IOSR Journal of Computer Engineering (IOSR-JCE)
e-ISSN: 2278-0661,p-ISSN: 2278-8727, Volume 26, Issue 2, Ser. 1 (Mar. – Apr. 2024), PP 53-62
www.iosrjournals.org

An Optimal Solution To The Relay Node Placement Problem In Wireless Sensor Networks

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Abstract:
Prolonging the lifetime of the wireless sensor networks (WSNs) is one of the important issues for the design of WSNs. One of the feasible approaches to prolong the lifetime of a WSN is to install relay nodes between sensors and the base stations. Relay nodes are usually designed to have more energy and better communication capability. Therefore, they are used to gather the information from the normal sensor nodes and forward the aggregated data to the base stations. The relay node placement problem is to study how to install the least number of relay nodes in a WSN such that each regular sensor in the network is within the communication range of at least one relay node. Although to find the optimal solution of the relay node placement problem has been proved to be an NP-Complete problem, it is still worth to find efficient algorithms to solve the problem while the number of sensor nodes is not too large. However, until now there are very few papers seriously studied how to obtain the optimal solutions to the problem. In this paper, we propose an efficient algorithm to obtain the optimal solution to the relay node placement problem by using 0/1 integer linear programming and give the solutions when the number of sensor nodes in a WSN is less than 200. For the case of large number of sensor nodes, we use a heuristic algorithm to get the approximation solution to the problem. Finally, we compare the performance of our proposed optimal algorithm and the heuristic algorithm to other well-known algorithms of the relay node placement problem.

Key Words*: Wireless sensor networks; Relay node placement; 0/1 integer linear programming.*

Date of Submission: 06-03-2024 Date of Acceptance: 16-03-2024

I. Introduction

Wireless sensor network (WSN) has gained worldwide attention in recent years. A WSN consists of spatially distributed autonomous sensors to cooperatively monitor a deployed region for its physical or environmental conditions, such as temperature, sound, vibration, pressure, motion, and pollutants.

Due to the recent advance of Micro-Electro- Mechanical Systems (MEMS) technology, the manufacturing of small and low-cost sensors has become technically and economically feasible. A sensor node can sense, measure, and gather information from the environment and, based on some local decision process, it can transmit the sensed data to the sink (or base station) via a wireless medium [1].

Since the transmission power of a wireless radio is proportional to distance squared or even higher order in the presence of obstacles, multi-hop routing will be usually considered for sending collected data to the sink instead of direct communication.

One of the main challenges in WSN is the limited power of the nodes. Sensor nodes have limited, generally irreplaceable power sources. There are many researches in the literature emphasis on how to save the energy expenditure. One of the effective approaches is to install relay nodes in the wireless sensor networks. Relay nodes usually have more energy resource and are with better communication capability. As a result they are usually much more expensive than the normal sensor nodes. Relay nodes are usually used to gather the information from their nearby sensor nodes, and then forward the aggregated data to the base stations. In order to save the cost of a WSN, it is important to install as less number of relay nodes as possible while the coverage of sensor field is preserved. In the paper, we propose an algorithm to install the least number of relay nodes, and for the case of large number of sensor nodes in the WSN, we derive a heuristic algorithm to obtain an approximation solution to the problem.

The rest of the paper is organized as follows. The related works of relay node placement algorithms of WSNs are reviewed in section II. Our proposed relay node placement algorithms are presented in section III. In section VI, we simulate our proposed optimal algorithm and heuristic algorithm, and evaluate their performance. In the last section we conclude the paper.

II. Related Work

In the realm of Wireless Sensor Networks (WSNs), innovative relay node placement strategies are crucial for enhancing connectivity, energy efficiency, and resilience. The Enhancing Connectivity Repairing in WSN with Void Regions (ECRVR) protocol, presented at [2], exemplifies this by using triangular geometry to minimize relay node numbers while effectively bridging network partitions. Similarly, [3] showcased the integration of Novel Improved Communication Steadiness Routing (ICSR) with Relay node Placement using Fermat Point (RPFP), focusing on optimal relay placement for stable, energy-efficient communication paths. ICSR notably surpasses RPFP in energy conservation and path stability, proving the value of strategic relay node positioning.

Further advancing these concepts, the Centralized Fault Tolerant Algorithm from [4] employs mobile nodes as dynamic relays to enhance fault tolerance and maintain network integrity under failure conditions. This approach underscores the adaptability of relay strategies in maintaining continuous network function.

Complementing these strategies, research featured in [5] introduces an obstacle-aware connectivity establishment (OACE) method, leveraging multiple mobile collectors to navigate obstacle-rich environments. This method not only addresses energy dissipation and network partitioning issues but also achieves greater energy efficiency and reduced latency, highlighting the effectiveness of mobile nodes in strategic relay placement.

Together, these studies underscore a collective movement towards sophisticated relay node placement and mobile node utilization in WSNs, aiming for networks that are not only more resilient and energy-efficient but also capable of overcoming complex environmental challenges.

Research interest in relay node placement of a WSN has increased significantly [6,7,8,9,10]. In [8], Tang, Hao, and Sen proposed approximation algorithms (we called them THS algorithms) to solve the relay node placement problem. The main idea of the THS algorithms is to place the relay nodes in the limited number of candidate positions call P-positions. If we consider the communication range as a circle for a sensor node, then the P-positions are the intersection points of the communication range of any two sensors. As shown in Figure 1, any relay node deployed within the intersection area of the communication range of three sensors can move to the P-position without loss its coverage.

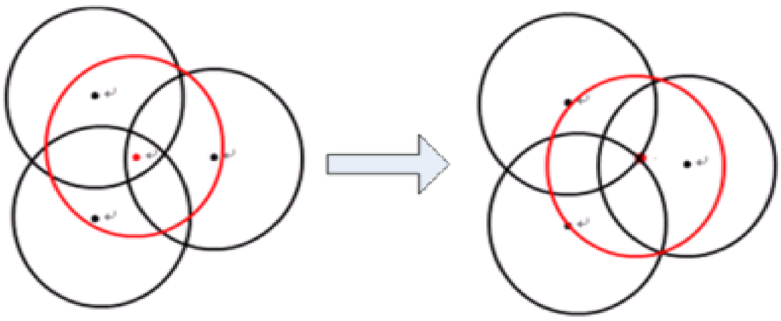

Figure 1. Any relay node (red node) in the intersection area of 3 sensors can move to the P-position without loss its coverage.

In the THS algorithms, they first divide the sensing area into grids such that each square box with length 2r or 4r, where r is the communication range of the sensors. Then, they compute all the P-positions for each square, and try to find the minimum number of possible relay nodes placing at the P-positions that can cover all the sensor nodes in the square. Finally, combine the solutions obtained in each square and thus get the whole solution of the problem.

In [6], the authors improve the THS algorithm by dividing the sensing area into grids with length $\sqrt{2}$ r. Instead of placing the relay node at the P-position, the authors place the relay nodes at the center of each grid. Figure 2 shows that we can cover the sensors in a square area of $2\sqrt{2}$ r×$2\sqrt{2}$ r by at most 4 relay nodes.

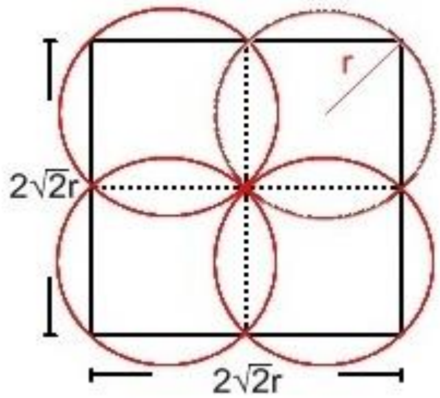

Figure 2. Sensors in the grid can be covered by at most 4 relay nodes.

The improved THS algorithm in [6] further reduce the number of relay nodes by moving relay nodes within each grid instead of placing at the center of the gird.

In [9], Wong, Jafari, and Potkonjak used integer linear programming to acquire the optimal solution to the relay node placement problems while the node density is limited. The authors define CRegions (Competitive Regions) as the overlapping communication ranges of a set of nodes. In each defined region a relay node may be placed which can communicate with the set of nodes defining the region. Therefore, to solve the relay node placement problem becomes to find the minimum number of CRegions that can cover all the sensor nodes. The authors developed two preprocessing steps for the relay placement problem in order to reduce the size and complexity of the ILP formulations. The first preprocessing step is the identification of continuous areas in the network for the placement of relay nodes, i.e., to identify the Cregions. The second preprocessing step is the calculation of the number of communication hops for each node in the network to communicate with each potential region for relay node placement.

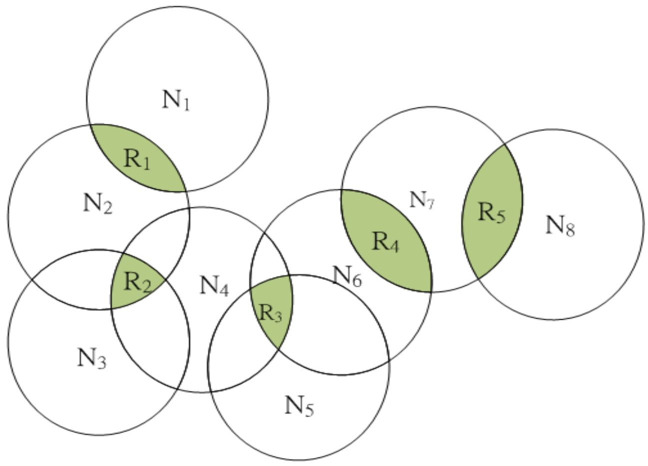

Figure 3. CRegions (R_1-R_5) of 8 nodes(N_1-N_8)

In [10], the authors model the relay node placement problem with the minimum set covering problem. They proposed a deterministic deployment strategy based on a recursive algorithm.

Recent studies have introduced various algorithms and protocols to address these challenges effectively.

One approach [11] introduced a Connectivity-Aware Approximation Algorithm leveraging a local search approximation algorithm (LSAA) to solve the relay node single cover (RNSC) problem, grouping sensor nodes and optimizing relay node placement to save system overhead significantly. This method was extended to address the double cover problem, incorporating a relay location selection algorithm (RLSA) with a minimum spanning tree heuristic for denser high-tier connectivity, substantially reducing the number of newly deployed relay nodes.

Another study [12] focused on fault-tolerance within cyber-physical systems (CPSs) using WSNs, proposing a replicated gateway architecture with energy-efficient, real-time Byzantine-resilient data communication protocols. This included a fault-tolerant trustful space-time protocol at the sensor level and a multigateway synchronization protocol, ByzCast, at the gateway level, improving system robustness and data availability despite potential malicious failures.

Research of [13] on relay node placement considering capacity limitations proposed an algorithm for a two-tiered WSN model. This algorithm optimizes the deployment of relay nodes to minimize energy consumption by constructing an optimum spanning tree, followed by a greedy strategy to remove surplus nodes while adhering to communication capacity limitations.

Lastly, in [14] an Approximation Algorithm for Relay Node Placement in single-tiered WSNs was explored, using Delaunay Triangle and Voronoi Graph for constructing neighbor components, optimizing placement with Spanning tree and Steiner heuristic. This resulted in an efficient algorithm that outperforms others in terms of the number of relay nodes and average hop count, showcasing a reasonable time complexity.

These studies [15,16,17,18,19,20] collectively highlight the importance of strategic relay node placement and robust protocols in optimizing WSN performance, demonstrating significant advancements in network design and fault tolerance.

III. Our Proposed Algorithms

In the paper, we use 0/1 Integral Linear Programming to solve the relay node placement problem of WSN. Firstly, we calculate the set of CRegions according the locations of sensor nodes. As the CRegions are the candidate regions for placing the relay nodes, our goal is to find the least number of CRegions to install the relay nodes such that each sensor connects to at least one relay node.

Since a CRegion is the communcation overlapping region of a set of sensor nodes, we can represent the CRigion as the set those sensor ndoes. We illustrate this idea by the following example.

Suppose there are 8 sensor nodes (N_1 to N_8) locate in the sensor field as in Figure 4. By calculate the distances between nodes we can identify the following CRegions:

$S_1=\{N_1,N_2,N_3\}$ $S_2=\{N_1,N_2,N_3,N_4\}$ $S_3=\{N_1,N_2,N_3\}$ $S_4=\{N_2,N_4,N_5\}$
$S_5=\{N_4,N_5,N_6\}$ $S_6=\{N_5,N_6,N_7\}$ $S_7=\{N_6,N_7\}$ $S_8=\{N_8\}$

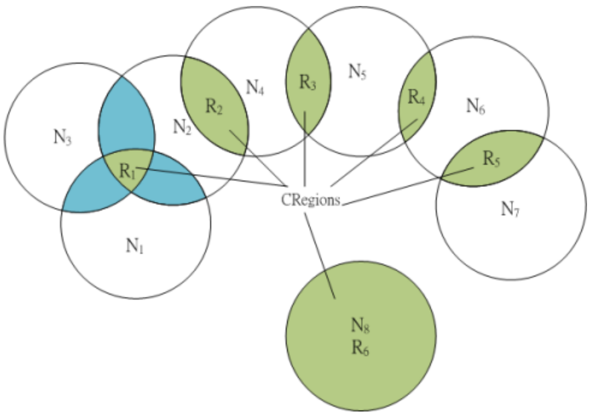

Figure 4. CRegions area

The second step, each sensor node will in turn make the intersection of the set. $S_1 \cap S_2$ was a collection of $\{N_1,N_2,N_3\}$, $S_1 \cap S_3$ was a collection of $\{N_1,N_2,N_3\}$, if the same set to take a representative. $S_1 \cap S_4$ can get set $\{N_2\}$, because we want the sensing range overlap, so we need set at least two nodes. We can be $S_8=\{N_8\}$ known N_8 does not intersect with other sensor nodes. But we still have to give it a relay node in order to return its data. Therefore, N_8 is we need to consider one of the CRegions. Finally available the following collections:

$R_1=\{N_1,N_2,N_3\}$ $R_2=\{N_2,N_4\}$ $R_3=\{N_4,N_5\}$ $R_4=\{N_5,N_6\}$
$R_5=\{N_6,N_7\}$ $R_6=\{N_8\}$

When calculating the collection, we found some exceptions, as shown in Figure 5. Figure 5 shows by the following formula:

$S_1=\{N_1,N_2,N_3\}$ $S_2=\{N_1,N_2,N_3\}$ $S_3=\{N_1,N_2,N_3\}$ $R=\{N_1,N_2,N_3\}$

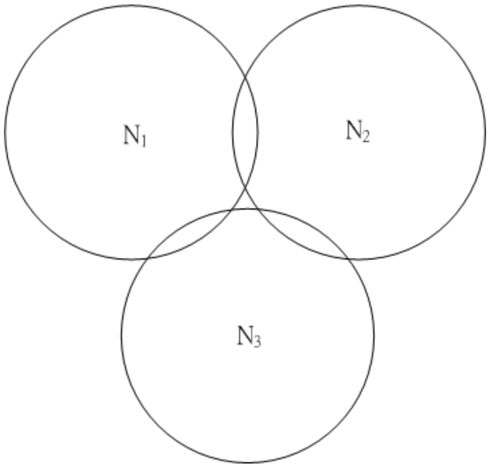

Figure 5. Exceptions(1)

We found that the calculated R does not exist. R is N_1,N_2,N_3 overlap region. To verify the calculated CRegions is correct, we use the method described below to do the verification.

After the count finished CRegions, then we calculate the sensor nodes in each CRegions the circle formed by the intersection. If the CRegions exist, then we can find at least one of these intersections in the intersection (Figure 6 that the red dot) and the CRegions all sensor nodes in the distance is less than or equal to R. That we can place on the relay node at this intersection. This relay node within the communication range R to cover itself among all the sensor nodes. If we can't find these intersections connected to CRegion all the sensor nodes, represents the CRegions wrong. We will delete this CRegions.

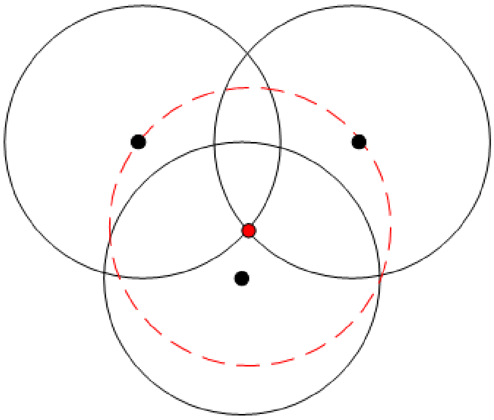

Figure 6. Relay node placement

The second step, before you remove the CRegions, we will have to find someone to replace it with another set. Avoid these sensor nodes have not been calculated.

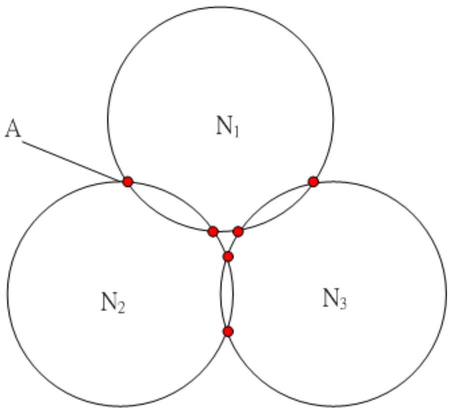

Figure 7. Exceptions(2)

Suppose in Figure 7, calculate the "A" is wrong, so we calculate the radius R of all the sensor nodes within the circle formed by the intersection (the red dot in Figure 7). Then we calculated for each intersection and the distance between each sensor node. If the "intersection" and "sensor nodes" in the distance is less than or equal to R, we will be it as CRegions. Figure 7 A and N_1, N_2, N_3 calculated distances. We can see that point A and N_1, N_2 within the distance R, so I can get the set of point A is the $\{N_1,N_2\}$. After calculating all intersections in sequence, if the set repeats only take a representative. The final set are $\{N_1,N_2\}$ 、$\{N_2,N_3\}$ 、$\{N_1,N_3\}$. These sets can be used to replace the original error CRegions.

When finished CRegions calculation, we can use integer linear programming to calculate what CRegions to place relay nodes.

Figure 4, we get the following formula after calculating CRegions:

$R_1=\{N_1,N_2,N_3\}$ $R_2=\{N_2,N_4\}$ $R_3=\{N_4,N_5\}$ $R4=\{N_5,N_6\}$
$R_5=\{N_6,N_7\}$ $R_6=\{N_8\}$

We use the formula and the third chapter (2), lists 0/1ILP formula:

$$Y=Min(R_1+R_2+R_3+R_4+R_5+R_6)$$

$$A=\begin{bmatrix}1&0&0&0&0&0\\1&1&0&0&0&0\\1&0&0&0&0&0\\0&1&1&0&0&0\\0&0&1&1&0&0\\0&0&0&1&1&0\\0&0&0&0&1&0\\0&0&0&0&0&1\end{bmatrix}\quad R=\begin{bmatrix}R_1\\R_2\\R_3\\R_4\\R_5\\R_6\end{bmatrix}\quad I=\begin{bmatrix}1\\1\\1\\1\\1\\1\\1\\1\end{bmatrix}$$

A matrix of every column represents each sensor node, each line is expressed as CRegions. Element 0-1 indicates whether the sensor nodes connected to the CRegions, there is connected to 1, not connected to the 0. For example: A [1,1] element that is 1, representing sensor nodes N_1 can be linked to CRegions. A [1,2] element that is 0, representing sensor nodes N_1 could not linked to CRegions. In order to determine each sensor node can be connected to at least a CRegions. According to Chapter III (3) to list the $Ax \geq 1$, the final formula to calculate the optimal solution:

$$R_1=1 \text{, } R_2=0 \text{, } R_3=1 \text{, } R_4=0 \text{, } R_5=1 \text{, } R_6=1 \text{。}$$

$R_1=1$ means to place the relay nodes in this region, $R_2=0$ is not placed.

Heuristic algorithm

Because only a few examples of sensor nodes and CRegions, so we can easily calculate the results. However, if the sensor nodes calculate a lot we can't answer simple. We can't find the optimal solution, but we can still use heuristic algorithms to find approximate solutions.

In Heuristic algorithm, we still use CRegions to computing. End of the calculation CRegions, we will sort by size CRegions set. Next we place the relay nodes in the largest set. If the greater CRegions set sensor nodes can be covered more. Then the rest of the set and the largest set difference set, because there is already the largest set of relay nodes. So we do not need to be taken into account, and finally we remove the largest set. We will re-sort the rest of the set, and then repeat the above steps until all of the set have been selected. The following example shows in Figure 13, we get CRegions and sorted as follows:

$R_6=\{N_8\}$ $R_2=\{N_2,N_4\}$ $R_3=\{N_4,N_5\}$ $R_4=\{N_5,N_6\}$
$R_5=\{N_6,N_7\}$ $R_1=\{N_1,N_2,N_3\}$

R_1 is the largest set, so let's choose R_1 relay node placement. Because the $\{N_1,N_2,N_3\}$ relay nodes have been placed, the other set in the $\{N_1,N_2,N_3\}$ we do not need to place. So we will be R_6, R_2, R_3, R_4, R_5, and R_1 do difference set, remove the $R_1$and resorting.

$R_6=\{N_8\}$ $R_2=\{N_4\}$ $R_3=\{N_4,N_5\}$ $R_4=\{N_5,N_6\}$
$R_5=\{N_6,N_7\}$

R_3, R_4, R_5 the set of the same size, choose one of them to place relay nodes. Here, select R_6, R_2, R_3, R_4, R_5, and R_1 do difference set can get the rest of set:

$R_6=\{N_8\}$ $R_2=\{N_4\}$ $R_4=\{N_5\}$ $R_3=\{N_4,N_5\}$

Then R_2, R_4, and R_3 to do differential set so the rest of $R_6=\{N_8\}$.Finally, select R_6 to place relay nodes, R_1, R_3, R_5, R_6 is the area we want to place the relay nodes.

IV. Experimental Results

According to the previous section we proposed the Optimal solution algorithm and Heuristic algorithms were to write code in Matlab. And compare the results under different environments.

Simulation environments:

Area size: 240*240m、480*480m、720*720m

The number of sensor nodes: 200、600、1000

Transmission range of sensor nodes (R)   R=24、30、40 m

Arrangement: random arrangement

We intend to compare Optimal, Heuristic, improving THS, THS and other differences in the algorithms under different environments. First, we compare the density of sensor nodes with lower results. We first placed 200 sensor nodes, and then assume that the sensor node transmission range is R = 24, 30, 40, sensing area size is 240 * 240 meters, 480 meters, 480 *, 720 * 720 meters.

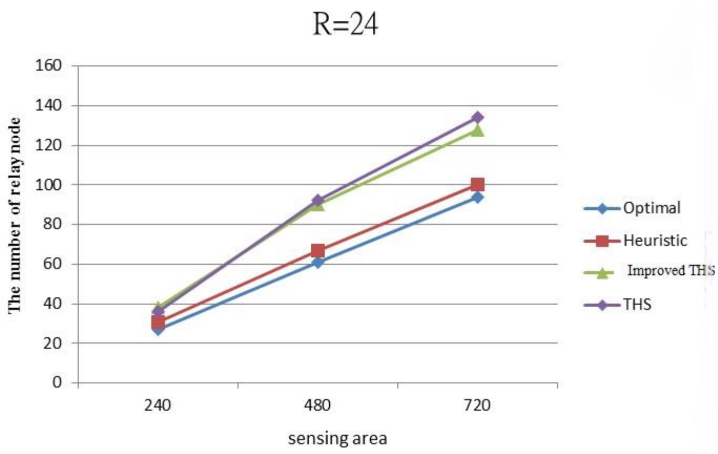

Figure 8. R = 24, number of sensor nodes 200.

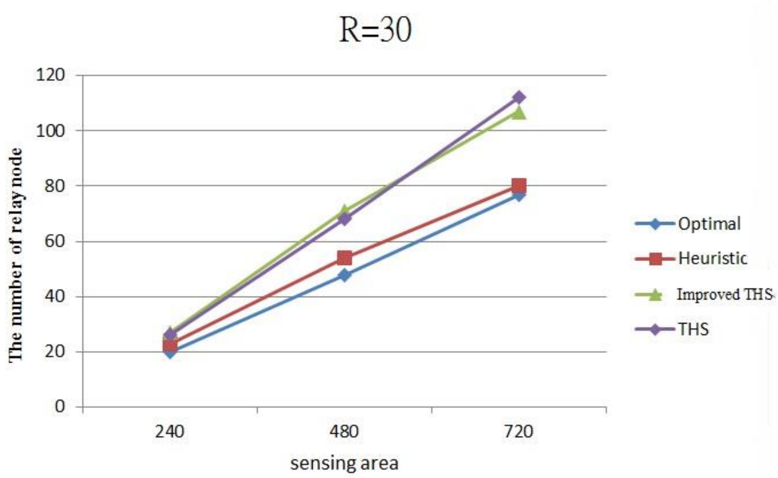

Figure 9. R = 30, number of sensor nodes 200.

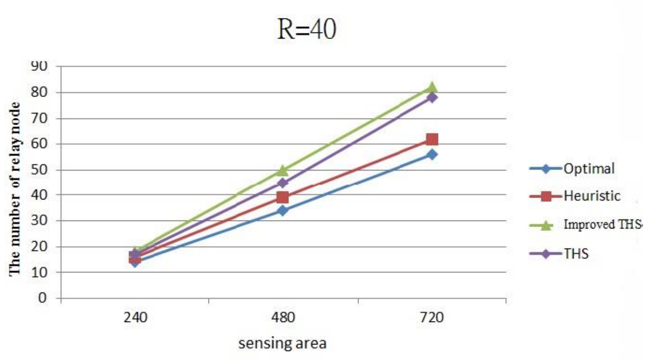

Figure 10. R = 40, number of sensor nodes 200.

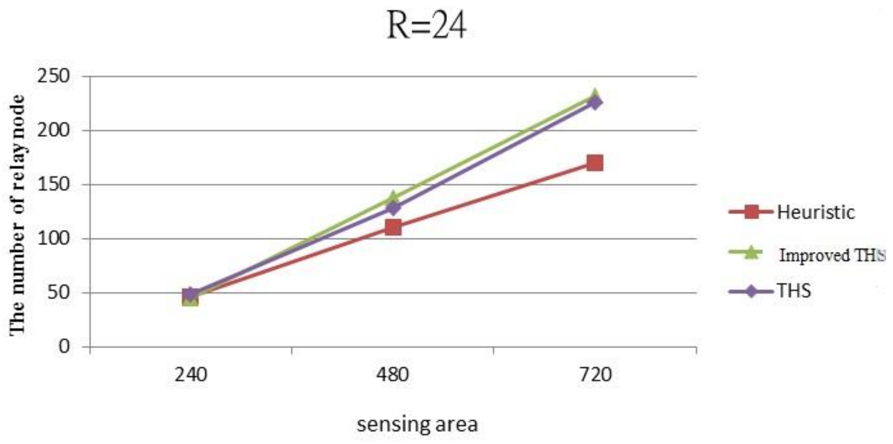

Figure 11. R = 24, number of sensor nodes 600.

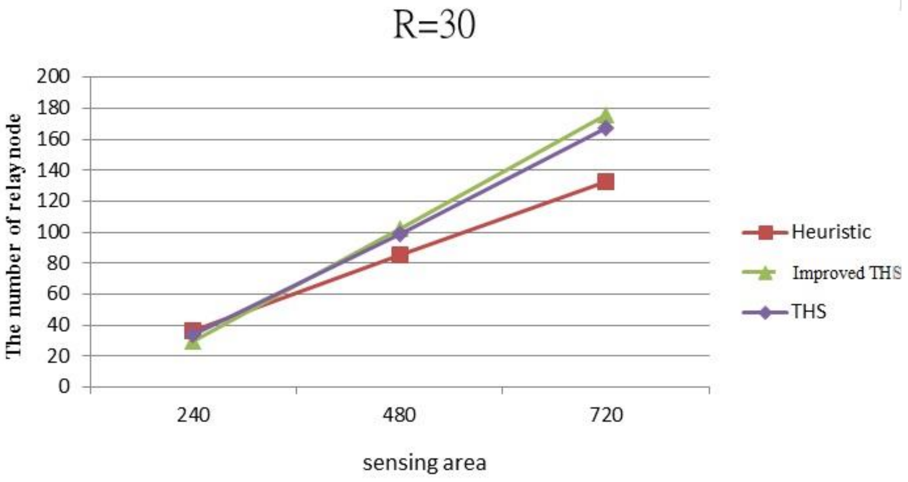

Figure 12. R =30, number of sensor nodes 600.

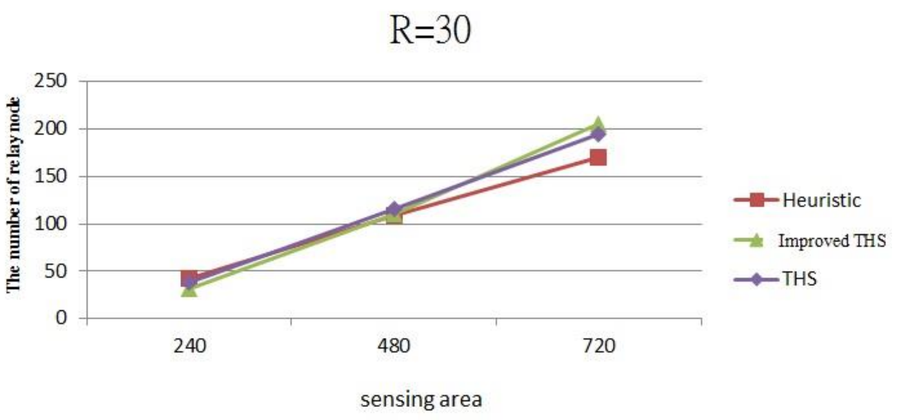

Figure 13. R =30, number of sensor nodes 1000

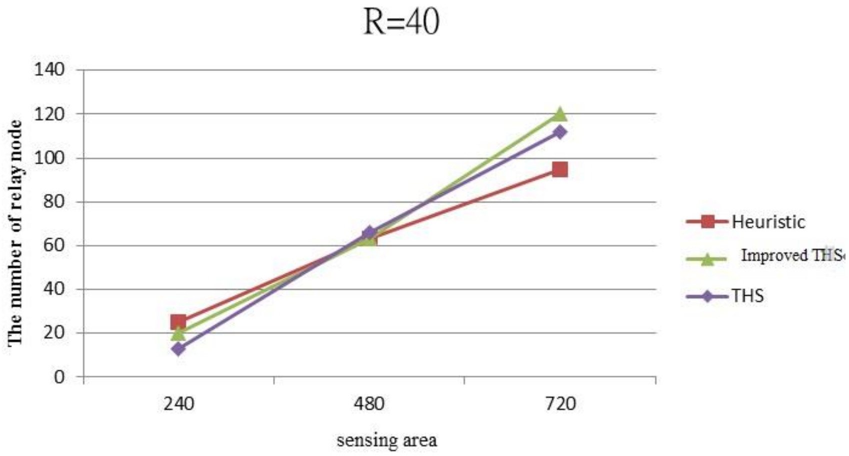

Figure 14. R =40, number of sensor nodes 600

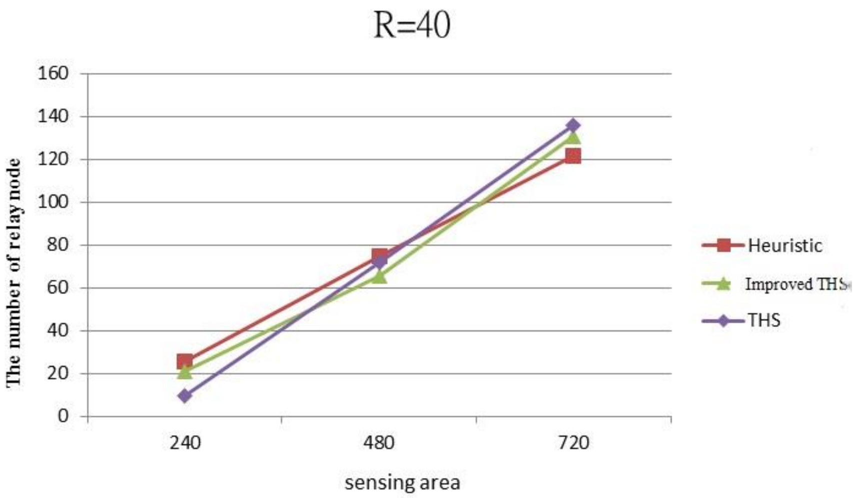

Figure 15. R =0, number of sensor nodes 1000

Figure 8 to Figure 15, we can find Optimal algorithms and Heuristic algorithms can be selected THS algorithm and improved THS algorithm less relay nodes. When the sensor node density is high, our Heuristic algorithm calculated the number of relay nodes and THS algorithms and improved THS algorithm is roughly the same. But we can still calculate the Optimal algorithm less relay nodes. When the larger sensing area and sensing node density is low, our Optimal algorithms and Heuristic algorithms are selected relay node than THS algorithm and improve THS algorithm a lot less.

V. Conclusions And Future Work

In this paper, we are hoping to find the best place to place relay nodes. The ability to relay nodes are usually even better than the sensor nodes. But the relay nodes price is usually more expensive, so if we can reduce the number of nodes can relay arranged relatively lower costs. Therefore, we expect future studies can then reduce the computation time. And operator time and compute the number of relay nodes, which can achieve an optimal balance.

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