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Relay node placement in wireless sensor network for manufacturing industry

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ABSTRACT

Relay nodes are necessary to maintain scalability and increase longevity as the number of manufacturing industrial sensors grows. In a fixed-budget circumstance, however, the cost of purchasing the bare minimum of relay nodes to connect the network may exceed the budget. Although it is hard to establish a network that connects all sensor nodes, in this case, a network with a high level of connection is still desirable. This paper proposes two metrics for determining the connectedness of a disconnected graph of sensor nodes and determining the optimum deployment method for relay nodes in a network with the highest connectedness while staying within a budget restriction. The metrics are the number of connected graph components and the size of the most significant connected graph component. Prim's algorithm and the approximation minimum spanning tree algorithm are applied to construct a disconnected graph and discover the best relay node placement to solve these two criteria. Compared to the other metrics, simulation findings suggest that prioritizing the most significant connected components in the disconnected graph can yield superior outcomes by deploying the fewest number of relay nodes while retaining the connectedness of the graph.

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1. INTRODUCTION

The manufacturing industry is going through progressive changes and is now moving toward smart manufacturing, which has attracted much attention [1], [2]. Many manufacturing companies are now having trouble sustaining communication between sensor nodes while performing activities in the production process. The manufacturing sector has progressively changed from conventional manufacturing systems to smart manufacturing, in which wireless connections and sensors are commonly used, in line with the transition to industry revolution 4.0 (IR4.0) [3]–[5]. Smart manufacturing is a large manufacturing category that uses computer-integrated manufacturing, high degrees of adaptability and frequent shifts in architecture, modern information processing, and more agile preparation for technical human resources. Massive amounts of data have been produced during the production process, along with the permeation and applications of advanced manufacturing technology [6], [7].

The world has undergone a gradual yet steady transition in wireless communication networks, allowing users to experience three important eras–voice digitizing, multimedia and wireless broadband [8]. With an increasing number of smart devices user, demand for higher data rates has steadily risen to satisfy the consumer's need for a faster, safer and smarter network which ultimately contributes to the driving forces toward the future wireless communication network [9]–[11]. The industry expects more spectrum resources to be allocated to the future wireless communications network to accommodate more consumers at higher data rates, reliability, coverage, and lower latency for developing and implementing the future smart manufacturing industry. The future wireless communication network is envisioned as the foundation to ensure steady connectivity, which has a huge potential to benefit the smart manufacturing industry. It embraces various devices and applications such as the internet of things (IoT) [9], [12], augmented reality, artificial intelligence and smart automation that are widely used in the smart manufacturing industry [2], [13]. The latest wireless communication network technology was offered to the public, creating significant electronic gadgets and manufacturing systems changes. When industries start deploying wireless network technology in their locations, many apps will operate more smoothly than previously. The manufacturing process, in particular [13], [14], has seen an improvement in productivity and dependability. Control systems and robot-assisted assembly lines are examples of this type of technology [15], [16].

Wireless sensor network has been studied progressively as an efficient way of achieving smart manufacturing in the industrial world [13], [17]–[25]. The wireless sensor network consists of various low-cost and low-power sensor nodes that use wireless links to perform designated sensing operations and gather information before it is sent to at least one sink of the network. Heterogeneous wireless sensor networks consist of several wireless sensors equipped with various communication and computing capabilities [19]–[24]. In the manufacturing industry, various types of sensors with different transmission rates and radii will be used, resulting in a heterogeneous wireless sensor network [17], [18]. The transmission radius is similar to the deployed relay nodes in a heterogeneous wireless sensor network.

There are several techniques for relay node placement to maintain sensor connectivity [18], [26]–[32], and also the tasks include basic information, different duration, deadline, and payoff. To get the greatest payout, we may apply a mathematical method to calculate the optimal relay node location and number of relay nodes required to accomplish the assignment. Some businesses have many manufacturing lines, and sensors must transfer data from one line to the next to fulfil tasks. Sustaining communication is critical when sensors aid industrial sectors, even if relay node placement is costly. Align with the progress of the industrial revolution, as a tool, 5G technology allows for faster, more reliable, and higher-bandwidth data transmission.

Many research focused on examining relay node placement difficulties by developing a one-tier network model. Each sensor node does not need to communicate directly with a relay node because they may forward packets received from other sensor nodes. Data collected at a sensor node is transmitted to the data collecting point via numerous sensor and relay nodes in a single-tier network. The single-tier network model is the subject of this research, in which a set of sensor nodes has already been deployed, and the aim is to deploy at most a specific number of relay nodes to fulfil a specific goal.

In contrast, sensor nodes may use different transmission radii, introducing asymmetric communication links between nodes loaded with numerous functionalities [18]. A heterogeneous wireless sensor collaborates from a flexible multi-purpose sensor network and enables several sensing activities, including oceanographic data collection [19], emissions monitoring, offshore exploration and tactical monitoring [30]. The concept of IR4.0 is gaining popularity among corporations, and sensors are increasingly being used in the industrial sector. A sensor network with many sensor nodes is usually required to cover a large geographic area. New sensor nodes may be added to the network, and existing sensor nodes can be decommissioned. Scalable protocols and algorithms are necessary for this large-scale, continuously changing network. Battery depletion, harsh weather conditions, and intentional assaults are possible causes of node failure in a wireless sensor network. As a result, the longevity of sensor networks is a major problem. However, most manufacturing industries have a budget allocated for most projects and efforts in maintaining the connectivity of sensors are not excluded [7], [13].

Many manufacturing companies are now having trouble sustaining communication between sensor nodes while performing activities in the production process. Relay nodes are required as the number of sensors in factories grows to maintain scalability and extend lifetime. Latest wireless network technology is being used in businesses to provide optional performance among sensors that conduct autonomous jobs. Most factories have more than hundreds of sensors that work simultaneously. In a manufacturing industry, there will not only be a task to do; there will be thousands of tasks executed simultaneously. However, most factories have allocated a budget for deploying relay nodes to maintain the system working smoothly. If there is even one sensor loss functionality even in a few seconds only, it can give a big loss to the manufacturers. As the deployment of relay nodes involves cost and most manufacturers have already allocated a specific budget for this problem, most industries must discard the idea of having all sensor nodes connected with relay nodes.

This paper presents the importance of relay node placement and its applications in a wireless sensor network for the manufacturing industries. Unlike [7], [13], which consider optimizing the wireless network, we focused on a sensor node environment with the appropriate placement of relay nodes. We investigate the connectivity of the sensor by leveraging the prim's algorithm presented in [22] and the approximation

k-minimum spanning tree (k-MST) algorithm [25]. Our work develops the system model based on a wireless network cluster environment, subject to budget constraints conditions for the manufacturing industries. We evaluate the performance of the proposed algorithm in terms of optimal relay node placement and investigate the impact of the number of relay nodes deployed to achieve maximum connectedness of sensor nodes in the deployment area. The simulation result shows that minimum relay node placement to achieve maximum connectedness of sensor nodes in the deployment area, which indicates that the manufacturer under budget constraints will have to spend a lesser budget and achieve better connectedness between sensor nodes when applying a suitable relay node placement technique in the manufacturing industry.

2. SYSTEM MODEL

Let P is set of sensor nodes $P = \{P_1, P_2, \ldots, P_n\}$ where n is the total number of sensor nodes. Let B define as the total relay nodes that can be deployed in deployment area which indicates the maximum transmission radius of nodes to communicate neighboring nodes. Consider p, q are two points in euclidean n-space, and p_i, q_i is its Euclidean vectors, such that $E = E(p_i, q_i)$ is the edges in between nodes. The number and position of sensor nodes need to be known as it will be needed to calculate the Euclidean distance between point p and q, can be written as:

$$l(p_i, q_i) = \sqrt{\sum_{i=1}^{n} (q_i - p_i)^2} \quad (1)$$

Let R is the communication range of sensor nodes. From (1), the length of edges is established to obtain the weight of edges denoted by $w(E(p_i, q_i))$ for all sensor nodes, are determined by:

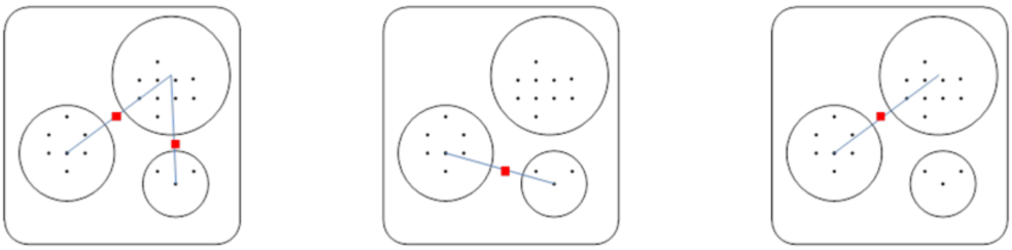
$$w(E) = \frac{l(p_i, q_i)}{R} - 1 \quad (2)$$

the objective function aims to find the best placement of the relay node by finding the intersection point between the remaining edges and the circumference of the node circle with R as the transmission radius.

Two notions can measure connectedness for a disconnected graph. The notions introduced are described as follows:

a. Metric I: the number of connected components of the graphs. To measure the effectiveness of this notion, the indicator of a high degree of connectedness will be the lower number of connected components in the disconnected graph. In this study, we presented metric II, which uses prim's algorithm to measure this metric.
b. Metric II: the size of the largest connected component of the graph. The high degree of connectedness indicator will be the target size of the largest connected components in a disconnected graph. In order to measure this metric, we presented algorithm 3, which uses the approximation k-MST algorithm.

In order to visualize these metrics, we represent this in a wireless network cluster environment. Also, include relay node deployment involving certain budget constraints. There are three clusters of sensor nodes, as shown in Figure 1, where there are ten, seven, and three sensor nodes in three respective clusters. Suppose there is a scenario where there is no budget constraint. The optimal solution for delaying relay nodes will be illustrated in Figure 1(a). However, when there is a budget constraint where only one relay node is allowed to be deployed, Figure 1(b) is the best solution that can fit metric I but not metric II. This scenario is fulfilled metric I as two clusters are connected, which can only be achieved by deploying one relay node. However, it does not fulfil the metric II as the largest cluster is not connected. Thus, as shown in Figure 1(c) is the optimal solution that can achieve metric II and metric I simultaneously.



(a) (b) (c)

Figure 1. Visualization of metrics to measure connectedness in disconnected graph for (a) optimal solution if no budget constraint, (b) solution of metric I but not metric II, and (c) solution of both metrics

3. RELAY NODES ALGORITHM

In this section the proposed heuristic solution for the relay node placement is introduced. Firstly, we must obtain the initial graph of sensor nodes, graph G. We need to know the number of sensor nodes present in the graph and their location. Based on this, the weight of edges is determined. In order to determine the weight, the Euclidian distance obtained first will be determined by using the concept of ceiling function. This function always rounds a number up to the next largest integer. Then, the weight of edges is based on (2). Let A is the relay node that needs to be deployed. The location of A is in the disconnected graph of sensor nodes and its edges, denoted by $G = (P, E)$. Here, every edge is observed to determine the need for a relay node in between the sensor. For simplicity of notation, we denote this set of edges as $E(i, j)$. To fulfil this, if the length of the edge is more than the communication range, R, the number of relay nodes needed will be equal to the total weight of all edges in the disconnected graph, and if the length of edges is lesser or equal than communication range, then no relay node is needed. Before deploying the relay node, the highest weighted nodes are removed until the disconnected graph is achieved. It will provide the best route with the smallest weight for the graph as shown in Figure 2.

For example, in Figure 2(a), the high weighted edges that are being removed are $E(1,5)$, $E(2,3)$, $E(2,4)$ and $E(4,5)$, producing a disconnected graph as in Figure 2(b). To determine position A, assuming only $E(1,3)$ is the only edge that needs a relay node, a circle with a radius same as communication is drawn on one of the nodes from edges that need to deploy relay nodes. In this case, radius of R is drawn. To find the best placement of relay nodes between the sensor nodes, the intersection points of a circle of every vertex with R as the radius and the edges will be the placement of the relay node, which point A in an augmented graph as illustrated in Figure 2(c). As the final product, graph G' with relay nodes is produced as presented in Figure 2(d).

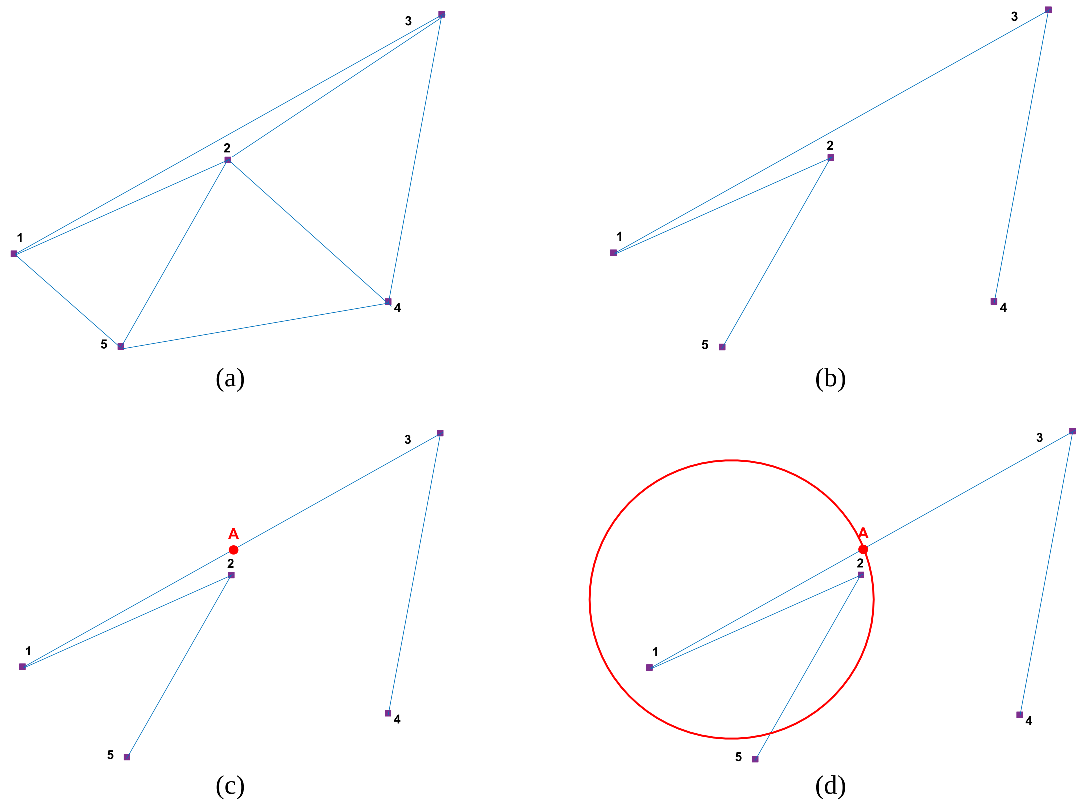


Figure 2. Example of (a) initial (b) disconnected (c) augmented and (d) final graph for metric solution

3.1. Heuristic solution for metric I

The Heuristic solution for the first metric, referred as metric I, is based on the MST problem. We replicate the algorithm presented in [23] to solve this problem, shown in Figure 3(a). As the first step, a graph with sensor nodes with a weight of edges. The weight of the edges is determined based on (2). This weight is represented as the total number of relay nodes needed in order to establish communication between two nodes at two ends of the edge. With this information, a MST graph is produced. To find the best route for this disconnected graph, G, prim's algorithm is used.

As for the following phase of this method, we must note that if the length of the edge is less than R, no relay node is required. If the length of the edges exceeds R, the number of relay nodes required is equal to the weight of the edges between the two nodes. Then, we must ensure that the number of relay nodes required is sufficient. If the total weight of the edges is less than B, the number of relay nodes required will be the solution's direct output. However, if the overall weight of the edges exceeds B, we must remove more edges until the total weight of the edges falls within the budget, B. By performing this procedure, each edge removal increases the number of linked components by one.

3.2. Heuristic solution for metric II

In order to solve the second metric, we presented a solution based on a k-MST problem. We replicate the algorithm presented in [19], to solve this problem where an undirected graph, G, is produced with a set of sensor nodes, P and edges of the graph, E. We introduced an integer, k, in this metric. It will be utilized to discover the lowest-cost tree in G that covers at least k vertices. In this problem, k-MST with decreasing value of k starting k is equal to total number of sensor nodes, n. Once k-MST is obtained, the number of relay nodes required to connect k-MST is computed using the technique established in Figure 3(b). Suppose the total number of relay nodes needed does not exceed the budget. In that case, the procedure is terminated, and the resultant graph G' is the final output. Otherwise, it recalculates k-MST by decreasing k by one until the number of relay nodes is within the budget.

Heuristic solution for metric I

Create an MST (Graph G) of set of sensor nodes, P
Assign each edge, E a weight for $w(E)$. Compute (2).
while total weight of edges $w(E) > B$, **do**
    Remove the edges that has maximum weight of edges.
end while
Return resulting graph obtained from G.

(a)

Heuristic solution for metric II

for $k \in$ n to 2, **do**
    Create an MST (Graph **G**) of set of sensor nodes, P
    Assign each edge, E a weight for $w(E)$. Compute (2).
    if total weight of edges $w(e) \leq B$, **then**
        Return G' as the solution of metric II.
    end if
end for
Return any arbitrary nodes as solution.

(b)

Figure 3. Heuristic solution for (a) metric I and (b) metric II

4. RESULTS AND DISCUSSION

In this section, we present the result of our simulation evaluations for both algorithms. The simulation result for one of the data sets with several sensor nodes, $n = 5$ is presented in Figure 4. The graph produced, and the information that has been gathered for this data set will be needed in order to execute all algorithms.

As the first step has been conducted, we execute with a circle radius equal to R. The augmented graph with simulation settings is presented in Figure 4. It can be seen that to establish communication between all sensor nodes. Three relay nodes are needed, and each weighted edge needs only one relay node. First, the complete graph on all sensor nodes which in this simulation, $n = 5$ with the weight of edges as shown in Figure 3. Then, we compute that the MST is at $R = 5$. The forest connection in between the nodes is determined by using prim's algorithm. The forest connection for this solution and the optimal solution executed have a slight difference due to the usage of the algorithm in determining the forest connection is different. The augmented graph for metric II based on graph G is shown in Figure 5(a). The budget for this simulation is set as $B = 5$. The result shows that graph G only needs one relay node in $E(1,3)$. With that, the budget constraint is not violated. However, there are some cases where the deployment of sensor nodes is in a poor coverage area. This budget constraint might be violated. In most cases, this is because the length of edges is too long, and the number of relay nodes needed might exceed the budget allocated.

Figure 5(a) shows the entire network of all sensor nodes, with $n = 5$ in this experiment, using the k-MST. As a result, we find that MST is at most five times R. To calculate the forest connection between nodes, the approximation k-MST algorithm is used. Forest connection between this solution and the ideal solution obtained by utilizing method 1 differs by a very small amount. For this reason, multiple algorithms are employed to determine the connections for the forest. The augmented graph for metric II based on graph G in Figure 4, is shown in Figure 5(b). This graph G only requires one relay node in $E(1,3)$, with $B = 5$. Budget constraints are not breached in this manner. However, there are some cases where the deployment of sensor nodes is at a poor coverage area, and this budget constraint might be violated. In most cases, this is because the length of edges is too long, and the number of relay nodes needed might exceed the budget allocated.

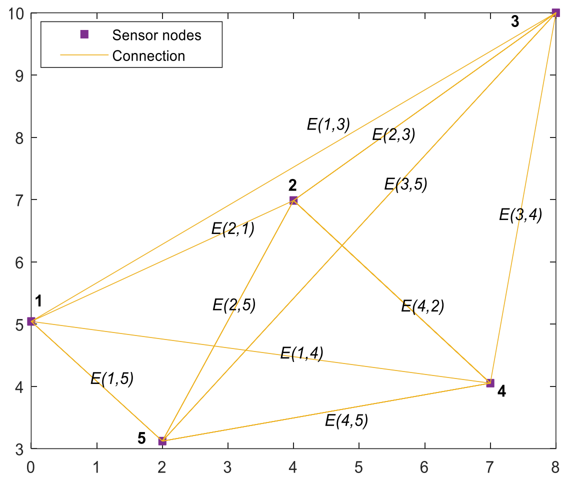
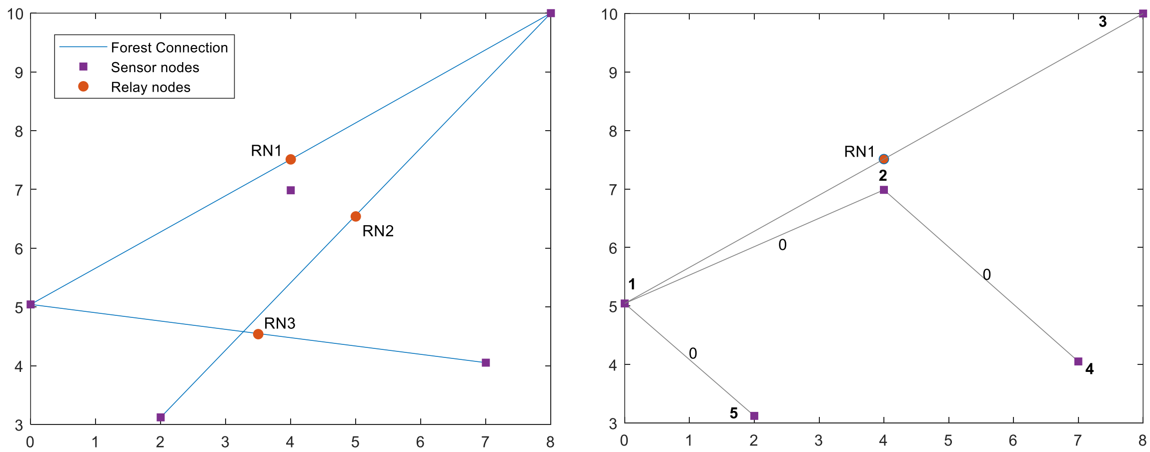


Figure 4. Initial graph that consists of sensor nodes

In order to compute MST, we use prim's algorithm for metric I and *k*-MST for metric II. To present the performance of the heuristic method, we first obtain the optimal solution of relay node placement for the given data set. Whereas the approximate solution for these metrics is obtained by executing both algorithms. There are two experiment evaluations conducted to analyse the performance for both metrics: the ratio of heuristic to optimal for metric I and metric II and the performance of relay node placement in terms of the number of relay nodes needed.



(a) (b)

Figure 5. Augmented graph that consists of (a) sensor nodes and relay nodes and (b) best placement

Figure 6(a) shows the ratio between heuristic and optimal solution for metric I and metric II for 10 data sets. In this analysis, we created 10 data sets by placing the sensor nodes at specific locations in deployment area. This is to ease in obtaining optimal solution for every data set for specific budget. In each data dets there are 10 sensor nodes will be deployed and fixed communication range and budget. For all data sets, the communication range, R is set to 5 and the maximum number of relay nodes that can be deployed, B is set to 5. The size of deployment area is set 10×10. It can be observed that the ratio between heuristic to optimal is always lower than 1 for metric II whereas for metric I, the ratio was as large as 1.7. There's no doubt that the execution of *k*-MST for metric I may suffer from inadequate sensor node placement. This project's major goal is to decrease the number of relay nodes deployed in the deployment region, and it appears that metric II performs better than metric I in this regard.

Figure 6(b) shows the performance of relay node placement with various sensor nodes for metric I and metric II. In this analysis also, we created 10 data sets by placing the sensor nodes at specific locations in the deployment area. This approach is to ease obtaining optimal solutions for every data set for a specific budget. Ten sensor nodes will be deployed with a fixed communication range and budget in each data set. For all data sets, the communication range, R, is set to 5, and the maximum number of relay nodes deployed, B is set to 5. The size of the deployment area is set to 10x10. metric II uses a lesser number of relay nodes compared to metric I. This condition is because of the nature of metric I. It will try to connect as many components as possible without having any priority. Unlike metric II, it will focus on connecting largest components. By this information, it is shown that metric II performs better to achieve the objective of the study, which is to have minimum relay node placement in order to achieve maximum connectedness of sensor nodes in deployment area.

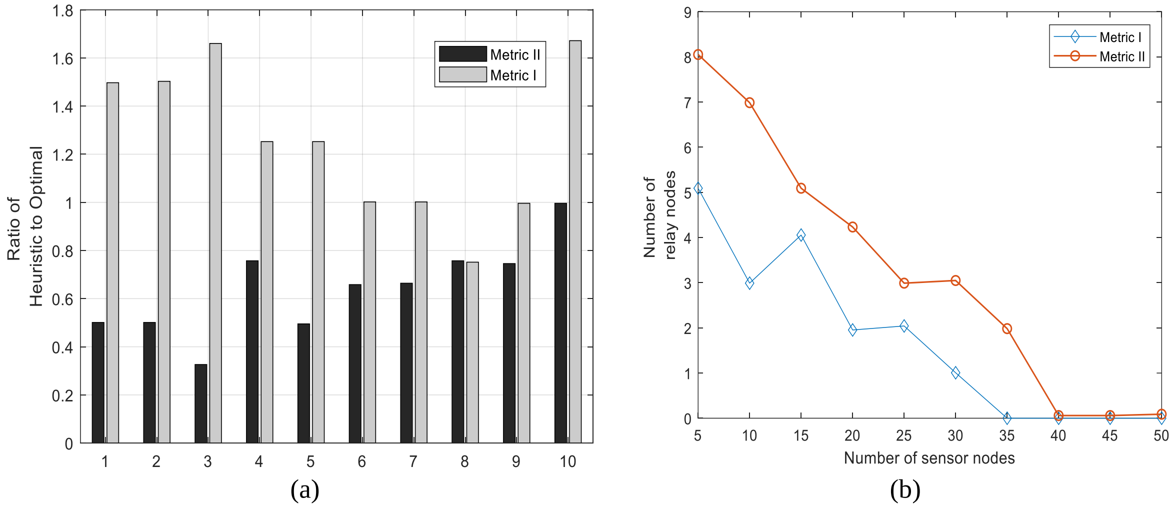


Figure 6. Performance for metric I and metric II (a) ratio of heuristic to optimal and (b) relay nodes placement

5. CONCLUSION

Most manufacturing firms have a budget for each project, and maintaining connections also demands a budget. In keeping prices down, most manufacturers must forego the idea of connecting all sensors to relay nodes due to budget concerns. This paper used two measurements to assess the components' interconnectedness. The goal is to locate the best relay node site to improve connection while deploying as few relay nodes as possible. Executing these algorithms may aid them in developing the most acceptable heuristic ways for locating the optimal relay node placement. Then, the performance of these two metrics was compared with the ideal solution. The comparative performance of the two measures shows that metric II outperforms metric I in reducing the number of relay nodes deployed. The comparison was represented in two ways; the first is a heuristic to optimum ratio bigger than one for metric I and less than one for metric II. In some cases, metric I can reach 1.7, indicating inadequate performance in deploying relay nodes to maintain connectivity. On the other hand, metric II is the heuristic to ideal ratio, which is always less than one, suggesting that the relay node required will always be less than the optimal option. Next, as the number of sensor nodes required increases, the number of relay nodes necessary for metric I is always greater than for metric II. As a result, it may be concluded that metric II outperforms metric I in terms of attaining the study's purpose. Thus, when using a suitable relay node placement approach in the industry or workplace under budget limits, the maker will have to spend less money and gain better connectivity between sensor nodes.

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