國立交通大學

電機學院 IC 設計產業研發碩士班

碩 士 論 文

無線感測網路中繼節點佈建方法之研發-以室內環境為例

Development of a Relay Node Deployment Method for Disconnected Wireless Sensor Networks: Applied in Indoor Environments

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摘 要

中繼節點佈建方法乃是用較少量的中繼節點佈建於適當的位置以增進無線感測網路的通訊品質。由於無線感測網路的感測節點廣泛的應用在各個領域，為了讓節點間達成無線通訊的行為，必須在不相連的節點中有效的佈建中繼節點，因此如何有效地佈置中繼節點是個困難且耗費時間的問題。本論文係以二維幾何搜尋演算法為基礎並採用無線電傳播效應之網路拓撲評估模式，提出一種嶄新的無線感測網路中繼節點佈建方法，其特性分別為逐一計算每個候選中繼節點連接至其所有鄰近節點的數量，並根據鄰近節點的連接數，選擇一個擁有最多鄰近節點的候選中繼節點而佈建；以及藉由精確評估鏈結狀態方法來決定網路拓撲型態。模擬的結果指出本研究所提出之佈置中繼節點方法與相關文獻所提之佈建方法相比，本方法大幅降低中繼節點的佈建數量，其中在網路節點密度為 1/250 節點數/平方公尺的條件下，本文所提出之精確評估鏈結狀態方法對中繼節點的佈建數量的改善，降低 30% 的中繼節點之佈建數量；而二維幾何搜尋演算法亦可降低 20% 的中繼節點之佈建數量。

關鍵詞：無線感測網路、佈建、中繼節點

Development of a Relay Node Deployment Method for Disconnected Wireless Sensor Networks: Applied in Indoor Environments

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ABSTRACT

The connectivity of a given static, disconnected wireless sensor network can be improved by deploying additional relay nodes in the network, forming connections between separate clusters of connected nodes. Finding optimal locations to place the relay nodes is a difficult and time-consuming problem. In this research, we propose a heuristic relay node deployment method to provide more efficient relay node deployment comparing to related works. In this method, a two dimension geometric search algorithm is proposed to discover a proper location where adding a single relay node results in connecting as many as possible disconnected node pairs. Besides, in order to devise a practical method, a realistic model for link connectivity estimation and network topology determination is proposed, which takes into account radio propagation effects, including the large-scale path loss, shadow fading, and small-scale fading. Simulation results indicate that the proposed method significantly reduces the number of relay nodes required for repairing disconnected WSNs. There are about 20% of improvements contributed by the proposed two dimension geometric search algorithm, and about 30% of improvements donated by the proposed link connectivity estimation model.

Keyword: wireless sensor network, deployment, relay node

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劉蓓縝

民國 96 年 7 月 新竹

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1. Introduction

A wireless sensor network (WSN) is a wireless network consisting of spatially distributed autonomous devices using sensors to cooperatively monitor physical or environmental conditions, such as temperature, sound, vibration, pressure, motion or pollutants, at different locations [1-2]. These sensor nodes usually consist of a processing unit with limited computational power and limited memory, sensing devices (including specific conditioning circuitry), a wireless communication device (usually radio transceivers or alternatively optical), and a power source usually in the form of a battery [2]. Figure 1-1 depicts general system blocks of a sensor node.

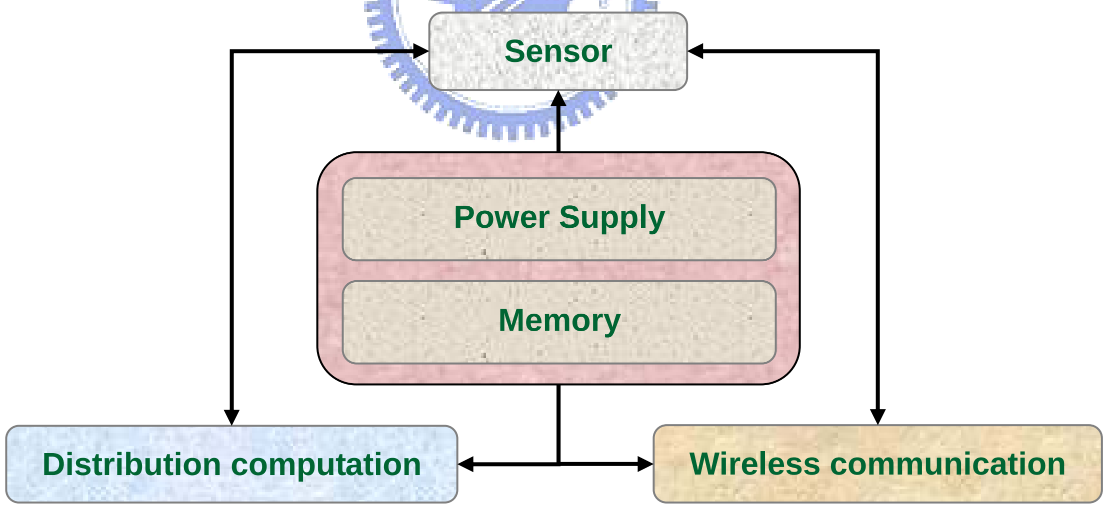


Figure 1-1. The general system blocks of a sensor node.

WSNs aim to achieve high reliability, flexible utilization, cost-effectiveness and ease of deployment. The problem of deployment of a WSN could be formulated generically as follows [3-4]: given a particular application context, and operational region, and a set of wireless sensor nodes, how and where should these nodes be placed? The cost and deployment constraints on sensor nodes result in corresponding wireless communication constraints on resources such as energy, memory, computational speed and bandwidth. Although it is very important to optimize the placement of sensors, it is often difficult to do that [5]. Two major performance metrics when deploying a WSN are considered in the literature: (i) *Network Coverage*, which measures the degree of covered sensing area of a given network, and (ii) *Network Connectivity*, which determines whether the network topology over which information routing can take place [6-10]. By considering network coverage, a rich number of works could be found in literatures. In [11], the authors provide a way to compute the minimum number of sensors needed for guaranteed coverage, and then deploy that number of sensors randomly in the target area. Some works focus on κ-coverage [12-15], or even differentiated coverage deployment [16] whereby higher degrees of coverage result in better localization accuracy and there is more tolerance of false activation of sensors.

By considering network connectivity, most research effects have been concentrated on either analyzing the asymptotic connectivity of large-scale WSNs [7, 9, 17] or devising topology control protocols to maintain connectivity in the presence of limited mobility [18]. In [7], Gupta and Kumar show that the critical common range r_n for connectivity of n randomly distributed wireless nodes in a disk of unit area satisfies that, if $\pi r_n^2 = (\log n + c(n))/n$, the network is asymptotically connected almost surely if $\lim_{n\to\infty} c(n) = \infty$ and is disconnected asymptotically almost surely if $\lim_{n\to\infty} c(n) = -\infty$. This result also implied by the work of Penrose [17] on the longest edge of the minimal spanning tree of a random graph. That M_n, the length of the longest edge in the minimum spanning tree of n points uniformly distributed in a unit square area, satisfies that $\lim_{n\to\infty} \Pr(n\pi M_n^2 - \ln n \le \alpha) = e^{-e^{-\alpha}}$. The relationship between connectivity and node degree studied [9] from another angle by Xue and Kumar. They assumed the same number of nearest neighbors are maintained for each node, and showed that (i) the network is asymptotically disconnected with probability 1 as n increases, if each node is connected to less than $0.074\log n$ nearest neighbors; and (ii) the network is asymptotically connected with probability 1 as n increases, if each node is connected to more than $5.1774\log n$ nearest neighbors. Further studied [10] the critical number of neighbors for κ-connectivity and found the upper bound to be $\alpha e\log n$, where $\alpha > 1$ is a real number and $e \approx 2.718$ is the natural base.

WSNs are by nature constructed automatically, by the nodes connecting to the neighboring nodes and building up a network. In this context, the network topology is random, and in particular, no connectivity is guaranteed: the nodes may be so sparsely located that they are unable to make up a connected network. Besides, given that the connectivity of a WSN is susceptible to node mobility, node failure, and unpredictable environment influences, it is important to continuously maintain connectivity under all these unfavorable conditions. This has motivated the research with primary interest in the connectivity improvement by deploying relay nodes for a given disconnected network.

To the best of our knowledge, little attention has been paid to improving network connectivity or repairing disconnected network by deploying additional nodes. Besides, most of existing works utilize a deterministic physical model, the Unit Disk Graph model [6], for representing network connectivity, which ignores signal attenuation and fading effects of wireless communications. In order to properly estimate network connectivity, more realistic models such as probabilistic graph model [6, 19] are need.

2. Problem Definition and Related Works

2.1 Problem Definition

We consider the problem of deploying additional relay nodes to improve the connectivity of an existing WSN. Specifically, given a disconnected WSN, we investigate how to deploy as few as possible additional relay nodes to connect all existing nodes. Here we define the investigating problem as *Relay Node Deployment* problem in WSNs. Let the initial network topology be represented by an undirected simple geometric graph $G = (V, E)$ in a Euclidean plane R^2, where $V = \{v_1, v_2, \ldots, v_n\}$ is the set of initial sensor nodes. E is the set of links and is defined by $E = \{(a, b) : I(a, b) > \lambda, a, b \in V\}$, where $I(a, b)$ denotes the estimated probability that a message is correctly transmitted from node a to node b, and λ is a threshold value for determining whether the node pair (a, b) is connected. We would like to find a set of relay nodes $U = \{u_1, u_2, \ldots, u_k\}$ with the minimum cardinality, such that the augmented graph $G^* = (V^*, E^*) = (V \cup U, E^*)$ is connected, where E^* is the set of links in the augmented graph G^* and is defined by $E^* = \{(a, b) : I(a, b) > \lambda, a, b \in V^*\}$. Nodes in V and U are termed as initial sensor nodes and relay nodes, respectively.

The proposed relay node deployment method for solving above problem has several applications in practice. For example, telemetry applications such as automated water meter reading [20] can utilize associated sensor network technologies to construct data communication channels between meters and access points and service center. Due to the fixed locations of the meters' sensors, the initial sensor nodes may not form a connected network. The node deployment method is used to construct a connected WSN for data collection and data dissemination. Besides, a WSN may partitioned if some sensor nodes cease to function due to battery depletion or system failures, and an effective solution to the above problem can be used to restore the affected network. The node deployment method may also provide a solution of the problem where many small community wireless mesh networks are integrated to form a metropolitan-scale mesh network [21]. Again, it would be most cost effective to deploy as few relay nodes as possible for this purpose.

2.2 Related Works

2.2.1 MST-based relay node deployment method

Using Minimum Spanning Tree (MST) [22] to solve the *Relay Node Deployment* problem provides a baseline heuristic solution. Given a connected, undirected graph, a spanning tree of that graph is a subgraph (called cluster) which is a tree and connects all the vertices together. A single graph can have many different spanning trees. We can also assign distance length as a weight to each edge, which is a number representing how unfavorable it is, and use this to assign a weight to a spanning tree by computing the sum of the weights of the edges in that spanning tree. A MST, T is then a spanning tree with weight less than or equal to the weight of every other spanning tree.

A straightforward solution is to first group the initial nodes into connected clusters that communication range is r, and then add relay nodes to merge the clusters. This can be implemented using the MST. We first build the tree, T, of the node set V. Then for each edge $e \in T$ that is not in E (or equivalently, $|e| > r$), we add some relay nodes along e to connect the two terminal nodes. In particular, the number of the relay nodes added to connect an edge e is $\left\lceil \frac{|e|}{r} \right\rceil - 1$.

It is obvious that the resulting augmented network is connected. The description of the MST-based relay node deployment method is given in Figure 2-1, where x_u and y_u are the coordinates of a relay node u.

Procedure: MST-based $(\boldsymbol{G}, \boldsymbol{r})$

Input: $\boldsymbol{G}(\boldsymbol{V}, \boldsymbol{E})$, a simple graph;

Output: $\boldsymbol{U}$, a set of relay nodes;

begin

$\boldsymbol{U} := \varnothing$;

Let $\boldsymbol{T} := (\boldsymbol{V_T}, \boldsymbol{E_T})$ be the **MST** of $\boldsymbol{G}$;

for each edge $(v_a, v_b) \in \boldsymbol{E_T}$ **do**

  if $(d(v_a, v_b) > r)$ **then**

    $\boldsymbol{L} := \left\lceil \frac{d(v_a, v_b)}{r} \right\rceil$;

    for $i = 1$ to $\boldsymbol{L} - 1$

      $x_p := (1 - i/\boldsymbol{L}) \cdot x_a + i/\boldsymbol{L} \cdot x_b$;

      $y_p := (1 - i/\boldsymbol{L}) \cdot y_a + i/\boldsymbol{L} \cdot y_b$;

      $\boldsymbol{U} := \boldsymbol{U} \cup \{u_p\}$;

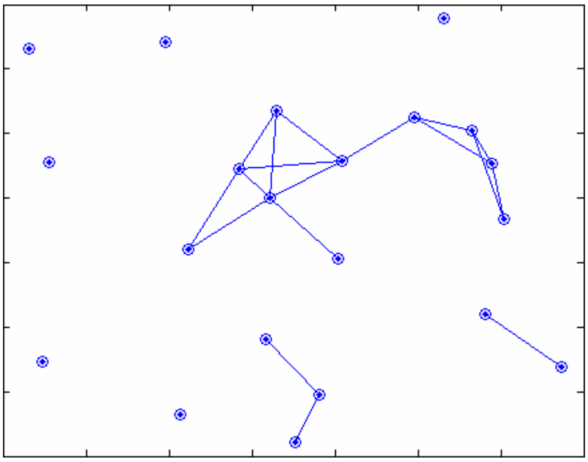
    end

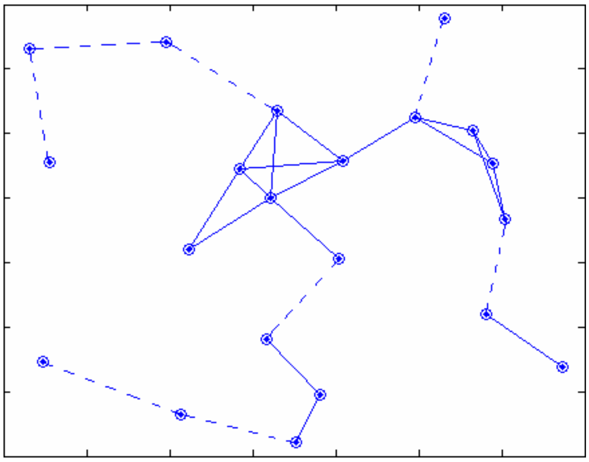
  end

end

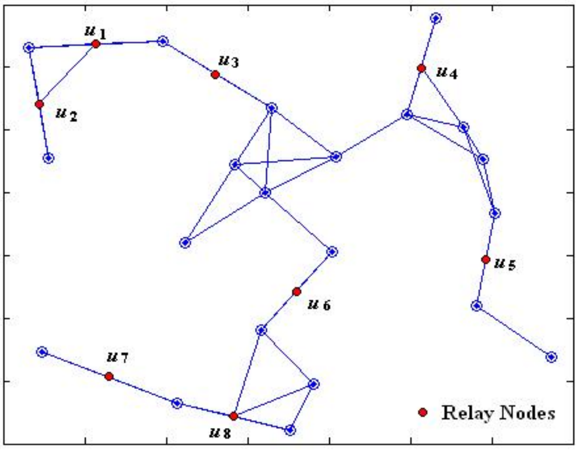
Figure 2-1. MST-based relay node deployment method.

An example is given in Figure 2-2, where the solid lines are used to indicate links in E, and dashed lines are links incident to the positions of the relay nodes. The initial network topology is shown in Figure 2-2(a), used to build the MST (Figure 2-2(b)) of the initial network. In Figure 2-2(c) is deploying the relay nodes in the dashed lines to become the connectivity network topology.



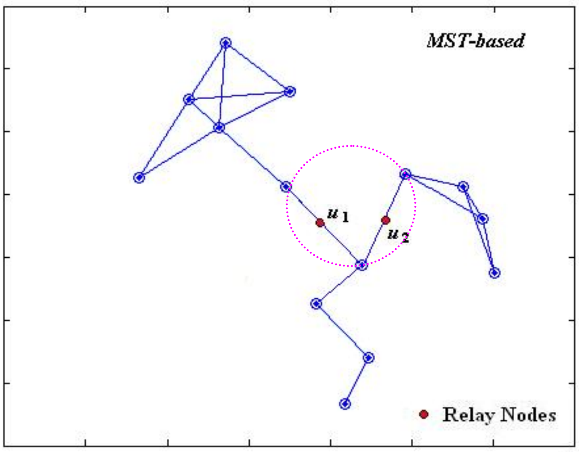


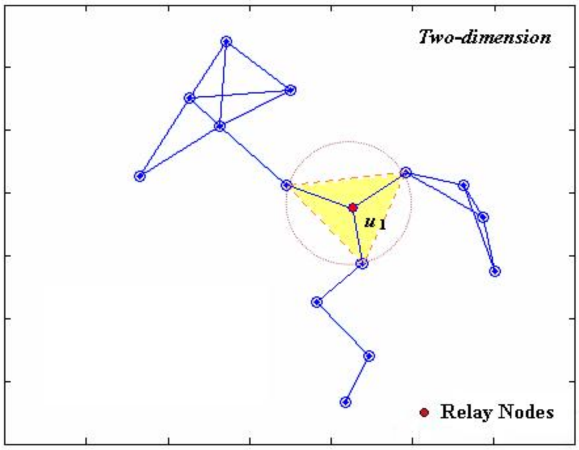
(a) The initial network topology. (b) The MST of the node set V.



(c) The augmented network topology (after adding relay nodes).

Figure 2-2. An example of the MST-based relay node deployment method.





(a) MST-based relay node deployment (b) Two-dimension relay node deployment

Figure 2-3. MST-based relay node deployment method is not optimal.

The time complexity of building the MST varies from $O(e\log n)$ (the original Prim's algorithm [23]) to almost linear of e (the optimal algorithm [24]), where n is the number of vertices and e is the number of edges. The time complexity of the rest of the algorithm is $O(e)$. Therefore, the time complexity of the MST-based method is the same as that of MST. The MST-based method will be used as baseline algorithm for comparison. Its shortcoming is, however, that each relay node can only be used to connect at most two clusters. As shown in Figure 2-3, the MST-based method would have placed 2 relay nodes to connect all three clusters, while in fact one (placed at the position of u_1 in Figure 2-3) is sufficient.

2.2.2 Virtual-Wiring relay node deployment method

The sensor nodes have considered their position predefined and fixed [20]. The transmission or communication range of each node, i.e., the circular range within which the message transmitted could diffuse is known. The nodes are not very powerful in terms of their communication range. The communication range of the node is limited and neighboring nodes in the vicinity alone can send and receive data packets between themselves. Establish the basic terminology, and provide the foundation concepts. The value l_{ij} gives the value of the length of the shortest path distance between v_i and v_j. One could adopt different means to generate these values but we employ matrix calculations so that a unified matrix based computations are used for the whole process.

The first step of the Virtual-Wiring (VW) relay node deployment method is to assess the connectivity of the graph G. If the graph is not a connected graph or rather a forest, then the selected nodes in disjoint components are connected by adding a new link between them to make the whole graph connected. In reality, this is reflected in the sensor network scenario as the process of inserting new sensor nodes so that a new path of communication is resulted. Intuitively the process is explained as follows. The *Network Connectivity Matrix* L is scanned for any ∞ entries. If there are any, it is implied that there are more than one component that are not connected in G.

We consider the distance matrix D along with network connectivity matrix L to prioritize the pair of nodes that are to be connected. The pair with the highest priority is connected first (as explained in the following depiction) and then G is updated (with new nodes and links). The new nodes inserted whose purpose is to join a particular pair may have consequential connections with other neighboring nodes as well. Matrix L is computed again and the connectivity of G is checked again.

To affect that action in the sensor networks scenario, we place as many new relay nodes needed to bridge the distance along the straight line between them, considering the range radius of the fixing nodes. Let us call the first pair of nodes that are to be connected as v_i and v_j, where i and j values are obtained from the value minimum distance $\min(d_{ij})$ such that $l_{ij} = \infty$. By connecting those nodes, we mean to add new relay nodes along the straight line connecting them so that they act as routers.
If we start from sensor node v_a, then we put a new fixing sensor node u_p in the vicinity of the range of v_a along the straight line between v_a and v_b.

Then the position of u_p is defined in Figure 2-4.

$$P(\boldsymbol{u}_p) = (x_p, y_p) \mid x_p, y_p \in \boldsymbol{U}$$

Where x_p and y_p are given by

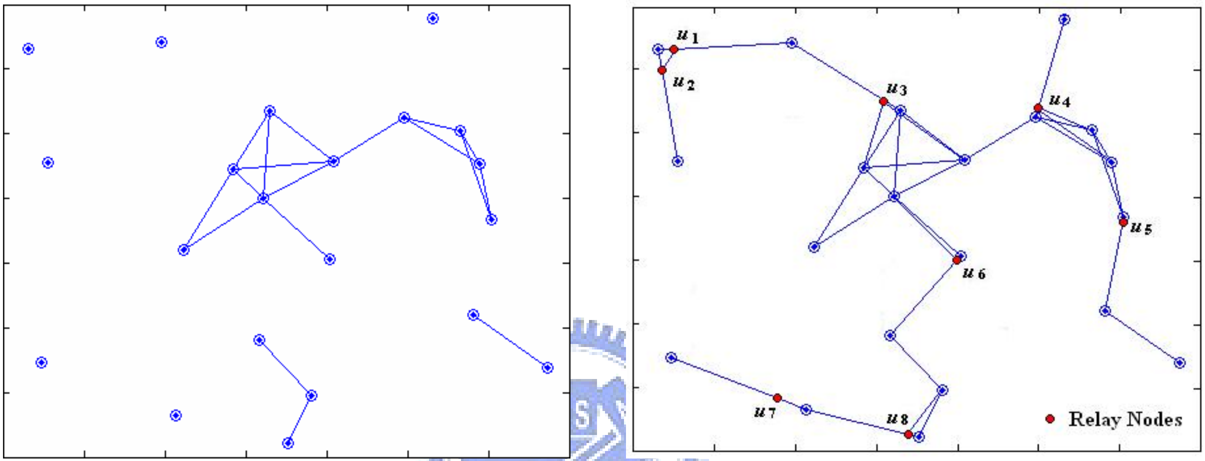
$$x_p = x_a \pm \min(r_a, r_p) \times \cos\theta \quad \text{and} \quad y_p = y_a \pm \min(r_a, r_p) \times \sin\theta$$

($\pm$ Depends on whether $x_a > x_b$ or not) and θ = arc tan(m), where $m = \frac{(y_a - y_b)}{(x_a - x_b)}$

Figure 2-4. VW relay node deployment method.

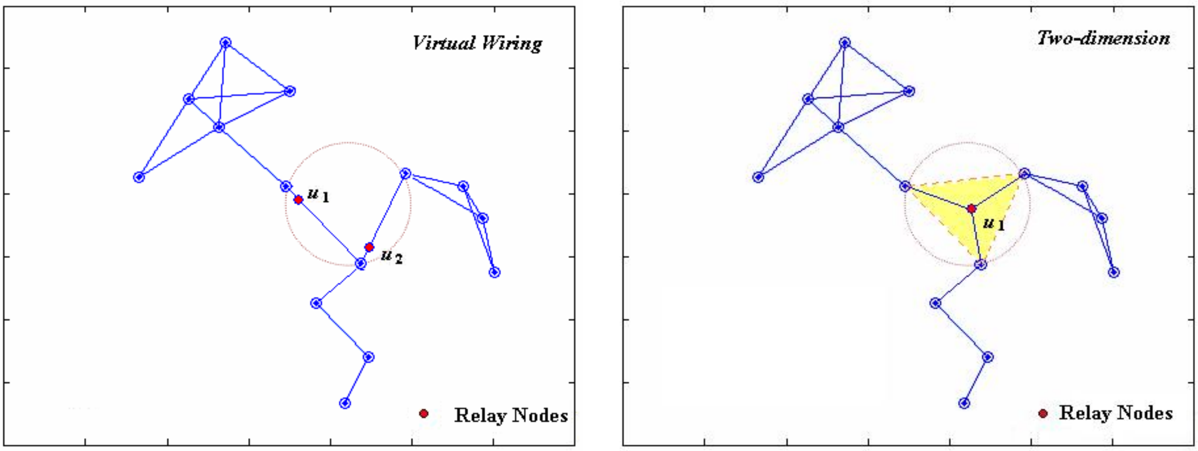
where 'm' is the slope of the straight line that joins the two points (x_a, y_a) and (x_b, y_b).

An example is given in Figure 2-5, where the initial network topology is in Figure 2-5(a), used to place as many new relay nodes needed to bridge the distance along the straight line between them. In Figure 2-5(b) is deploying the relay nodes in the disconnected link of the network connectivity matrix dependence with the minimum distance to become the connectivity network topology. However, VW relay node deployment method has drawback as the same as MST-based method that would have place 2 nodes to connect all three clusters, while in fact one placed at the position of u_1 in Figure 2-6(b) is sufficient.



(a) The initial network topology. (b) The augmented network topology. (after adding relay nodes)

Figure 2-5. An example of the VW relay node deployment method.



(a) VW relay node deployment (b) Two-dimension relay node deployment

Figure 2-6. VW relay node deployment method is not optimal.

A deployment strategy given definitions of two problems: The augmented network is connected by deploying the minimal number of additional relay nodes, and deployed relay nodes possible that the augmented network with maximum node degree. The straightforward solution is to place the relay nodes along the edges of the Euclidean MST calculated for the clusters, when the distance between two clusters is defined as the shortest distance between two terminal nodes in these distinct clusters. This can be seen by considering Kruskal's algorithm for finding the MST [24]. The algorithm is to calculate the Euclidean MST for the initial node set, and place the relay nodes on the edges of the MST that are longer than the transmission rang r.

The extra solution is a simple heuristic method to provide the graph connectivity, Virtual Wiring (VW) [20], that place as many new relay nodes needed to bridge the distance along the straight line between them, considering the range radius of the fixing nodes.

MST-based and VW methods will be used as baseline algorithm for comparison. Its shortcoming is, however, that each relay node can only be used to connect at most two terminal nodes. Not all necessary edges can be spanned, the better selection of edges generally requires going through all possibilities. In those case, we propose the two dimension geometric search algorithm of deploying the few additional relay nodes to improving the connectivity of exiting WSNs.

2.3 Research Objective

We aim to propose an efficient relay node deployment method to connect disconnected WSNs. To reach the purpose of reducing number of relay nodes, we propose a two dimension geometric search algorithm in order to discover a proper location where adding a single relay node results in connecting as many as possible disconnected node pairs in a given WSN. Furthermore, in order to devise a practical method, here we use the probabilistic graph model for the WSNs. This implicitly means that we assume the dominating factor affecting communications to be the path loss of radio signals coupled with radio propagation effects, including shadow fading and small-scale fading. Within this model, the transmission power employed be the sensor nodes (which we assume to be the same for all nodes), the radio propagation model, and the receiving sensitivity at reception for a desired rate of communication are woven into a single parameter, the link connectivity of a node pair, which equals to the probability that a message is correctly received from the source node to the destination node.

3. The Proposed Relay Node Deployment Method

The proposed method is composed of 5 major processes. Firstly, the link connectivity of each node pair is estimated from *Initialization* and *Link Connectivity Estimation* processes. Then, the topology and disconnected node pairs of the initial network are determined in *Network Topology Determination* process. When the network is disconnected, the *Relay Node Deployment* process places a relay node in order to bridge one or more disconnected node pairs each time, where the location of the relay node is chosen from several alternatives that is discovered by *Candidate Relay Nodes Discovery* process. The processing flow repeats until the augmented network is connected. The flowchart of the proposed relay node deployment is given in Figure 3-1. In the following paragraphs, we elaborate on the procedure in the proposed method.

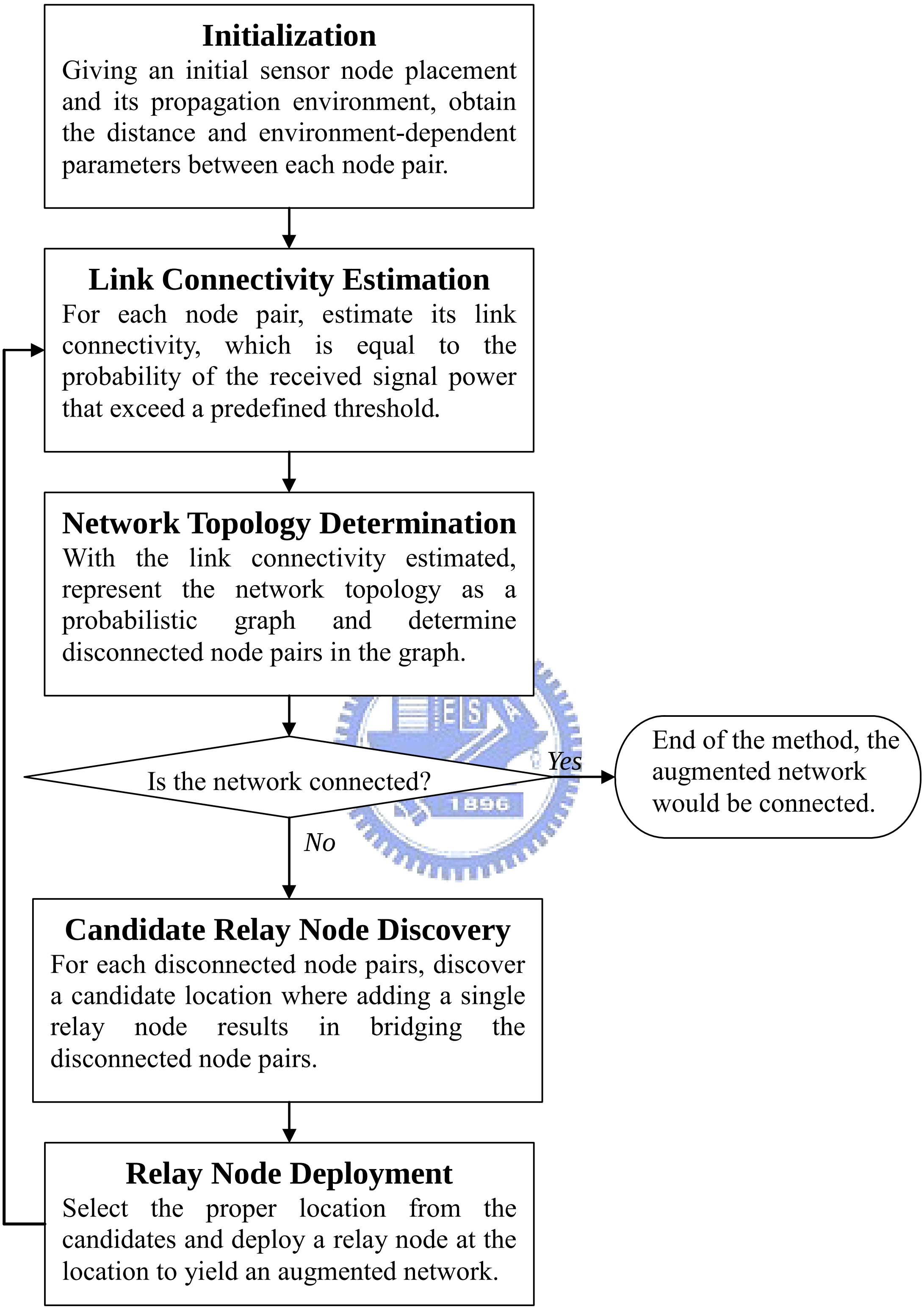


Figure 3-1. Flowchart of the proposed relay node deployment method.

3.1 Link Connectivity Estimation

In order to devise a practical relay node deployment method, a realistic model for link connectivity estimation is proposed [25]. In this model, the link connectivity of the link from node i to node j, $l(i, j) = s_{ij}$, is equal to the probability of the received signal power $P_R(i, j)$ (dBm) which exceed a threshold value δ, the receiving sensitivity of sensor node. Here the link connectivity s_{ij} is given by

$$l(i, j) = s_{ij} = \Pr\{P_R(i, j) > \delta\} = \exp\left(-\frac{\delta}{P_R(i, j)}\right) \tag{1}$$

where $P_R(i, j)$ is represent by a continuous random variable which takes into account radio propagation effects, including the large-scale path loss, shadow fading, and small-scale fading. The $P_R(i, j)$ is given by

$$P_R(i, j) = P_T(i, j) - \left[PL(d_{ij}) + \sum PAF + (R - \overline{R})\right] \tag{2}$$

where

$P_T(i, j)$ denotes the transmitted signal power (dBm) from node i to node j,

$PL(d_{ij})$ represents the large-scale path loss (dB) with propagation distance d_{ij} and is equal to

$$PL(d_{ij}) = PL(d_0) + 10n\log\left(\frac{d_{ij}}{d_0}\right) \tag{3}$$

where

$PL(d_0)$ is the path loss (dB) of reference distance d_0 (m),

n is the path loss exponent,

d_{ij} is propagation distance (m) from node i to node j.

$\sum PAF$ represents the power attenuation (dB) due to shadow fading and is equal to

$$\sum_{t \in T} N_t \cdot PAF_t \qquad (4)$$

where

N_t is the number of obstacles,

PAF_t is the partition loss (dB) of an obstacle.

$R - \overline{R}$ denotes a zero-mean Rayleigh distribution random variable which represents the small-scale fading effects.

It is noted that the path loss exponents *n*, the path loss $PL(d_0)$ of reference distance d_0, and the shadowing fading $\sum PAF$ should be made adaptive to the propagation environment (which is determined in the *Initialization* process in the proposed method). Here we made sufficient field test in the applied environment to derive the environment-dependent parameters. Table 3-1 depicts the obtained value of the parameters from field test at 9th floor of Engineering Building 4, National Chiao Tung University. Then, these parameters are adaptively assigned while deploying the relay nodes.

Table 3-1. The obtained value of the parameters from field test at 9th floor of Engineering Building 4, National Chiao Tung University.

	Channel Parameters	**Value Obtained**
δ	Receiving Sensitivity (dBm)	-89.5
P_T	Transmitter Power (dBm)	-35.5
$PL(d_0)$	Path Loss (d_0) (dB)	15 (avg.)
n	Path Loss Exponent	1.8~3
PAF_P	A plasterboard loss (dB)	5~9
PAF_B	A brick wall loss (dB)	7~15
PAF_C	A concrete block wall loss (dB)	13~17

3.2 Network Topology Determination

Based on the estimated link connectivity of each node pairs, the network topology would be represented by a probabilistic graph. Figure 3-3 depicts an example of the determined network topology. In order to estimate the quality of the determined topology, the best route of each node pair, the multi-hop route with maximum transmission probability, is discovered by using an *All-Pairs Strongest Path Search Algorithm* that modified from known *all-pairs shortest path search algorithm* [26]. The maximum transmission probability w_{ij} of a node pair (i, j) is given by

$$w_{ij} = \max_{\forall p \in P_{ij}} \left\{ \prod_{(a,b) \in p} s_{ab} \right\} \tag{5}$$

where

p is a set of node pairs that forms a multihop route,

P_{ij} the route set formed by all available route with source node a and destination node b.

A network is connected if each node can find a multi-hop route to communicate with any other node in the network. Here we consider the node pair (i, j) as being neighbors if and only if its link connectivity s_{ij} is larger than a threshold value λ. Assuming that the route q_{ij} represents the best route of node pairs (i, j), if there exists a link (c, d) in q_{ij} whose link connectivity $s_{cd} < \lambda$, we define the node pair (i, j) is disconnected node pair and belongs to the disconnected set D. As a result, a network topology with empty set D implies that the whole network is connected. Otherwise, more relay nodes are required in order to bridge disconnected node pairs.

3.3 Candidate Relay Node Discovery

In this process, candidate locations for relay node deployment are discovered. The stricter requirement that a single relay node should, when possible, connect more than one disconnected node pair in D as potential locations of relay node placement. Here a two dimension geometric search algorithm is proposed to find out a proper location for connecting a given disconnected node pair. The search method has the following steps:

step 1. For a given disconnected node pair (i, j) in D, determine all feasible locations of relay node placement for connecting node pair (i, j). These locations form an area $\mathcal{A}$ in the plane.

step 2. Find the location in $\mathcal{A}$ where adding a single relay node results in connecting the largest number of disconnected node pairs in D.

step 3. If there are more than one feasible locations in step 2, select the location where adding a relay node results in connecting the largest number of neighboring nodes.

step 4. If there are more than one feasible locations in step 3, select the location where adding a relay node yields the maximal rms value of link connectivity between the node α and its neighboring nodes.

step 5. The proper location for connecting node pair (i, j) is discovered in step 4 and is regarded as a candidate location for relay node deployment.

Repeating the previous steps for each disconnected node pair in D would results in multiple candidate locations for relay node deployment. Figure 3-2 depicts an example of *Candidate Relay Node Discovery*.

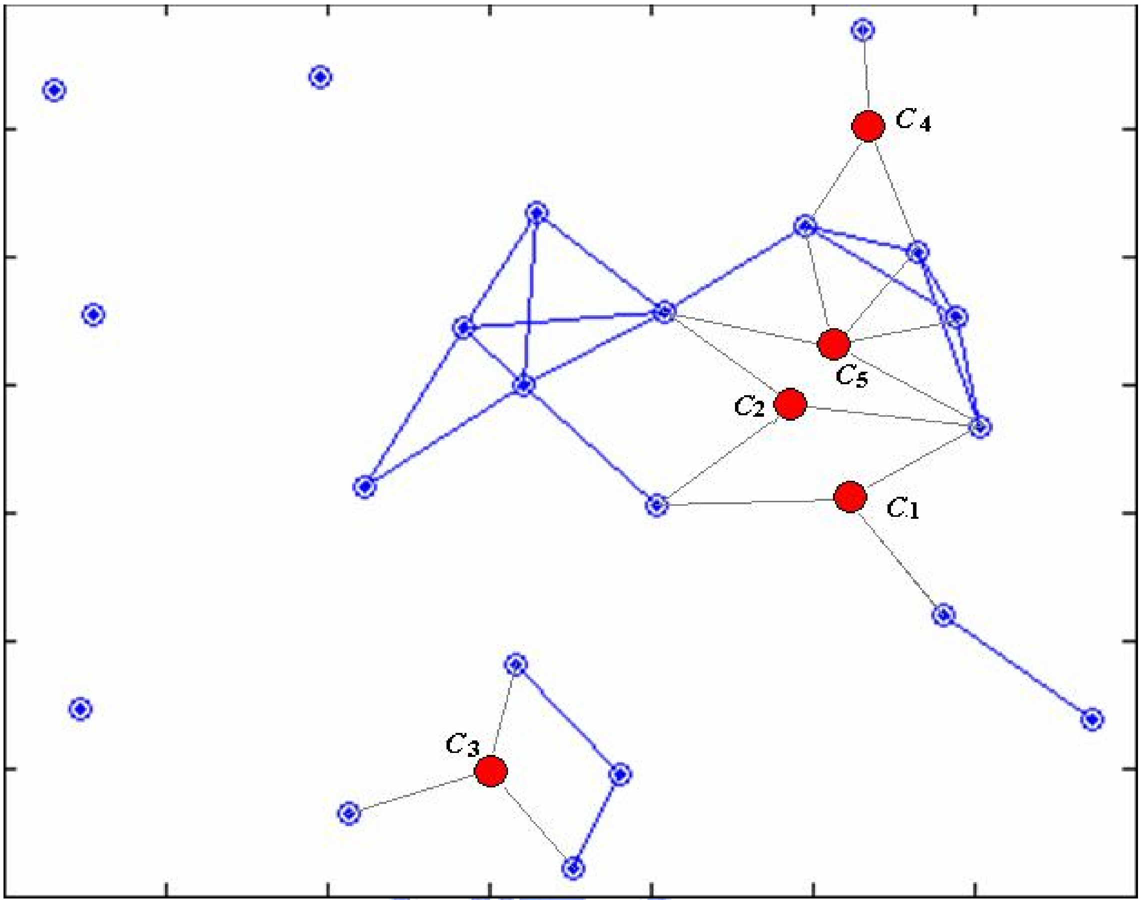


Figure 3-2. An example for the *Candidates Relay Nodes Discovery*.

3.4 Relay Node Deployment

Since only one relay node is deployed in each round of proposed method, the best location for relay node deployment should be selected from candidate locations discovered by previous process. Here we consider similar criteria in *Candidate Relay Node Discovery* process to determine the best candidate:

step 1. Select the candidate location where deploying a single relay node can connect maximal number of disconnected node pairs in D.

step 2. From step 1, if multiple candidates are available, select the candidate location where can be used to connect most number of neighboring nodes.

step 3. From step 2, if multiple candidates are still available, select the candidate location, which yields the maximal rms value of link connectivity between the relay node and its neighboring nodes.

step 4. The proper candidate is selected in step 3. Adding a relay node at the selected location and go back to *Link Connectivity Estimation* process.

Figure 3-3 depicts an example of candidate selection from Figure 3-2. Due to C_1 is the best candidate that can solve three disconnected node pairs in D, it would be select to deploy in the WSN. By repeating the process flow of the method, the connectivity of initial network is improved by deploying additional relay nodes and thereafter the network would be connected. An example of proposed relay node deployment method is given in Figure 3-4, where the initial network topology is the same as that in Figure 2-2(a) and Figure 2-5(a). By examining the example, the proposed method deploys 7 relay nodes for connecting the initial WSN, while both MST-based and VW methods require 8 relay nodes.

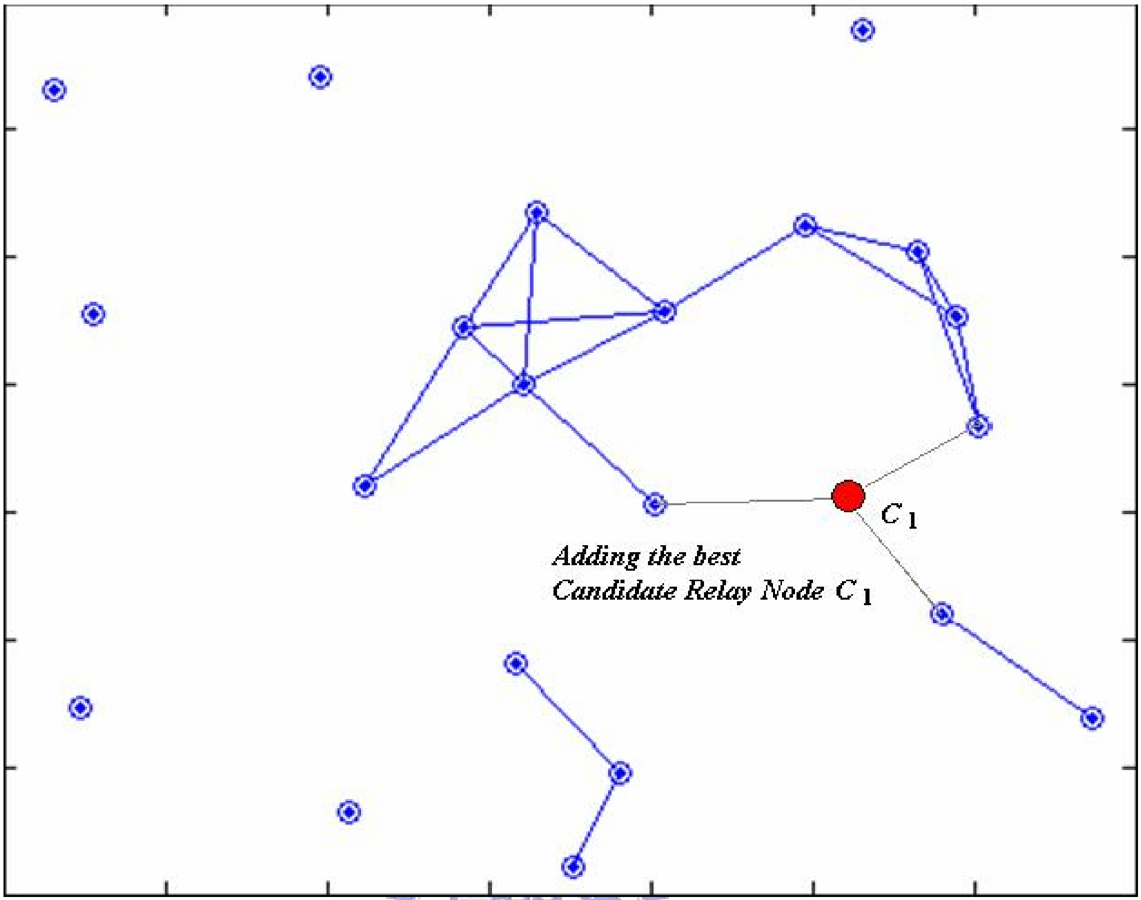
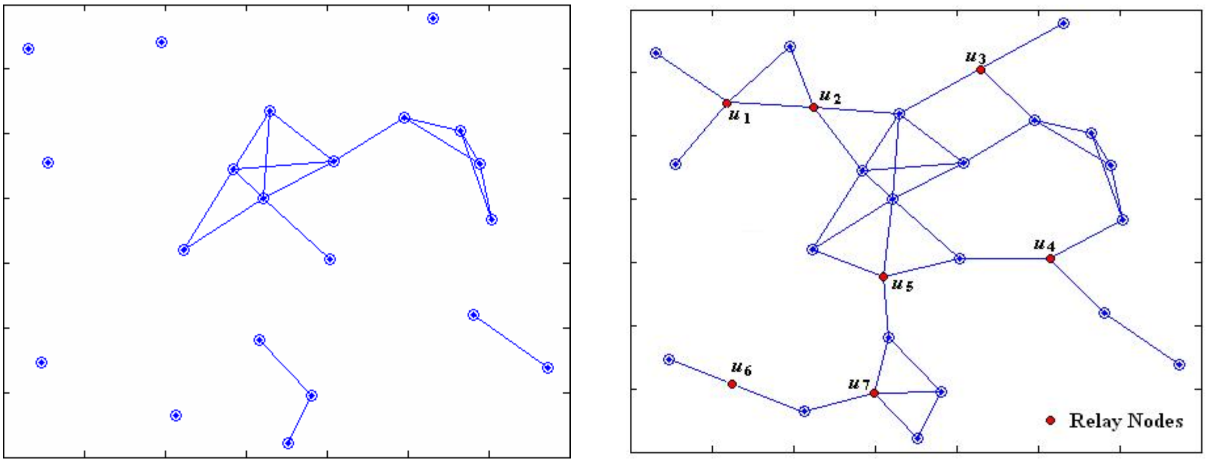


Figure 3-3. The C_1 is the best candidate that can solve three disconnected node pairs in Figure 3-2.

The proposed method would select the node to deploy in the WSN.



(a) The initial network topology.

(b) The augmented network topology. (after adding relay nodes)

Figure 3-4. An example of proposed relay node deployment method.

4. Simulation Results and Comparison

In order to evaluate the performance of our work, we present and analyze the simulation results from applying the proposed relay node deployment method for connecting randomly and uniformly distributed initial nodes in a square-shaped plane. For comparison, related works, including MST-based and VW node deployment method are also evaluated. These methods are implemented and simulated by using the MATLAB toolboxes [27].

To include the random characteristics of radio propagation channels, the propagation model shown in Eq.(2) is used to determine the augmented network by applying methods. Three types of propagation environments are considered. They are Line-Of-Sight (LOS), Non-Line-Of-Sight (NLOS) with obstacles, and NLOS with obstacles and small-scale fading. The assigned values of environment-dependent parameters in our simulation are listed in Table 4-1, which are derived from our field tests in indoor environment.

Table 4-1. The assigned values of environment-dependent parameters in our simulation.

(a) The LOS environments.

	Input parameters (unit)	**Value assigned**
D_{LOS}	Maximum Transmission Distance of UDM (m)	36.3
δ	Receiving Sensitivity (dBm)	-89.5
P_T	Transmitter Power (dBm)	-35.5
$PL(d_0)$	Path Loss (d_0) (dB)	15 (avg.)
n	Path Loss Exponent	2.5

(b) The NLOS environments.

	Input parameters (unit)	**Value assigned**
D_{NLOS_light}	Maximum Transmission Distance of UDM with Light Obstacles (m)	26.3
D_{NLOS_heavy}	Maximum Transmission Distance of UDM with Heavy Obstacles (m)	13.8
N	Average Number of Obstacles	0.5 (light)、1.5 (heavy)
δ	Receiving Sensitivity (dBm)	-89.5
P_T	Transmitter Power (dBm)	-35.5
$PL(d_0)$	Path Loss (d_0) (dB)	15 (avg.)
n	Path Loss Exponent	2~3
PAF	A Obstacle Loss (dB)	7、15

Here, effects of node-density and topology-size on performance metrics are investigated. Each obtained data point is an average of 200 simulation runs.

4.1 Performance Metrics

Three of significant metrics are considered in order to determine the performance of the relay node deployment methods in our simulations.

(1) *Average Number of Relay Nodes*

Average Number of Relay Nodes (ANRN) is defined as the average of all sampled number of relay nodes deployed by an adopting method. The less the relay nodes are required to connect a disconnected WSN, the more efficient the method would be. For comparison purpose, we further examine the improvement ratio of ANRN, which is defined as

$$\rho(A,B) = \frac{\text{difference of ANRN between method } B \text{ and } A}{\text{ANRN using method } B} \tag{6}$$

where method B denotes a benchmark method. Here we consider the performance of MST-based method as a benchmark for the proposed method.

(2) *Average Node Degree*

The Average Node Degree (AND) is defined as the average of all sampled node degree by an adopting method, where the node degree is defined as the average number of neighbors of all nodes in a WSN. The node degree of a WSN is strongly correlated with network connectivity [10]. The higher the node degree, the better the network connectivity would be.

(3) *Average Number of Network Clusters*

Average Number of Network Clusters (ANNC) is defined as average number of network clusters of augmented network by an adopting method, where a network cluster represents a portion of a network formed by a group of connected nodes. It is noted that the number of network cluster is equal to 1 when the network is connected. All of investigated relay node deployment methods aim to construct a connected WSN, however, the augmented network might be still disconnected when the chosen method is inadequate in the application/environment context. The larger the network cluster, the worse the network connectivity would be.

4.2 Node Density Effect

In this simulation, the performance with varying node density using each of the investigating method is evaluated. The size of operational region is considered: 150m×150m. In each simulation run, all initial nodes are uniformly distributed in the confined region. We vary the number of initial nodes in the region from 10 to 300 that results in the increasing of node density. First of all, the simulation results obtained in LOS environment are present. Figure 4-1 and Figure 4-2 show the ANRN and improvement ratio of ANRN, respectively, of the proposed GS method comparing with that of MST-based and VW method.

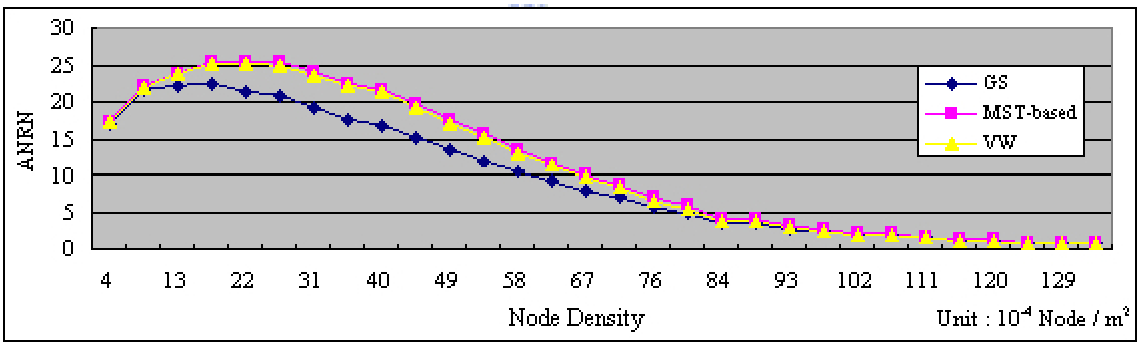


Figure 4-1. ANRN versus node density in LOS environment.

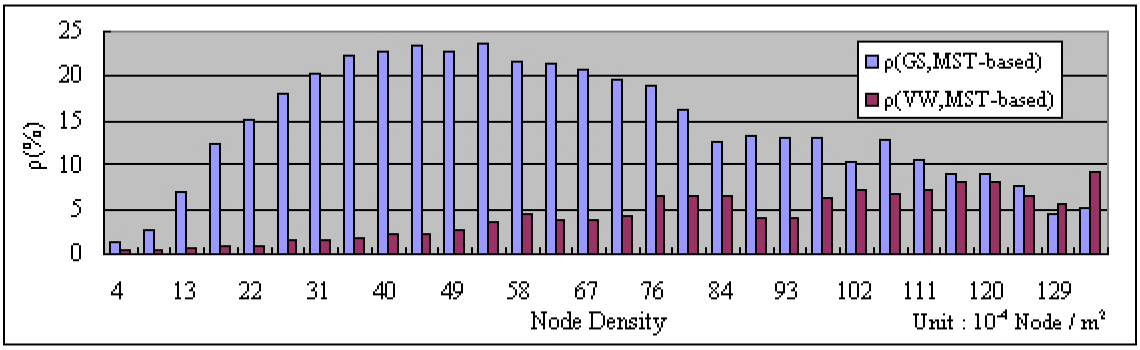


Figure 4-2. Improvement ratio of ANRN versus node density in LOS environment.

By examining Figure 4-1 and Figure 4-2, the proposed GS method always yields minimum number of relay nodes. It is found that the improvement ratios of ANRN, ρ, by using GS method are larger than 10% when the node density is in the region of 0.002~0.011 nodes/m^2. With the node density of initial network increases, all of evaluated methods yield a small ANRN that tend to be 0. This phenomenon is due to the nature that a WSN with a higher node density is allocated, the larger the probability that the WSN would be connected. It is also shown in [10]. By summarizing the simulation results, the GS method improves 14.41% and 10.1% of ANRN comparing to MST-based and VW method, respectively, when the sensor nodes are placed in a 150×150 m^2 square region.

Figure 4-3 depicts the AND of the proposed GS method comparing with that of MST-based and VW method. It is shown that the GS method provides higher node degree comparing to other method when the node density is less than 0.008 nodes/m^2. However, with the node density increasing, the obtained ANDs are also increasing and all of evaluated method provide equivalent ANDs.

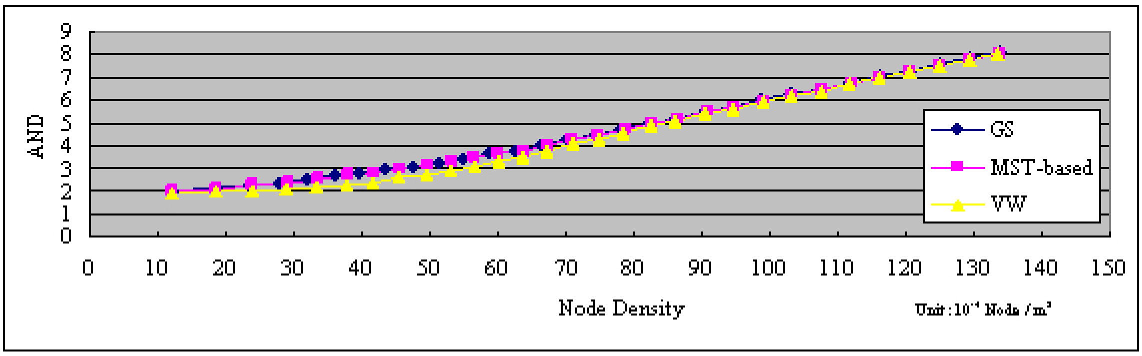
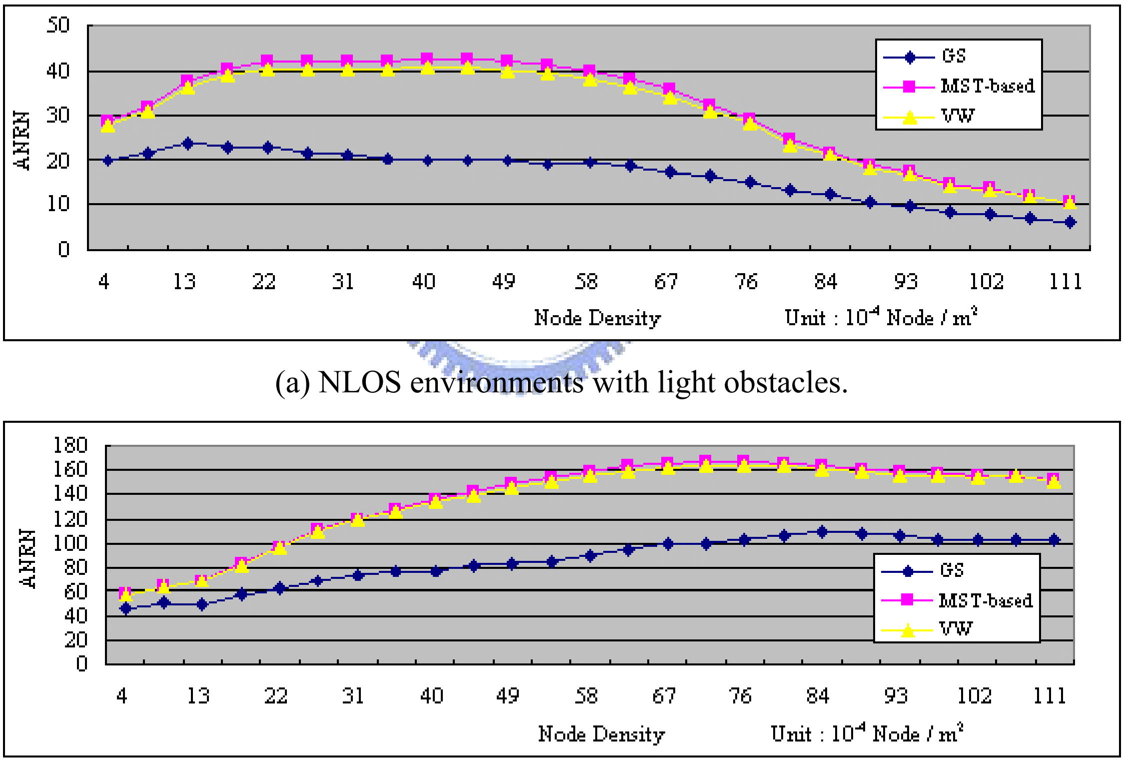


Figure 4-3. AND versus node density in LOS environment.

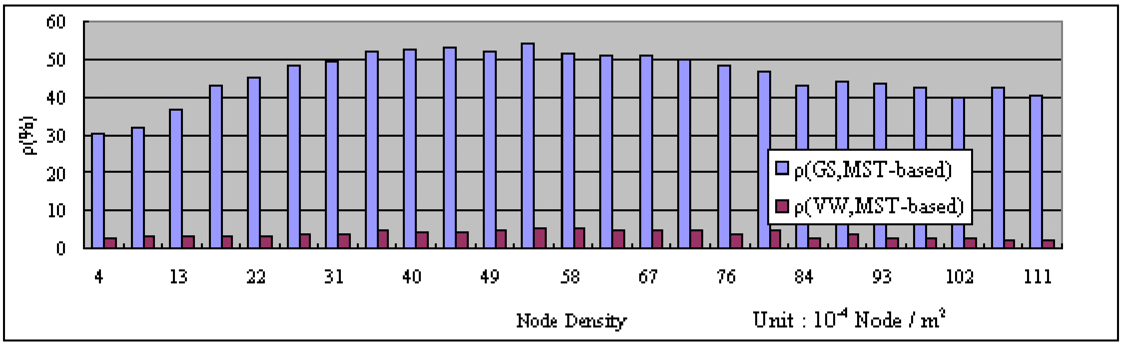
Thereafter, the simulation results obtained in NLOS environment are present. Figure 4-4 and Figure 4-5 show the ANRN and improvement ratio of ANRN, respectively, when the partition loss of an obstacle is set as 7 dB. By examining the simulation results, the proposed GS method always yields best performance in ANRN. By comparing Figure 4-2 and Figure 4-5, the proposed method provides better improvements in NLOS than in LOS, which indicates that the method is practical for applying in indoor environment. It is found that the more light the obstacles, the better the improvement by using GS method would be obtained. The averaged improvement ratios by using GS method are 45.8% and 35.8% with light obstacles and heavy obstacles, respectively.



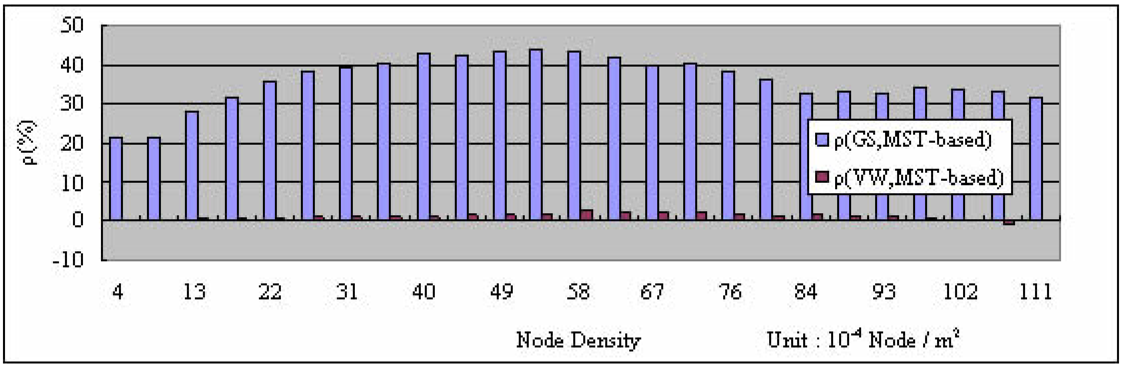
(a) NLOS environments with light obstacles.

(b) NLOS environments with heavy obstacles.

Figure 4-4. ANRN versus node density in NLOS environment. (The partition loss of an obstacle is 7dB).



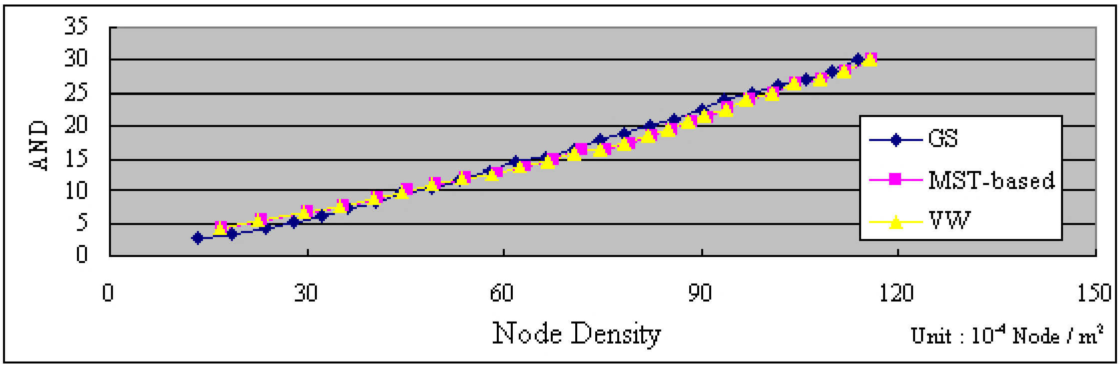
(a) NLOS environments with light obstacles.



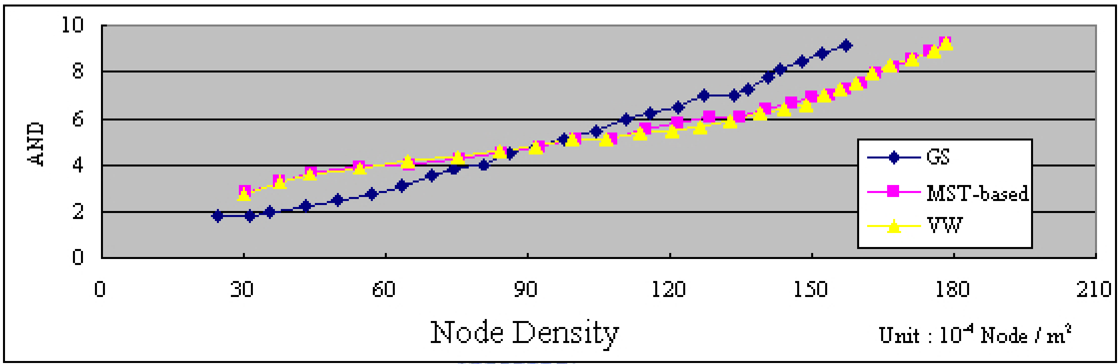
(b) NLOS environments with heavy obstacles.

Figure 4-5. Improvement ratio of ANRN versus node density in NLOS environment. (The partition loss of an obstacle is 7dB).

Figure 4-6 depicts the AND of the proposed GS method comparing with that of MST-based and VW method in NLOS environment. It is shown that the GS method significantly improves the performance of ANRN while at the same time provides equivalent or slightly smaller node degree comparing to other method.



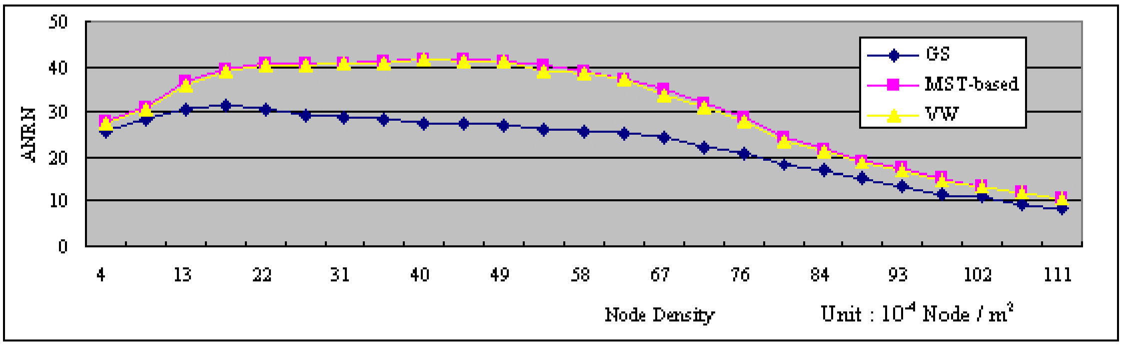
(a) NLOS environments with light obstacles.



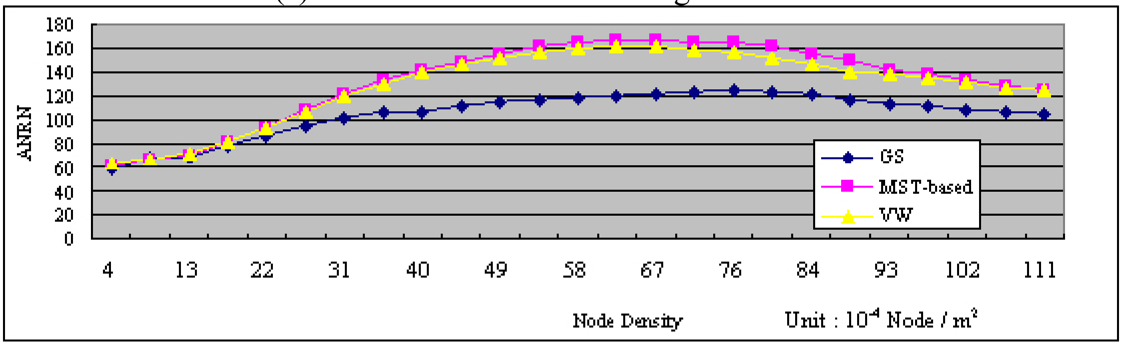
(b) NLOS environments with heavy obstacles.

Figure 4-6. AND versus number of nodes in NLOS environment. (The partition loss of an obstacle is 7dB).

Figure 4-7 and Figure 4-8 show the ANRN and improvement ratio of ANRN, respectively, when the partition loss of an obstacle is set as 15dB. By comparing the NLOS cases when the partition loss of an obstacle is set as 7dB, analogous results are obtained. Here the averaged improvement ratios by using GS method are 25.4% and 20.6% with light obstacles and heavy obstacles, respectively, which are slightly smaller than the results in NLOS environment when the partition loss of an obstacle is set as 7dB.

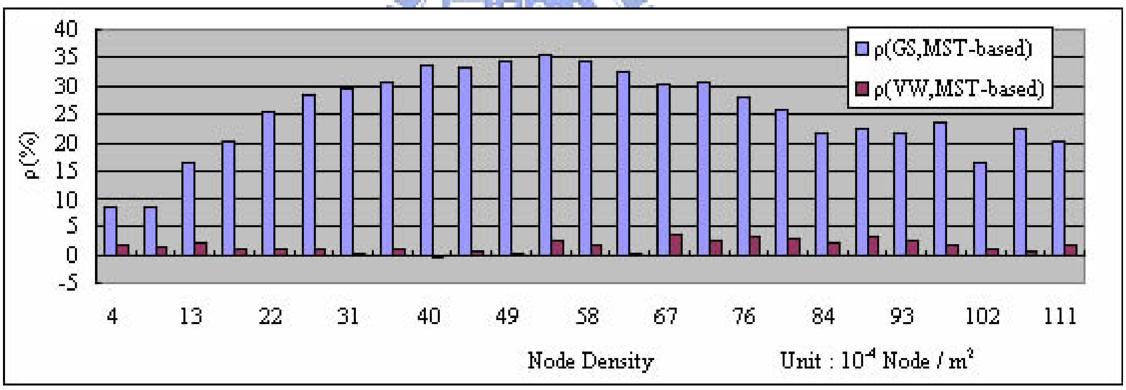


(a) NLOS environments with light obstacles.

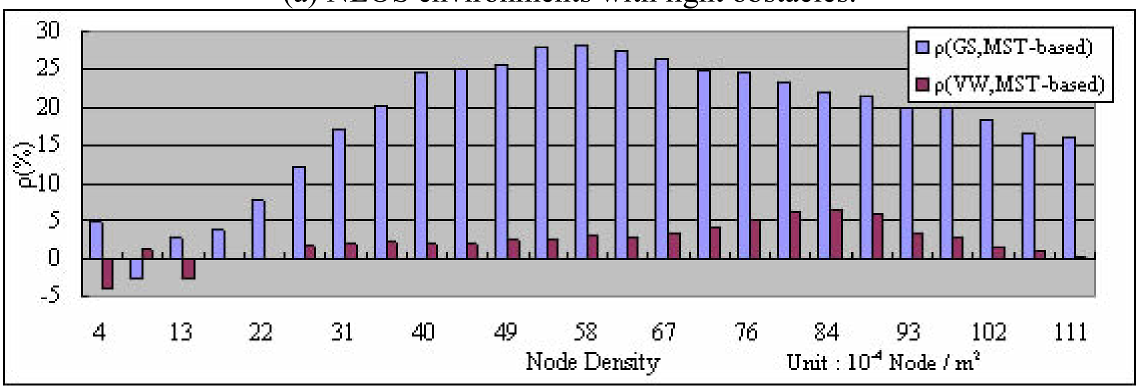


(b) NLOS environments with heavy obstacles.

Figure 4-7. ANRN versus node density in NLOS environment. (The partition loss of an obstacle is 15dB).

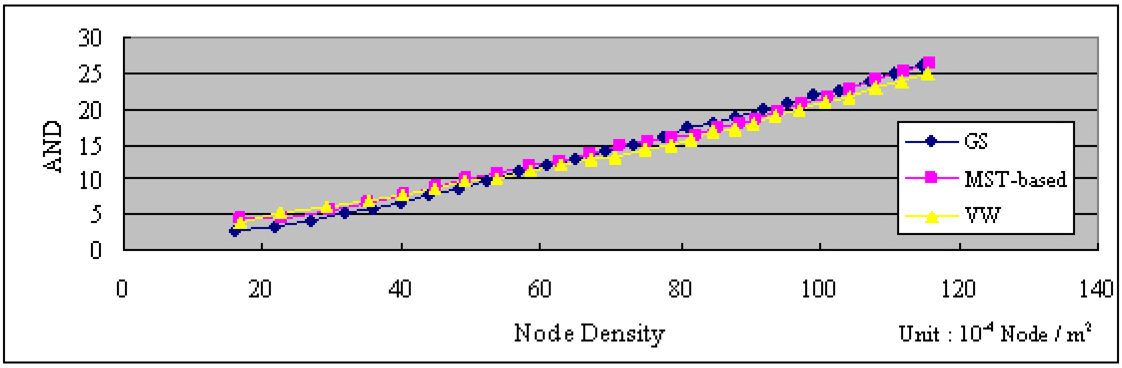


(a) NLOS environments with light obstacles.

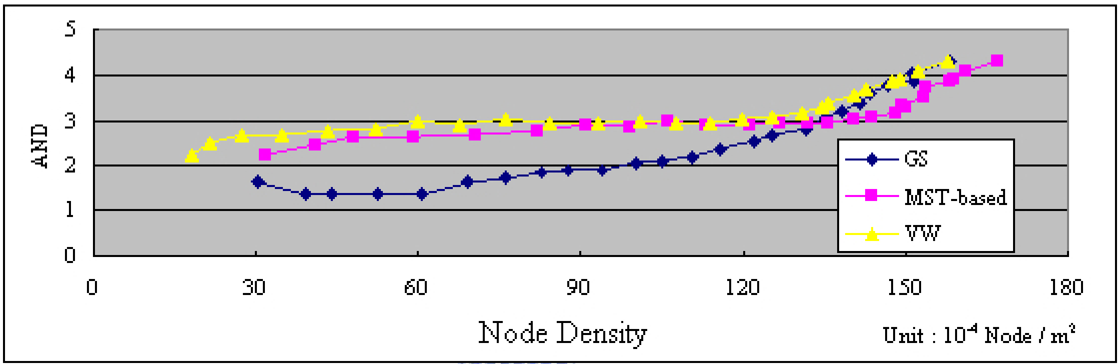


(b) NLOS environments with heavy obstacles.

Figure 4-8. Improvement ratio of ANRN versus node density in NLOS environment. (The partition loss of an obstacle is 15dB).



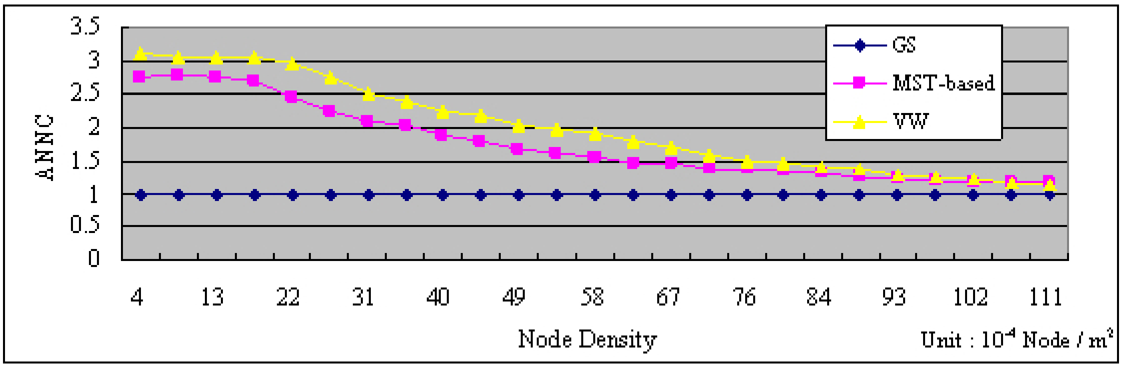
(a) Environments with light obstacles.



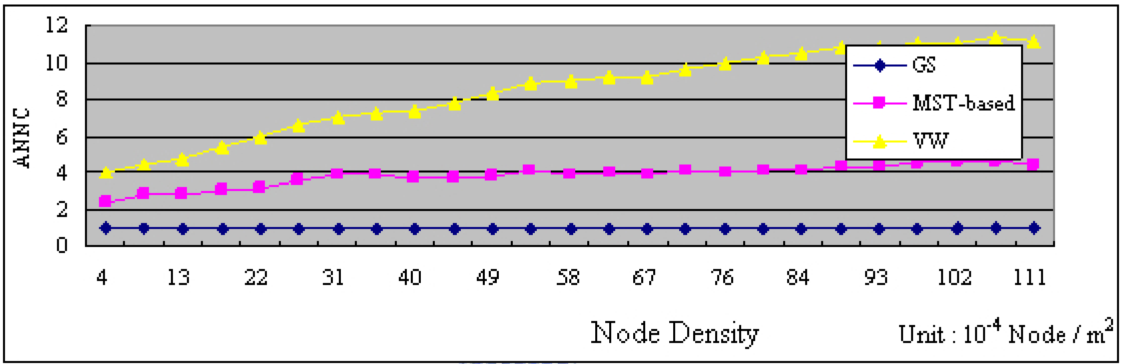
(b) Environments with heavy obstacles.

Figure 4-9. AND versus number of nodes in NLOS environment. (The partition loss of an obstacle is 15dB).

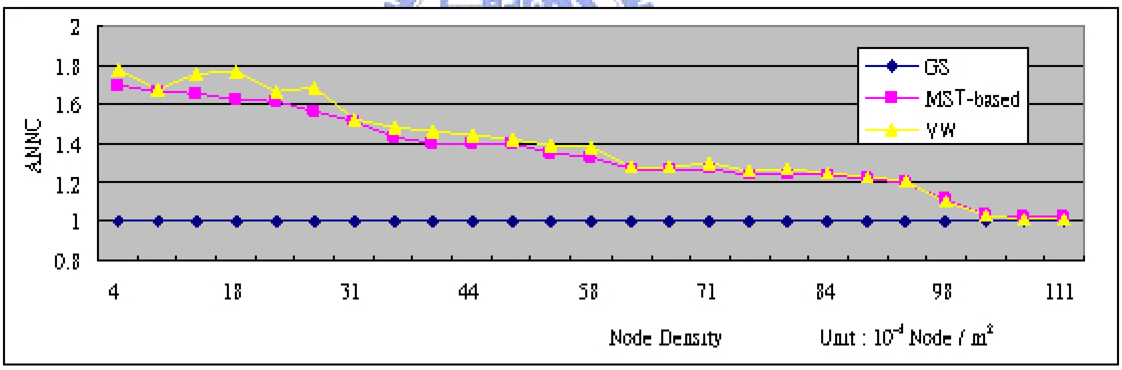
As to the ANNC by using each of the methods in NLOS environment, the proposed GS method always provides connected WSNs after deploying relay nodes. On the other hand, both MST-based and VW method might be inadequate in NLOS environment, especially when the obstacles are heavy. The evidence is showed in Figure 4-10.



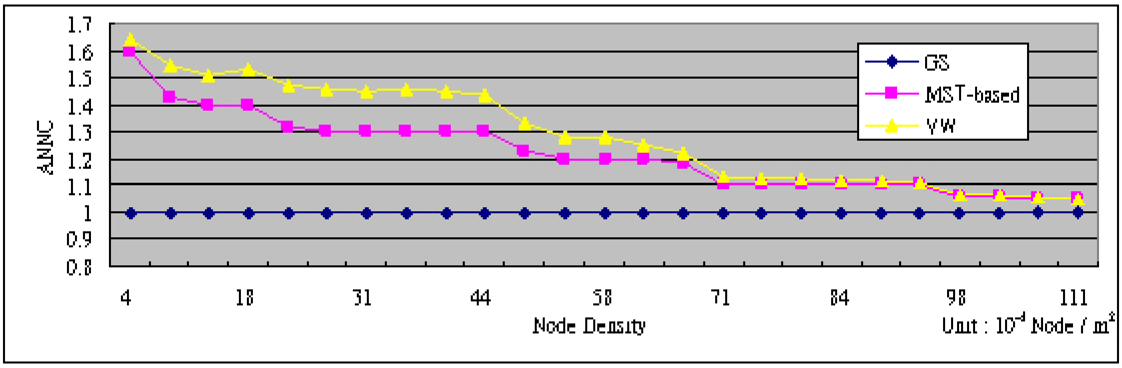
(a) NLOS environments with light obstacles (7dB).



(b) NLOS environments with light obstacles (15dB).



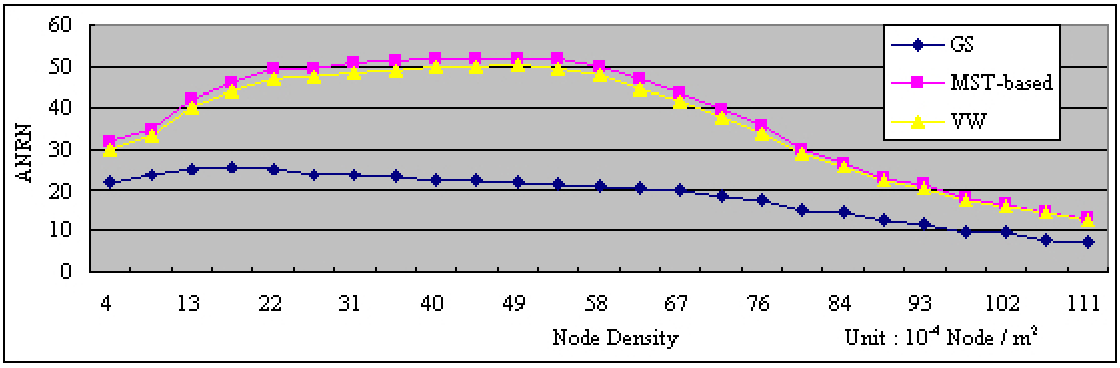
(c) NLOS environments with heavy obstacles (7dB).



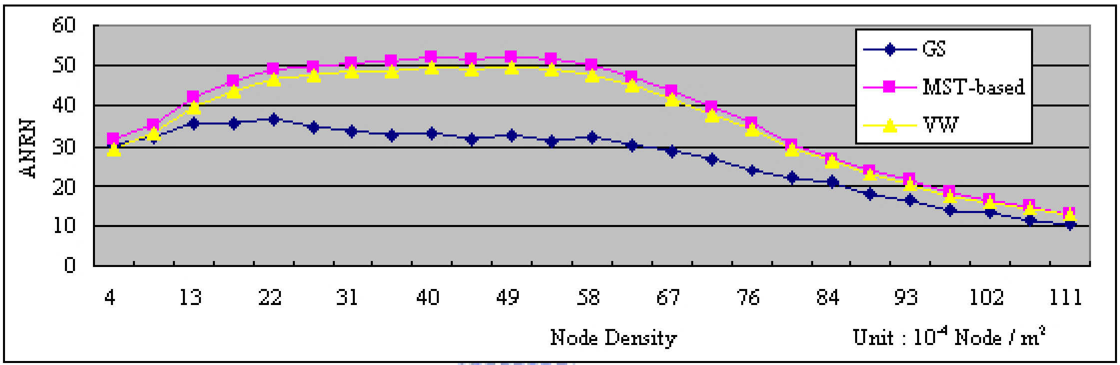
(d) NLOS environments with heavy obstacles (15dB).

Figure 4-10. ANNC versus node density in NLOS environment.

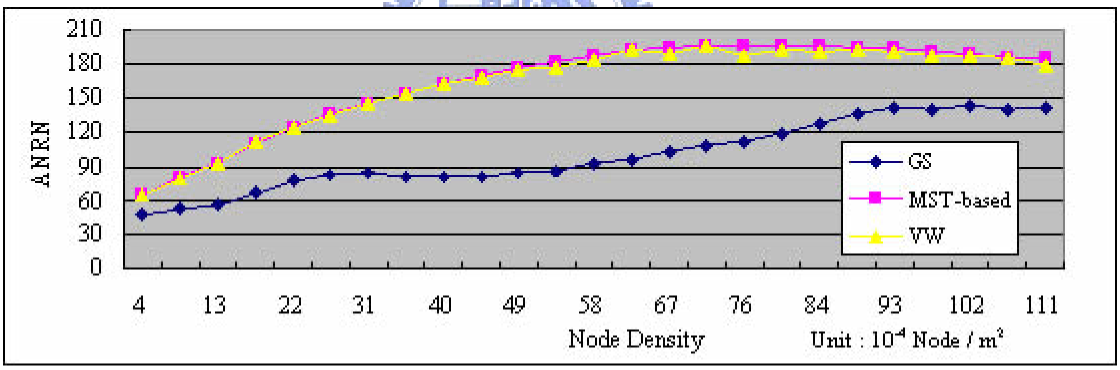
Simulation results obtained in NLOS environment with small-scale fading effect are present in the following figures. Figure 4-11 and Figure 4-12 show the ANRN and improvement ratio of ANRN, respectively, which yield similar curves comparing to Figure 4-4 and Figure 4-5. The average improvement ratios of ANRN are 38% and 29.9% with light obstacles and heavy obstacles, respectively. It is noted that the improvement ratios are slightly larger than prior results, which indicates that the proposed method is adequate in indoor environment, especially when the small-scale fading effect is considered. Figure 4-13 and Figure 4-14 depict the AND and ANNC, respectively, of the proposed GS method comparing with that of MST-based and VW method. It is shown that the GS slightly decreases node degree but always provides connected WSNs after deploying relay nodes.



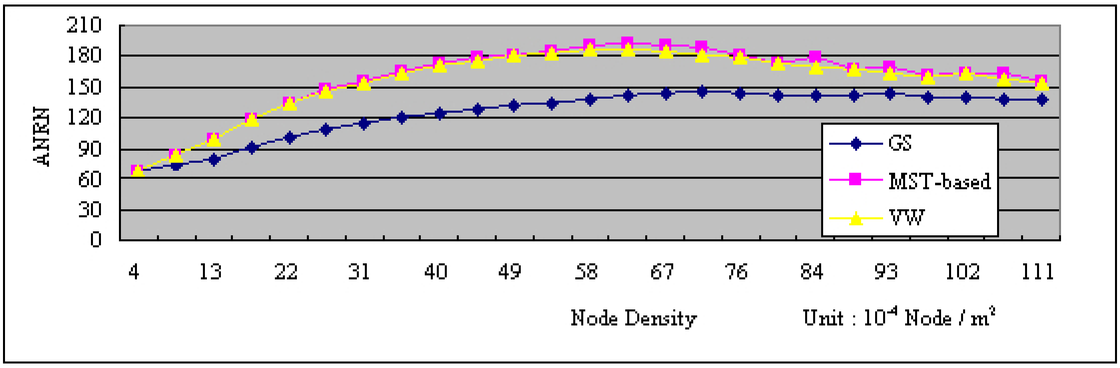
(a) NLOS environments with light obstacles and small-scale fading (7dB).



(b) NLOS environments with light obstacles and small-scale fading (15dB).

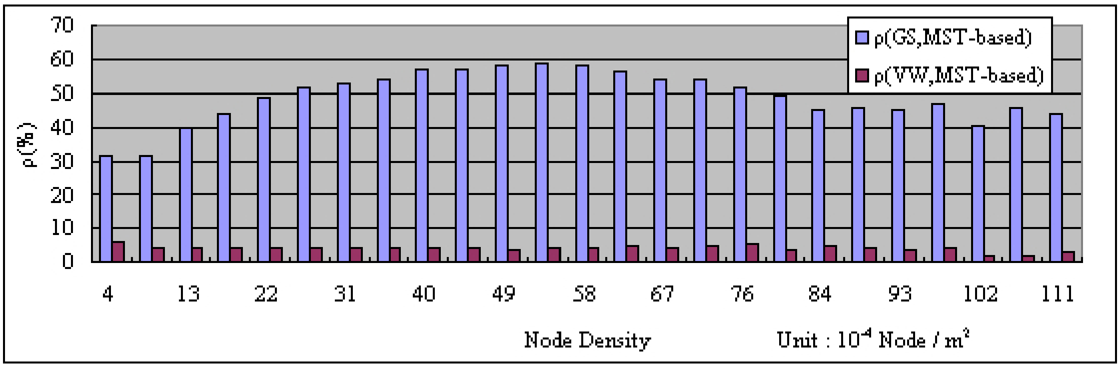


(c) NLOS environments with heavy obstacles and small-scale fading (7dB).

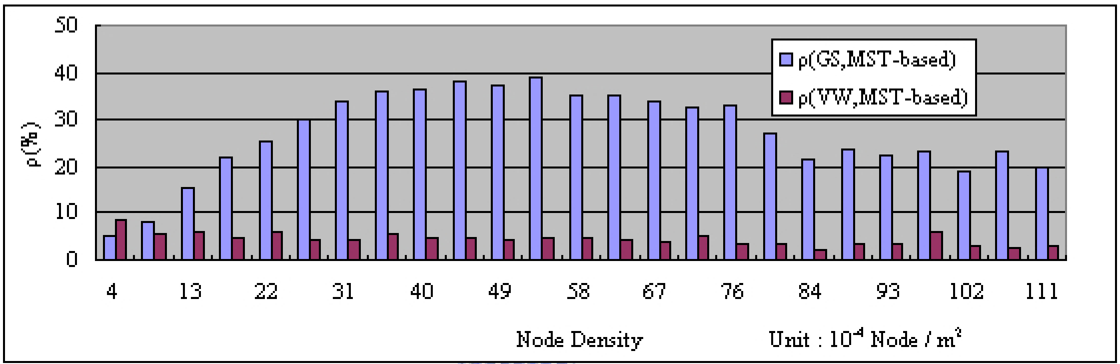


(d) NLOS environments with heavy obstacles and small-scale fading (15dB).

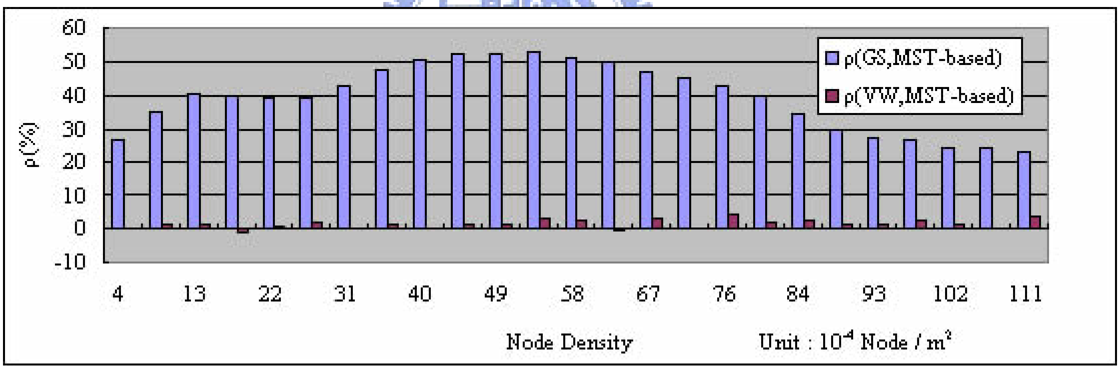
Figure 4-11. ANRN versus node density in NLOS environment with small-scale fading.



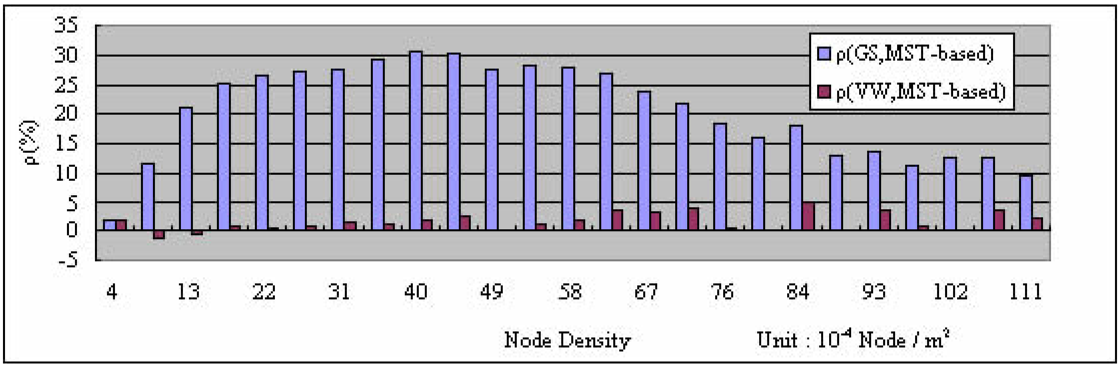
(a) NLOS environments with light obstacles and small-scale fading (7dB).



(b) NLOS environments with light obstacles and small-scale fading (15dB).

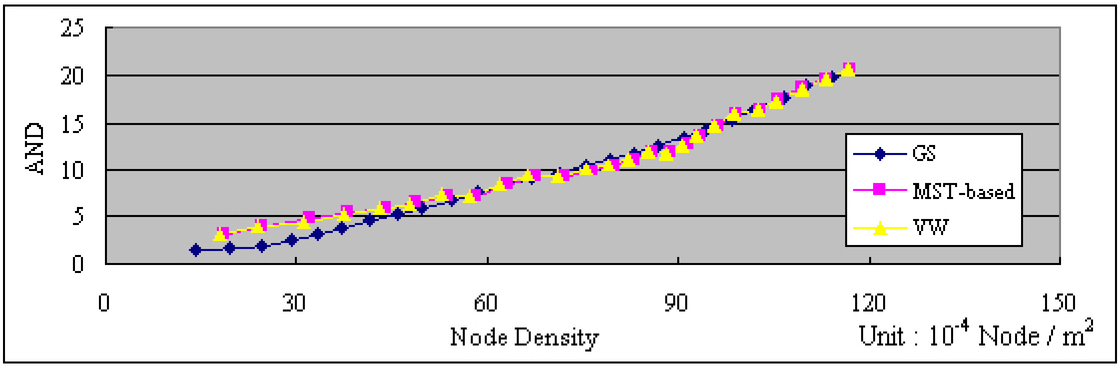


(c) NLOS environments with heavy obstacles and small-scale fading (7dB).

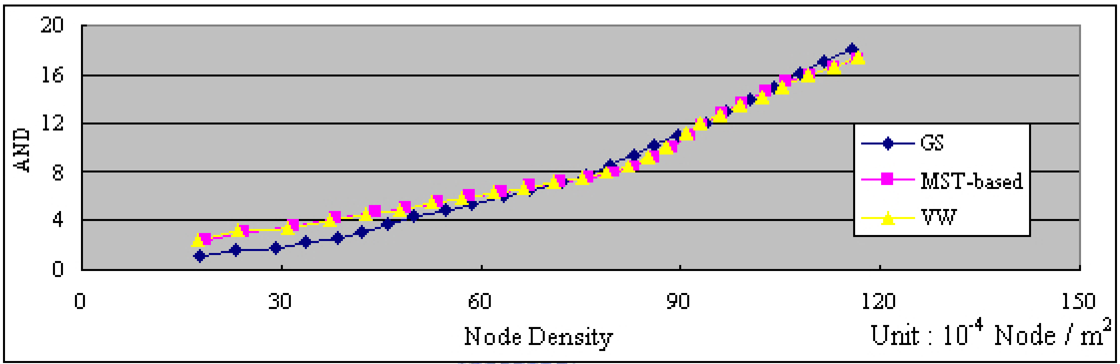


(d) NLOS environments with heavy obstacles and small-scale fading (15dB).

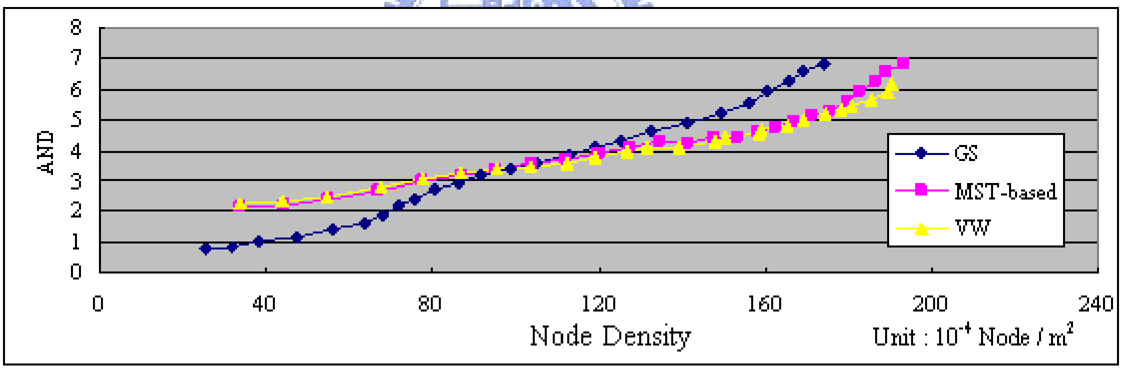
Figure 4-12. Improvement ratio of ANRN versus node density in NLOS environment with small-scale fading.



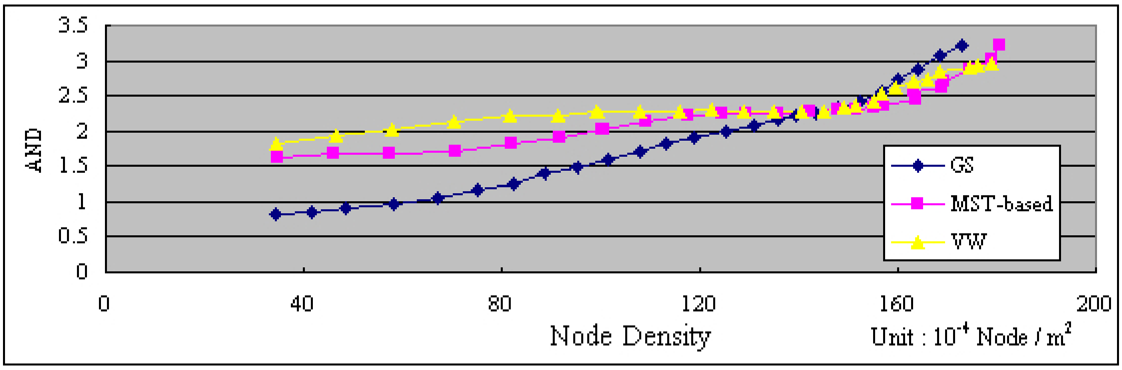
(a) NLOS environments with light obstacles and small-scale fading (7dB).



(b) NLOS environments with light obstacles and small-scale fading (15dB).

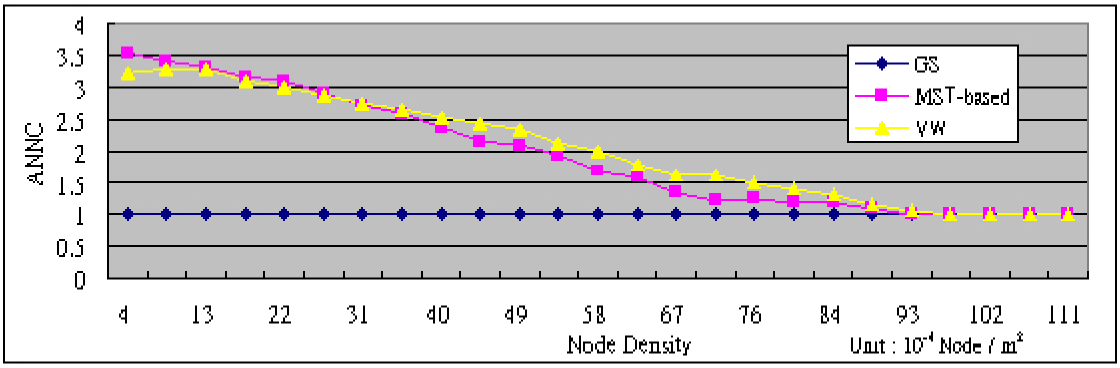


(c) NLOS environments with heavy obstacles and small-scale fading (7dB).

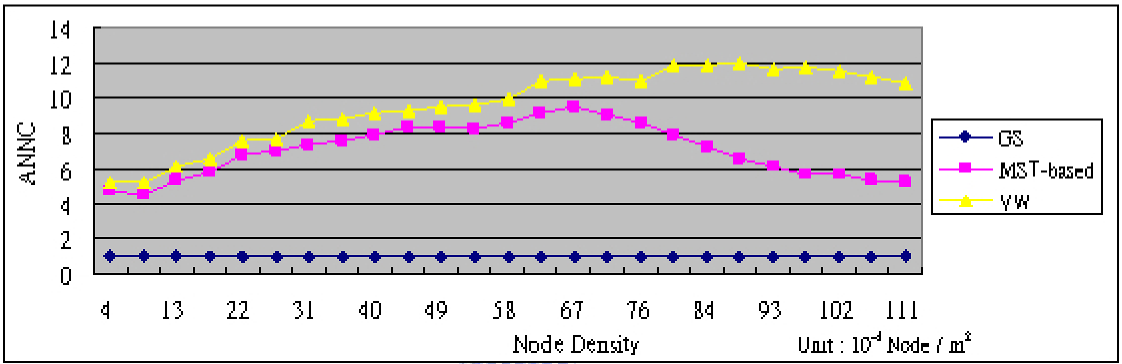


(d) NLOS environments with heavy obstacles and small-scale fading (15dB).

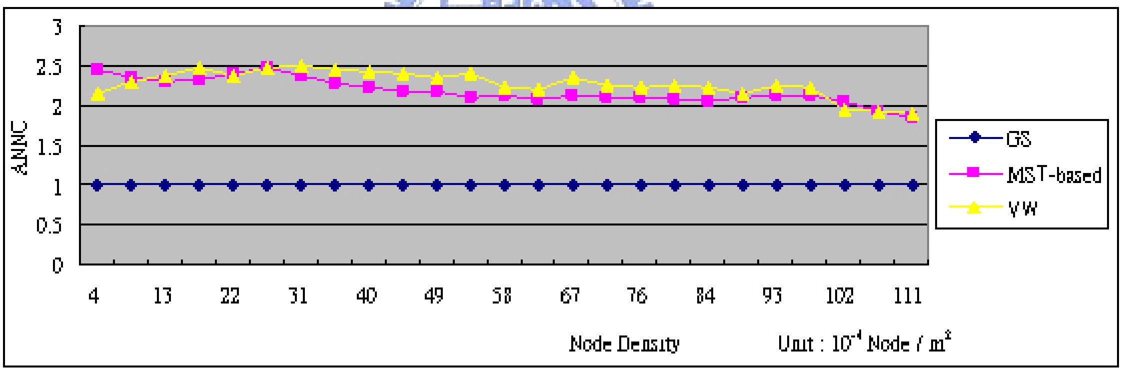
Figure 4-13. AND versus number of nodes in NLOS environment with small-scale fading.



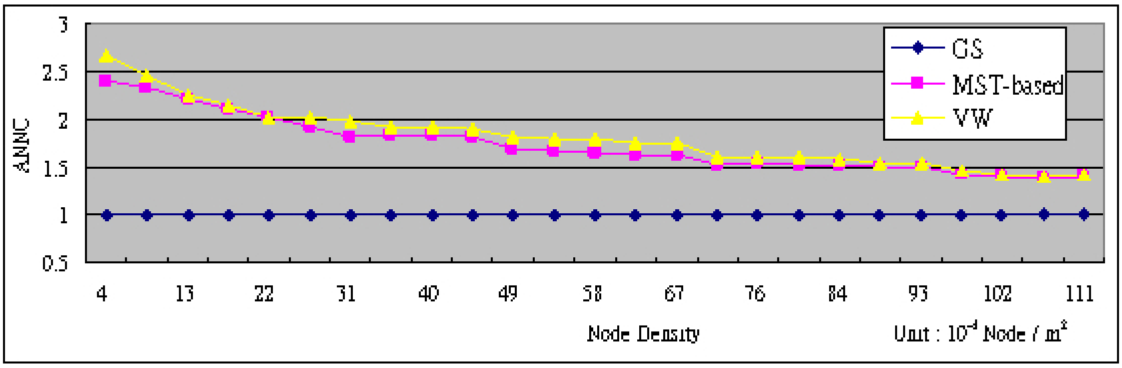
(a) NLOS environments with light obstacles and small-scale fading (7dB).



(b) NLOS environments with light obstacles and small-scale fading (15dB).



(c) NLOS environments with heavy obstacles and small-scale fading (7dB).



(d) NLOS environments with heavy obstacles and small-scale fading (15dB).

Figure 4-14. ANNC versus node density in NLOS environment with small-scale fading.

4.3 Topology Size Effect

Here, the topology size is defined as the number of initial nodes. In each simulation run, all initial nodes are uniformly distributed in an square area with associated size. A constant node density is kept and it is equal to 1/250 nodes/m^2. We vary the number of initial nodes in the region from 10 to 200 that results in the increasing of topology size. First of all, the simulation results obtained in LOS environment are present. Figure 4-15 and Figure 4-16 show the ANRN and improvement ratio of ANRN, respectively, of the proposed GS method comparing with that of MST-based and VW method.

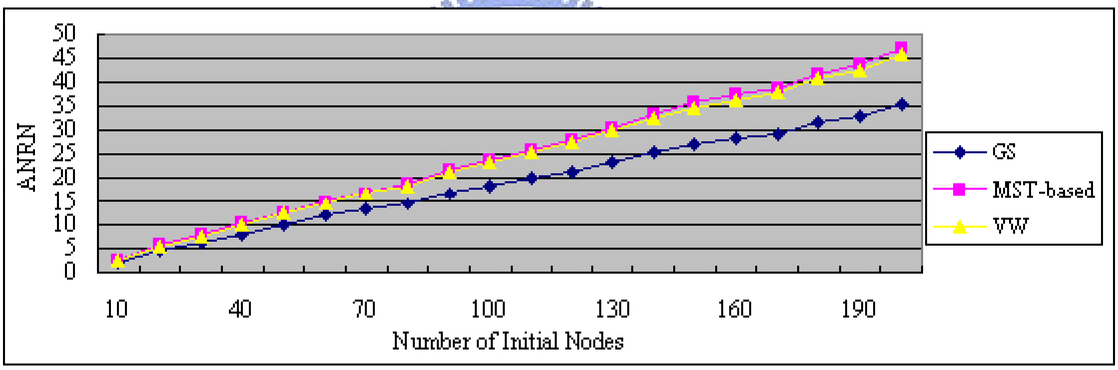


Figure 4-15. ANRN versus number of initial nodes in LOS environment.

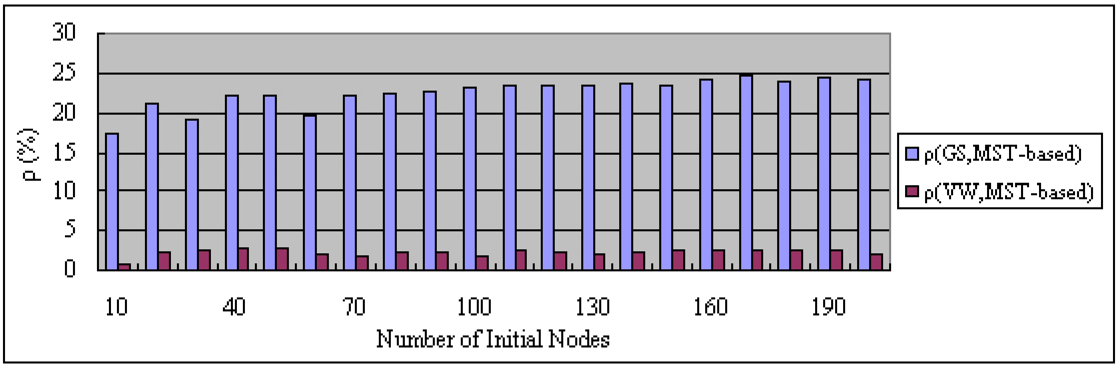


Figure 4-16. Improvement radio of ANRN versus number of initial nodes in LOS environment.

By examining Figure 4-15 and Figure 4-16, the proposed GS method yields the minimum number of relay nodes in all of investigated topology sizes. It is found that the obtained improvement ratios ρ by using GS method are tend to converge to a constant. This phenomenon indicates that the complexity of the problem increases linearly with the increasing of topology size, and the proposed method is expected to be scalable when the topology size is large. With the topology size increases, improvement ratios are scattered in a confined range of 20%~25% and the GS method improves 22.5% and 20.3% of ANRN comparing to MST-based and VW method, respectively.

Figure 4-17 depicts the AND of the proposed GS method comparing with that of MST-based and VW method. It is shown that the GS method provides almost equivalent node degree comparing to MST-based method, while the VW method always provides worst node degree. The AND converges to a constant as about 3.05 with the increasing of topology size.

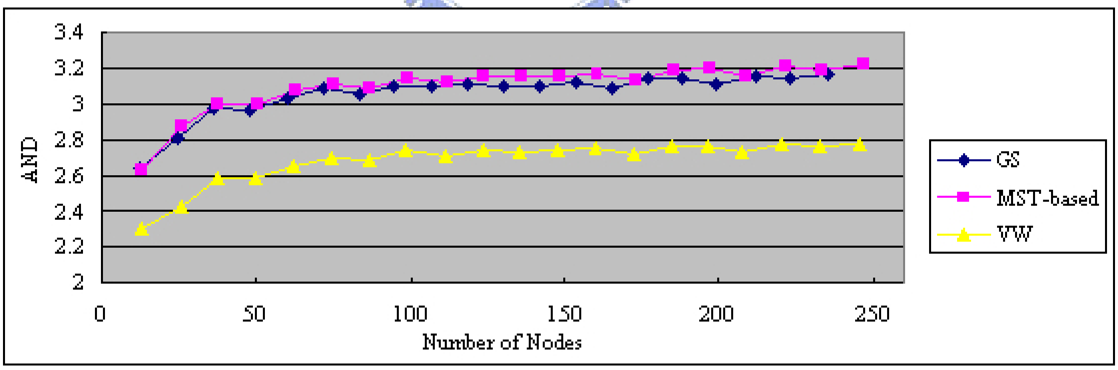
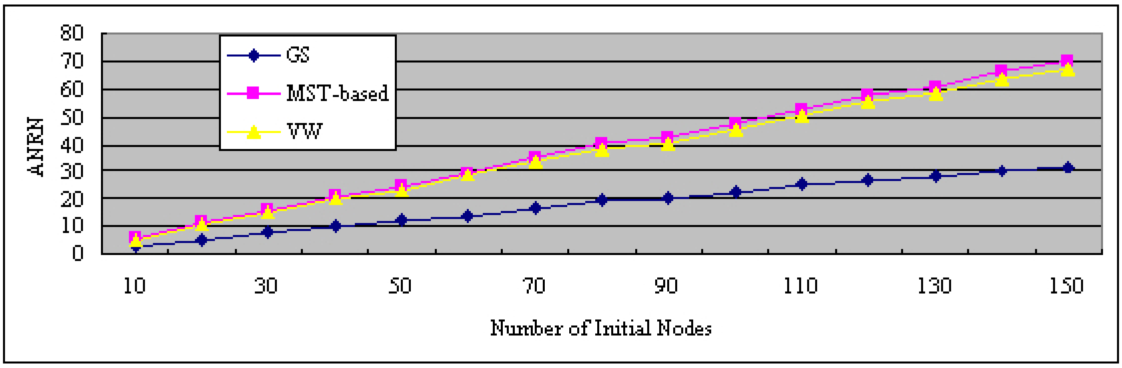
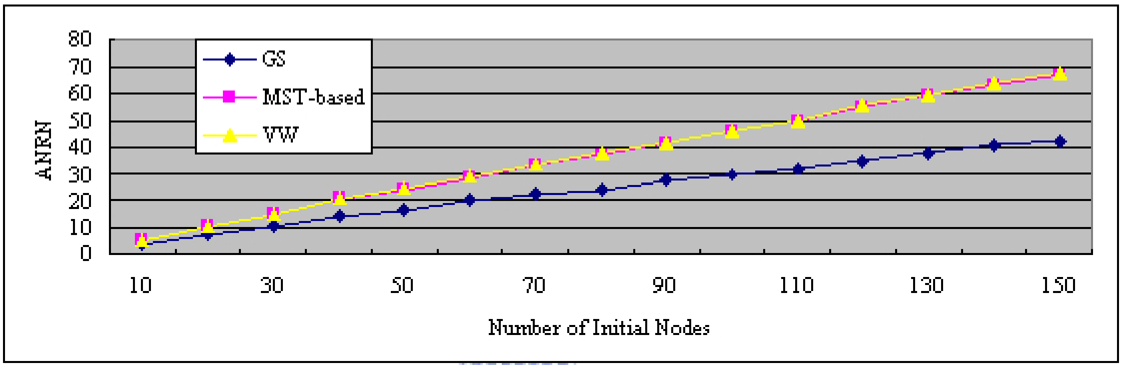


Figure 4-17. AND versus number of initial nodes in LOS environment.

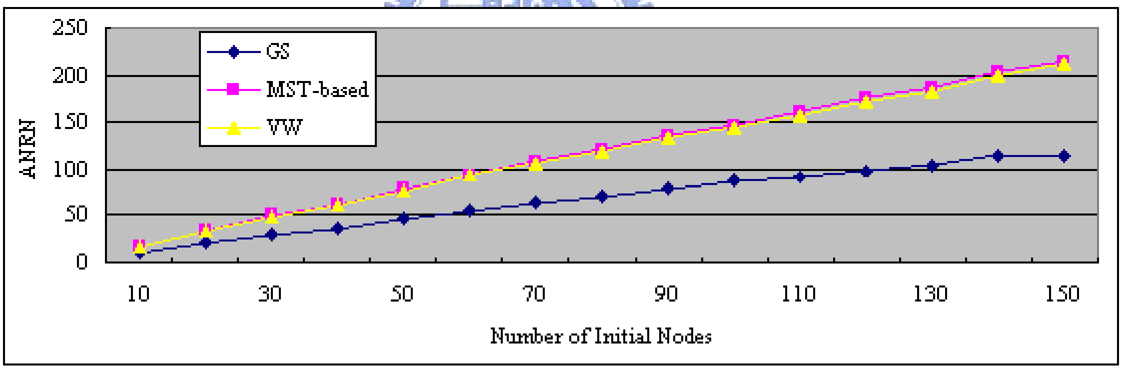
Thereafter, the simulation results versus topology sizes obtained in NLOS environment are present. Figure 4-18 and Figure 4-19 show the ANRN and improvement ratio of ANRN, respectively. The less the obstacles, the better the improvement by using GS method would be obtained. Here the proposed GS method always yields best ANRNs. Their improvement ratios are about 52.7% and 41.6% with light obstacles and heavy obstacles, respectively, when the partition loss of an obstacle is set as 7dB. (They are about 32.9% and 27.2% with light obstacles and heavy obstacles, respectively, when the partition loss of an obstacle is set as 15dB.) It is found that the proposed method provides better improvements in NLOS than in LOS in most of topology sizes. An analogous phenomenon is observed when we investigation node density effect on ANRN in previous section.



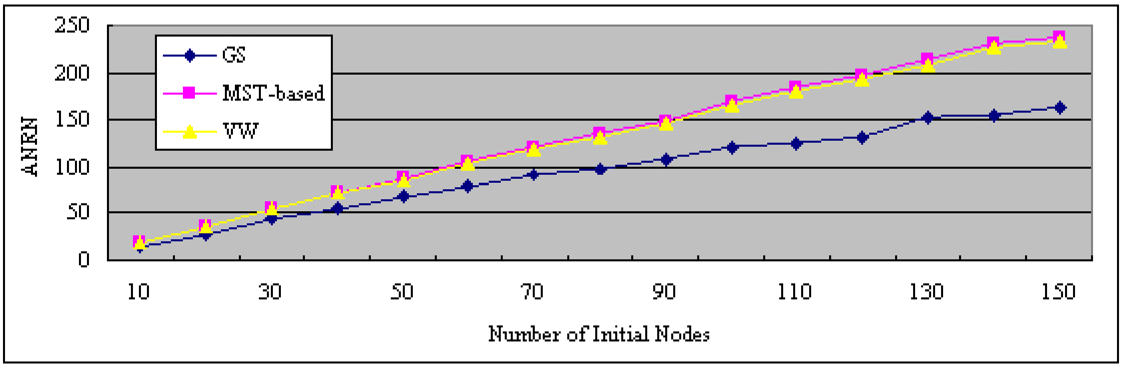
(a) NLOS environments with light obstacles (7dB).



(b) NLOS environments with light obstacles (15dB).

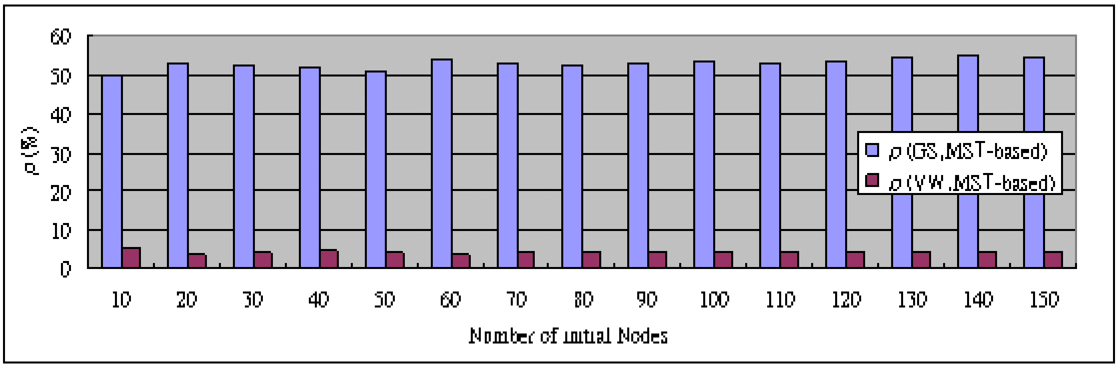


(c) NLOS environments with heavy obstacles (7dB).

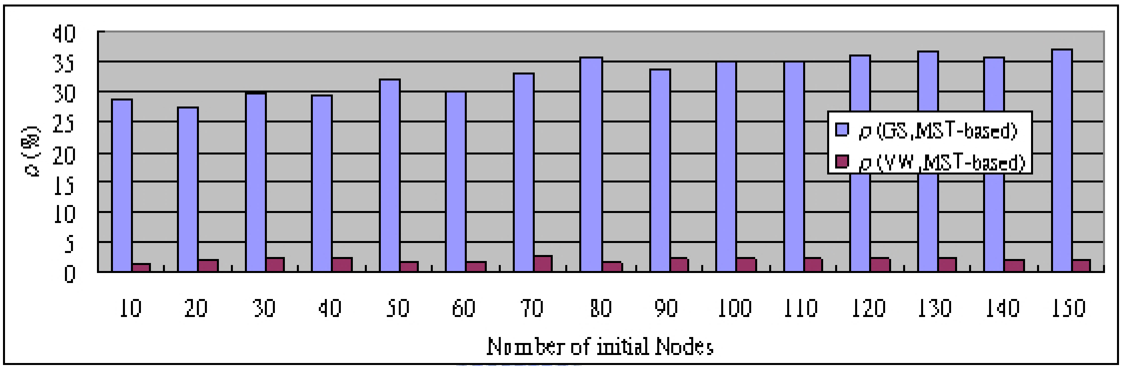


(d) NLOS environments with heavy obstacles (15dB).

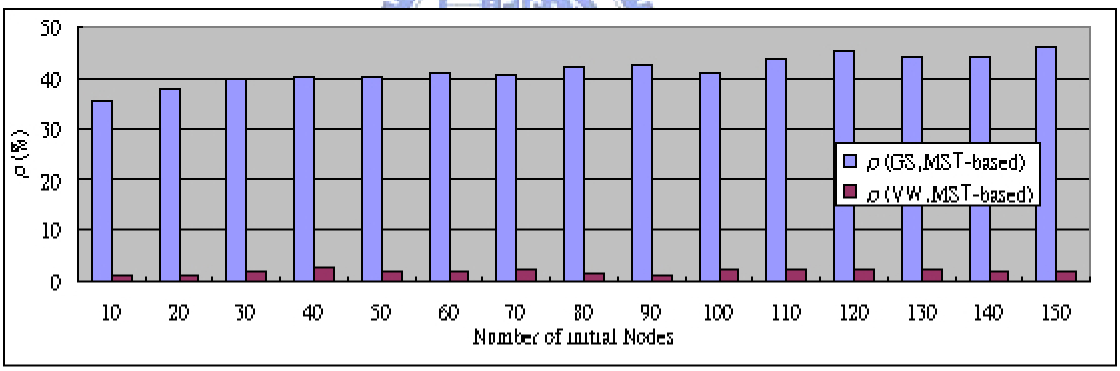
Figure 4-18. ANRN versus number of initial nodes in NLOS environment.



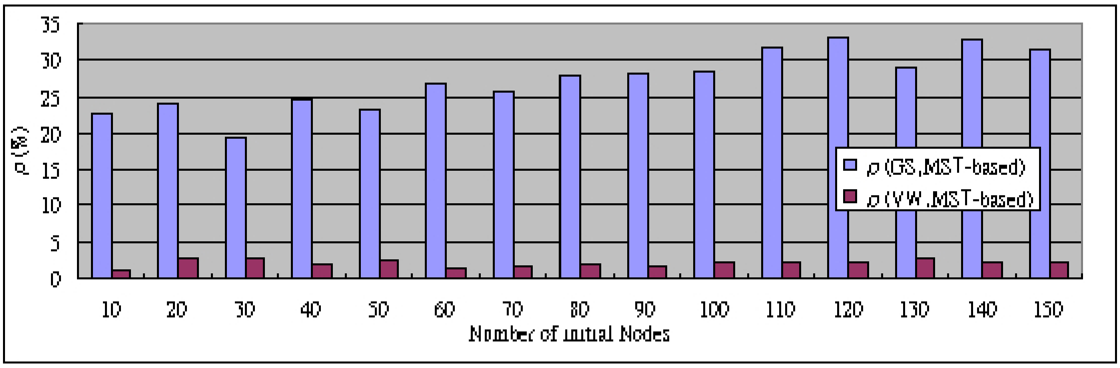
(a) NLOS environments with light obstacles (7dB).



(b) NLOS environments with light obstacles (15dB).



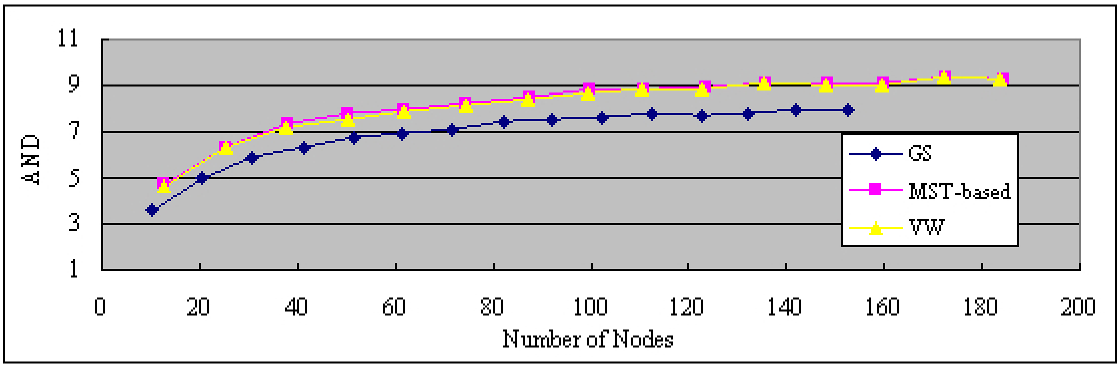
(c) NLOS environments with heavy obstacles (7dB).



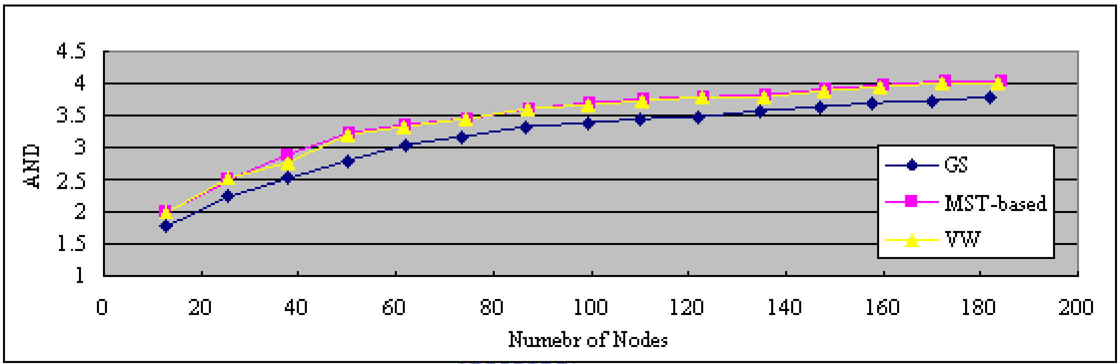
(d) NLOS environments with heavy obstacles (15dB).

Figure 4-19. Improvement ratio of ANRN versus number of initial nodes in NLOS environment.

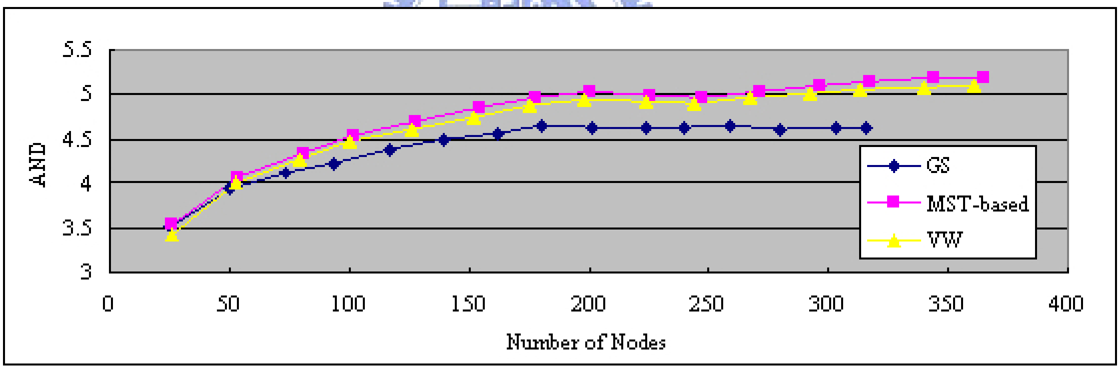
Figure 4-20 depicts the AND versus topology sizes by using all the investigated methods in NLOS environment. Due to the nature that the more nodes placed in a confined area results in higher node degree, the obtained ANDs by using either MST-based method or VW method are slightly larger than the ANDs obtained by proposed method. However, the proposed GS method always provides connected WSNs even in a smaller AND. The evidence is showed that the obtained ANNCs of proposed method are equal to 1 in Figure 4-21.



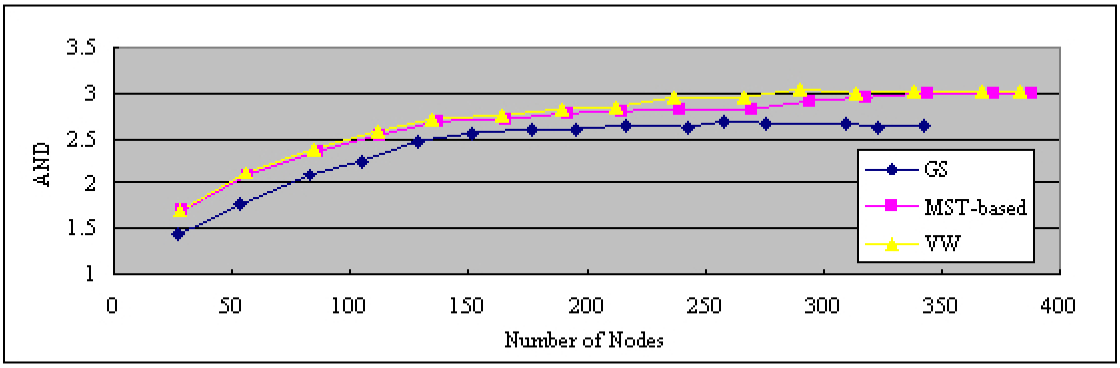
(a) NLOS environments with light obstacles (7dB).



(b) NLOS environments with light obstacles (15dB).

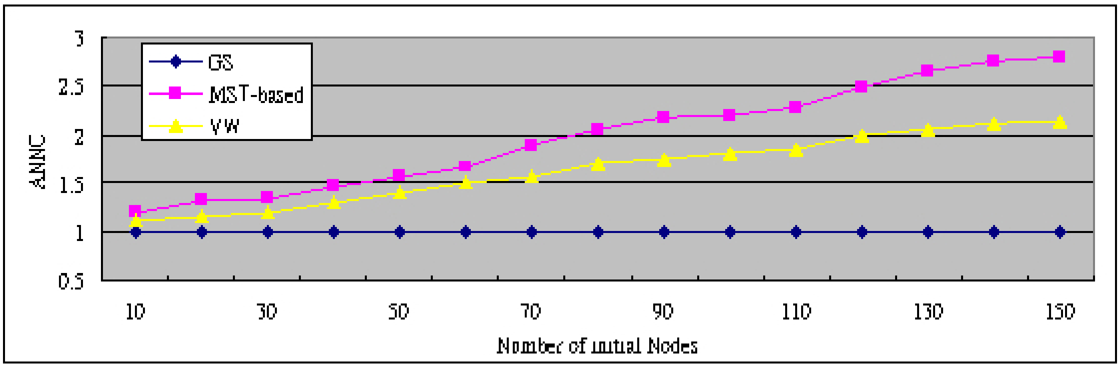


(c) NLOS environments with heavy obstacles (7dB).

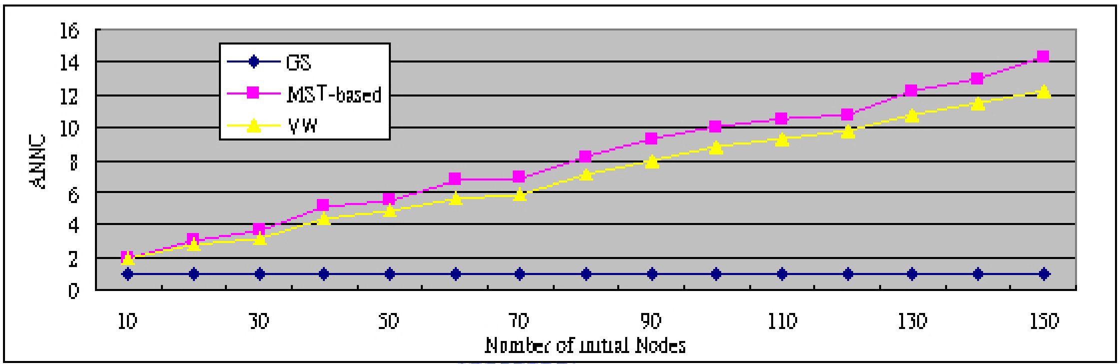


(d) NLOS environments with heavy obstacles (15dB).

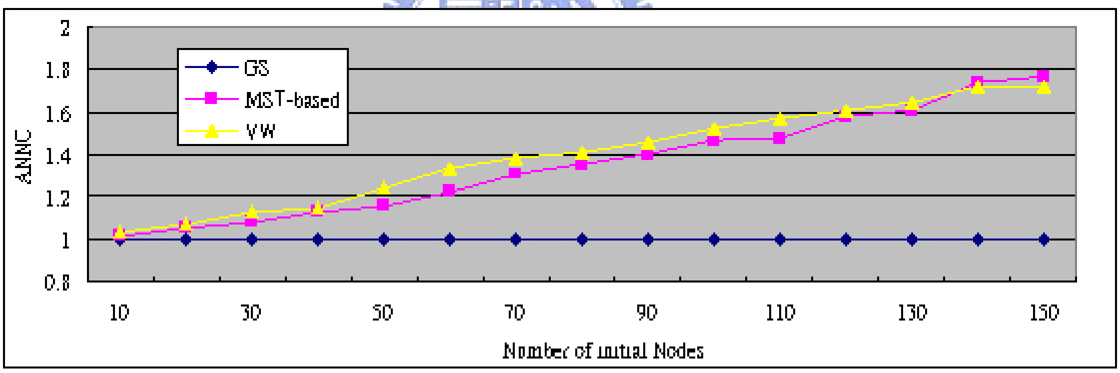
Figure 4-20. AND versus number of initial nodes in NLOS environment.



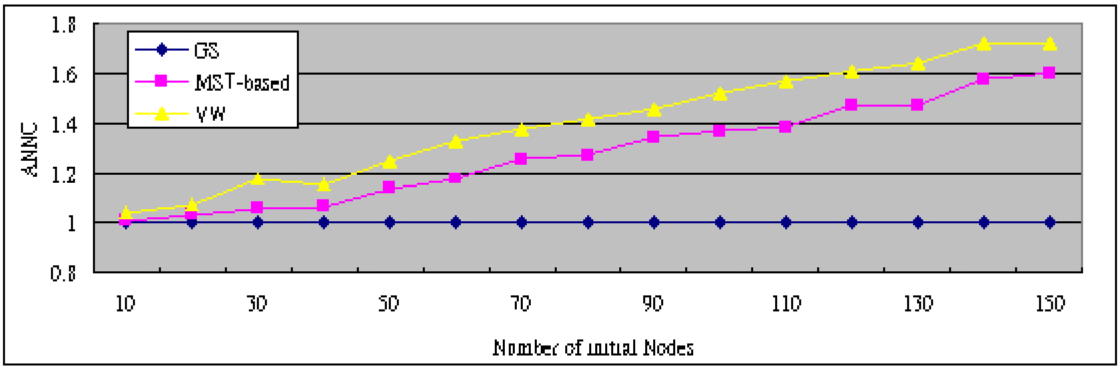
(a) NLOS environments with light obstacles (7dB).



(b) NLOS environments with light obstacles (15dB).



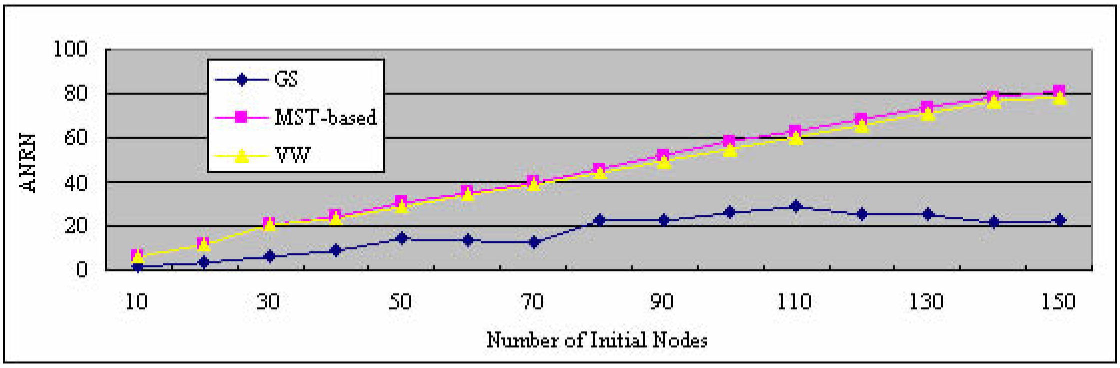
(c) NLOS environments with heavy obstacles (7dB).



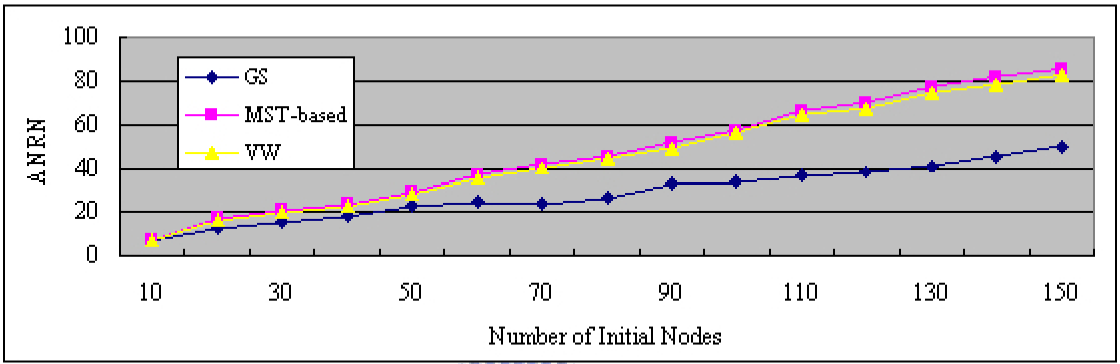
(d) NLOS environments with heavy obstacles (15dB).

Figure 4-21. ANNC versus number of initial nodes in NLOS environment.

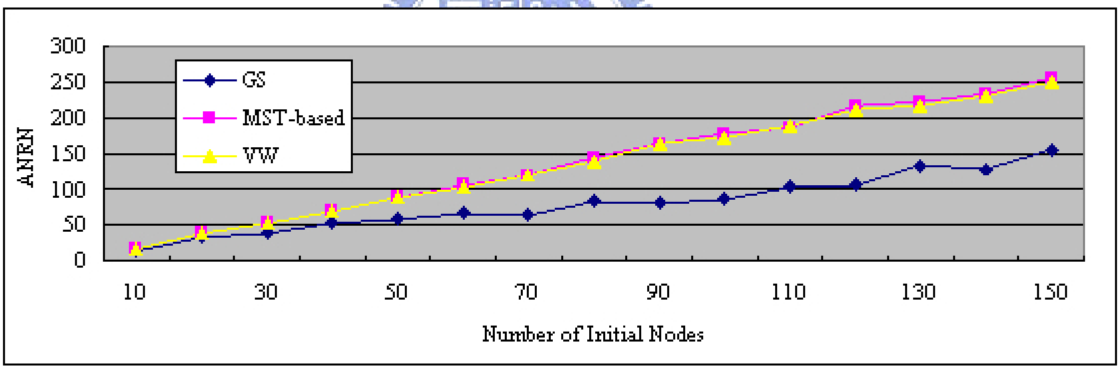
Furthermore, the simulation results obtained in NLOS environment with small-scale fading effect are present in the following figures. Figure 4-22 and Figure 4-23 show the ANRN and improvement ratio of ANRN, respectively. The average improvement ratios of ANRN are 48.95% and 31.9% with light obstacles and heavy obstacles, respectively. It is also found that the improvement ratios are slightly larger than prior results in Figure 4-19. Figure 4-24 and Figure 4-25 depict the AND and ANNC, respectively. It is shown that the GS has less AND than other methods, but always provides connected WSNs after deploying relay nodes.



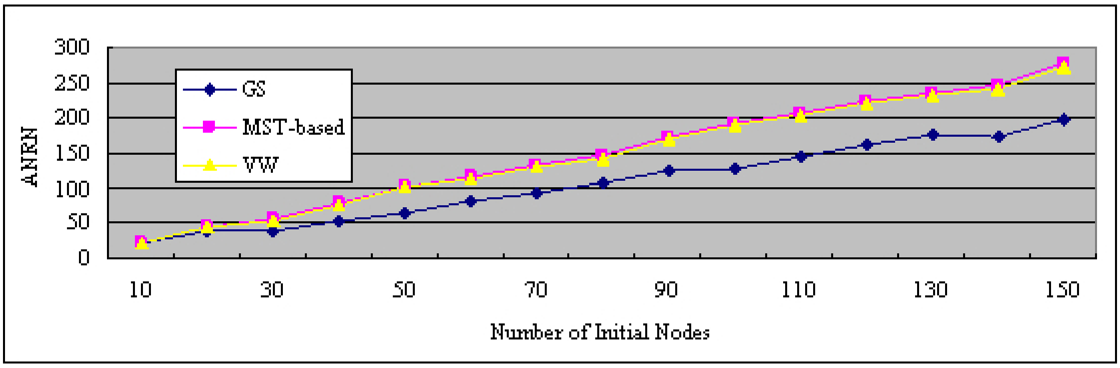
(a) NLOS environments with light obstacles and small-scale fading (7dB).



(b) NLOS environments with light obstacles and small-scale fading (15dB).

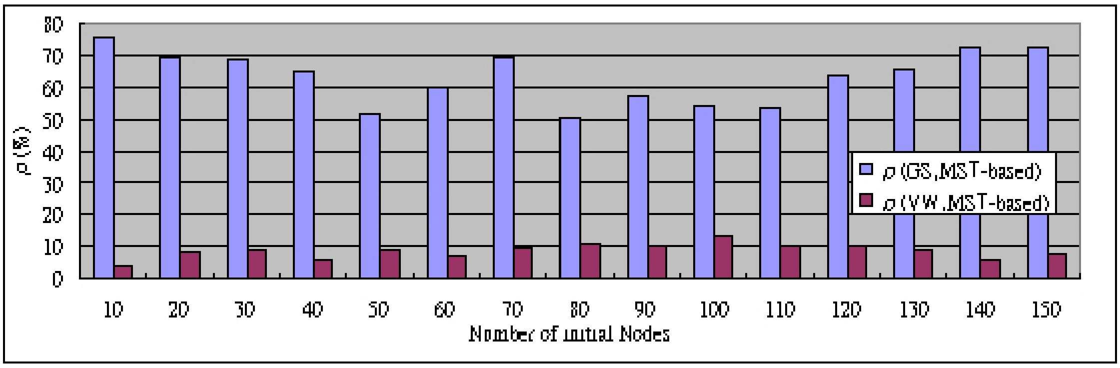


(c) NLOS environments with heavy obstacles and small-scale fading (7dB).

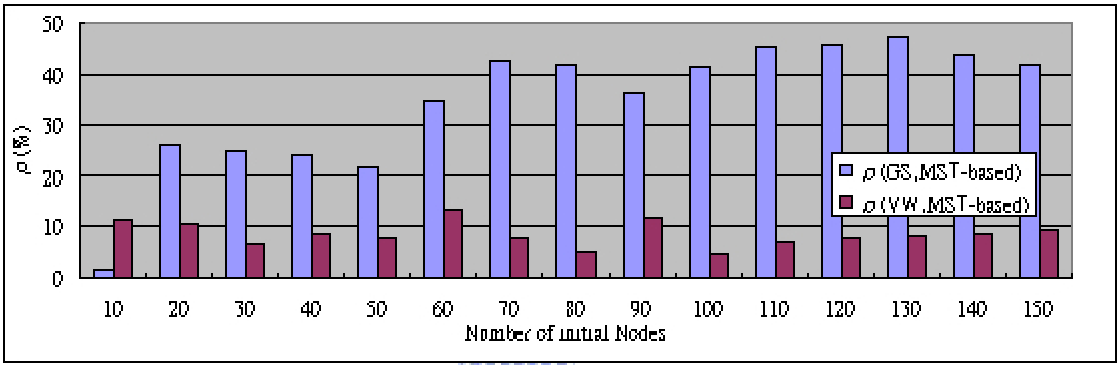


(d) NLOS environments with heavy obstacles and small-scale fading (15dB).

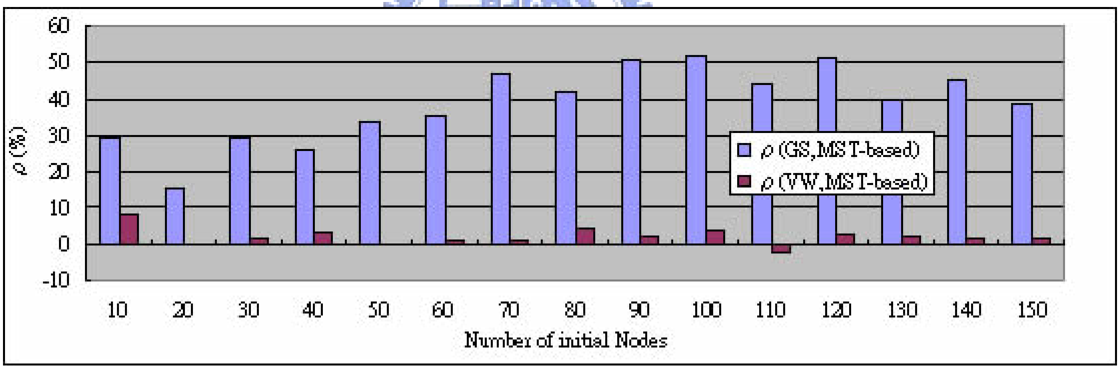
Figure 4-22. ANRN versus number of initial nodes in NLOS environment.



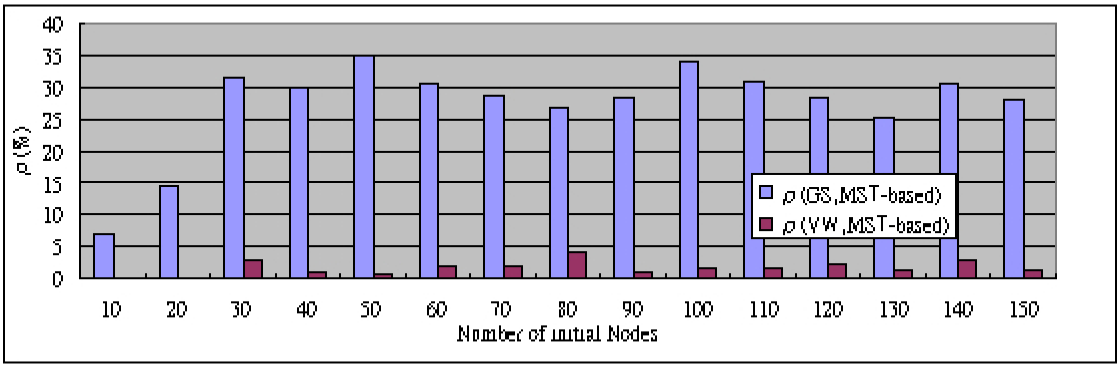
(a) NLOS environments with light obstacles and small-scale fading (7dB).



(b) NLOS environments with light obstacles and small-scale fading (15dB).

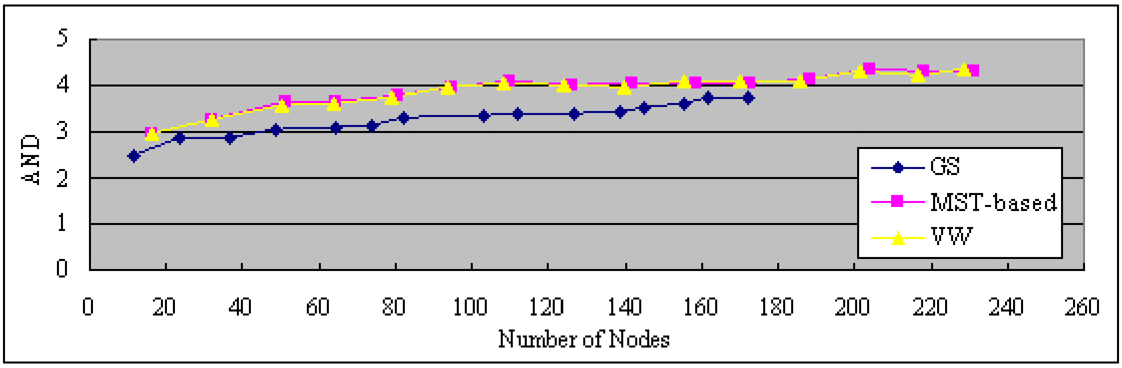


(c) NLOS environments with heavy obstacles and small-scale fading (7dB).

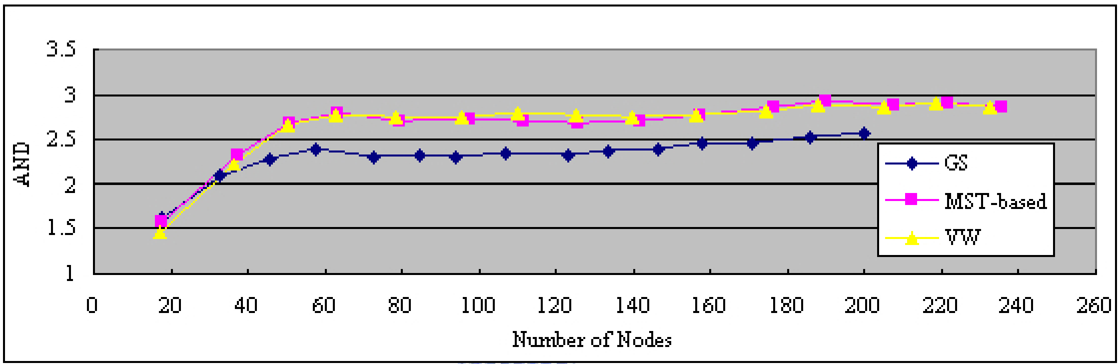


(d) NLOS environments with heavy obstacles and small-scale fading (15dB).

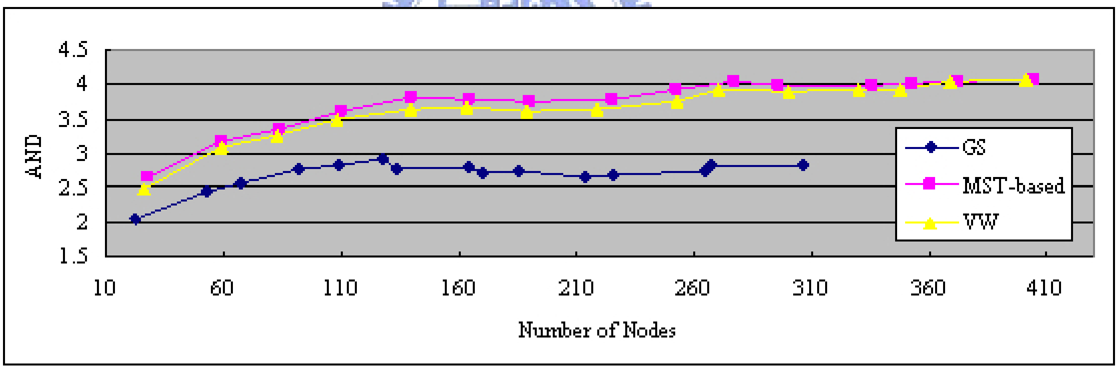
Figure 4-23. Improvement ratio of ANRN versus number of initial nodes in NLOS environment.



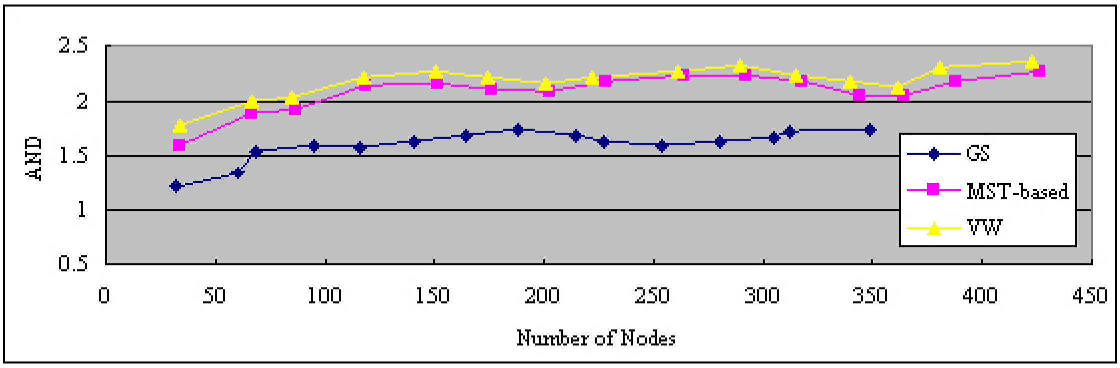
(a) NLOS environments with light obstacles and small-scale fading (7dB).



(b) NLOS environments with light obstacles and small-scale fading (15dB).

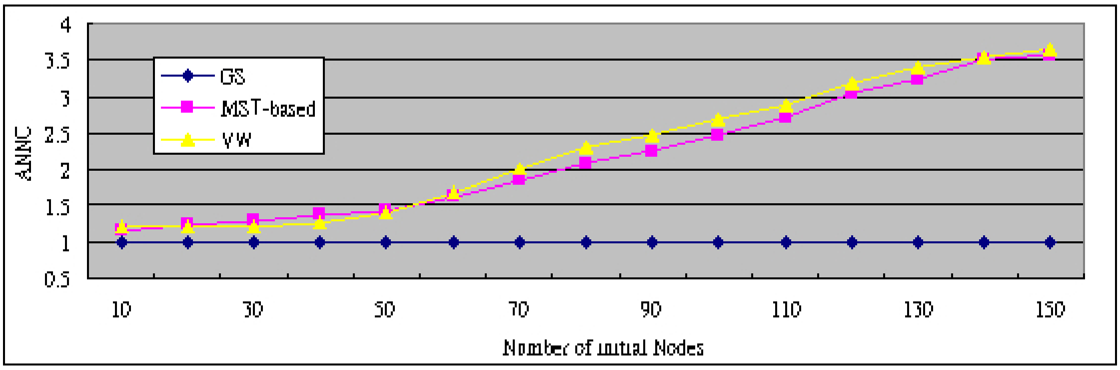


(c) NLOS environments with heavy obstacles and small-scale fading (7dB).

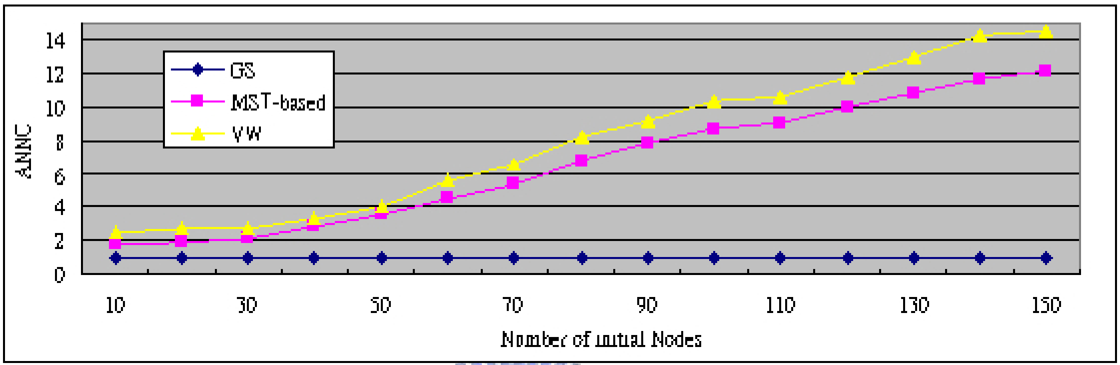


(d) NLOS environments with heavy obstacles and small-scale fading (15dB).

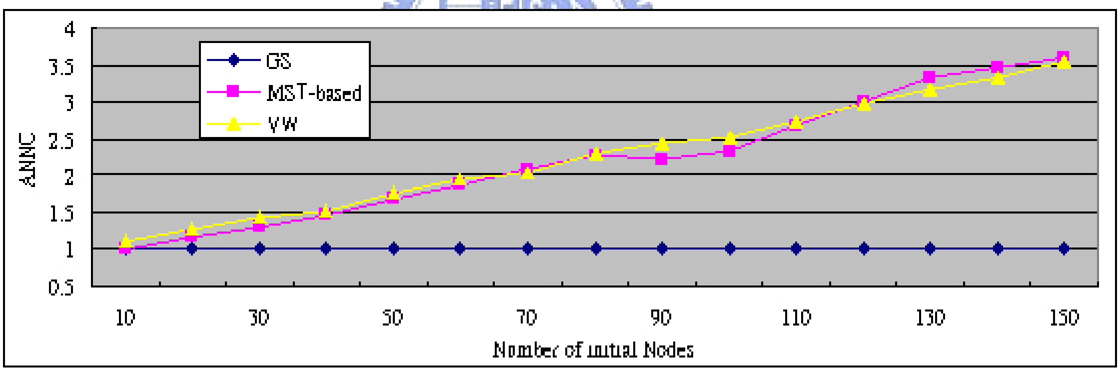
Figure 4-24. AND versus number of initial nodes in NLOS environment.



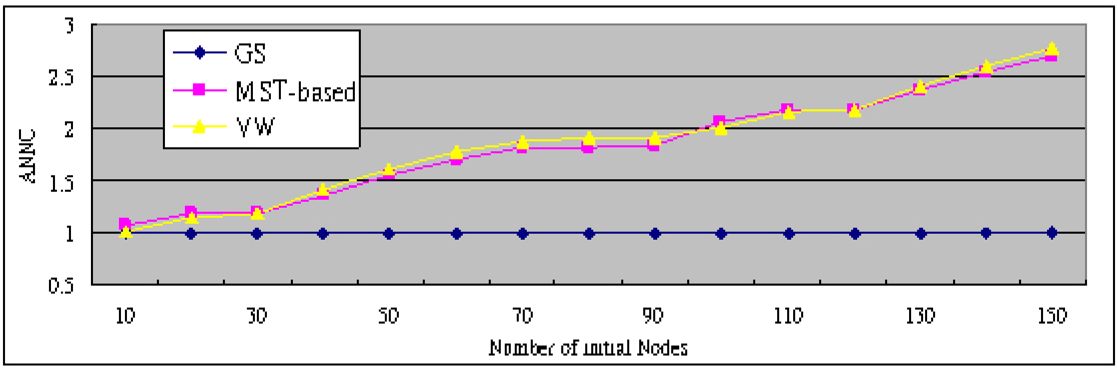
(a) NLOS environments with light obstacles and small-scale fading (7 dB).



(b) NLOS environments with light obstacles and small-scale fading (15 dB).



(c) NLOS environments with heavy obstacles and small-scale fading (7 dB).



(d) NLOS environments with heavy obstacles and small-scale fading (15 dB).

Figure 4-25. ANNC versus number of initial nodes in NLOS environment.

5. Conclusion

In this research, we propose a relay node deployment method, named as Greedy-Search (GS) method, for placing additional relay nodes to improve the network connectivity of disconnected WSNs. By using a geometric search algorithm, every relay node is placed at a proper location, which results in significant reducing the number of required relay nodes. Besides, by considering radio propagation effect, a realistic model for estimating the connectivity of a radio link is proposed, which yields accurate network topology determination especially for applying the method in indoor environment. Simulation results prove that the proposed method has the best performance in average number of relay nodes comparing to related works. It is found that the proposed method provides significant improvements on ANRN comparing to related works, when the node density is in the region of 0.002~0.011 nodes/m^2. The average improvement ratio of ANRN is 22.5%, 38.6%, and 40.9%, in LOS, NLOS with obstacles, NLOS with obstacles and small-scale fading, respectively, when the node density is equal to 1/250 nodes/m^2. It indicates that there are about 20% of improvement contributed by the proposed two dimension geometric search algorithm, and about 30% of improvement due to the accurately determining of network topology by using the proposed link connectivity estimation model. Due to the proposed method significantly reduces the number of relay nodes, it slightly decrease node degree comparing to the MST-based and VW methods. However, by examining the obtained ANNCs, the proposed method always provides connected WSNs after deploying relay nodes, especially in NLOS environment with heavy obstacles. Above all, the proposed method is an effective and efficient method for relay node deployment.

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