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A relay node deployment method for disconnected wireless sensor networks: Applied in indoor environments

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ABSTRACT

In this paper, a 2-D geometric and adaptive relay node deployment method with polynomial-time complexity is proposed to reduce relay nodes for bridging all disconnected node pairs of a wireless sensor network (WSN). In this method, proper locations for placing relay nodes are discovered on a plane, which gives a much larger degree of freedom to compare with the traditional 1-D search algorithm. In this way, the deployed relay node can bridge as many disconnected node pairs as possible around it. Besides, the method can also adapt to radio environments because that a sophisticated propagation model including large-scale path loss, shadowing, and multipath fading effects is used to estimate link connectivity. Simulation result validates its robustness and efficiency compared with the existing relay node deployment methods. The proposed method significantly reduces the total number of relay nodes compared with the related works in all of the investigated indoor environments.

1. Introduction

A wireless sensor network (WSN) is a network consisting of spatially distributed sensing devices that cooperatively observe physical/environmental conditions, such as temperature, sound, vibration, pressure, motion of objects, or pollutants (Romer and Mattern, 2004; Tubaishat and Madria, 2003). However, deploying a network with proper allocation of sensor nodes for a WSN is critical to prior operations. Two performance metrics when deploying a WSN are considered in literatures (Krishnamachari, 2006; Haenselmann, 2006; Wang et al., 2003): (1) *network coverage*, which measures the degree of covered sensing area of a given network (Huang and Tseng, 2003), and (2) *network connectivity*, which determines whether the network topology over which information routing can take place (Wan and Yi, 2004). Although it is very important to optimize the placement of sensors, it is often difficult to do that.

Connectivity of a WSN is critical to many of its fundamental operations such as data gathering, data dissemination, and peer-to-peer ad hoc routing. WSNs are by nature constructed automatically, 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. For disconnected WSNs, additional relay nodes are deployed firstly to bridge disconnected node pairs and to reduce hop count number of shortest path, which can enhance network connectivity. Secondly, it also can increase the total number of available paths between two nodes to enhance network survivability. However, finding an optimal network that reaches prior goals is NP-complete and is also constrained by applied environments. This has motivated the research with primary interest in the connectivity improvement by deploying relay nodes for disconnected WSNs. Most research effects have been concentrated on either analyzing the asymptotic connectivity of large-scale WSNs (Gupta and Kumar, 1998; Xue and Kumar, 2004; Penrose, 1997; Bettstetter, 2002) or devising topology control protocols to maintain connectivity in the presence of limited mobility (Li and Hou, 2004).

Several researchers have proposed relay node deployment methods; such as minimum spanning tree based (MST-based) (Pettie and Ramachandran, 2002) method and virtual wiring (VW) method (Vairamuthu et al., 2005) for solving related problem in practice, e.g., telemetry (Vairamuthu et al., 2005) and metropolitan-scale mesh network (Audeh, 2004). In the MST-based method, sensor nodes of a given WSN are firstly grouped into network clusters, where a network cluster is formed by a set of initially connected nodes. In order to merge these clusters, the MST-based method constructs a tree with a minimum-cost link set, i.e., the minimum spanning tree. Thereafter, the method deploys relay nodes along the links of the tree to connect these clusters. The MST-based method is a straightforward solution for

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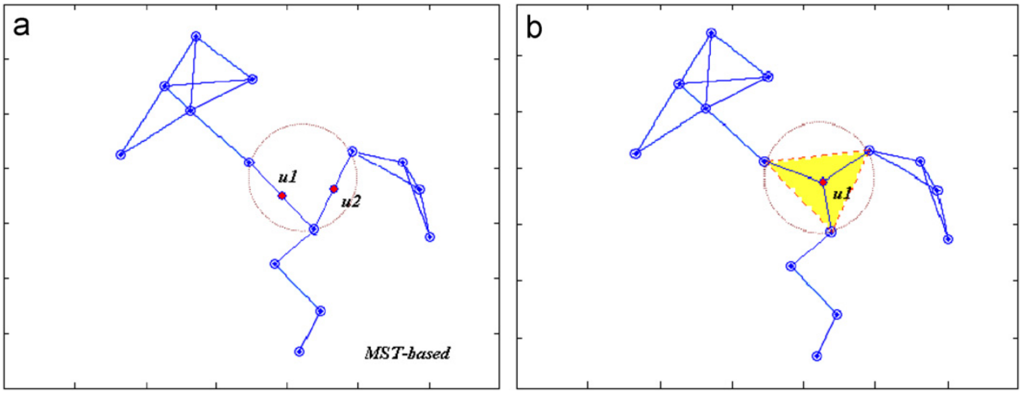

Fig. 1. An example of relay node deployment: (a) two nodes are deployed by using the MST-based method, and (b) an optimal deployment that requires only one relay node.

deploying relay nodes. Its shortcoming is, however, that each relay node can only be used to connect at most two clusters. As shown in Fig. 1(a), the MST-based method would have placed two relay nodes to connect all three clusters, while in fact one node (placed at the position of u_1 in Fig. 1(b)) is sufficient. Here the MST-based method is regarded as a baseline method for performance comparisons in this research. In the VW method, every disconnected node pair in a WSN is connected by placing required number of relay nodes along the corresponding virtual wire, which is a straight line between the disconnected node pair. Although the VW method considers not only the network connectivity but also survivability, it may not provide an efficient solution in minimizing the total number of relay nodes.

In this paper, we propose a relay node deployment method, which aims to reduce the total number of relay nodes effectively. Under the assumption of meshed network topologies and shortest path (minimum-hop) routing protocols are utilized, proper locations for deploying relay nodes are discovered on a 2-D plane. This method should be better than the MST-based and VW methods (that are based on 1-D search algorithm) by nature as these relay nodes are allocated on a horizontal plane, which gives a large degree of freedom. With the proposed method, a deployed relay node can enlarge in bridging number of disconnected node pairs around it. In addition, a sophisticated propagation model including shadowing and multipath fading is employed in estimating link connectivity, which can reflect radio channel effects more properly to compare with the traditional model, the unit disk graph model (Khadar and Simplot-Ryl, 2007) utilized by most of the existing works. To the best of our knowledge, paper (Li and Hou, 2005) presents a 2-D relay node deployment method, named as the connectivity improvement Delaunay triangulation (CIDT). This method constructs a Delaunay triangulation in the disconnected network, and place relay nodes in selected triangles. We also made comparison with this method based on simulation results.

2. The proposed relay node deployment method

2.1. Problem statement

Given a set of initial sensor nodes to form a disconnected WSN, solving the problem of deploying as few as relay nodes to yield a connected WSN is our major goal. Let $\mathbf{V}=\{v_1, v_2,\ldots, v_n\}$ is the set of sensor nodes and there exists a link formed by a 1-hop path between any node pairs in $\mathbf{V}$ and is denoted by (v_a, v_b), $v_a, v_b \in \mathbf{V}$. Therefore, the topology of a WSN is represented by an undirected simple geometric graph $\mathbf{G}=(\mathbf{V}, \mathbf{E})$ in a Euclidean plane $\mathbf{R}^2$, where $\mathbf{E}$ is the set of connected links and is defined by $\mathbf{E}=\{(v_b, v_b): l(v_b, v_b)>\lambda,\ v_b, v_b\in \mathbf{V}\}$. Here $l(v_b, v_b)$ denotes the probability that the message transmitted by node v_b is received by node v_b, and λ is a threshold value. For every source and destination pair (SD pair) (i, j) in $\mathbf{V}$, if there exists a connected route, which is a path formed by a set of connected links in $\mathbf{E}$, the graph $\mathbf{G}$ is connected. Otherwise, the graph $\mathbf{G}$ is disconnected and the network is regarded as a disconnected WSN.

Here, a relay node deployment method is designed to insert a set of additional relay nodes $\mathbf{U}=\{u_1, u_2,\ldots, u_k\}$ in a disconnected WSN in order to yield a connected topology $\mathbf{G}^*=(\mathbf{V}^*, \mathbf{E}^*)=(\mathbf{V}\cup\mathbf{U}, \mathbf{E}^*)$, where $\mathbf{E}^*$ is the set of connected links in the augmented graph $\mathbf{G}^*$ and is defined by $\mathbf{E}^*=\{(v_c, v_d): l(v_c, v_d)>\lambda,\ v_c, v_d \in\mathbf{V}^*\}$.

2.2. The proposed method

The flowchart of the proposed relay node deployment method, named as 2-D geometric and adaptive (2DGA) method, is given in Fig. 2. Firstly, with a given WSN, the link connectivity of every link is estimated by the proposed estimation method and the topology of the network is determined. Then, the SD pairs without any connected route are regarded as disconnected SD pairs. If there exists disconnected SD pairs in the network, a 2-D geometric deploying algorithm is employed to discover candidate locations for deploying relay nodes and places a relay node at the best location among candidates. The processing flow repeats until none of disconnected SD pairs exists in the augmented network. In the following paragraphs, we elaborate on the procedures in the proposed method.

2.2.1. Estimate link connectivity

In order to devise a relay node deployment method to be able to adapt radio environments, a sophisticated propagation model including large-scale path loss, shadowing, and multipath fading effects is employed to estimate link connectivity. The connectivity of a link from node a to node b, $l(a, b)=s_{ab}$, is defined as the probability of the received signal power $R(a, b)$ exceeding a threshold value δ, i.e., $s_{ab}=\mathrm{Prob.}\{R(a, b)>\delta\}$, where $R(a, b)$ is represented by a continuous random variable which takes into account radio propagation effects. It is noted that the probabilistic distribution function for the $R(a, b)$ random variable should be selected adaptive to the propagation environment where sensor nodes and relay nodes are located. Proper distributions for either outdoor or indoor environments are available in literature (Rappaport, 2001; Bettstetter and Hartmann, 2003). However, the indoor applications are our major concern and the applied $R(a, b)$ is presented in Section 3 for further investigation.

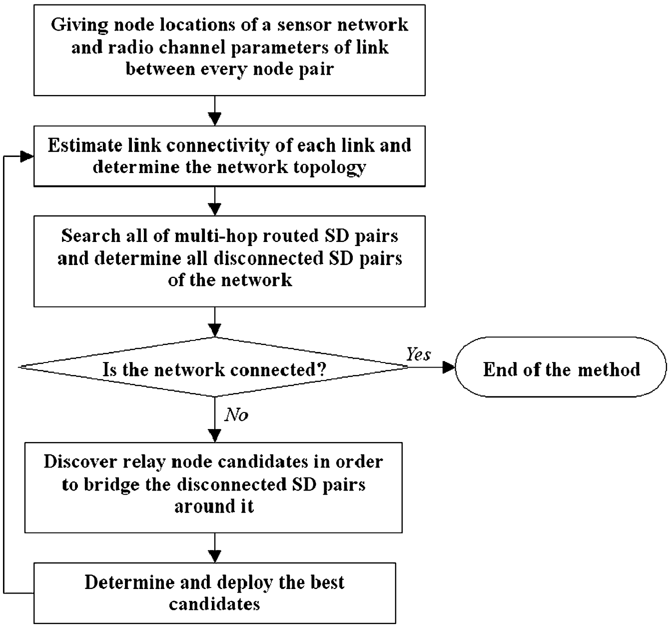

Fig. 2. The flow chart of the 2-D geometric and minimum relay nodes (2DGMRN) method.

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Procedure: 2DGD(D)
begin
1:  $C \leftarrow \Phi$;
        // C denotes the set containing candidate relay nodes
2:  while D is not empty do
3:      Select SD pair $(i, j)$ in D with maximum route connectivity;
4:      Put a relay node $\alpha$ on the line $ij$, which yields $s_{\alpha i} = s_{\alpha j}$;
5:      $I_\alpha \leftarrow \{i, j\}$; $c \leftarrow \alpha$;
            // $I_\alpha$ denotes a set of nodes bridged by node $\alpha$; $c$ denotes a candidate relay node.
6:      $K_{ij} \leftarrow \{k: \exists k \in (V - \{i, j\}), (k, i) \in D \text{ or } (k, j) \in D\}$;
            // $K_{ij}$ denotes the set of nodes disconnected with either node $i$ or node $j$.
7:      for select $m$ in $K_{ij}$ where pair $(m, i)$ and $(m, j)$ lead to maximum average of
        their route connectivity do
8:          $I_\alpha \leftarrow I_\alpha \cup \{m\}$
9:          Put the relay node $\alpha$ on line $m\alpha$, which yields the maximum $\sum_{\exists n \in I_\alpha} s_{\alpha n}$;
10:         if $\left( \sum_{\exists n \in I_\alpha} s_{\alpha n} / |I_\alpha| \right) < \lambda$ then $C \leftarrow C \cup \{c\}$; goto step 14;
11:         else $c \leftarrow \alpha$, $K_{ij} \leftarrow K_{ij} - \{m\}$;
                // $\alpha$ is a feasible, record $\alpha$ in $c$.
12:         end if
13:     end do
14:     $D \leftarrow D - \{(u, v) : u, v \in I_\alpha\}$
            // Discard examined SD pairs from D.
15: end do
16: return C
end
```

Fig. 3. The pseudo code of the proposed 2-D geometric deployment algorithm.

2.2.2. *Determine disconnected SD pairs*

With the estimated link connectivity, the network topology would be represented by a probabilistic graph (Khadar and Simplot-Ryl, 2007; Stojmenovic et al., 2005). In the graph, there would exist multiple routes between a given SD pair, where a route is a path formed by a set of links. Here the shortest path (minimum-hop) routing algorithm is utilized as a baseline routing method. However, in order to determine the disconnected SD pairs in a probabilistic graph, the best route of every SD pair that with the maximum route connectivity is discovered by using a search algorithm modified from the well-known all-pairs shortest path search algorithm (Cormen et al., 1990). Here the route connectivity of a SD pair (i, j) is given by

$$w_{\mathbf{p}_{ij}} = \prod_{\exists (a,b) \in \mathbf{p}_{ij}} s_{ab}, \quad \forall \mathbf{p}_{ij} \in \mathbf{P}_{ij} \tag{1}$$

where $\mathbf{P}_{ij}$ is the set formed by all routes with source node i and destination node j; $\mathbf{p}_{ij}$ the denotes a route in $\mathbf{P}_{ij}$; and s_{ab} the connectivity of a link (a, b) belonging to route $\mathbf{p}_{ij}$.

With Eq. (4), the best route $\mathbf{q}_{ij}$ for SD pair (i, j) is found. However, we need to justify whether the best route is connected or not. Here an SD pair (i, j) is connected when the following conditions are met: (1) $w_{\mathbf{q}_{ij}}$ is larger than a threshold $\kappa = \lambda^h$, where h denotes the maximum possible hop count number for constructing a route in the network. Here, $h = 7$, and (2) every link in $\mathbf{q}_{ij}$ with its link connectivity is larger than λ. The SD pairs that do not fulfill the above conditions forms a set of disconnected SD pairs, denoted by **D**. The flow of the proposed method stops when **D** is empty. Otherwise, the method starts to deploy proper relay nodes in order to bridge the SD pairs in **D**.

2.2.3. *Discover relay node candidates*

With disconnected SD pairs, relay node candidates for bridging these SD pairs are discovered by the proposed 2-D geometric deploying algorithm. The pseudo code of proposed algorithm is depicted in Fig. 3. Firstly, one SD pair in D need to be selected for further relay node discovering. From our preliminary study, three criteria for selecting SD pair, including (1) select the SD pair with max route connectivity, (2) select the SD pair with min route connectivity, and (3) select SD pair randomly, have been investigated. The SD pair with maximum route connectivity usually leads to better solution than other criteria and is utilized in step 3. A relay node candidate is discovered from steps 4 to 13. It fulfills the requirements that the node is close to the disconnected SD pair found in step 3 and bridges as many as possible other disconnected SD pairs around it. The disconnected SD pairs that are bridged by the relay node candidate are removed from **D** in step 14, and the procedure repeats until D is empty.

2.2.4. *Deploy relay nodes*

The best relay node is selected from the candidates discovered by the previous process by using the following metrics:

- $|\mathbf{B}_c|$, the number of disconnected SD pairs that could be bridged by deploying a relay node candidate c, where

  $\mathbf{B}_c = \{(a, b) : \exists (a, b) \in \mathbf{D}, \quad s_{ca} > \lambda \text{ and } s_{cb} > \lambda\}$
- $|\mathbf{N}_c|$, the number of neighboring nodes of a relay node candidate c, where

  $\mathbf{N}_c = \{m : \exists m \in V, \quad s_{cm} > \lambda\}$
- s_c^{avg}, the averaged link connectivity of the links connecting relay node candidate c and its neighboring nodes, where

  $$s_c^{\text{avg}} = \frac{1}{|\mathbf{N}_c|} \sum_{m \in \mathbf{N}_c} s_{cm}$$

Here the maximum $|\mathbf{B}_c|$ is the first criteria to screen candidate locations of relay nodes. If more than one candidate is left, the maximum $|\mathbf{N}_c|$ is the second criteria for screening. If again more than one candidate is left, maximum s_c^{avg} criteria are applied. Fig. 4 depicts network topologies of an initial network and the augmented networks after deploying relay nodes by using the proposed method, the MST-based method, and the VW method, respectively. It is obvious that most of relay nodes are placed at proper locations by using the proposed method. These relay nodes can bridge more initial nodes compared with that of the MST-based or the VW method, which effectively reduce the

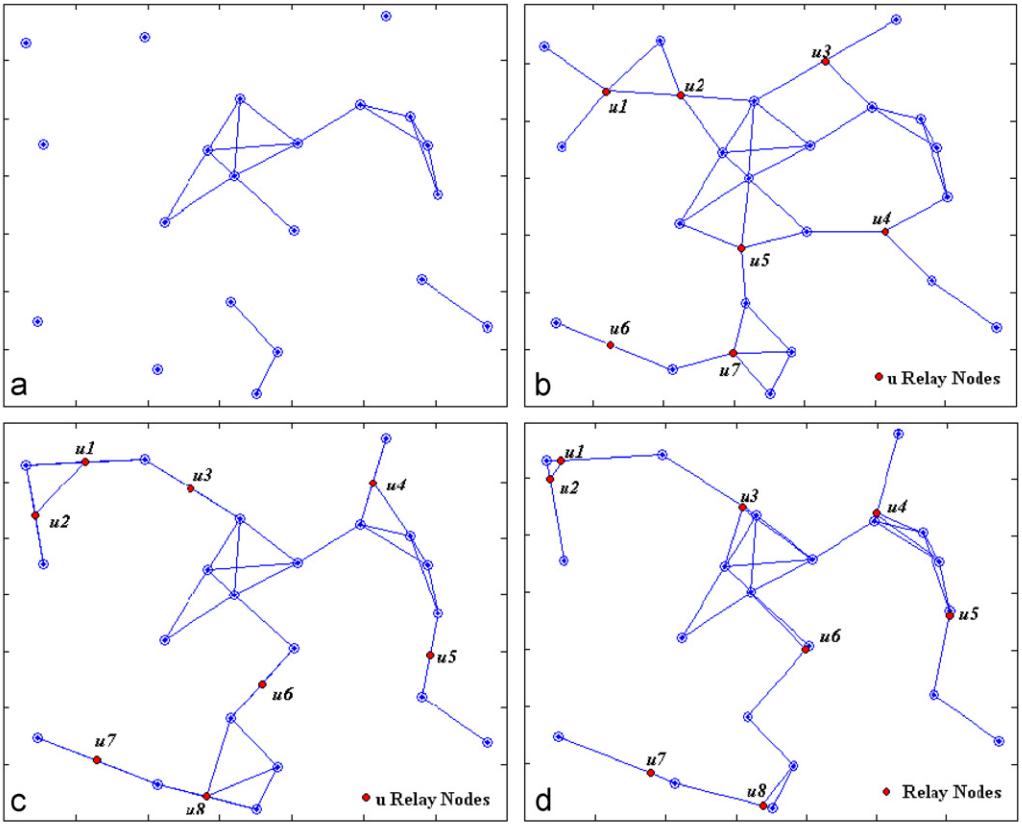

Fig. 4. Network topologies of an initial network and the augmented networks after deploying relay nodes: (a) the initial network, (b) augmented network by using the proposed method, (c) augmented network by using the MST-based method, and (d) augmented network by using the VW method.

number of required relay nodes for constructing a connected network.

2.2.5. Complexity of proposed method

From the problem statement and Fig. 1, the proposed method is divided into multiple parts. Let $V = |\mathbf{V}|$ that denotes the nodes number of a WSN G and $D = |\mathbf{D}|$ denotes the number of disconnected SD pairs in G. The running time of link connectivity estimation would be $O(V^2)$ and the determination of disconnected SD pairs is based on the all-pairs shortest path search algorithm which has its complexity as $O(V^3 \log V)$ (Cormen et al., 1990). As to the 2DGD algorithm, for each (i, j) pair in $\mathbf{D}$, it takes $|K_{ij}|$ times for discovering the candidate relay node, which leads to a overall time complexity as $O(DV)$. Due to only one relay node is deployed within one iteration, the total time complexity of the whole method would be $O(D^*(V^2+V^3 \log V+DV)) = O(DV^3 \log V)$.

3. Simulation results and comparisons

In order to evaluate the performance of the proposed relay node deployment method, some performance metrics are computed in solving a disconnected WSN. For comparison, related works, including the MST-based and VW node deployment methods are also evaluated. These methods are implemented and simulated by using the MATLAB toolboxes (MATLAB Version 7.2.0.232 (R2006a)). The following performance metrics are considered:

(1) *Averaged number of relay nodes* (ANRN): It is defined as the average number of deployed relay nodes over the samples. The less the relay nodes are required, the more efficient the method is. For comparison, we further examine the reduction ratio of ANRN, which is defined as

$$\rho(A, B) = -\frac{\text{ANRN difference between methods } A \text{ and } B}{\text{ANRN using method } B}$$

where method B denotes a benchmark method. Here the MST-based method is chosen as a benchmark.

(2) *Averaged node degree* (AND): It is defined as the average number of node degree over the samples, where the node degree is defined as the average number of neighbors of all nodes in a WSN.

(3) *Averaged number of network clusters* (ANNC): It is the average number of network clusters of the augmented network over the samples. A cluster is formed by a group of connected nodes that belong to the network. It is noted that the number of network cluster is equal to 1 when the network is connected.

From Section 2.1, since indoor applications are our major concern, the received power in decibels (dB) is described by a model including large-scale path loss, shadowing, and multipath fading effects and is given by (Rappaport, 2001)

$$P_{\mathrm{R}}(a,b) = P_{\mathrm{T}}(a,b) - [\mathrm{PL}(d_{ab}) + \sum_{t\in\mathbf{T}} N_t\, \mathrm{PAF}_t + (r - \bar{r})] \quad (\mathrm{dB}) \tag{2}$$

where $P_{\mathrm{T}}(a, b)$ denotes the transmitted power of node a in dB and $\mathrm{PL}(d_{ab})$ represents the large-scale path loss in dB with propagation distance d_{ab} and is equal to

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

Here, PL(d_0) is the path loss of reference distance d_0; n is the path loss exponent; t denotes a type of partition in a enumerative set $\mathbf{T}$, e.g., $\mathbf{T}=\{$plasterboard, brick wall, concrete block wall$\}$; N_t is the number of type t partitions; PAF$_t$: is the unit partition loss in dB of type t partition; $r-\bar{r}$: a zero-mean random variable which represents the non-coherent part of multipath fading effect, which is mainly due to local scatters.

Table 1
Measured value of 2.45 GHz indoor radio channel parameters

	Radio channel parameters	Measured value
PL(d_0)	Reference path loss (d_0) (dB)	15 (avg.)
n	Path loss exponent	1.8–3
PAF$_P$	Partition loss of a plasterboard (dB)	5–9
PAF$_B$	Partition loss of a brick wall (dB)	7–15
PAF$_C$	Partition loss of a concrete wall (dB)	13–17

Since it is assumed that the received signal amplitude follows a Rayleigh distribution, after some derivation, s_{ab} is given by

$$s_{ab}=\exp\left(-\frac{\delta}{1.2733\overline{R(a,b)}}\right) \tag{4}$$

where $\overline{R(a,b)}$ denotes the mean of the received signal power from node a to node b.

It is noted that initial nodes of each sample are randomly distributed in a $150\times150\,\mathrm{m}^2$ area, and each value of the performance metrics is averaged over 200 samples. In simulation, two types of propagation scenarios are considered: (1) all direct

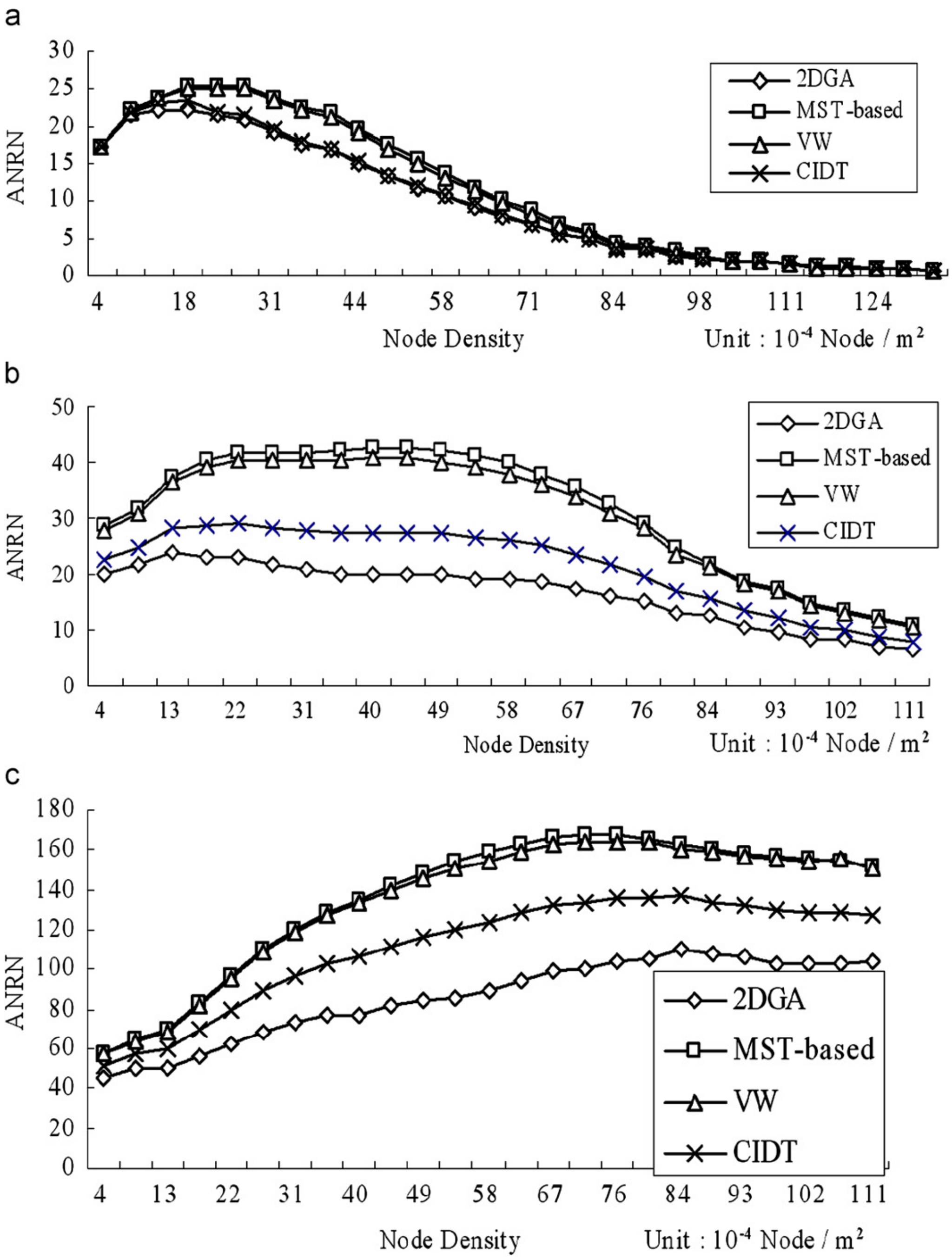

Fig. 5. The ANRNs versus node density: (a) in LOS situation, (b) in NLOS with light blockage, and (c) in NLOS with heavy blockage.

paths are not blocked, and (2) part of the direct paths are blocked by one, two, or three walls. In the second type, the percentage of zero, one, two, or three blockage is given as the followings: (1) light blockage: 50%, 50%, 0%, and 0%, respectively; and (2) heavy blockage: 25%, 25%, 25%, and 25%, respectively. Here, sufficient field measurements have been carried out at 9th floor of Engineering Building Four in the National Chiao-Tung University, to abstract value of indoor channel parameters such as PL(d_0), n, and PAF$_t$. Their ranges are shown in Table 1 (d_0 is equal to 1 m).

According to the above table, for simplification, PAF$_t$ is chosen as 7 dB and PL(d_0) = 15 dB for simulation. In LOS (line-of-sight) situations, n is equal to 2.5. In non-line-of-sight (NLOS) situations, n is ranged from 2 to 3 due to diversified indoor environments compared with LOS situations.

Fig. 5 depicts the ANRN versus node density and shows that the proposed method always yields less number of relay nodes than other methods. It is noted that the proposed method provides significant reductions of ANRN compared with MST-based and VW methods in most of samples but trivial

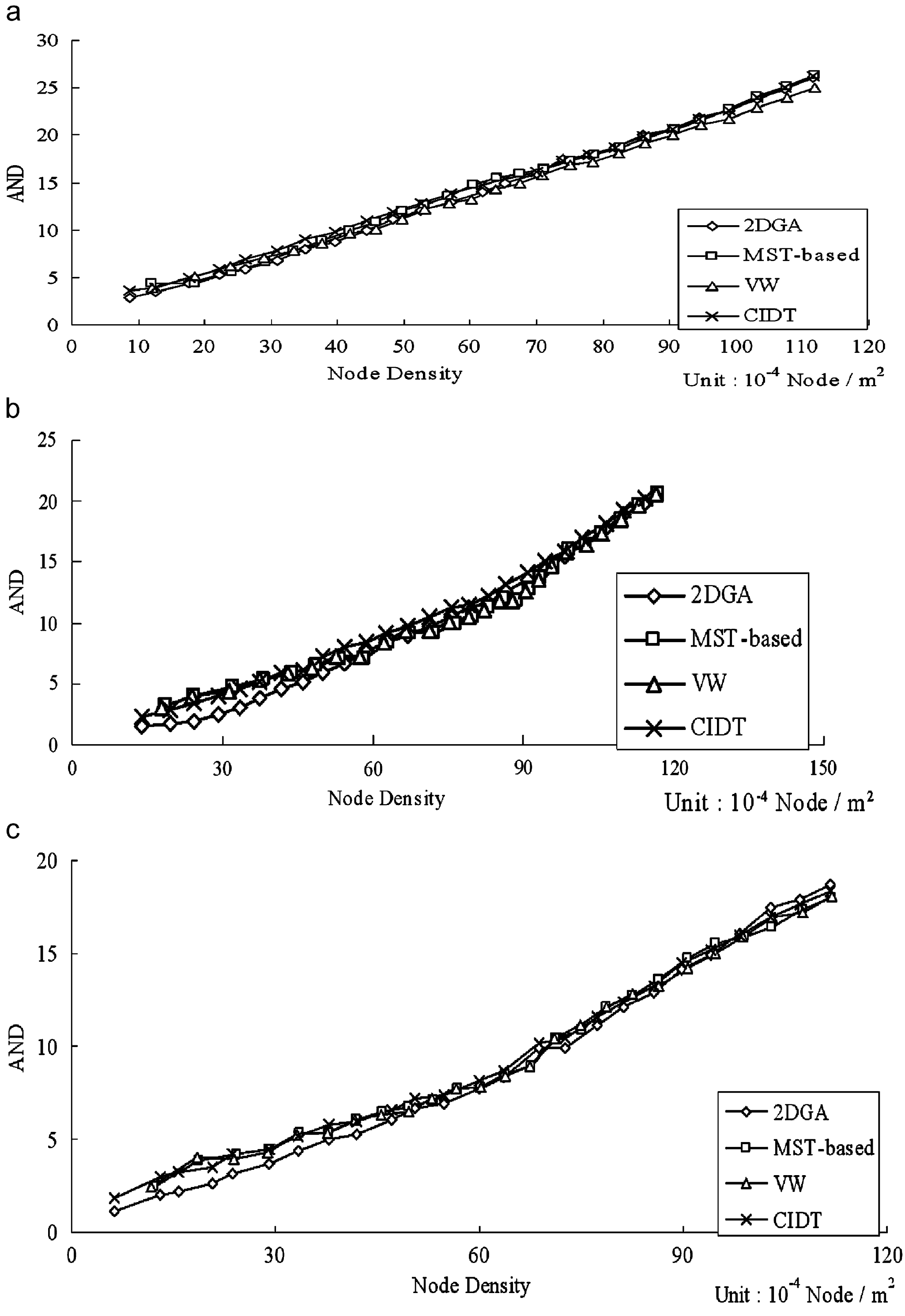

Fig. 6. The ANDs versus node density: (a) in LOS situation, (b) in NLOS situation with light blockage, and (c) in NLOS situation with heavy blockage.

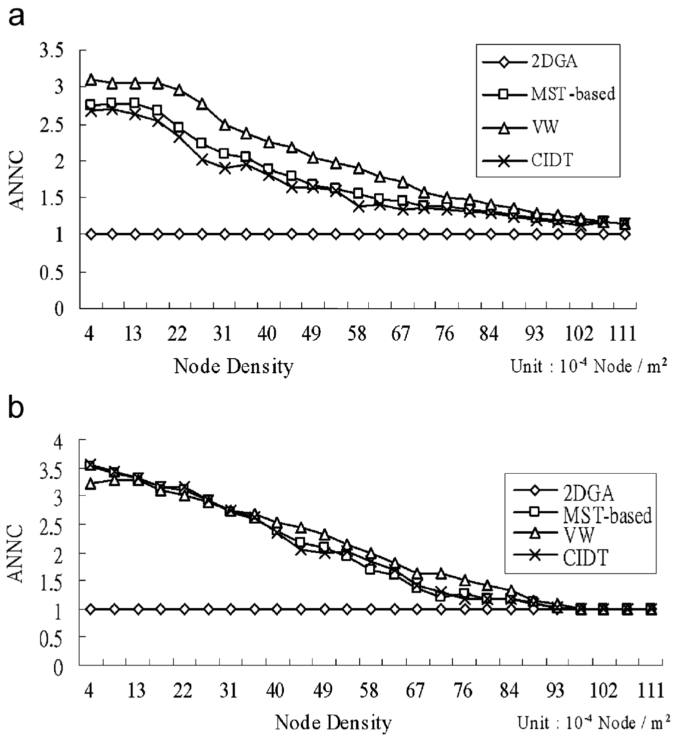

Fig. 7. The ANNCs versus node density: (a) in NLOS situation with light blockage, and (b) in NLOS situation with heavy blockage.

reductions compared with CIDT in LOS situation. Besides, the reductions decrease when the node density is extremely small or is increasing. It is because that when the initial nodes are distributed sparsely (the node density is small), most of optimal locations for deploying relay nodes are on the line between disconnected SD pair, which can be effectively discovered by either 1-D or 2-D methods. It is also easy to understand that when the node density is large and there is a small need to add relay nodes. Therefore, ANRN is approaching to zero when the node density is large and increasing as well. It is found that the averaged reduction ratios of ANRN, ρ, by using the 2DGA method are 14.41%, 45.8%, and 35.8% in LOS situation, in NLOS situation with light blockage, and in NLOS situation with heavy blockage, respectively. By examining results in NLOS situations, it is found that the less the blockages, the better the reduction is obtained by using the proposed method. It is also noted that the proposed method performs better reduction than another 2-D method, i.e., CIDT, in NLOS situation. With better reduction in both NLOS and LOS situations indicates that our method is robust and is adaptive to complicated indoor radio environments.

AND versus node density is depicted in Fig. 6. The node degree of each method increases linearly with the increasing of node density in nature. It is shown that the proposed method provides near equivalent node degree comparing to other methods by deploying less number or relay nodes. As to the ANNC in NLOS situations, which is depicted in Fig. 7, the 2DGA method always provides a connected WSN after deploying relay nodes. On the other hand, the 2-D method (i.e. CIDT) without precisely estimating link connectivity would lead to near equivalent ANNC as 1-D methods. With Figs. 6 and 7, the proposed method can guarantee to provide a connected network without increasing node degree. On the other hand, all of other methods are not robust in the NLOS situation, especially when the blockage is heavy.

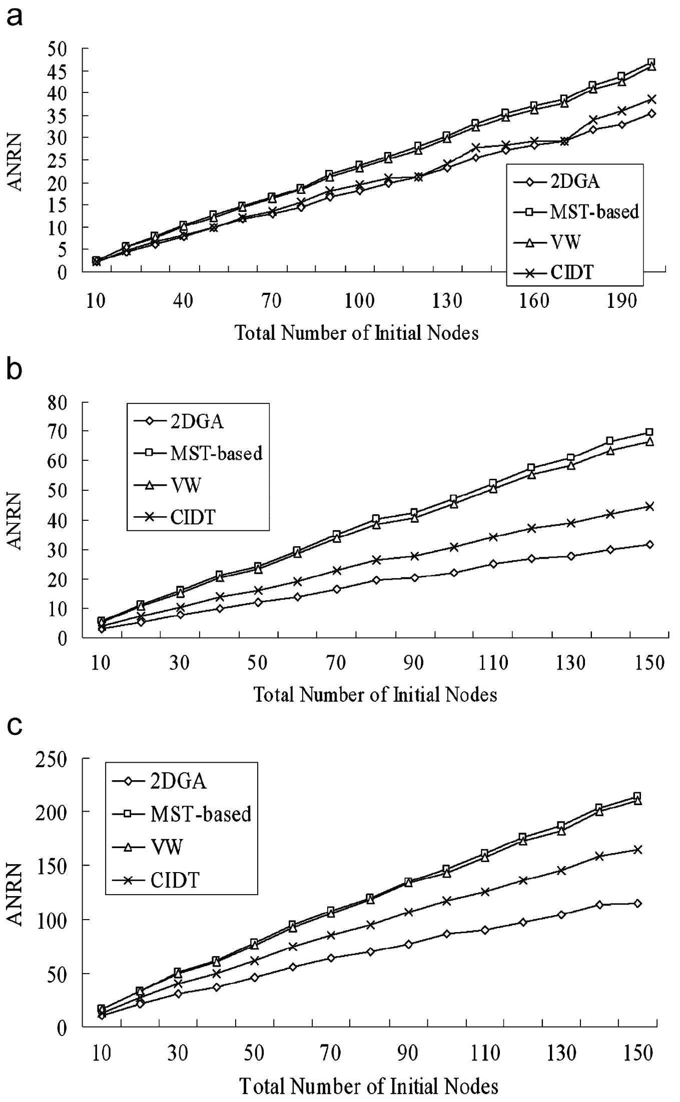

Fig. 8. The ANRNs versus number of initial nodes: (a) in LOS situation, (b) in NLOS situation with light blockage, and (c) in NLOS situation with heavy blockage.

Fig. 8 shows ANRN versus total number of initial node with constant node density as $\frac{1}{250}$ nodes/m^2. It is found that reduced ANRN is achieved in all of the investigated topology sizes compared with other methods. It is noted that ANRN increases linearly with number of initial nodes. The averaged reduction ratios of ANRN are equal to 22.5%, 52.7%, and 41.6% in LOS situation, in NLOS situation with light blockage, and in NLOS situation with heavy blockage, respectively. The proposed method always provides a connected WSN whether the number of initial nodes is small or large.

4. Conclusion

In this research, we propose a heuristic method to reduce number of relay nodes for bridging all disconnected node pairs of a randomly dispersed WSN. This method has two major advantages over the traditional methods: (1) it improves the methodology for discovering relay node locations by utilizing a 2-D search algorithm, which yields every relay node to bridge maximum number of disconnected node pairs around it; (2) it enhances the robustness of the 2-D search algorithm by employing a sophisticated radio propagation model for estimating link connectivity adaptively over applied radio environments. Simulation result validates its efficiency and robustness compared with existing methods. Above all, the proposed method is not only cost effective but also adaptive to complicated radio environments for deploying relay nodes.

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