ISSN: 3065-0437

Columbia Journal of Engineering and Technology

Research Article

# A DETAILED EXAMINATION OF ENHANCED ALGORITHMS FOR EFFICIENT 2-CONNECTED NODE PLACEMENT IN WIRELESS NETWORKS

**Wei Hong Zhang**

Institute of Logistics Science and Engineering, Shanghai Maritime University, Shanghai, China

**Abstract**

Wireless Sensor Networks (WSNs) have become an integral part of various industries and applications. However, frequent link interruptions and network unreliability caused by electromagnetic interferences may lead to high delay and packet loss, posing a challenge in achieving high reliability and stability in WSNs. In this paper, we propose an algorithm called Improved Cover-based 2-Connected Node Placement (IC2NP) to solve the Delay Constrained Relay Node Placement (DCRNP) problem in WSNs. The algorithm aims to build at least two node-disjoint paths meeting the hop constraint between each sensor and the sink by deploying certain relay nodes (RNs). IC2NP provides a feasible solution with a time complexity of O(N^4) and an approximation ratio guaranteed to be O(ln n). Through extensive simulations, we validate that IC2NP outperforms the existing method in terms of success rate, deployment budget, and running time. This paper also summarizes related work on the Relay Node Placement (RNP) problem and previous research on the DCRNP problem. The proposed algorithm can enhance the deployment success rate of 2-connected DCRNP by changing the deployment rules.

**Keywords:** Wireless Sensor Networks, Delay Constrained Relay Node Placement, Improved Cover-based 2-Connected Node Placement, Relay Node Placement, Hop Count Constraint.

## I. INTRODUCTION

Wireless sensor networks (WSNs) technology attracts considerable attentions in recent years and has been widely spread in industry, agriculture, smart home and other fields for their immense potentials [1-4]. Typically, in WSNs, the sensor nodes (SNs) are spatially distributed to monitor or gather data from the workplace and at least one sink node should be deployed to collect information from all of SNs. The vast majority of sensors use batteries as energy supply, which makes WSNs portable, but this also limits their power supply and communication radii [5-6]. So, in order to extend the lifetime of WSNs and improve the network scalability, some specific nodes with sufficient power and suitable communication radii are introduced into the network. These nodes act as relay nodes (RNs) to forward the received data from the SNs or other RNs to sink nodes [7]. To save the deployment cost, the number of deployed RNs should be as small as possible with the limitations of network delay, connectivity, lifetime and reliability, etc. This problem is known as the Relay Node Placement (RNP) Problem in many literatures, which has been proven to be NP-hard [8].

As an important branch of this subject, the Delay Constrained RNP (DCRNP) problem has received great attention because of its practical significance in the fields such as industrial automation and smart grid [9-10]. For example, in industrial automation, real time data collected by precision instruments functioned as sensor nodes must be sent to the control center functioned as the sink node timely and reliably [10]. However, the existing RNP problem only focuses on reliability and fairness of transmission, and does not give priority to real-time performance. Hence, existing methods cannot be introduced into such applications directly. Basically, delay is divided into response delay and transmission delay in which transmission delay is very short and normally can be neglected. So, many literatures use response delay that is also the hop count as the criterion of delay [11]. Besides, due to the electromagnetic interference, network unreliability, etc., the network structure of industrial site changes frequently. In view of the above problems, this paper studies the DCRNP problem in 2-connected network where at least two node-disjoint paths meeting the hop constraint are built between each SNs and the sink by deploying certain RNs.

In [12], researchers are committed to the study of the 2-connected DCRNP problem and have achieved groundbreaking results. Their proposed algorithm, Cover-based 2-connected Node Placement algorithm (C2NP), successfully realizes the requirement that each sensor can connect to the sink through two node-disjoint paths in most scenarios and guarantee the hop count constraint in the meantime. However, in practice, we find that the deployment success rate of C2NP can be effectively improved by changing the deployment rules. Therefore, based on the mentioned reasons, a polynomial-time algorithm called Improved Cover-based 2-connected Node Placement algorithm (IC2NP) is proposed in this paper. In addition, there are many fruitful achievements in the research of the RNP problem, which will be briefly summarized in next chapter.

In summary, the contributions of this paper are listed as follows：

1) First, in order to provide a solution to the DCRNP problem, we propose an algorithm- IC2NP. The IC2NP is composed of three steps. The first step is to find the shortest path from the sink node to each SN and verify whether there is a feasible solution that satisfies the hop constraint. The second step is to deploy routes layer by layer so that there are at least two node-disjoint paths meeting the hop constraint between each SN and the sink. In each layer， we check each SN and an additional RN will be allocated to the SN with less than two disjoint paths by the father supplement algorithm. In third step, we traverse all of the selected RNs in the previous step and remove redundant nodes so as to reduce the number of RN.

2) Second, we prove that the proposed algorithm is a polynomial-time algorithm whose approximation ratio is O (ln $n$) whenever it finds a feasible solution. To the best of our knowledge, there have been very few algorithms providing an explicit performance guarantee for the 2-connected DCRNP problem in the literature.

3) Finally, we conduct extensive simulations on a computer to evaluate the performance of IC2NP. We compare IC2NP with C2NP in the same scenario and prove that IC2NP is feasible and effective and has an

improvement in the three key performance indicators of saving deployment costs, reducing running time and increasing deployment success rate.

The rest of this paper is organized as follows. In Section 2, the related works are presented. Sections 3 describe and analyze the IC2NP algorithm. Section 4 shows the simulation results.

Finally, the paper is concluded in Section 5.

**Related Work**

Extensive works have been done to solve the RNP problem. In [13], Lin and Xue studied the problem when the deployment location is unconstrained and formulated it as the Steiner Minimum Tree with Minimum number of Steiner Points and bounded edge length (SMT-MSP) problem and proved it is a NP-complete problem. They proposed a

5-approximation algorithm to solve it. Chen et al. first demonstrated the algorithm proposed above was actually a 4-approximation algorithm, and proposed a 3-approximation algorithm on their basis [14]. Then they put forward a 3-approximation algorithm and a

2.5-approximation algorithm based on a three-star structure [15]. Lloyd and Xue studied the single-tiered and two-tiered RNP problem, respectively [16]. They presented a 7-approximation algorithm for the former one and a (5+ε)-approximation algorithm for the latter one, where ε can be an arbitrary positive constant. Misra et al. [17]–[18] and Yang et al. [19] studied the location constrained RNP problem with respect to survivability requirement in WSNs. In [17-18], Misra et al. proposed a polynomial time O (1)-approximation algorithm about the single-tiered network. In [19], Yang et al. studied the constrained RNP problem in two-tiered WSNs and proposed dubbed TTCR solution, which can be implemented in three steps: remove the SNs neighbor to the sink node, connect the rest of SNs to a set of activated relay position, use Steiner Tree Problem to determine the positions of relay nodes placements. Ali Chelli et al. [20] proposed a One-Step Approach OSRP, which can get approximate global optimal placements for relay nodes by reducing communication between SNs and assigning targeted weights. Ma et al. [21] improved the minimum spanning tree algorithm to solve the geometric disc covering problem, which aims to build the network connectivity. But for the DCRNP problem, the fruitful research is much less. Some of the constructive conclusions come from the following papers [22-27]. In [22-23], Bhattacharya et al. made a systematic study on this problem. They described the DCRNP problem as a Rooted Steiner Tree-Minimum Relays-Delay Constraint (RST-MR-DC) problem and proved the NP-hardness of the problem. Shortest Path Tree based Iterative Relay Pruning (SPTiRP) algorithm was proposed for it and the preserved deployed RNs found by SPTiRP are all contained in the steiner tree, leading the lack of the optimal RNs nodes. Nigam et al. studied the structure of the projection polyhedron of the DCRNP problem and developed valid inequalities in form of the node-cut inequalities[24]. Then a branch-and-cut algorithm, based upon the projection formulation, was formulated to solve DCRNP. But in large-scale problems, this algorithm is easy to fail. The fault-tolerant RNP problem with respect to hop constraint was studied in [25]. Sitanayah et al. proposed local search based heuristic algorithms without providing the time complexity analysis and approximation guarantee. Wang et al. were committed to the 2-connected DCRNP in harsh environments to avoid the problem of single point of failure(SPOF) [26]. They proposed 2-Connected Relay Placement Problem (2CRPP) and achieved good results, but in large-scale occasions, the execution of the algorithm becomes difficult. In [27], Hwang et al. tried to connect multiple disjoint segments caused by large scale damage and put forward a relay node placement scheme in WSNs that federates disjoint segments to form a 2-connected topology with fewer relay nodes. These literatures all provide us with some ideas to solve the 2-connectivity problem and our approach will be shown below.

## II. PROBLEM FORMULATION

As described in [12], some necessary and reasonable assumptions are given here to facilitate the analysis of the 2-connected DCRNP problem.

1) This paper only considers the many-to-one communication pattern which means there is only one single sink node in the network.

2) The end-to-end delay is represented by hop count in this paper as mentioned above. 3) The delay and packet loss introduced by collision, queuing, and congestion are not considered in this paper. In other words, the success rate of sending and receiving data is 100 percent.

4) The location of SNs and the sink node is known and fixed. RNs can only be placed at some predetermined candidate deployment locations.

In order to facilitate writing, this paper defines some symbols and abbreviations as shown in Table 1.

**Table 1.** Symbols and Abbreviations

| Notation | Description |
|---|---|
| $S$ | the set of SNs |
| CDL | the set of predetermined candidate deployment locations |
| $C$ | the set of CDLs |
| $R$ and $r$ | the communication radii of RNs and SNs, $R \geq r$ |
| $z$ | the sink node, the communication radius of $z$ is larger than $R$ |
| $N(u)$ | the neighbors of node $u$ |
| $p(u, v)$ | a path between nodes $u$ and $v$ |
| $H(p(u, v))$ | the hop count of $p(u, v)$ |

| | |
|---|---|
| $\Delta(u)$ | the maximal hop count from $u$ to the sink $z$ the least hop court between $u$ and $v$ the |
| $D(u, v)$ $p_T(u, v)$ | path of $u$ and $v$ in the tree $T$ the nodes selected at layer $k$ the set of the sensors that |
| $\boldsymbol{I_k}$ | cannot build two node-disjoint paths to the sink node through the existing network |
| $S'$ | deployment the feasible region the minimum set of $\Phi$ |
| | the number of sensors covered by $u$ |
| $\Phi$ | the number of nodes contained from $u$ to the covered sensor the number of parent |
| $\phi$ $q(u)$ $w(u)$ $p(u)$ | nodes of $u$ the set of son sensor of $u$ |
| $Sons(u)$ | |

For $\forall u, v \in S \cup C \cup \{z\}, (u \neq v)$, when $u$ and $v$ can communicate directly without the help of other nodes, which can be called neighbors, $u$ and $v$ should meet the following requirements:

$\|u\text{-}v\| \leq r \ \exists\ u, v \in S$

{

$\|u\text{-}v\| \leq R \ \forall\ u, v \notin S$

where $\|u\text{-}v\|$ denotes the Euclidean distance between u and v .

For a path p(z, u), if $H(p(z,u)) \leq \Delta(u)$, $p(z,u)$ can be called a feasible path. And the least hop court between $u$ and $v$ is called the shortest path, denoted by $D(u, v)$.

The definition of the 2-Connected DCRNP Problem is given as follow:

*Definition 1 (2-Connected DCRNP Problem):* Given a set $S$ of SNs, a set $C$ of CDLs and the sink $z$, the 2-Connected DCRNP problem seeks a minimum subset of CDLs to place RNs such that there are at least two node-disjoint feasible paths between each SN and the sink.

When the 2-Connected DCRNP problem has a feasible solution, the network topology constitutes an extended tree originated from sink $z$, through routers or sensors, and ended at $S$. So, for a given tree $T$ and two different nodes $u$ and $v$ in the tree, the path of $u$ and $v$ in the tree $T$ is defined as $(u, v)$. According to the Definition 1, if each path from sensor to sink in tree $T$ is a feasible path, i.e., $\forall s \in S$, $H(p_T(s,z)) \leq \Delta(s)$, furthermore, if there are at least two node-disjoint feasible paths between each sensor and sink, tree T is a feasible tree of the 2-connected DCRNP problem. In this paper, there is a preset hop limit to sink for each SN,

i.e., $\forall s \in S$, $\Delta(s) > 0$; but not for RNs.

In [12], the author focused on the 2-connected DCRNP problem with delay constraints for single-tired networks where sensors can both collect data and forward data and proposed a heuristic algorithm, C2NP. Its idea is: the RNs are deployed layer by layer from the sensor until all the newly deployed RNs are within the single hop of the sink. When deploying new layer, the candidate deployment locations are formed by the single hop neighbors of the RNs deployed in the previous layer, and the candidate deployment locations covering the same sensors should be deleted to avoid the feasible paths of each sensor intersecting at these locations. As shown in Figure 1, the algorithm starts from the SNs ($s_1$, $s_2$) in the first layer. In Figure 1(a), RNs $y_1$ and $y_2$ satisfy the double cover for $s_1$, RNs $y_3$ and $y_4$ satisfy the double cover for $s_2$. In the next layer, $y_1$−$y_4$ must have their own independent parent nodes. In Figure 1(b), the single hop neighbor of $y_1$ and $y_2$ is $y_5$, the single hop neighbor of $y_3$ and $y_4$ is $y_6$ and $y_7$ , respectively. Follow the rules in [12], $y_5$ will be deleted for $y_1$ and $y_2$ covering the same SN $s_1$. Finally, the network topology constructed by this method is shown in the figure 1(c), which fails to build a feasible tree for the 2-connected DCRNP problem. However, two node-disjoint feasible paths from $s_1$ to sink can be built as "$s_1$-$y_1$-$y_5$-sink" and "$s_1$-$y_3$-$y_6$-sink". Therefore, to improve the solution success rate for the 2-connected DCRNP problem, a new solution based on heuristic algorithm is proposed in this article.

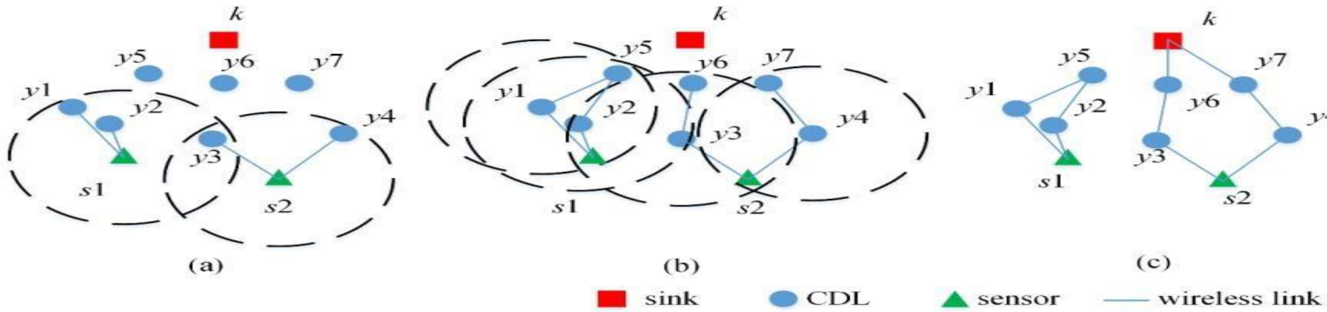



**Fig.1.** An example of the 2-connected DCRNP problem.(a) Iteration 1 (b) Iteration 2 (c) Final topology.

## III. ALGORITHM FOR 2 -CONNECTED DCRNP PROBLEM

*A. Algorithm Description*:

In this section, a new solution IC2NP for the 2-connected DCRNP problem is detailed as shown in Algorithm 1, which can be divided into three steps. In the first step, IC2NP checks whether the problem is solvable based on the existing network topology or without any more RNs. If so, the algorithm terminates. If not, search the sensor in the neighbors of the sink and remove it from $S$ to get $S'$. Then the algorithm goes to the second step.

In the second step, the RNs are deployed layer by layer from sensors to the sink as shown in the Algorithm 2. In the first iteration, the double greedy set-cover algorithm is executed [28]. Firstly, the feasible region Φ that double covers all nodes in $S'$ are searched from the neighbors of $S'$. Then, the double greedy set-cover algorithm is used to find the minimum set $\phi$ covering $S'$ from Φ. The construction of feasible region Φ is based on the coverage information, which is defined as follows:

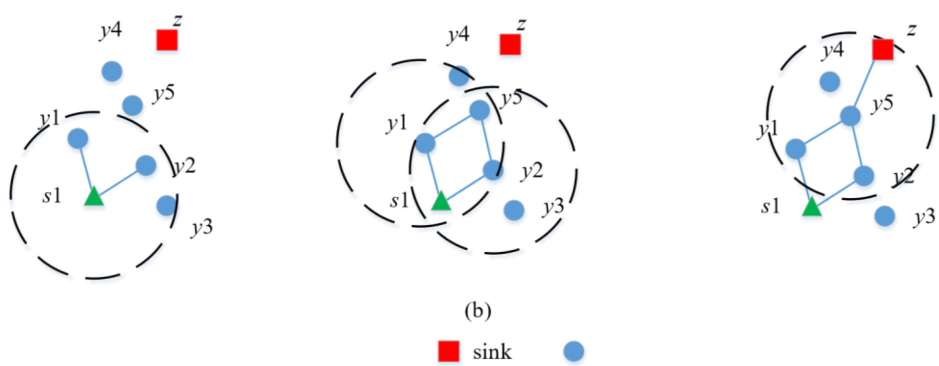
*Definition 2 (SN $s_i$ covered by SN $s_k$ or RN $y_j$):* If the following conditions are met, SN $s_i$ is covered by SN $s_k$ or RN $y_j$:

$H(D(s_i, y_j)) + H(D(y_j, z)) \leq \Delta(s_i),\ s_i \in S',\ y_j \in C$ (1a)

H $(D(s_i,s_k))$ + H$(D(s_k, z)) \leq \Delta(s_i)$, $i \neq k$, $s_i \in S'$,, $s_k \in S$ (1b)

Intuitively, the newly deployed RNs should be closer to the sink to reduce the amount of RNs. So, if sensor $s_i$ is covered by route $y_j$ (or sensor $s_k$) and the hop court of the shortest path from sink to $y_j$ (or sensor $s_k$ ) is less than that from sink to the sensor $s_i$ , i.e. H $(D(y_j, z))$ =H$(D(s_i, z))$-1, (or H$(D(s_k, z))$=H$(D(s_i, z))$-1), then $y_j \in \Phi$, (or $s_k \in \Phi$).

Here $y_j$ is a single hop neighbor node of , $y_j \in N(s_i)$(or sensor $s_k$, $s_k \in N(s_i)$) . In this case, $y_j$ (or ) is the father node of $s_i$ , and $s_i$ is the son node of $y_j$ (or $s_k$ ). The relationship of the parent node can be inherited. According to the number $q(u)$ of covered sensors by node $u$ in Φ, Φ is arranged in descending order. For nodes with the same $q$ value, they are further arranged according to the number of nodes $(u)$ contained in their shortest path to the covered sensor and the number of parent nodes $(u)$ . The sorted results are used as input to the double greedy set-cover algorithm. So far, the first iteration is completed.




In later iterations, different from the first iteration, the greedy single set-cover [29] is used to search the feasible region Φ and the father nodes supplement algorithm is executed after finding Φ. Only using greedy set-cover algorithm can't guarantee that each sensor has at least two node-disjoint paths to the sink in each iteration. As shown in Figure 2, after the first iteration, the greedy single set-cover algorithm is used to deploy $y_1$ and $y_2$ RNs to realize the double coverage of $s_1$. After the second iteration, $\Phi = \{y_{4,5}\}$, and both

$y_4$ and $y_5$ have the same $q$ value, $w$ value and $p$ value. $y_5$ will be selected randomly and $\phi = \{y_5\}$, but such a network topology cannot satisfy that $s_1$ has two node-disjoint paths (the two path of $s_1$intersect at $y_5$).

ISSN: 3065-0437

Columbia Journal of Engineering and Technology

Research Article

(a) (c)

CDL sensor wireless link

**Fig.2.** A failure example. (a) Iteration 1 (b) Iteration 2 (c) Final topology Therefore, the father nodes supplement algorithm is executed after the single greedy set-cover algorithm. The algorithm will traverse the nodes in *S'* to detect whether these SNs all have at least two parent nodes in $\phi$. For the failure example in Figure 2, the father nodes supplement algorithm will detect each sensor and find that $s_1$ does not have two father nodes in the current layer. Then, the father nodes supplement algorithm can select a father node different from $y_5$ in $\Phi$. Here, we have $(y_1) = 2$ and $(y_2) = 1$, and $y_5$ is the father nodes of $_1$ and $y_2$. Therefore, $_1$ can be removed from the son nodes of $y_5$ . After checking the

$\Phi$ in decending order, $y_4$ is selected, and then $\phi = \{y_{4,5}\}$. Finally, $s_1$ has two node-disjoint feasible paths to the sink, and the father nodes supplement algorithm ends. When the set *S'* is empty, the second step is finished.

An example of the second step algorithm is shown in Figure 3. The blue solid line represents the established wireless link, the blue dot represents CDLs, the green triangle represents sensor, and the red square represents sink. Initially, $' = \{s_1, s_2\}$. In the first iteration, the double greedy set-cover algorithm is used to select $y_1 - y_3$ to realize the double coverage of $s_1$ and $s_2$, see figure 3 (a). In the second iteration, the feasible region

$\Phi = \{y_4, y_{5,6}, y_7\}$, $y_5$ and $y_6$ have the same $q$ value, but $y_5$ has a smaller $w$ value. So select

$y_5$ to cover $s_1$ .$\phi = \{y_{5,}y_6\}$ or $\phi = \{y_{5,}y_7\}$. After the father nodes supplement algorithm,

$y_4$ is added to $\phi$. Figure 3 (c) selects $y_7$ to cover $_2$ , $\phi = \{y_4, y_{5,}y_7\}$. Now, $y_4$ and $y_5$ can communicate with sink directly, $s_1$ can be removed from *S'*. *S'* = $\{s_2\}$. In the third iteration, Figure 3(d), $y_8$ is chosen and $s_2$ can communicate with sink though two node-disjoint paths.

*S'* is empty set. The second step ends, see figure 3(e).

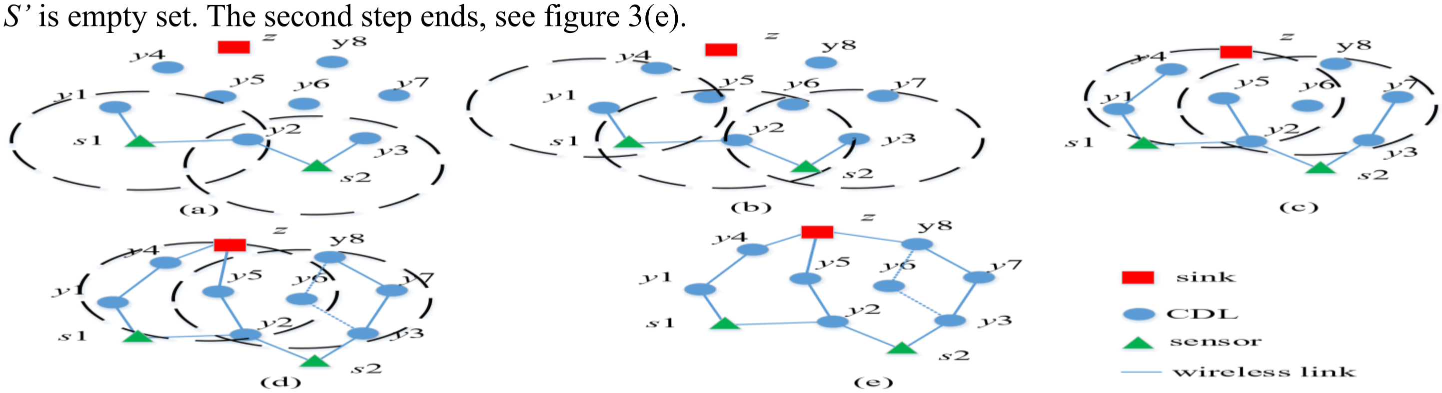



**Fig.3.** An example of the second step algorithm. (a) Iteration 1 (b) Iteration 2(a
(c) Iteration 2(b (d) Iteration 3 (e) Final topology

In the third step, IC2NP tries to reduce the number of CDLs selected in $\phi$. In Figure 3,

$y_6$ and $y_7$ can be both selected to cover $_2$ , which leads to the existence of redundant nodes. The third step is shown in Algorithm 3, which is similar as the Algorithm 7 in [12]. If the feasible paths from $s_i$ to sink can pass through

$u$, $s_i$ can be called a son sensor of $u$, the set of son sensor of $u$ is denoted as $(u)$. The third step finds $u$ that minimizes the set $(u)$, then judges whether $u$ can be deleted. If $u$ cannot be deleted, mark it as checked. When all the CDLs are marked, the third step terminates.

---

**Algorithm 1:** Improved Cover-based 2-Connected Node Placement Algorithm (IC2NP)

---

**Input**: A set $S$ of SNs, a set $C$ of CDLS, a sink $z$.
**Output**: A subset $C'$ of CDLs.

$T$ = a tree spanning by the shortest path tree algorithm taking $z$ as root and connecting $S$ and $z$ with the help of $C$;
**if** $\forall x \in S$, $p_T(x, z) \leq \Delta(x)$ **then**
$T$ = a feasible tree satisfying the hop constraints;
input $S$, $C$, $z$ into the second step;
$C'$ = a subset of $C$ returned by the second step;
input $S$, $C'$, $z$ into the third step;
$C'$ = a subset of $C$ returned by the third step;
**else**
$T \neq$ a feasible tree;
$C' = \emptyset$; declare the failure of the algorithm and terminate;
**endif**
**return** $C'$;

---

**Algorithm 2:** the Second Step of IC2NP

---

**Input**: A set $S$ of SNs, a set $C$ of CDLS, a sink $z$.
**Output**: A subset $C'$ of CDLs.

$k = 0$; $I_0 = S$; $U = S \cup C$; $C' = \emptyset$;
**foreach** $u \in U$ **do**
$H(S(z, u))$ = the minimum hop court according to tree $T$;
**foreach** $u \in I_0$ **do**
**if** $u \in N(z)$ **then**
$S' = S - u$;

**endif**
**while** $S' \neq \emptyset$ **do**
$\Phi_k$ = the feasible region for $I_k$;
**if** $k$ =0 **then**
$\phi_k$ = a subset of $\Phi_k$ searched by the double greedy set-cover algorithm to fully cover the nodes in $I_k$;
**foreach** $u \in C_T$ **do**
$(u)$ = the set of son sensor of $u$.
**else** $k \geq 1$ **then**
$\phi_k$ = a subset of $\Phi_k$searched by the greedy set-cover algorithm to fully cover the nodes in $I_k$;
input $\phi_k$ into the father supplement algorithm;
$\phi_k$ = the nodes in $\phi_k$ after using the father supplement algorithm;
**foreach** $u \in \phi_k$ **do**
$Sons(u)$ = the set of son sensor of $u$
**endif**
$C = C \cup \phi_k$; $k = k+1$; $I_k = \phi_k$
**foreach** $u \in S'$ **do**
**if** $u$ has two node-disjoint paths through $C$ **then**
$S' = S' - u$;
**endif**
**endwhile**
$C = C - S$;
**return** $C$;

---

**Algorithm 3:** the Third Step of IC2NP

---

**Input**: A set $S$ of SNs, a set $C$ of CDLS, a sink $z$.
**Output**: A subset $C$ of CDLs.
**while** $C \neq \emptyset$ && $\exists u \in C$, $u$ = unchecked **do**
$u = \{u|$ min $Son(u)\}$;

ISSN: 3065-0437
Columbia Journal of Engineering and Technology
Research Article

$u \in \check{C}$

3 $tmp$ = all the nodes on the feasible paths except the paths passing through $u$ between $Sons(u)$ and $z$.

4 $\check{C}' = \check{C} - tmp - \{u\}$, $S' = S - tmp$;

5 $t$ = a tree spanning by the shortest path tree algorithm taking $z$ as root and connecting $S'$ and $z$ with the help of $\check{C}'$;

6 **if** $\forall x \in d(u)$, $p_t(x, z) \leq \Delta(x)$ **then**

7 $\check{C} = \check{C} - \{u\}$;

8 **foreach** $x \in Sons(u)$ **do**

9 **foreach** $y \in p_t(x, z)$ **do**

10 $Sons(y) = Sons(y) \cup \{y\}$;

11 **else**

12 $u$ = checked;

13 **endif**

14 **endwhile**

15 **return** $\check{C}$;

---

**Algorithm 4:** the father nodes supplement algorithm.

---

**Input**: A set $S$ of SNs, a sink $z$, $\phi_k$, $\Phi_k$

**Output**: $C_T$ after applying the father nodes supplement algorithm.

1 sort the nodes in $\Phi_k$ in a descending order according

2 $\bar{S}$ =the nodes in $S$ which don't have two father nodes in $\phi_k$;

3 **while** $\bar{S} \neq \emptyset$ **do**

4 **foreach** $s \in \bar{S}$ **do**

5 **foreach** $u \in \Phi_k$ **do**

6 **if** $\exists u \in \Phi_k - \phi_k$, $u$ can cover $s$ **then**

7 $\phi_k = \phi_k \cup \{u\}$;

8 Update the number of parent nodes of sensors in $\phi_k$;

9 $\bar{S} = \bar{S} - s$;

10 **goto** line 3**;**

ISSN: 3065-0437

Columbia Journal of Engineering and Technology

Research Article

```
else
declare the failure of the algorithm and terminate;
endif
endwhile
ruturn φk;
```

---

*B. Algorithm Analysis:*

*1) Time Complexity:*

Here the time complexity of IC2NP is discussed, which consists of three steps. $N$ is the sum of all nodes. The first step constructs a shortest path tree between the sink and all of the SNs, the time complexity is O($N$lg$N$) which can be found in [29].Then, the time complexity of the second step mainly depends on the *while* loop in Algorithm 2. The double greedy set-cover algorithm, the greedy set-cover algorithm and the father nodes supplement algorithm are included in the *while* loop. The former one is executed once, and the latter two is close to $N$-1 times, so time complexity mainly depends on the latter two. The father nodes supplement algorithm consists of three nested loops and the time complexity is O($N^4$), which is the time complexity of step two. The inner loop of the third step is O($N^2$) which will be iterated for $N$ times, the time complexity of the third step is O($N^3$). So, we can get that the time complexity of IC2NP is O($N^4$).

*2) Approximation Ratio:*

The approximation ratio of IC2NP is analyzed to study its deployment accuracy. Here *OPT* denotes the optimal deployment solution. *APT* denotes the solution by IC2NP. Then, the approximation ratio $R_{IC2NP}$ is given by

$$R_{IC2NP}=\frac{|APT\text{-}S\text{-}\{z\}|}{|OPT\text{-}S\text{-}\{z\}|}\leq\frac{|APT|}{|OPT\text{-}S\text{-}\{z\}|} \quad (2)$$

Due to $S$, $R$ and $\{z\}$ are pairwise disjoint,

$$R_{IC2NP}\leq\frac{|APT|}{|OPT\text{-}S\text{-}\{z\}|}=\frac{|APT|}{|OPT|-|S|-1}<\frac{|APT|+|S|+1}{|OPT|}=\frac{|APT|}{|OPT|}+\frac{|S|+1}{|OPT|}$$

Because $|OPT|\geq|S|+1$,then $|OPT|-|S|-1\geq 0$, we can get

$$R_{IC2NP}\leq\frac{|APT|}{|OPT|}+\frac{|S|+1}{|OPT|}<\frac{|APT|}{|OPT|}+1$$

Then, $I_i$ denotes the set of RNs deployed in the $i$th iteration, $I_0=S$.

$$R_{IC2NP}<\frac{|APT|}{|OPT|}+1=\frac{\sum_{i=0}^{l}|I_i|}{|OPT|}+1=\frac{|I_0|}{|OPT|}+\frac{|I_1|}{|OPT|}+\frac{\sum_{i=2}^{l}|I_i|}{|OPT|}+1<\frac{|I_1|}{|OPT|}+\frac{\sum_{i=2}^{l}|I_i|}{|OPT|}+2 \quad (3)$$

ISSN: 3065-0437

Columbia Journal of Engineering and Technology

Research Article

Let $OPT_k$ be a minimum set cover for the $k$th iteration. The double greedy set-cover algorithm and the greedy set-cover algorithm have the same approximation ratio, as follows

$|I_k|$

$\forall k \in \{1,2,3,\ldots,l\}$, $\frac{|I_k|}{|OPT_k|} \le \ln|I_{k-1}|+1$

Then， for the first layer

$|I_1|+ \sum_{i=2}^{l} |I_i| +2 = \frac{1}{} \cdot \frac{1}{} + \frac{\sum_{i=2}^{l} |I_i|}{} +2 \le \sum^{l}$ $|I|$ $|I|$ $|OPT|$ $\Sigma^l$ $|I$ $|$

$|OPT_1|\Sigma^l_{i=2}|I_i|$

$RIC2NP<$ $|OPT|$ $|OPT|$ $|OPT_1|$ $|OPT|$ $|OPT||OPT|$ $\cdot\ln S+1+$ ( | | ) $|OPT|$ $+2$

When $i \ge 2$, the greedy set-cover algorithm and the father node supplement are used in the RNs deployment. Based on the father node supplement at most one additional relay node in the $i$th $(i \ge 2)$ iteration is deployed to cover the SN, so as to satisfy the double cover for each SN and make sure there are two father nodes in $i$th layer. So, we get

$$\frac{|I_i|}{|OPT|} \le \frac{|I_i'|+|S_i'|}{|OPT|} \quad (4)$$

Where $I_i'$ denotes the set of RNs deployed before using the father node supplement algorithm, $S_i'$ denotes the set of supplement RNs. Then

$l$

$|OPT_1|$ $\Sigma^l$ $\frac{|I}{|OPT|}$ $\frac{|}{|OPT|}$ $\ln|S|+1)+ \frac{\sum_{i=2}^{} i}{} +2 \le \frac{1}{} \cdot (\ln|S|+1$ $\sum$ $|OPT|$ $|I_i'|+|S_i'|$ $RIC2NP\le$ $|OPT|$ $($ $)^+(|OPT|)$ $+2$

$i=2$

1

$|OPT_1||OPT_i||S_i'|$

$\le \frac{}{} \cdot (\ln|S|+1)+ \left( (\ln|S|+1) \frac{}{} \sum + \frac{}{} \right) +2$ $|OPT||OPT|$ $|OPT|$

i=2

Obviously, $|OPT_i| \le 2|S_i'| \le 2|S| = 2S$, so

$l$

$$RIC2NP < (\ln|S|+1)\frac{2S}{S+1} + \sum_{i=2}\left((\ln|S|+1)\frac{2S}{S+1} + \frac{S}{S+1}\right) + 2$$

$$= (\ln|S|+1)\frac{2S}{} + (L-1)\left((\ln|S|+1)\frac{2S}{} + \frac{S}{}\right) + 2$$

ISSN: 3065-0437

Columbia Journal of Engineering and Technology

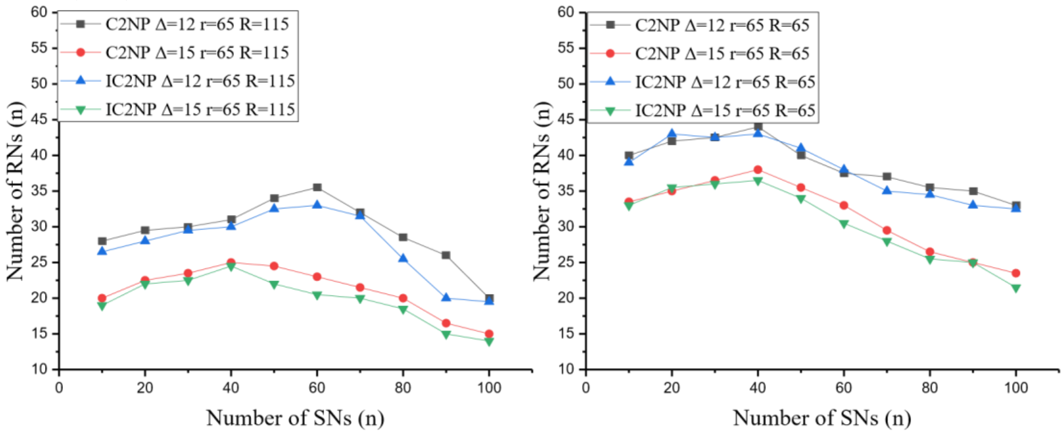
Research Article

$S+1$ $S+1$ $S+1$

$<2\Delta\max\ln|S|+2\Delta\max+\Delta\max+1=2\Delta\max\ln|S|+3\Delta\max+1$ So the approximation ratio of IC2NP is O(ln $n$).

**IV. SIMULATIONS**

Extensive simulations are presented in this section to analyze the robustness and efficiency of the proposed IC2NP. The simulation environment is set as follows: In a square area of 600m × 600m, both SNs and CDLs are randomly distributed. The number $n$ of SNs varies from 10 to 100 with an interval of 10. Similarly, the number of CDLs varies from 50 to 500 with an interval of 50. Simulations are executed in both homogeneous scenarios and heterogeneous scenarios. In homogeneous scenarios, sensors have the same communication radii with the route nodes, ie., $R = r = 65$m. In heterogeneous scenarios, $R = 115$m, $r = 65$m. Besides, all sensors have the same hop count constraints $\Delta = 15$ or 12. Furthermore, in order to avoid the interference of random factors, 50 simulations are repeated in each case. All simulations are performed on a computer with a 2.20 GHz Intel(R) Core(TM) i5-5200U CPU and Matlab 14.




(a) (b)

**Figure 5.** The number of RNs deployed by C2NP and IC2NP

(a) homogeneous scenarios (b) heterogeneous scenarios

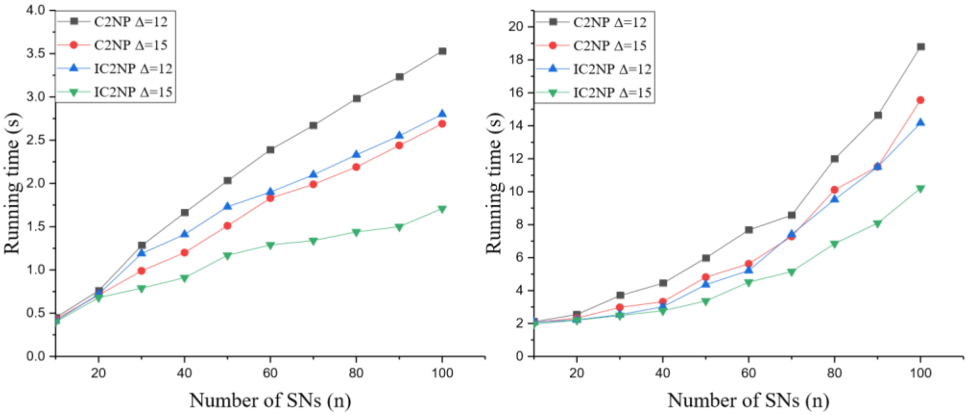
*A. Deployment Cost*

Deployment cost refers to the number of deployed RNs. As the only existing work solving the DCRNP problem and employing the similar methods, the C2NP is used comparatively here [12]. In Figure 5, CDLs are fixed to 400. At the beginning, as the number of SNs increases, the number of deployed RNs also increases, but when the number of SNs reaches a certain level, the number of RNs required decreased rapidly due to the sensors' participation in data forwarding. Besides, it is seen that the less the hop count constraint, the more the number of RNs required, but the influence of communication distance is the opposite. Overall, simulations in both homogeneous scenarios and heterogeneous scenarios show that the deployed RNs by IC2NP are less than that of C2NP in most comparisons.

*B. Running Time*

The simulation results of running time are shown in Figure 6. In general, as the scale of deployment increases, the running time of the algorithm shows an approximate linear growth trend. Comparing the two algorithms, the time required for IC2NP is obviously less than that for C2NP. In Figure 6(a), the maximum time saving point is at SN=100, Δ=15, the saving rate reaches $\frac{(2.7-1.7)}{2.7}\approx$58%. In Figure 6(b), the maximum time saving point is at SN=100,

Δ=15, the saving rate reaches $\frac{(15.6-10.2)}{15.6}\approx$34%. As the number of CDLs increases, IC2NP saves more time. The performance difference is mainly due to the fact that in the process of detecting whether there is a path intersection, the father node supplement algorithm requires fewer cycles than the C2NP.



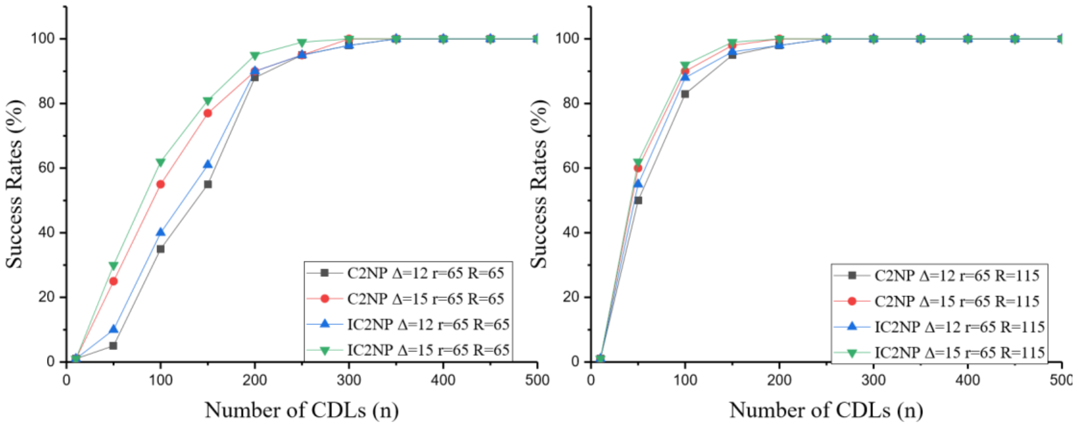

(a) (b)

**Figure 6.** The running time of C2NP and IC2NP (a) CDL=400 (b) CDL=1000

*C. Success Rate*

Figure 7 shows the success rate of the algorithms in different scenarios. With the increase in the number of CDLs, the deployment success rate has increased significantly. When the CDLs reaches 350 or 250, respectively, in homogeneous scenarios, seeing Figure 7(a), or in heterogeneous scenarios, seeing Figure 7(b), the success rate is close to 100%.

This is because as the number of CDLs increases, the number of alternative routes used for communication also increases. The success rate will increase accordingly. Similarly, when the communication radius of the route increases, the number of routes covered by each route will increase, and the success rate will increase accordingly. Contrasting between the two algorithms, in either case, the success rate of IC2NP is higher than that of C2NP.




(a) (b)

Figure 7. The success rate of C2NP and IC2NP (a) homogeneous scenarios

(b) heterogeneous scenarios

Finally, based on the simulations results, the proposed IC2NP algorithm is proven to feasible and effective and compared with the best existing method, it has a slight progress in three key indicators of saving deployment costs, reducing running time and increasing deployment success rate.

## V. CONCLUSION

In this paper, we have studied the 2-connected DCRNP problem in wireless sensor network. A polynomial-time algorithm-IC2NP is proposed to build at least two node-disjoint paths meeting the hop constraint between each SNs and the sink. Whenever IC2NP finds a feasible solution, the time complexity of IC2NP is proven to be $O(N^4)$ and the approximation ratio is guaranteed to be $O(\ln n)$. Extensive simulations have been carried out to compare with the best existing method, C2NP, and the results show that the proposed IC2NP method can always make improvement in three key indicators of saving deployment costs, reducing running time and increasing deployment success rate. In future, the exploration of new heuristic methods to RNP problems facing multi constraints in rechargeable wireless sensor network will be our new direction.

## REFERENCES

M. Raza, N. Aslam, H. Le-Minh, S. Hussain, Y. Cao, and N. M. Khan, "A Critical Analysis of Research Potential, Challenges, and Future Directives in Industrial Wireless Sensor Networks," IEEE Communications Surveys and Tutorials, Article vol. 20, no. 1, pp. 39-95, 2018.

N. Lu, N. Cheng, N. Zhang, X.M. Shen, and J. W. Mark, "Connected Vehicles: Solutions and Challenges," IEEE Internet of Things Journal, Review vol. 1, no. 4, pp. 289-299, Aug 2014.

J. Lin, W. Yu, N. Zhang, X. Y. Yang, H. L. Zhang, and W. Zhao, "A Survey on Internet of Things: Architecture, Enabling Technologies, Security and Privacy, and Applications," IEEE Internet of Things Journal, Article vol. 4, no. 5, pp. 1125-1142, Oct 2017.

X. M. Li, D. Li, J. F. Wan, A. V. Vasilakos, C. F. Lai, and S. Y. Wang, "A review of industrial wireless networks in the context of Industry 4.0," Wireless Networks, Review vol. 23, no. 1, pp. 23-41, Jan 2017.

H. Zhang, H. Xing, J. Cheng, A. Nallanathan, and V. Leung, "Secure resource allocation for OFDMA two-way relay wireless sensor networks without and with cooperative jamming," IEEE Trans. Ind. Informat., vol. 12, no. 5, pp. 1714–1725, Oct. 2017.

K. Wang, Y. Wang, Y. Sun, S. Guo, and J. Wu, "Green industrial internet of things architecture: An energy-efficient perspective" IEEE Commun. Mag., vol. 54, no. 12, pp. 48–54, Dec. 2016

Z. Ning, X. Wang, X. Kong, and W. Hou, "A social-aware group formation framework for information diffusion in narrowband internet of things," IEEE Internet Things J., vol. 5, no. 3, pp. 1527–1538, Jun. 2018.

D.J. Yang, S. Misra, X. Fang, G.L. Xue, and J. S. Zhang, "Two-Tiered constrained relay node placement in wireless sensor networks: Computational complexity and efficient approximations," IEEE Trans. MobileComput., vol. 11, no. 8, pp. 1399–1411, Aug. 2012.

V. C. Gungor and G. P. Hancke, "Industrial wireless sensor networks: Challenges, design principles, and technical approaches," IEEE Trans.Ind. Electron., vol. 56, no. 10, pp. 4258– 4265, Oct. 2009.

A.A. Kumer S., K. Øvsthus, and L.M. Kristensen, "An industrial perspective on wireless sensor networks—A survey of requirements, protocols and challeges," IEEE Commun. Survey Tuts., vol. 16, no. 3, pp. 1391–1412, Jan. 2014.

L. Gouveia, "Multicommodity flflow models for spanning trees with hop constraints," Eur. J. Oper. Res., vol. 95, no. 1, pp. 178–190, Nov. 1996.

Chaofan M, Wei L, Meng Z, et al. Relay Node Placement in Wireless Sensor Networks with Respect to Delay and Reliability Requirements[J]. IEEE Systems Journal, 2018:1-12.

Lin G, Xue G (1999) Steiner Tree Problem with Minimum Number of Steiner Points and Bounded Edge-length. Inf Process Lett69(2):53–57

Chen D, Du DZ, Hu XD, Lin G, Wang L, Xue G (2000) Approximations for Steiner Trees with Mnimum Number of Steiner Points.J Glob Optim 18(3):17–33

Cheng XZ, Du DZ, Wang LS, Xu BG (2007) Relay Sensor Placement in Wireless Sensor Networks. Wirel Netw 14(3):347–355

Lloyd E, Xue G (2007) Relay Node Placement in Wireless Sensor Networks. IEEE Trans Comput 56(1):134–138

S. Misra, S. Hong, G. Xue, and J. Tang, "Constrained relay node placement in wireless sensor networks to meet connectivity and survivability requirement," in Proc. IEEE INFOCOM, 2008, pp. 879–887.

S. Misra, S. Hong, G. Xue, and J. Tang, "Constrained relay node placement in wireless sensor networks: Formulation and approximations," IEEE/ACM Trans. Netw., vol. 18, no. 2, pp. 434–447, Apr. 2010.

Yang DJ, Misra S, Fang X, Xue GL, Zhang JS (2012) Two-Tiered Constrained Relay Node Placement in Wireless Sensor Networks: Computational Complexity and Efficient Approximations. IEEE Trans Mobile Comput 11(8):1399–1411

A. Chelli, M. Bagaa, D. Djenouri, I. Balasingham, and T. Taleb, "One-Step Approach for Two-Tiered Constrained Relay Node Placement in Wireless Sensor Networks," IEEE Wireless Communications Letters, vol. 5, no. 4, pp. 448-451, 2016.

C. Ma, W. Liang, M. Zheng, and H. Sharif, "A connectivity-aware approximation algorithm for relay node placement in wireless sensor networks," IEEE Sensors J., vol. 16, no. 2, pp. 515–528, Jan. 2016.

A. Bhattacaya and A. Kumar, "Delay constrained optimal relay placement for planned wireless sensor networks," in Proc. IEEE 18th Int. Workshop Quality Service, 2010, pp. 1–9. [23] A. Bhattacharya and A. Kumar, "A shortest path tree based algorithm for relay placement in a wireless sensor network and its performance analysis," Comput. Netw., vol. 71, no. 4, pp. 48–62, 2014.

A. Nigam and Y.K. Agarwal, "Optimal relay node placement in delay constrained wireless sensor network design," Eur. J. Oper. Res., vol. 233, no. 1, pp. 220–233, 2014. [25] L. Sitanayah, K.N. Brown, and C.J.

Sreenan, “A fault-tolerant relay placement algorithm for ensuring k vertex-disjoint shortest paths in wire less sensor networks,” Ad Hoc Netw., vol. 23, no. 2014, pp. 145–162, 2014.

Wang WL, Liou BH, Solomon A. 2-Connected relay placement problem in wireless sensor networks[C]// Second International Conference on Digital Information & Communication Technology & Its Applications. IEEE, 2012.

Hwang S F, Chao W L, Wu C L, et al. 2-Connected Relay Node Placement Scheme in Disjoint Wireless Sensor Networks[C]// 2014 IEEE 5th International Conference on Software Engineering and Service Science. 0.

S. Rajagopalan and V. Vazirani, “Primal-Dual RNC approximation algorithms for set cover and covering integer programs” SIAM J. Comput. vol. 28, pp. 525–540, 1998. T.H. Cormen, C. E. Leiserson, R.L. Rivest, and C. Stein, Introduction to Algorithm.

Cambridge, MA, USA: The MIT Press, 2009, pp. 1117–1122.