. The algorithm [18] covers the most critical fields by using maximum possible set covers. In this algorithm, the set covers which can cover a high number of uncovered points in an area are given priority. This algorithm also avoids field coverage redundancy. There exist several distributed solutions which can achieve 1-coverage, that is, can cover the target or area by using only one set cover. In [16], a pruning method is presented, where each node switches off its radio to conserve energy if its area can be covered by some of its neighbours. Unlike a centralized solution for the k-coverage problem in [18], a distributed solution for the same problem has been proposed in [46].

In our work, we formulate a decision version of the target coverage problem called EMDC. The EMDC problem is to achieve the maximum disjoint coverage using two disjoint set covers D_1 and D_2 with minimum E_{relay} energy. Our problem aims to find a set cover D_2 with minimum E_{relay} energy to maximize the target coverage in such a way that disjoint set cover D_1 with minimum E_{relay} still completely covers all the targets. Further, E_{relay} of D_1 is less than or equal to E_{relay} energy of D_2.

3. Related Works

Recently, there is a trend in WSNs to discover set covers that are disjoint and are connected with a sink for target reporting. These disjoint sets can be activated alternatively to conserve energy or can be activated simultaneously to ensure reliable coverage. I. Cardei and M. Cardei [48] addressed the problem known as Connected Set Covers (CSC) problem which computes the maximum possible set covers connected to a sink node and proved this problem as an NP-complete problem. To address this problem, authors proposed two different heruistics based on integer programming and breadth-first search. Ostovari et al. presented an edge-cost based approach for the connected point coverage [49]. In this approach, a node can decide to act as a relay node by evaluating its edge cost in the Minimum Spanning Tree (MST) [50, 51].

Zhao and Gurusamy formulated the connected target coverage problem as maximum cover tree (MCT) problem [52]. They proved MCT problem as an NP-complete problem and established an upper bound for the network lifetime. Zorbas et al. [53] also considered the target coverage problem and proposed a power efficient coverage algorithm to select disjoint and nondisjoint cover sets with particular focus on weakly monitored targets. Yu et al. [54] presented a k-coverage working set construction (CWSC) algorithm. CWSC algorithm is able to produce different degrees of coverage according to the application selected. In [55], Shih et al. modelled the target coverage problem by considering multiple sensing units. They reduced it to a connected set cover problem. Further, they presented two distributed heuristics: the energy efficiency first scheme (EEFS) and remaining energy first scheme (REFS). In [56], authors have proposed a centralized algorithm called CCTC_k and a distributed algorithm called DCTC_k for connected target k-coverage problem in heterogeneous WSNs. Both algorithms construct connected cover sets to achieve connectivity and coverage in an energy efficient way.

Zhao and Gurusamy [52] proposed a distributed approximation algorithm known as Communication Weighted Greedy Cover (CWGC). The primary objective of the CWGC is to maximize the covering sets by considering minimum total weight from each node to the sink node. CWGC algorithm maximizes network lifetime compared to some existing work; however it does not take into account poorly covered targets. Yang et al. considered the special instance of k-connected coverage and designed two distributed solutions based on clustering and pruning [57]. In [58], authors have considered the target coverage problem by considering two types of sensor nodes including resource rich sensors and energy-constrained sensors.

Zorbas and Razafindralambo [34] proposed Optimized Connected Coverage Heuristic (OCCH) to compute set covers, and each node is assigned a weight which exempts the critical nodes from acting as relay nodes. OCCH prolongs network lifetime by conserving the energy of energy-constrained node. Experiments reveal that OCCH has better lifetime compared to CWGC. Some other popular approaches which satisfy the energy and connectivity have been discussed in [34, 59].

Henna and Erlebach [60] formulate a problem called Maximum Disjoint Coverage Problem (MDC). Main objective of MDC is to construct two disjoint set covers S_1 and S_2, where S_1 completely covers all the targets and S_2 covers the maximum of these targets. Authors proved the problem as an NP-complete problem and presented an efficient approximation algorithm called DSC-MDC to solve it. However, DSC-MDC just computes the disjoint set covers but does not consider the relay energy of the sensor nodes. DSC-MDC therefore is not an energy efficient fault tolerance solution to target coverage.

Coverage, connectivity, and fault tolerance are primary objectives for most of the target tracking sensor networks. However, in order to achieve connectivity and coverage, we cannot ignore critical nodes, especially nodes with critical energy. Hence, it is necessary to select disjoint set covers which take into account E_{relay} energy of nodes to report an event to a particular sink. However, as discussed in the aforementioned work, most of the existing schemes discussing target coverage problem to compute cover sets ignore the issue of critical nodes as relay nodes. In this study, we propose an approximation Energy Efficient Maximum Disjoint Coverage (EMDC) algorithm to construct two disjoint cover sets to achieve both the fault tolerance and energy efficiency. We establish that approximation ratio of EMDC is $\sqrt{m}$, where m denotes the number of fixed targets.

4. Preliminaries

4.1. Set Cover Problem. Let U denote the set of elements and C be a collection of subsets of set U. Given both U and C, the set cover problem targets to cover all the elements of set U by selecting the minimum number of sets from C. Basically, set cover problem aims to cover all the elements of set U. The set cover problem is illustrated below with the help of an example.

Let $U = \{a, b, c, d\}$ be the universal set. Given the following collection of sets S, $S = \{S_1, S_2, S_3, S_4\}$, where $S_1 = \{a, b\}$, $S_2 = \{b, c\}$, $S_3 = \{c, d\}$, and $S_4 = \{d, a\}$. Both S_1 and S_3 together form a minimum set cover, that is, $Set\_cover_1 = \{S_1, S_3\}$. Another possible minimum set cover is $Set\_cover_2 = \{S_2, S_4\}$. Both minimum set covers have size 2.

4.2. Disjoint Set Covers (DSC). Given a finite set of sensor nodes W to cover a finite set of targets, T, the DSC problem is to construct disjoint set covers from W to cover all the elements of T [23]. A set cover $W_i \subset W$ is selected such that $t_j \in T$ is covered by at least one of the elements of W_i and for W_i and W_k, $W_i \cap W_k = \emptyset$.

4.3. Maximum Disjoint Coverage Problem (MDC). Given a set W of subsets of a given finite target set T, construct two disjoint set covers W_1 and W_2 for T, such that each element of target T is covered by at least one element of set W_1, and an element of W_2 covers the maximum elements of T, and, for the set covers W_1 and W_2, $W_1 \cap W_2 = \emptyset$.

The decision variation of the MDC called Disjoint Coverage (DC) is defined as follows.

Disjoint Coverage (DC). Given a finite set of targets T for a collection W of subsets of T, determine if S can be divided into two set covers with no common element, and these set covers can completely cover all the elements of set T.

4.4. Energy Efficient Disjoint Target Coverage Problem (EMDC). Given a collection of W of subsets with E_{relay} energy of a given set T, EMDC problem seeks two disjoint cover set D_1 and D_2 for T such that the following objectives are achieved:

(i) Each element of T is being covered by at least one element of D_1.

(ii) D_2 covers maximum elements of T.

(iii) Set covers D_1 and D_2, $D_1 \cap D_2 = \emptyset$.

(iv) E_{relay} energy of D_1 is less than or equal to E_{relay} energy of D_2.

5. Energy Efficient Maximum Disjoint Coverage (EMDC)

EMDC is an approach to the fault tolerant energy efficient problem and is performed by each sensor. EMDC selects two energy efficient disjoint sets D_1 and D_2 based on the following principles: (i) select a sensor node as a candidate for D_1 or D_2 if it can cover maximum possible targets; (ii) favour sensor nodes that consumes minimum energy to report an event to the sink node; (iii) make sure both the set covers D_1 and D_2 cover the target nodes T and are completely disjoint, with no common nodes.

It is worth mentioning that EMDC favours a sensor node to be added in the set cover D_1 or D_2 depending on the E_{relay} energy which is calculated according to (1). For a subset M_i representing neighbours of node i, $E_{\text{Relay}_i}(M_i)$ is calculated according to

$$E_{\text{relay}_i}(M_i) = \frac{1}{|M_i|} + \frac{\sum_{j \in M_i} E_{\text{relay}_j}}{|M_i|}. \quad (1)$$

In (1), the first term denotes the expected waiting time a node from a set of sensor nodes W takes to report an event to a fixed sink node and is inversely proportional the number of its 1-hop neighbours. The second terms represents the average expected time a node has to wait to report the event to a particular sink node B. $E_{\text{relay}_i}(M_i)$, therefore, represents the total expected waiting time a node will take to report the event to the sink node B. $E_{\text{relay}_i}(M_i)$ is a better choice to select the nodes with less energy consumption to report an event to a particular sink node.

EMDC determines two energy efficient disjoint set covers D_1 and D_2 with minimum E_{relay} energy. Algorithm first constructs D_2 by including sensor nodes which have minimum E_{relay} energy and can cover the maximum elements of set T. On the other hand, D_1 includes sensor nodes with minimum E_{relay} energy and are able to cover all the given targets from the set T. In order to compute two disjoint sets D_1 and D_2, algorithm takes subsets $T = \{t_1, t_2, \ldots, t_m\}$ and $W = \{w_1, w_2, \ldots, w_n\}$. EMDC assumes that each subset from the collection W knows its E_{relay} energy. Each subset from the collection W is mapped to a certain number of subsets from the collection T. EMDC selects a set w_i from the collection W by using a greedy approach. EMDC selects w_i from W to be added into the set D_2 if w_i covers the maximum number of elements from the set T and has minimum E_{relay} energy, and there exists a set w_j which covers the same or more number of targets as w_i. Further, EMDC evaluates if w_j has less or equal E_{relay} energy as w_i, if it is true, EMDC adds the set w_i in D_2. The algorithm EMDC repeats until all the possible subsets from the collection W have been added in the set cover D_2. Subsets in W, that is, $W \setminus D_2$, are passed to the *DisjointSet*(W) algorithm. *DisjointSet*(W) adds a subset w_i in set D_1 if it covers maximum targets from the set T and has minimum E_{relay} energy among all the subsets covering the same number of targets. *Dis jointSet*(W) repeats until all the targets are covered from T. At the end, *DisjointSet*(W) returns a disjoint set cover D_1 with minimum E_{relay} energy which covers all the targets from the set T. Finally, EMDC returns D_1 and D_2 set covers with minimum E_{relay} energy, where D_1 covers all the targets from the set T, and D_2 covers maximum of them. Algorithm EMDC and its counterpart *DisjointSet*(W) are shown in Algorithms 1 and 2.

We can explain the operation of Algorithm 1 with an example given in Figure 2. Figure 2 shows a bipartite graph with two sets W and T. W is a covering set which can cover the elements in set T. The coverage relationship between the elements of set W and T is illustrated with the help of an edge. From the bipartite graph given in Figure 2, Algorithms 1 and 2 compute two disjoint set covers D_1 and D_2.

Algorithm 1 computes D_2 to cover the set of targets T as follows:

(1) EMDC chooses w_2 greedily to cover maximum targets, that is, $\{t_1, t_2, t_3, t_4\}$, such that still it is possible to cover these targets by w_3 and w_5 which has less E_{relay} than w_2 and adds w_2 to D_2.

$$D_2 = \{w_2\}. \tag{2}$$

(2) EMDC chooses w_6 greedily to cover maximum targets, that is, $\{t_4, t_5, t_6\}$, such that still it is possible to cover these targets by w_1 and w_5 having less E_{relay} energy compared to w_6 and adds w_6 to D_2.

$$D_2 = \{w_2, w_6\}. \tag{3}$$

(3) EMDC chooses w_4 greedily to cover maximum targets, that is, $\{t_2, t_5, t_7\}$, such that still it is possible to cover these targets by w_1 and w_5 which has less E_{relay} energy compared to w_4 and adds w_4 to D_2. EMDC does not select w_3 or w_1 because then t_3 or t_4 cannot be covered by D_1.

$$D_2 = \{w_2, w_6, w_4\}. \tag{4}$$

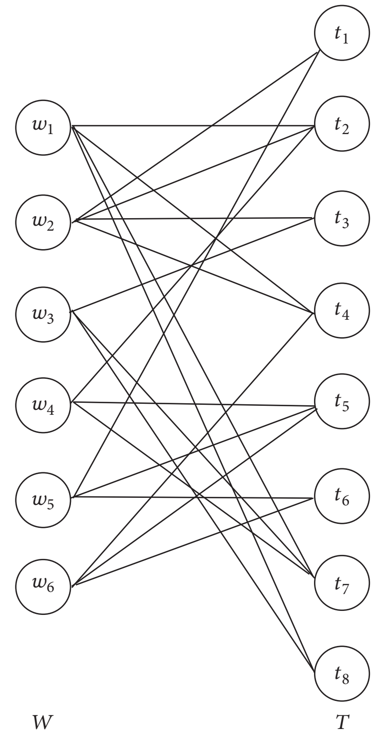

Figure 2: A bipartite graph with two energy efficient disjoint set covers.

Targets covered by set cover D_2 are

$$\begin{aligned} T &= \{t_1, t_2, t_3, t_4\} \cup \{t_4, t_5, t_6\} \cup \{t_2, t_5, t_7\} \\ &= \{t_1, t_2, t_3, t_4, t_5, t_6, t_7\}. \end{aligned} \tag{5}$$

From the remaining sets, that is, $\{w_1, w_2, w_3\}$, Algorithm 2 computes D_1 greedily to cover the set of targets T as follows:

$$D_1 = \{w_1, w_5, w_3\}. \tag{6}$$

Targets covered by set cover D_1

$$\begin{aligned} T &= \{t_2, t_4, t_7, t_8\} \cup \{t_1, t_5, t_6\} \cup \{t_3, t_7, t_8\} \\ &= \{t_1, t_2, t_3, t_4, t_5, t_6, t_7, t_8\}. \end{aligned} \tag{7}$$

In this example, D_1 and D_2 are selected disjoint set covers. By using Algorithms 1 and 2, D_1 achieves complete coverage of set T, and D_2 covers maximum elements of set T.

Data: Subsets $W = \{w_1, w_2, \ldots, w_m\}$ with E_{relay_i}
Result: Disjoint Set Covers D_1, and D_2 with minimum E_{relay_j}
$D \Leftarrow W$
$D_2 \Leftarrow \emptyset$
while $D \neq \emptyset$ **do**
  Let $w_i \in D$ be a set with minimum E_{relay_i} which covers the maximum number of targets from T
  if *all targets covered by* w_i *can still be covered by some other set* w_j *in* D *which has less or equal* E_{relay_j} *compared to* E_{relay_i} *of* w_i **then**
    $D_2 \Leftarrow D_2 \cup \{w_i\}$
    $W \Leftarrow W \setminus \{w_i\}$
  end
  $D \Leftarrow D \setminus \{w_i\}$
end
$D_1 \Leftarrow DisjointSet(W)$
Output Disjoint Set Covers D_1 and D_2 with minimum E_{relay}

Algorithm 1: Energy Efficient Maximum Disjoint Coverage $\sqrt{m}$-approximation Algorithm (EMDC).

Data: Subsets $W = \{w_1, w_2, \ldots, w_m\}$
Result: Set Cover D_1 with minimum E_{relay}
$D_1 \Leftarrow \emptyset$
while D_1 *does not cover all targets* **do**
  Let $w_i \in W$ be a set that increases the coverage of D_1 by as much as possible
  Let w_i has less E_{Relay_i} compared to E_{Relay_j} of some other nodes $w_j \in W$
  Let w_j covers the same or less number of targets as w_i
  $D_1 \Leftarrow D_1 \cup \{w_i\}$
  $W \Leftarrow W \setminus \{w_i\}$
end
Return D_1

Algorithm 2: *DisjointSet*(W) to compute set cover D_1 with minimum E_{relay}.

6. Approximation Analysis

Theorem 1. *Approximation ratio of EMDC is not worse than* $\sqrt{m}$*, where* m *denotes the number of elements in the set* T.

Proof. Given a finite set of targets T with m elements, let us have a collection of subsets in S which cover all m elements of T. Let EMDC selects w_i which has minimum E_{relay_i} and adds it in set D_2 which can cover k_i elements from the target set T. Let us say EMDC adds M number of sets with minimum E_{relay} to set D_2. Let us say in each iteration, i, number of targets covered by particular set s_i with minimum E_{relay} is represented by m_i. Then, the total number of targets covered by EMDC using D_2 with minimum E_{relay} in C iterations is given as follows:

$$\left|D_2\right| = c_1 + c_2 + c_3 + \cdots + c_C. \tag{8}$$

Let us say in order to cover T targets with D_2 with minimum E_{relay}, we have an $\mathcal{OPT}$ solution. Given that $\mathcal{OPT}$ solution, we can prove that in the worst case EMDC is a $\sqrt{m}$ approximation compared to $\mathcal{OPT}$. Let us say that EMDC computes $|D_2|$ which covers the number of targets which are greater than or equal to $\sqrt{m}$. In this case optimal algorithm $\mathcal{OPT}$ is able to cover maximum m elements. We can compare the maximum number of targets covered by both EMDC and $\mathcal{OPT}$ as follows:

$$\begin{gathered} \left|D_2\right| \geq \sqrt{m} \\ |\mathcal{OPT}| \leq m \Longrightarrow \\ \frac{|\mathcal{OPT}|}{\left|D_2\right|} \leq \sqrt{m} \Longrightarrow \\ \sqrt{m}\text{-Approximation.} \end{gathered} \tag{9}$$

On the contrary, let the number of targets covered by D_2 using EMDC be less than or equal to $\sqrt{m}$. Let for each iteration, i, EMDC selects a set w_i for D_2 and w_i is the last available set in W. Let us say w_i covers m_{i-1} targets in each iteration. In worst case for all iterations and for each set s_i, EMDC loses at most $m_i(m_{i-1})$ elements, where $1 < i < M$. It means EMDC loses at most $m_1(m_1-1)+m_2(m_2-1)+m_3(m_3-1) + \cdots + m_A(m_A-1)$ denoted by $|\text{Loss}_{D_2}|$, that is,

$$\left|\text{Loss}_{D_2}\right| \leq \sum_{i=1}^{A} m_i\left(m_i - 1\right). \tag{10}$$

On the other hand, $|\mathcal{OPT}|$ is able to cover all the targets either part of $|D_2|$ or $|\text{Loss}_{D_2}|$. For all the iterations, A, the maximum number of targets covered by $|\mathcal{OPT}|$ can be represented as follows:

$$|\mathcal{OPT}| \leq \left|\text{Loss}_{D_2}\right| + \left|D_2\right| \leq \sum_{i=1}^{A} m_i\left(m_i - 1\right) + \sum_{i=1}^{A} m_i. \tag{11}$$

Table 2: Simulation setting for EMDC.

Parameter	Value
Simulation area	1000 × 1000
Node sensing range	100 m
Transmission range	200 m
Number of sensors	50–150
Number of targets	10–80

Table 3: Energy consumption model for EMDC.

State	Energy
Listening	10.9 mA
Transmit	11.6 mA
Receive	7.0 mA

We compare the number of targets covered by EMDC to the maximum number of targets covered by $\mathscr{OPT}$ algorithm as follows:

$$\begin{aligned} |D_2| &\le m_1 + m_2 + m_3 + \cdots + m_A \le \sqrt{m} \\ |\mathscr{OPT}| &\le m_1^2 + m_2^2 + m_3^2 + \cdots + m_A^2 \\ &\le (m_1 + m_2 + mk_3 + \cdots + m_A)^2 \\ &\le (m_1 + m_2 + m_3 + \cdots + m_A) \cdot \sqrt{m} \Longrightarrow \\ \frac{|\mathscr{OPT}|}{m_1 + m_2 + m_3 + \cdots + m_A} &\le \sqrt{m} \Longrightarrow \\ \sqrt{m}&\text{-Approximation.} \end{aligned} \tag{12}$$

From the above analysis, it is proved that EMDC is a $\sqrt{m}$-approximation. □

7. Performance Evaluations

In our simulation scenarios, we use a sensor network with static sensor and target nodes randomly deployed in a 1000 m × 1000 m area. We specify the number of sensors and targets in each simulation scenario. In the sensing region, deployed targets and sensors are fixed during whole simulation time. If not stated otherwise, all deployed sensor nodes use uniform sensing range of 100 m. Sensing range of each node is assumed to be twice of its transmission range. All results are averaged over 10 runs. The simulation parameters for the evaluation of EMDC are summarized in Table 2.

For the average network lifetime, energy model of MICA2 is considered. Each sensor is assumed to has an initial energy of 200 J. We assume that energy consumed by each sensor is J/minute. Each simulation run lasts for 100 minutes. Table 3 summarizes the energy model for our simulations.

In the first scenario, sensors are varied from 50 to 150 to cover 50 targets deployed in an area of 1000 × 1000. All sensor nodes have uniform sensing range of 100 m. Figure 3 shows the average disjoint set covers generated under varying number of sensor nodes for EMDC and DSC-MDC [60]. We can see that disjoint set covers tend to increase with an increase in sensor nodes for both EMDC and DSC-MDC. Disjoint set covers increase with an increase in the number of sensors, since more sensor nodes are available to qualify as set covers.

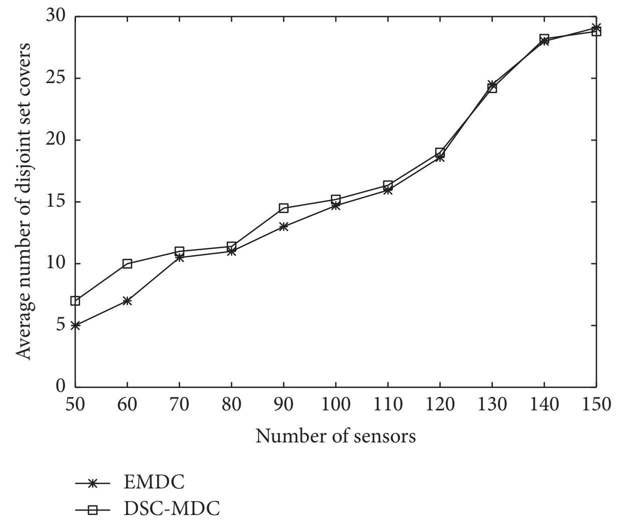

Figure 3: Number of disjoint set covers versus Number of Sensors.

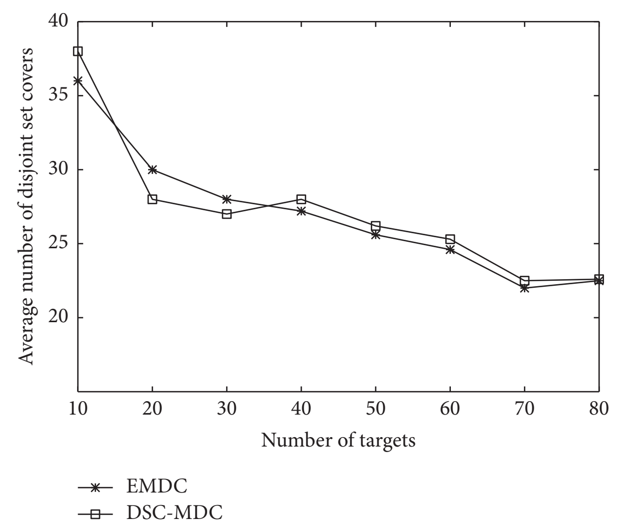

Figure 4: Number of disjoint set covers versus Number of Targets.

In the second scenario, 100 nodes with sensing range of 100 m are deployed in a fixed simulation area of 1000 m × 1000 m to cover targets varying from 10 to 80. Figure 4 shows disjoint set covers generated for varying number of targets. We observe that average disjoint set covers decreases as targets increase for both. The reason is that when targets increase while keeping the number of sensor nodes fixed, disjoint set covers decrease as likelihood of disjoint target coverage decreases. We can observe that EMDC has less disjoint set covers for all the targets due to the constraint of energy during the selection of set covers.

In third scenario, 100 sensors are deployed in a fixed simulation area of 1000 m × 1000 to cover 50 targets. Sensing range of each node is varied from 100 m to 500 m. In Figure 5,

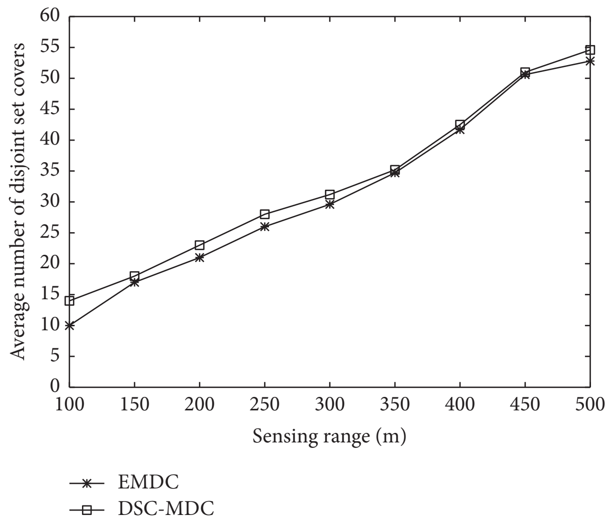

Figure 5: Number of disjoint set covers versus Sensing Range (m).

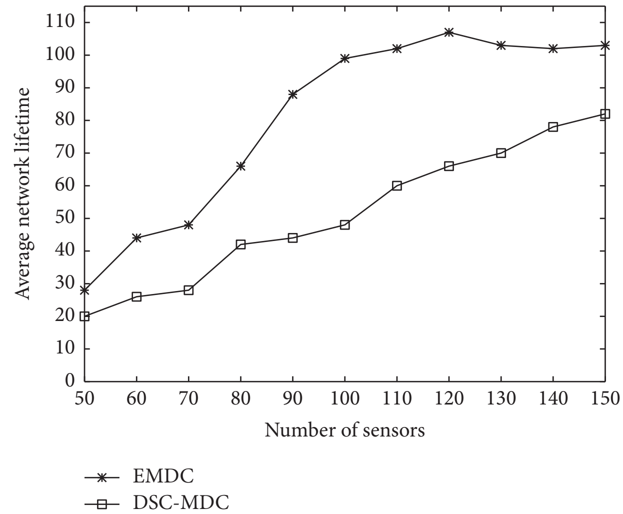

Figure 6: Network Lifetime versus Number of Sensors.

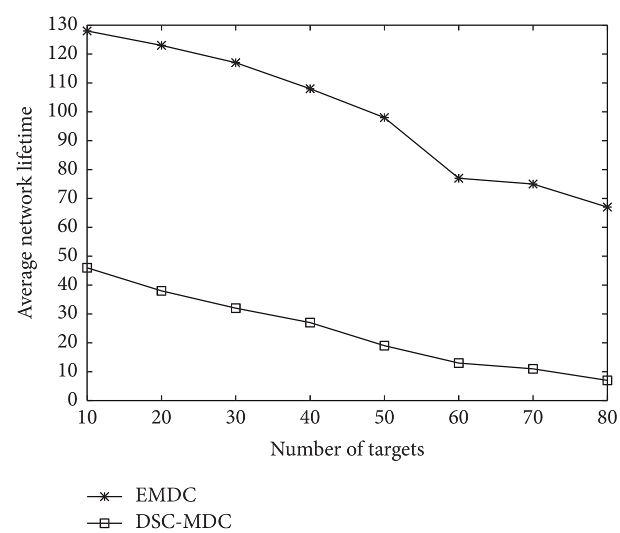

Figure 7: Network Lifetime versus Number of Targets.

we observe the effect of sensing range on disjoint set covers. We can observe that for both the EMDC and DSC-MDC, with an increase in the sensing range, number of disjoint set covers increases. Disjoint set covers tend to increase consistently for all sensing ranges since each sensor node is able to cover more targets. This coverage increase results in an increase in disjoint set covers. However, we can observe that EMDC consistently has less disjoint set covers compared to the DSC-MDC due to the minimum energy constraint on the selection of disjoint set covers.

Simulation parameters used in this experiment are same as used in scenario 1. All the nodes consume energy by using the energy model shown in Table 3. In Figure 6, we observe the effect of varying number of sensors on the average network lifetime. In case of DSC-MDC, more number of disjoint set covers is computed compared to EMDC since there is no constraint on the sensor nodes to qualify as a member of the set covers. Average network lifetime for both EMDC and DSC-MDC is directly proportional to disjoint sets produced. We already observed that EMDC has less disjoint set covers compared to the DSC-MDC as shown in Figure 4. However, we can observe that EMDC is still competitive to DSC-MDC for the average network lifetime because EMDC always selects disjoint set covers by taking into account the minimum energy.

Simulation parameters used in this experiment are the same as those used in scenario 2. All the nodes use the energy model as listed in Table 3. Figure 7 shows the network lifetime while increasing sensor nodes. It is clear from the Figure that network lifetime of EMDC is better than DSC-MDC when number of nodes increases. In case of DSC-MDC, assuming constant energy consumption for each node to forward the event, we can observe that average network lifetime consistently drops with an increase in targets. In order to monitor more targets, more energy is consumed to notify the event to the sink node. EMDC has better network lifetime compared to DSC-MDC because EMDC considers the nodes with minimum energy in order to qualify for the set covers for both the disjoint sets. Results show that network lifetime is significantly improved when set covers are selected according to minimum energy. This observation is still valid when the number of targets tends to increase. For example, with 60 targets, average lifetime of EMDC is more than 80% better compared to DSC-MDC.

8. Conclusion

The proposed algorithm EMDC maximizes network lifetime by using two energy efficient disjoint set covers in a single hop WSN with a single sink. EMDC achieves energy efficiency and fault tolerance by selecting two disjoint set covers with minimum relay energy. On one hand, two disjoint set covers achieve fault tolerance by providing double coverage, and on the other hand they maximize network lifetime by considering the relay nodes with minimum energy required to report the event to the sink node. The experimental results reveal that EMDC achieves reasonable number of disjoint set covers to achieve fault tolerance under varying number of nodes and sensing ranges. Further, EMDC achieves better network lifetime compared to DSC-MDC for different number of nodes and sensing ranges.

Conflicts of Interest

The author declares no conflicts of interest.

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