A Dead-End Free Topology Maintenance Protocol for Geographic Forwarding in Wireless Sensor Networks

Chih-Hsun Anthony Chou, *Member*, *IEEE*, Kuo-Feng Ssu, *Member*, *IEEE*, Hewijin Christine Jiau, *Member*, *IEEE*, Wei-Tong Wang, and Chao Wang

Abstract—Minimizing energy consumption is a fundamental requirement when deploying wireless sensor networks. Accordingly, various topology control protocols have been proposed, which aim to conserve energy by turning off unnecessary sensors while simultaneously preserving a constant level of routing fidelity. However, although these protocols can generally be integrated with any routing scheme, few of them take specific account of the issues which arise when they are integrated with geographic routing mechanisms. Of these issues, the dead-end situation is a particular concern. The dead-end phenomenon (also known as the "local maximum" problem) poses major difficulties when performing geographic forwarding in wireless sensor networks since whenever a packet encounters a dead end, additional overheads must be paid to forward the packet to the destination via an alternative route. This paper presents a distributed dead-end free topology maintenance protocol, designated as DFTM, for the construction of dead-end free networks using a minimum number of active nodes. The performance of DFTM is compared with that of the conventional topology maintenance schemes GAF and Span, in a series of numerical simulations conducted using the ns2 simulator. The evaluation results reveal that DFTM significantly reduced the number of active nodes required in the network and thus prolonged the overall network lifetime. DFTM also successfully constructed a dead-end free topology in most of the simulated scenarios. Additionally, even when the locations of the sensors were not precisely known, DFTM still ensured that no more than a very few dead-end events occurred during packet forwarding.

Index Terms—Energy conservation, topology maintenance, geographic forwarding, dead-end, wireless sensor networks.

1 Introduction

A wireless sensor network consists of hundreds of sensor nodes, each equipped with the ability to sense the immediate environment, to communicate with nearby nodes through one-to-all broadcasts and to perform local computations based on information gathered from the surroundings. However, once a wireless sensor network has been deployed, network maintenance becomes difficult, if not impossible, since such networks are typically located in environments in which regular human intervention is either impossible or undesirable. The nodes in the network are battery operated, and hence, they have a limited service life since it is generally impossible to recharge the batteries once the sensors have been deployed. Accordingly, maximizing the lifetime of the network by improving the energy consumption of its nodes is a fundamental concern when designing and maintaining wireless sensor networks.

Recently, topology management schemes have emerged as a promising strategy for prolonging the lifetimes of wireless sensor networks. Several schemes have been proposed for constructing a virtual communication backbone by turning off redundant sensor nodes [1], [2], [3], [4], [5], [6], [7], [8], [9]. The most commonly employed approach involves constructing a connected dominating set (CDS) [10], [11], [12], [13], i.e., a subset of all the network nodes. The CDS is constructed in such a way that each node in the network is either a member of the subset or is a neighbor of one of the nodes in the subset. In such schemes, only those nodes belonging to the CDS are active; non-CDS members enter a sleep mode, and therefore conserve energy. To maximize the network lifetime, CDS schemes are designed specifically to ensure that each node in the network receives an equal opportunity to sleep. However, although CDS schemes can be integrated with most traditional ad hoc routing algorithms, few of them are designed to cope with the dead-end situation which may arise when they are integrated with geographic routing protocols.

Geographic routing mechanisms [14], [15], [16], [17], [18] assume that each node in the network has the ability to establish its location though the GPS system or some other form of localization technique [19], [20], [21], [22], [23]. In general, geographic forwarding strategies support a fully any-to-any communication pattern for packet forwarding

- *C.-H.A. Chou is with the Emerging Smart Technology Institute, Institute for Information Industry, 13F., No. 133, Sec. 4, Minsheng E. Rd., Taipei City 105, Taiwan, R.O.C. E-mail: chchou@iii.org.tw.*
- *K.-F. Ssu, H.C. Jiau, and W.-T. Wang are with the Department of Electrical Engineering, National Cheng Kung University, Electrical Engineering Building, No. 1 University Road, Tainan 701, Taiwan, R.O.C. E-mail: ssu@ee.ncku.edu.tw, jiauhjc@mail.ncku.edu.tw, wangwei@dcl.ee.ncku.edu.tw.*
- *C. Wang is with the Institute of Computer and Communication Engineering, National Cheng Kung University, 92627 Electrical Engineering Building, No. 1 University Road, Tainan 701, Taiwan, R.O.C. E-mail: doom.design@gmail.com.*

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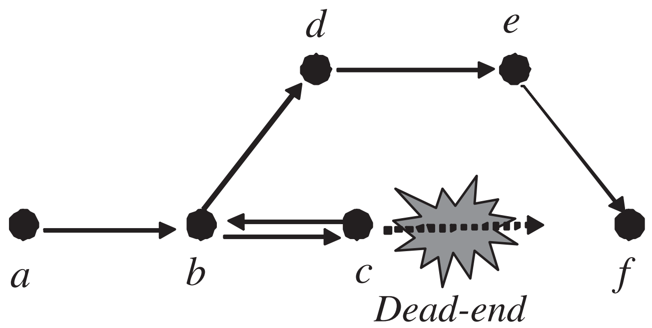


Fig. 1. Example of dead-end handling.

purposes without the need for explicit routes. As such, these schemes provide significant performance benefits compared to conventional on-demand routing schemes [24], [25], [26], [27] and have therefore emerged as an attractive solution for packet forwarding in wireless sensor networks. However, in geographic routing, a dead-end situation occurs when the current relay node is unable to locate any neighboring node closer to the packet's destination than itself. Fig. 1 illustrates the case where a packet sent from node a to node f encounters a dead end at node c. Since none of node c's neighbors are closer to node f than itself, an alternative path $(a - b - c - b - d - e - f)$ must be used to route the packet to the destination node. Although several recovery strategies have been proposed to deal with such dead-end events, the system performance is inevitably degraded as a result of the additional processes required to route the packet around the afflicted node.

This paper presents a topology maintenance scheme (designated as DFTM) for the construction of dead-end free topologies in wireless sensor networks. An initial node is chosen randomly at prescribed periodic intervals and is then used as the starting point for a global topology construction process. In constructing the topology, neighboring nodes to the initial node are activated based on their ability to satisfy the local dead-end free condition (as assessed using a local Voronoi diagram). The selected active neighbors then perform a similar activation procedure with their own neighboring nodes. This construction process continues iteratively until all the active nodes satisfy the local dead-end free (LDF) condition, and therefore, by definition, the network satisfies the global dead-end free condition (GDF).

To evaluate the performance of the proposed DFTM protocol, DFTM and two other traditional topology maintenance protocols GAF [1] and Span [2] were integrated with GPSR [28] using the ns2 simulator, and a series of benchmarking simulations were then performed. The results show that in a topology comprising 50 nodes, DFTM reduced the total number of active nodes required by approximately 20 percent compared to GAF. When the total number of network nodes was increased to 75 and 100, it is found that DFTM reduced the number of active nodes required by approximately 37 percent and 48 percent, compared to GAF, respectively. Since the network required fewer active nodes to carry out the packet forwarding task, DFTM yielded a significant improvement in the network lifetime. Significantly, even though DFTM used fewer active nodes for routing purposes, its packet delivery ratio performance was very similar to that of the compared schemes. Furthermore, the results show that DFTM ensured a remarkably low number of dead-end events even when the positions of the nodes were not accurately known. Though Span required approximately 23 percent fewer active nodes than DFTM, the average delivery path length was increased by approximately nine percent.

2 Related Work

2.1 Topology Maintenance

Existing topology maintenance protocols conserve energy by scheduling the network nodes to a sleep mode when a node is not currently involved in a communication activity. Based on the knowledge of the geographical locations of each of the nodes within the network, the GAF protocol divides the total network area into an arrangement of structured smaller grids such that each grid contains only one active node [1]. Span maintains the connectivity and forwarding capability of a wireless network by maintaining those nodes which constitute the backbone infrastructure in an active mode [2]. The idea of PEAS is similar to Span [3]. Each sleeping node periodically wakes up for checking if any active nodes are within its probing range. If it is the case, it sleeps again; otherwise, it becomes an active node. The probing range can be adjusted to achieve different levels of coverage redundancy. OGDC used a minimal number of sensor nodes to maintain the coverage without any blind spots [4]. Both coverage and connectivity can be proved if the transmission range is two times larger than the sensing distance. Wu and Dai proposed a distributed solution for reducing the network density by using an adjustable transmission range [5]. In ABEC [6], the operating modes of the network nodes are coordinated in accordance with the concentration of pheromone trails laid by proactive ants. Idle nodes located along a low concentration pheromone trail might alter the behavior of forwarding ants to eliminate pheromone trails passing through themselves before sleeping. Bai et al. presented a deployment pattern which achieved both full coverage and 2-connectivity, and demonstrated the optimality of the deployment pattern for all values of r_c/r_s, where r_c is the communication radius and r_s is the sensing radius [7]. Srinivas et al. proposed a novel hierarchical wireless networking approach in which some of the nodes served as Mobile Backbone Nodes for communication purposes [8]. The basic principle of the scheme involved controlling the mobility of the Backbone Nodes such that the network connectivity was maintained at all times.

2.2 Dead-End Handling in Geographic Forwarding

The Most Forward with fixed Radius (MFR) algorithm is widely used for next hop selection in geographic forwarding schemes [29]. In MFR, the current relay node always selects the neighbor closest to the destination as the next relay. However, when the current node cannot locate any neighbor closer to the destination than itself, the packet reaches a "dead end." Several recovery strategies have been proposed for dealing with such an event. For example, in the scheme proposed by Finn in [30], the current relay node recursively searches its neighbor's neighbors to find a node closer to the destination than itself. Woo and Singh proposed a scalable location update-based routing protocol in which the current relay node interrogates its neighbors for an alternative route to the destination [31]. Meanwhile, in GPSR [28], the current relay node first creates a planar subgraph using the relative neighborhood graph (RNG) [32] and then routes around the dead end in accordance with the right-hand rule. Various intermediate node forwarding techniques have also been proposed to resolve the dead-end situation by forwarding the packet to specific positions within the network [33], [34]. However, Frey and Stojmenovic provided a formal proof that these schemes cannot guarantee packet delivery in specific graph classes or even any arbitrary planar graphs [35].

3 Assumptions and Background

The sensor network considered in this study consists of a large number of stationary nodes distributed over the sensing field. The network is assumed to be sufficiently dense that it is physically possible to construct a dead-end free topology. Each node has an initial power source, a processing unit, memory, a radio, and one or more sensors of various types. The nodes have a fixed transmission range and communicate wirelessly with one another using a one-to-all broadcast primitive. Each node can be in either an active mode or a sleep mode. When in the active mode, the nodes can execute a variety of functions including receiving, transmitting, and processing data. However, in the sleep mode, the nodes turn off their radios and conserve energy by performing only critical functions, e.g., maintaining the system clock, and so forth. Finally, each node is aware both of its own geographic coordinates (by using some form of localization service, such as GPS) and the coordinates of its neighbors.

The distributed DFTM proposed in this study can be integrated with any MFR-based geographic forwarding algorithm [29]. For simplicity, the analytical and numerical investigation results presented in this paper assume that DFTM is integrated with GPSR [28]. GPSR operates in one of two different modes, namely the greedy forwarding mode or the perimeter forwarding mode. In the former mode, the current relay node always selects the neighbor closest to the destination as the next relay. When the relay node fails to locate a neighbor closer to the destination than itself, it marks the packet as the perimeter mode and records the location (L_p) at which the greedy forwarding mode failed to locate a suitable next hop for the packet. In the perimeter forwarding mode, the current relay node creates a planar subgraph using RNG and then routes the packet around the dead end in accordance with the right-hand rule. In GPSR, the perimeter forwarding mechanism is intended for use only as a dead-end recovery mechanism. When the packet arrives at a location closer to the destination than L_p, the forwarding strategy resorts to a greedy mode.

4 Dead-End Free Topology Maintenance Protocol

The DFTM scheme incorporates three separate strategies, namely 1) "dead-end free verification," designed to determine whether or not a particular node is dead-end free; 2) "dead-end free topology construction," designed to select active nodes with which to construct a dead-end free topology; and 3) "topology maintenance," designed to maintain the dead-end free property of the constructed topology over time.

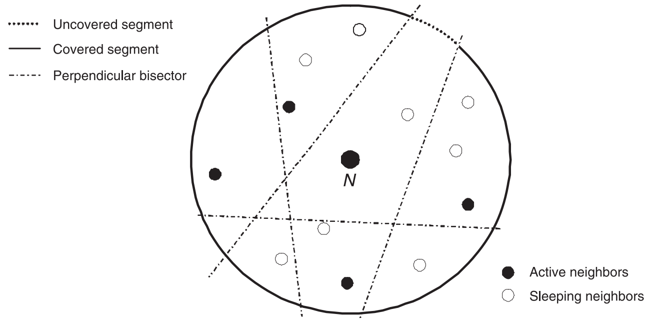


Fig. 2. A local Voronoi diagram for node N.

4.1 Dead-End Free Verification

In geographic forwarding, a network is said to be dead-end free if it satisfies the following GDF condition:

GDF condition. *The dead-end situation does not occur at any node in the network.*

In other words, each node in the system must be dead-end free in order to satisfy the GDF condition. The decision as to whether or not a particular node is dead-end free is made in accordance with the following LDF condition:

LDF condition. *If the transmission circle of the node is fully covered by the perpendicular bisectors with its neighbors, the node is dead-end free.*

Proof. In the local Voronoi diagram shown in Fig. 2, the area enclosed by the perpendicular bisectors is known as the Voronoi polygon. Any point within this polygon is closer to node N than to any of the other four active nodes. From the definition of the dead-end situation, it follows that a dead-end event will occur if the packet's destination lies within this area but falls outside of node N's transmission range. Conversely, if the node's transmission range covers the entire enclosed area, the packet will not encounter a dead end at node N. Clearly, if the transmission range of node N covers the entire Voronoi polygon, then the transmission circle is fully covered by the perpendicular bisectors. In other words, the LDF condition is proven. □

4.2 Dead-End Free Topology Construction

Intuitively, by ensuring that each node in the network satisfies the LDF condition, the global dead-end free condition is automatically satisfied. However, without using global information, it is difficult to ascertain with absolute certainty whether or not the network does indeed satisfy the GDF condition. Therefore, a distributed construction mechanism is developed for building a dead-end free network topology based on the LDF condition, i.e., based on local knowledge.

Fig. 3 presents the detailed state diagram for the proposed topology construction mechanism. Initially, all the nodes are considered to be in an *undecided* mode, i.e., the most

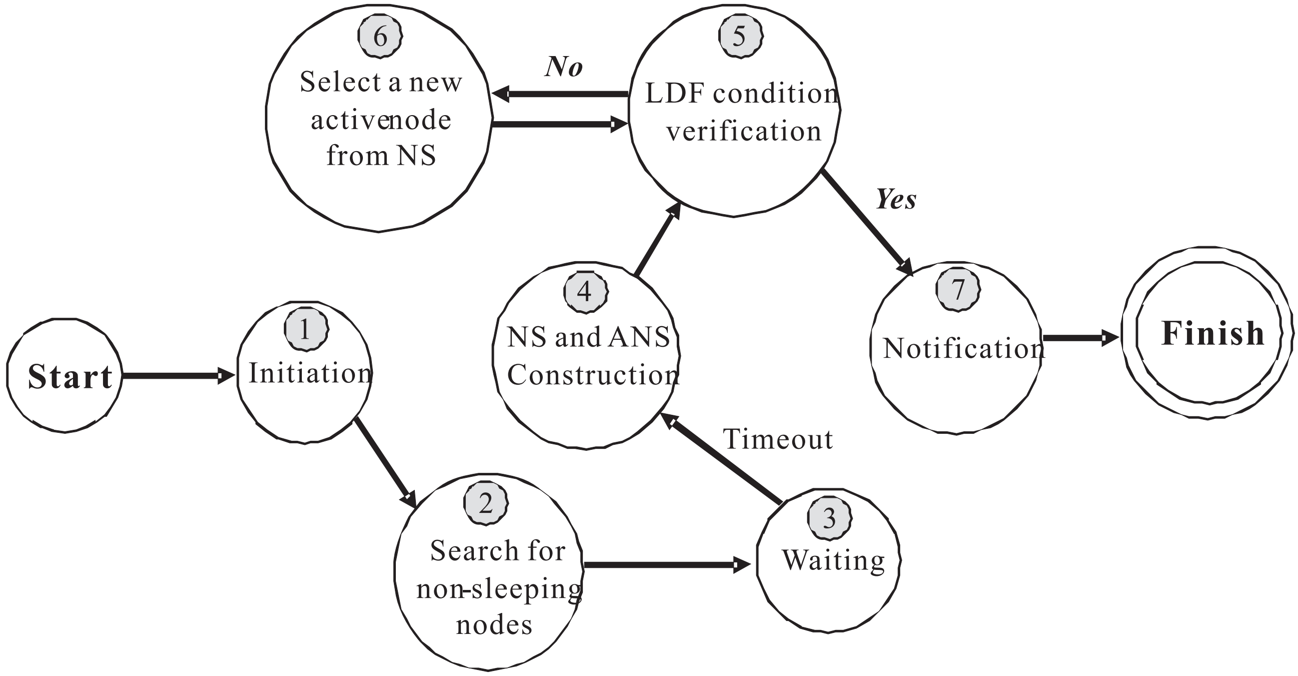


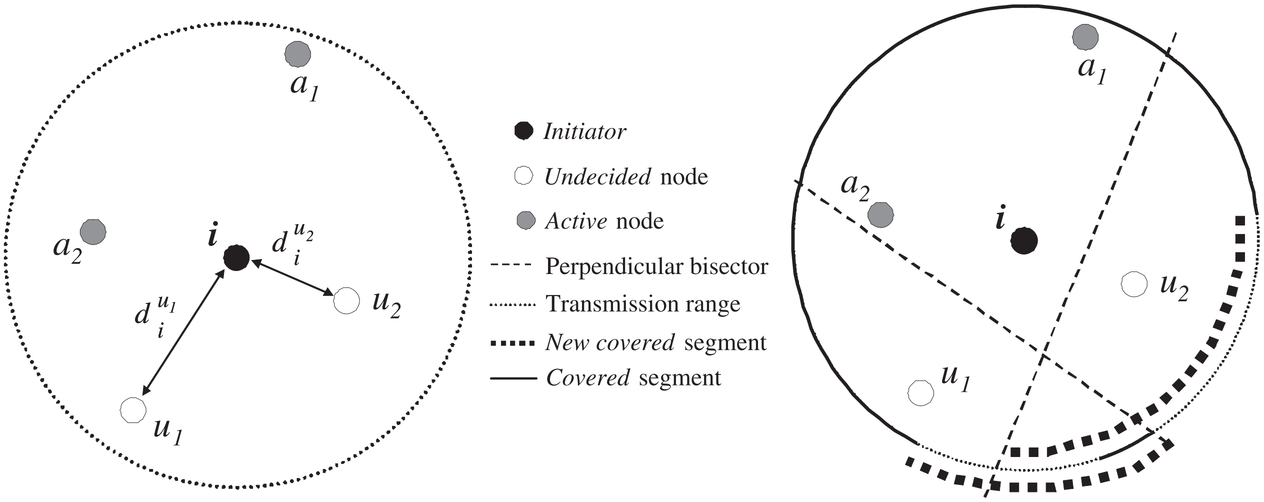
Fig. 3. The dead-end free topology construction operation.

appropriate mode for each node is yet to be determined. The process commences when the sink randomly nominates a node to become an active node, hence causing the node to transit to state 1. In state 1, the selected node (referred to hereafter as the **initiator**) sets its mode to *active* and enters state 2. The initiator then broadcasts a message to search for nonsleeping neighbors[1] and then transits to state 3 for receiving responses. Once a nonsleeping node receives the message from the initiator, it reports its operation mode to the initiator. When the initiator's timer expires, the process moves to state 4. The initiator first adds all the nodes which have replied to its broadcast to a neighbor set (NS), then adds those nodes which are in an active mode to an active neighbor set (ANS), and finally transits to state 5. From state 5, two transitions are possible, i.e., to state 6 or to state 7, respectively. The process transits to state 6 if the initiator fails to satisfy the LDF condition with the nodes in its current ANS; otherwise, it transits to state 7 (i.e., the initiator satisfies the LDF condition). In state 6, the initiator selects a new active node from its NS using an active node selection algorithm (described later in this section) and then adds this node to its ANS. The process then returns to state 5 to verify whether or not the updated ANS now satisfies the LDF condition. In state 7, the nodes which have been selected by the initiator to be active nodes are notified and they have been designated as new initiators. Each of these nodes then performs the topology construction process described above using its own local neighbors. Meanwhile, those nodes within the Voronoi polygon enclosed by the perpendicular bisectors between the original initiator and the nodes in its ANS are notified to enter the *sleep* mode. The process then transits to the end state, i.e., to **Finish**.

As described above, state 6 of the topology construction operation involves selecting appropriate nodes to act as initiators in the iterative construction process. The overriding objective of DFTM is to prolong the network lifetime by minimizing the number of active nodes required to ensure the dead-end free condition. In selecting new active nodes, DFTM applies one of two different rules, based, respectively, on 1) the distance between the candidate node and the initiator (referred to as $rule_d$); and 2) the length of the new covered segment (referred to as $rule_s$). Fig. 4a illustrates the $rule_d$ selection rule. As shown, undecided nodes u_1 and u_2 are located at distances $d_i^{u_1}$ and $d_i^{u_2}$ from the initiator i, respectively. Since the newly selected node will perform its own local construction process, the node which lies closer to the initiator should be eliminated in order to reduce the total number of active nodes involved in the construction processes. In Fig. 4a, $d_i^{u_1} > d_i^{u_2}$, and hence node u_1 is the more suitable node. In the $rule_s$ selection rule, the newly covered segment is defined as the segment which is covered by the newly selected node, but is not covered by the active neighbors of the initiator. Therefore, to achieve the LDF condition using the minimum number of active nodes, the initiator should choose the node which has the longest newly covered segment. In Fig. 4b, the newly covered segment of node u_2 is longer than that of node u_1, and hence, u_2 is the more suitable of the two nodes for the new active node.

Fig. 5 presents the pseudocode of the algorithm executed by the initiator when searching for an appropriate active neighbor. Using this algorithm, the initiator first builds a tentative neighbor set (TNS), which includes the nodes belonging to NS, but excludes those nodes within ANS. The appropriate candidate node is then selected from the nodes within TNS. The value of parameter (α) is used to determine the preference weighting of the different candidate nodes chosen using the two different selection rules. When α is less than 0.5, those nodes chosen in accordance with $rule_d$ have a higher preference weighting during the

1. The node operates either in *undecided* or *active* mode.



(a) (b)

Fig. 4. The active node selection rules.

selection process. Conversely, when α has a value greater than 0.5, those nodes chosen in accordance with $rule_s$ are viewed more favorably. The node which is determined to have the highest preference weighting overall is added to the ANS of the initiator, bringing the active node selection routine to an end.

Fig. 6 presents an illustration of the ANS construction process performed by an initiator (p) in the DFTM scheme. Initially (see Fig. 6a), p has two neighbors in an *active* mode (a and e), three neighbors in an *undecided* mode (b, c, and d), and two neighbors in a *sleep* mode. The ANS of p contains nodes {a, e}; however, these nodes do not satisfy the LDF condition at p. Hence, p executes the active node selection algorithm shown in Fig. 5 to choose a new active neighbor. According to the selection rules, node c is found to have the highest preference weighting. Therefore, this node is chosen as the new active neighbor and the ANS of node p is updated to {a, e, c} (see Fig. 6b). However, the new ANS still fails to satisfy the LDF condition (see Fig. 6c), and thus, another active node (d) is chosen and added to the ANS of node $p\{a, e, c, d\}$. The ANS of node p now satisfies the LDF condition. As shown in Fig. 6d, node b is located within the Voronoi polygon enclosed by the perpendicular bisectors between node p and {a, e, c, d}, and hence, it is instructed to enter the *sleep* mode. The topology construction process is then repeated using the newly chosen active nodes (i.e., c and d) as new initiators.

Definitions:
- i: the initiator node
- NS: the set for storing all I's neighbors in either *undecided* or *active* mode
- ANS: the set for storing all I's neighbors in *active* mode
- TNS: the tentative neighbors set
- r: the node's transmission range
- d_v^u: the distance from node u to node v
- ncs_k: the length of the new covered segment of node k
- α: the parameter for the selection rules

procedure *Active node selection*
begin
$TNS = \{n \mid n \in NS \wedge n \notin ANS\}$;
Select a node n_1 from TNS;
$TNS = TNS - n_1$;
while ($TNS \neq \phi$) {
Select a node n_2 from TNS;
$TNS = TNS - n_2$;
if $((\alpha * \frac{ncs_{n_1}}{\pi r} + (1-\alpha) * \frac{d_i^{n1}}{r}) < (\alpha * \frac{ncs_{n_2}}{\pi r} + (1-\alpha) * \frac{d_i^{n2}}{r}))$ **then**
$n_1 = n_2$;
endif
}
if (n_1 exists) **then**
$ANS = ANS + n_1$;
endif
end

Fig. 5. The active node selection algorithm.

4.3 Dead-End Free Topology Maintenance

4.3.1 Global Topology Maintenance

In order to ensure an even distribution of the power consumption among all the nodes in the network, DFTM features a global topology maintenance scheme designed to perform an active node handover procedure. In this scheme, all the currently active and sleeping nodes change their operating modes to *undecided* every T_{global} seconds. The sink node then chooses a node at random to be the initiator for the dead-end free topology construction process. The randomness of this selection procedure ensures that every node has an equal probability of becoming an active node, and therefore ensures that an even power consumption distribution is obtained.

4.3.2 Local Topology Maintenance

During operation, some of the active nodes may suddenly become unavailable as a result of node collisions, energy exhaustion, and so on. To preserve the dead-end free topology in the event of node failures, DFTM employs a local topology maintenance scheme to wake up sleeping nodes whenever it suspects that an active node has failed. In this scheme, each active node periodically exchanges messages with its active neighbors. When a node fails to receive an acknowledgment message from a specific neighbor following three consecutive attempts to make

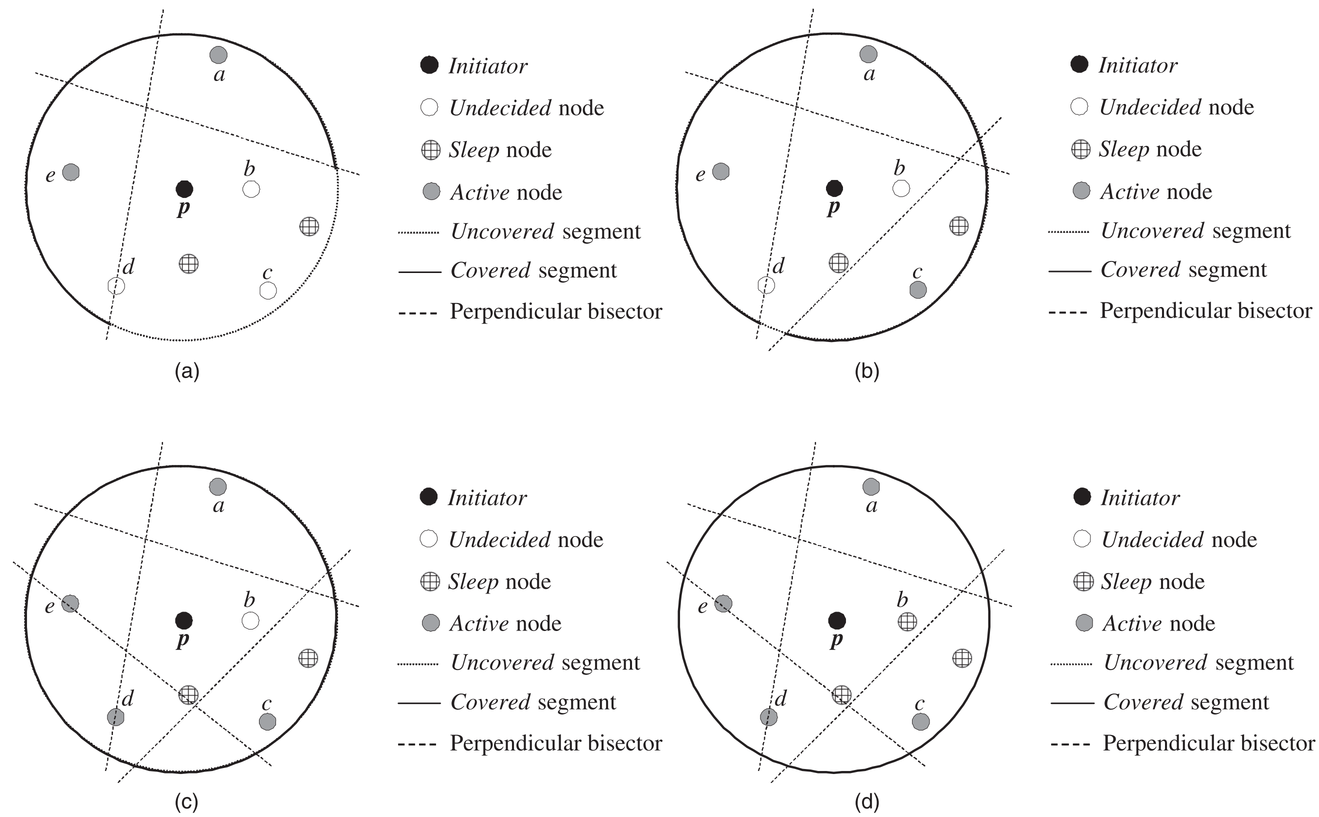


Fig. 6. An example for dead-end free topology construction.

contact, this neighbor is removed from the ANS. If the amended ANS no longer satisfies the LDF condition, the node selects a new active neighbor(s) using the topology construction process described in Section 4.2.

5 Discussions

This section proves that network full connectivity and coverage can be guaranteed with an active node set when the network is dense enough to construct a dead-end free topology using DFTM.

Lemma 1. *A network topology is fully connected if it satisfies the GDF condition.*

Proof. Let $N(G)$ be the set of all nodes in a network satisfying the GDF condition, and $n_d \in N(G)$ be an arbitrary destination node. Define $\succ_d$ ($\succ$ for short) as the relation on $N(G)$ having the property that for two nodes $n_1, n_2 \in N(G)$, $n_1 \succ n_2$ if the euclidean distance between n_1 and n_d is longer than or equal to the distance between n_2 and n_d. Then, each node in $N(G)$ except n_d can be labeled as a_i, where $1 \leq i \leq |N(G)| - 1$, such that $a_1 \succ a_2 \succ \cdots \succ a_{|N(G)|-1}$.

The GDF condition states that no dead end occurs at any node in the network. Hence, for each node $a_j \in N(G)$ having a packet to n_d, then a_j must have an adjacent node $a_k \in N(G)$ such that $a_j \succ a_k$ with $j < k < |N(G)|$, and therefore, a_j can forward the packet to a_k. For the destination n_d having l adjacent nodes ($l > 0$ due to the GDF condition), their labels must be a permutation among $a_{|N(G)|-l}, a_{|N(G)|-l+1}, \ldots, a_{|N(G)|-1}$. Thus, the hop count from a_j to n_d is at most $|N(G)| - l - j + 1$, and since $|N(G)|, l, j$ are finite numbers, the hop count is finite. It is clear that a_j is connected to n_d. For instance, Fig. 7 shows one of the possible data forwarding path from n_1 to n_d.

As a result, every node is able to pass packets to an arbitrary destination, and thus, the network is fully connected. □

Theorem 1. *A network topology constructed by DFTM is fully connected.*

Proof. In DFTM, each active node satisfies the LDF condition (the nodes in its ANS have fully covered its transmission circle), and once the LDF condition holds at each active node, it implies that the GDF condition holds for the topology comprising all active nodes. According to Lemma 1, the resultant topology is fully connected. □

6 Analysis for the Number of Active Nodes

This section analyzes the number of active nodes required in DFTM and GAF schemes. In the example shown in Fig. 8, the network is divided into $n * n$ squares and the transmission range of each node is R. Based on the conventional GAF assumptions, the sides of each square (r) should have a

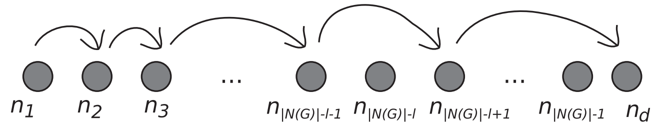


Fig. 7. An example of the data forwarding.

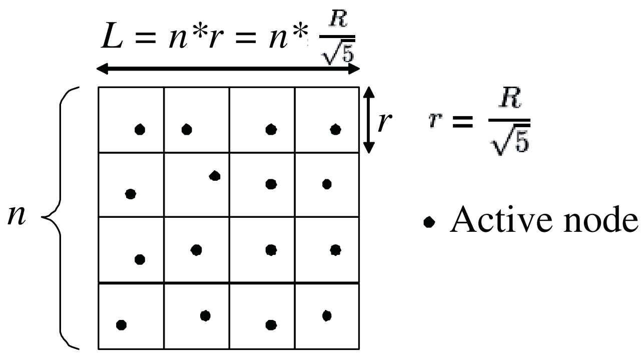


Fig. 8. Active nodes in GAF.

length greater than $\frac{R}{\sqrt{5}}$. Hence, the minimum number of active nodes required in the GAF scheme is n^2.

6.1 Best-Case Scenario for DFTM

For an arbitrary sensor node a, to satisfy the LDF condition, a must have at least three active neighbors; if a only has two or less active neighbors, then there are not enough perpendicular bisectors to form a polygon. In the best case of DFTM protocol, only three active neighbors are required for each sensor node, where the transmission circle can be fully covered. For example, in Fig. 9a, an active node (a) has three active neighbors, i.e., n_1, n_2, and n_3. The included angles $\angle n_1an_2$, $\angle n_2an_3$, and $\angle n_3an_1$ are all equal to $2\pi/3$. The Voronoi diagram of this DTFM best-case scenario has the form shown in Fig. 9b. Assuming that the average distance between any two active nodes is d, the area of each triangle is given by $\frac{3\sqrt{3}d^2}{4}$. Since the area of the network is n^2r^2 and each triangle contains only one active node, the total number of active nodes required ($Nodes_B$) is given by

$$Nodes_B = \frac{n^2r^2}{\frac{3\sqrt{3}d^2}{4}} = \frac{4n^2r^2}{3\sqrt{3}d^2}. \quad (1)$$

6.2 Worst-Case Scenario for DFTM

Consider the case where an active node (a) has k active neighbors, i.e., $n_1 \sim n_k$, and the included angles are $\angle n_1an_2 - \angle n_{k-1}an_k$. As shown in Fig. 10, if the included angle ($\angle n_1an_2$) is not less than $2\pi/3$, the segment $\overline{i_1i_2}$ may not be fully covered. Therefore, to ensure that the LDF condition is satisfied, when one of the included angles satisfies $\angle n_uan_v \geq 2\pi/3$, a new active neighbor should be inserted. In the worst-case scenario, a maximum of three included angles are no smaller than $2\pi/3$, and hence at most six active neighbors are required. The Voronoi diagram for the worst-case scenario is shown in Fig. 11. Assuming that the distance between any two active nodes is d, the hexagon has an area of $\frac{3d^2}{2\sqrt{3}}$. The number of active nodes required ($Nodes_W$) is then calculated by

$$Nodes_W = \frac{n^2r^2}{\frac{3d^2}{2\sqrt{3}}} = \frac{2\sqrt{3}n^2r^2}{3d^2}. \quad (2)$$

Consider the case where the network area is divided into $10 * 10$ grids. Based on Formulas (1) and (2), Fig. 12 illustrates the number of active nodes required in GAF, the best-case DFTM scenario (DFTM-B), and the worst-case DFTM scenario (DFTM-W), respectively. The results demonstrate that DFTM requires fewer active nodes than GAF when the distance between active nodes, d, is greater than r. In addition, it is apparent that the number of active nodes required reduces significantly with increasing d. DFTM provides $rule_d$ to adjust the distance between active nodes and hence requires fewer active nodes than GAF.

7 Experimental Results

7.1 Simulation Setup

The performance of DFTM was benchmarked against that of GAF and Span in a series of simulations performed using the ns2 simulator [36]. In the simulations, 50, 75, or 100 static nodes were randomly distributed within a sensing area measuring $60 * 30$ m. The transmission ability of each node was provided by a CSMA-type MAC (similar to the DCF of 802.11) radio with a transmission range of 15 m. The length of each GAF square was set to $\frac{15}{\sqrt{5}}$ m. In DFTM, the frequency of performing global topology construction process was specified as 150 seconds. As described in Section 4.2, the

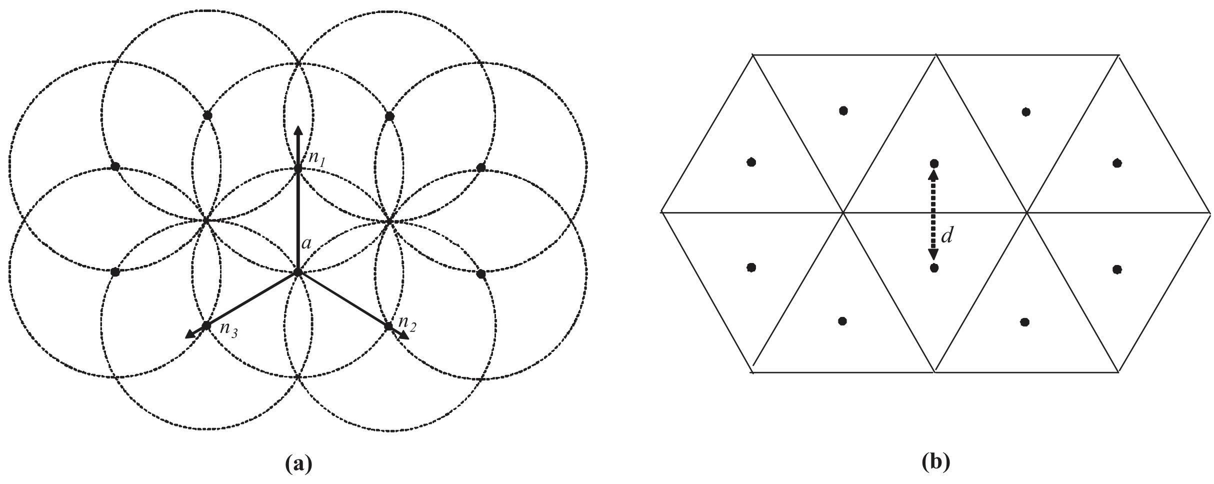


Fig. 9. (a) The best case for DFTM. (b) The constructed Voronoi diagram from the DFTM best case.

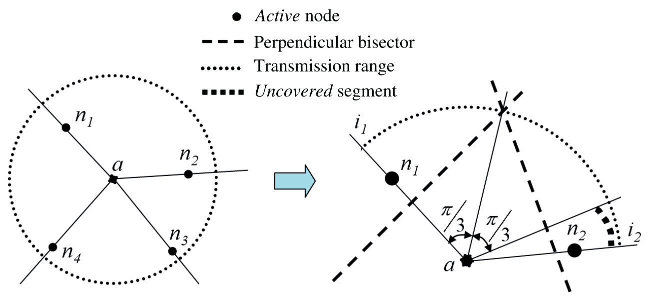


Fig. 10. A DFTM example.

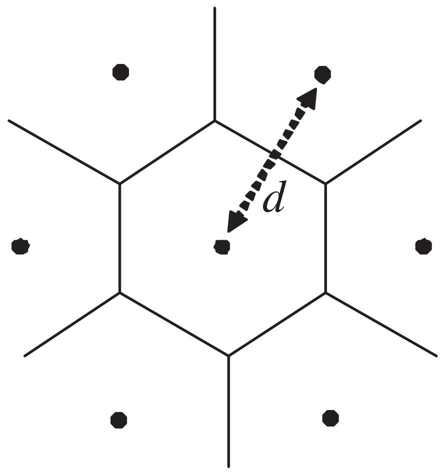


Fig. 11. The Voronoi diagram for the DFTM worst case.

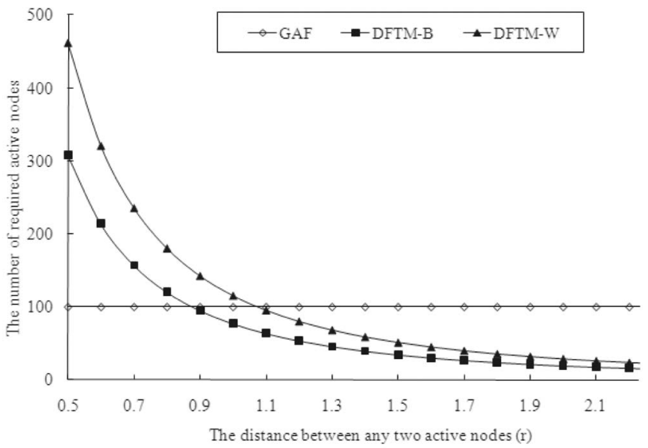


Fig. 12. The required active nodes for varying cases.

value assigned to the selection rule weighting factor, α, has a fundamental effect on the performance of the DFTM scheme. However, defining an optimal value for α is quite difficult. Therefore, several α values were selected in the simulations for evaluation (i.e., 0.3, 0.4, 0.5, 0.6, and 0.7). Each node was assigned an initial energy of 25 J. The energy consumption model was based on the MICA sensor mote, i.e., energy costs of 0.057 W when transmitting, 0.065 W when receiving, 0.050 W when listening, and 0.025 W when sleeping. Each simulation was run for a total of 900 seconds. The traffic pattern consisted of 30 constant bit rate (CBR) sources with data rate of 8 kbps. Note that in the figures below, each data point indicates the average result obtained from 10 separate simulation runs.

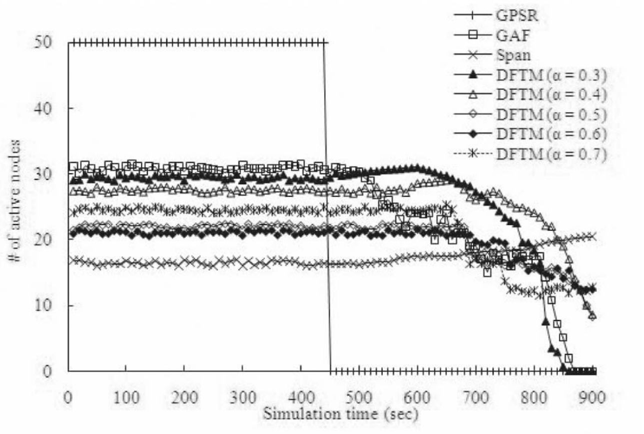


Fig. 13. Number of active nodes comparison ($\#$ of total nodes $= 50$).

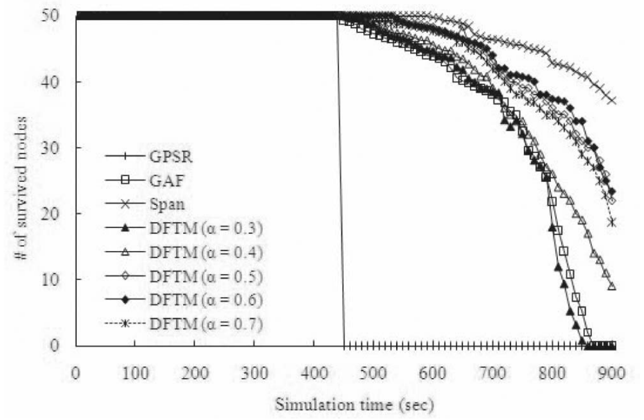


Fig. 14. Number of survived nodes comparison ($\#$ of total nodes $= 50$).

7.2 Simulation Results

7.2.1 Impact of Node Density

Figs. 13 and 14 compare the variations of the number of active nodes and the number of surviving nodes, respectively, over the duration of simulations performed using four different schemes (GPSR, GAF, Span, and DFTM) in a network containing 50 nodes. With GAF, Span, and DFTM, these three topology control schemes were, respectively, integrated with GPSR. In the pure GPSR scheme, all the nodes were maintained in an active mode at all times. As a result, it can be seen that none of the nodes survived longer than 440 seconds. In the GAF scheme, the number of active nodes reduced after 600 seconds since 20 percent of the nodes have exhausted their power by this time. Setting a suitable value for α helps to shutdown unnecessary nodes during OFTM active node selection process. However, it is not trivial to choose an optimal α value for all scenarios. If α is smaller than 0.5, $rule_d$ has a heavier weight than $rule_s$; otherwise, $rule_s$ is more important than $rule_d$. In this section, varying cases were evaluated to give a guideline for the selection of suitable α value. From Fig. 13, it can be seen that when α was assigned a value of 0.6, the number of active nodes was relatively minimized compared to the other DFTM cases. With the best DFTM case, the average number of active nodes was reduced by approximately 20 percent compared to the number required in GAF. After 750 seconds, approximately 50 percent of the nodes survived in GAF, whereas 80 percent of the

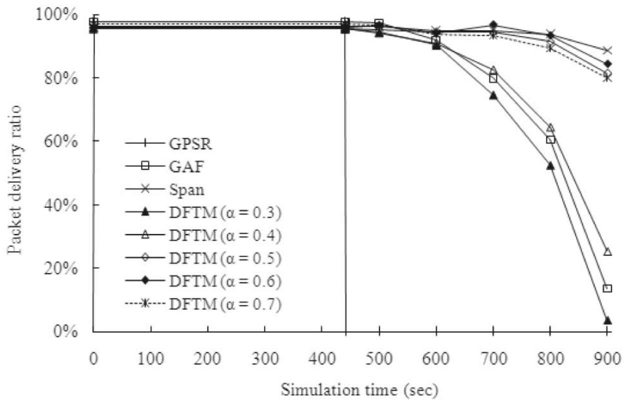


Fig. 15. Packet delivery ratio comparison ($\#$ of total nodes $= 50$).

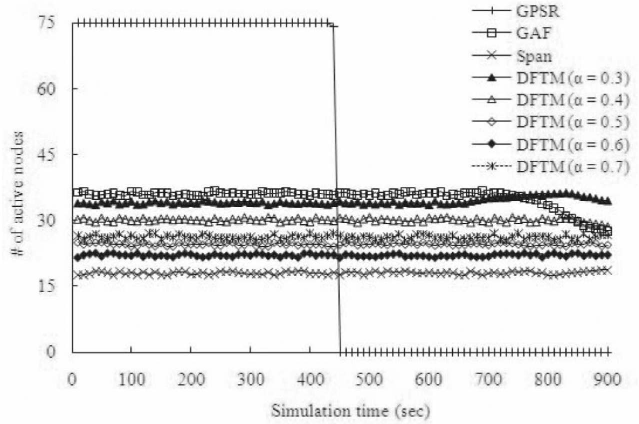


Fig. 16. Number of active nodes comparison ($\#$ of total nodes $= 75$).

nodes still survived in the best DFTM case. Since Span required the least active nodes of all compared schemes, more than 72 percent of the nodes still survived after the end of the simulation.

Fig. 15 compares the packet delivery ratios of the four schemes. It is observed that GPSR achieved the highest performance of the four schemes over the interval of 0 to 440 seconds. However, after 440 seconds, all the nodes exhausted their power, and hence, the packet delivery ratio fell to zero. In general, the results presented in Figs. 13, 14, and 15 show that the best DFTM case not only required fewer active nodes than GPSR and GAF, but also achieved a packet delivery ratio of more than 94 percent, even during the later stages of the simulation. In addition, the number of active nodes required in the best DFTM case was only raised by approximately 16 percent compared to Span.

Figs. 16 and 17 show the number of active nodes required and the number of surviving nodes for each of the four schemes in a network with a total of 75 nodes. As before, in the GPSR scheme, none of the network nodes survived beyond a simulation time of 440 seconds. Comparing the results for GAF, Span, and DFTM cases, it is found that the best DFTM case required approximately 37 percent fewer active nodes than GAF and approximately 20 percent more active nodes than Span. Fig. 17 shows that at the end of the simulation, only 59 percent of the nodes still survived in GAF. However, up to 92 percent of the nodes still survived in the best DFTM case. As shown in

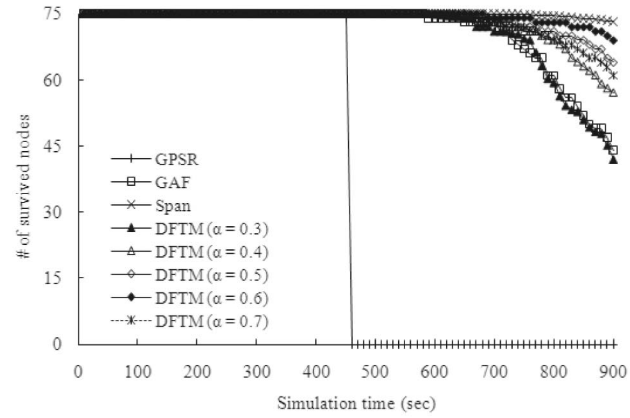


Fig. 17. Number of survived nodes comparison ($\#$ of total nodes $= 75$).

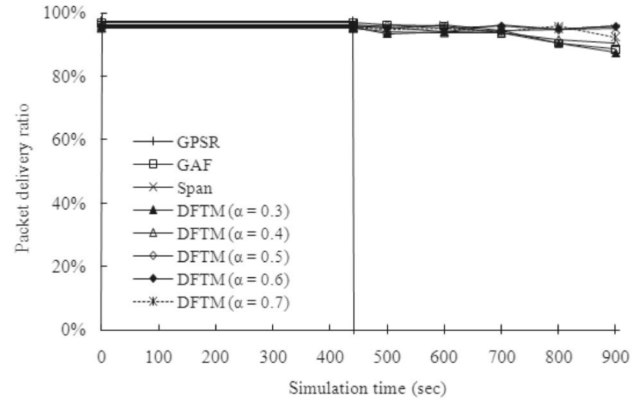


Fig. 18. Packet delivery ratio comparison ($\#$ of total nodes $= 75$).

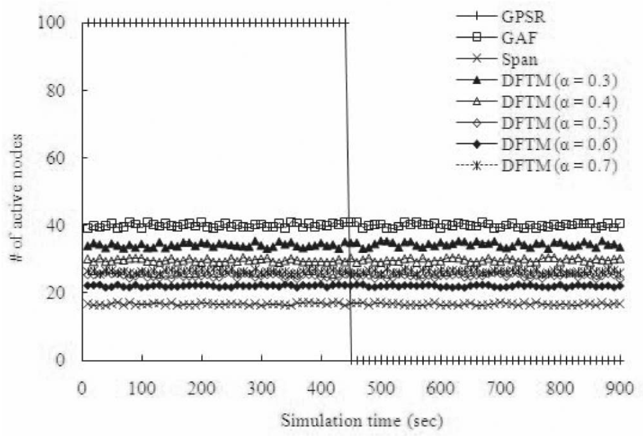


Fig. 19. Number of active nodes comparison ($\#$ of total nodes $= 100$).

Fig. 18 , DFTM achieved a higher packet delivery ratio than GAF after 700 seconds.

Figs. 19, 20, and 21 present the time-based variations of the number of active nodes, the number of surviving nodes, and the packet delivery ratio, respectively, for the case of a network with 100 nodes. In this high-density network, the best DFTM case reduced the number of active nodes required by approximately 48 percent compared to GAF, with no more than a one-percent reduction in the packet delivery ratio. On the other hand, Span required approximately 29 percent fewer active nodes than the best case of DFTM.

Tables 1 and 2 compare the average energy consumption and the average path length, respectively, for the GPSR,

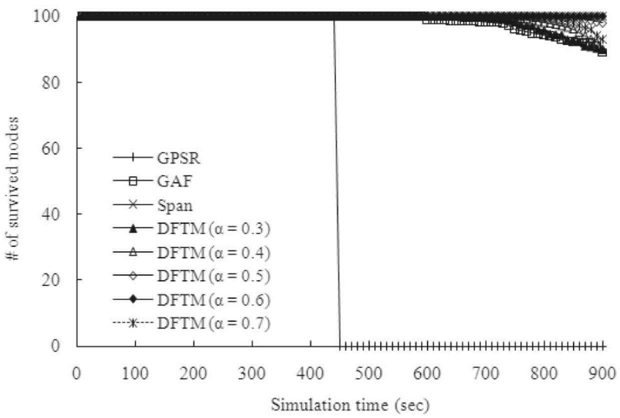


Fig. 20. Number of survived nodes comparison (# of total nodes = 100).

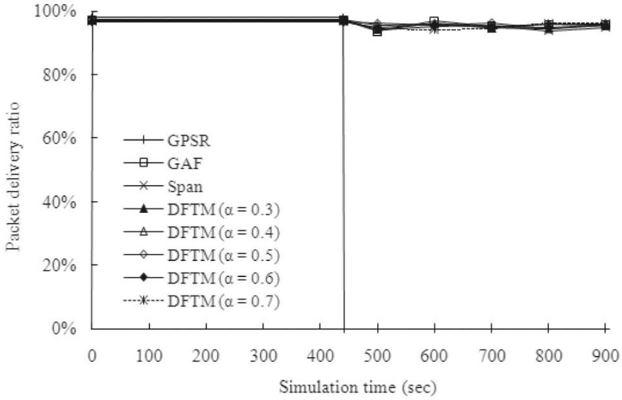


Fig. 21. Packet delivery ratio comparison (# of total nodes = 100).

TABLE 1
Average Energy Consumption

# of nodes	Energy consumption (J)							
	GPSR	GAF	Span	OFTM				
				$\alpha = 0.3$	$\alpha = 0.4$	$\alpha = 0.5$	$\alpha = 0.6$	$\alpha = 0.7$
50	25	25	19.83	25	23.77	22.28	21.09	23.16
75	25	21.91	13.60	21.03	19.87	18.91	17.13	19.66
100	25	18.75	9.34	18.11	16.54	13.33	11.96	14.80

TABLE 2
Average Path Length

# of nodes	Average path length (hops)							
	GPSR	GAF	Span	DFTM				
				$\alpha = 0.3$	$\alpha = 0.4$	$\alpha = 0.5$	$\alpha = 0.6$	$\alpha = 0.7$
50	5.81	7.53	7.14	7.96	7.34	6.74	6.79	6.79
75	5.23	6.25	7.26	6.29	6.50	6.58	6.59	6.36
100	5.10	5.41	6.82	5.50	5.56	5.83	5.94	5.87

GAF, Span, and DFTM schemes in the three network topologies. In the topology with 50 nodes, it is apparent that the best DFTM case achieved an energy consumption saving of approximately 16 percent compared to GAF. Furthermore, as the number of nodes in the topology was increased to 75 and then to 100, the energy consumption saving increased to 22 percent and 36 percent, respectively. Regarding the path length, in the GPSR scheme, all the nodes are maintained in an active state for forwarding purposes, and hence, the delivery path length is the shortest of the compared schemes. In the above evaluations, Span seems to outperform the other schemes. However, Span did not aim to construct a specific topology for geographic routing so more unnecessary routes occurred during packet forwarding and increased the path length compared to DFTM. As a result, the average path length was greater than the best DFTM case by approximately nine percent. In the topology with 50 nodes, though GAF required more active nodes than both DFTM and Span, it had the longest path length due to the survived nodes fell rapidly in the simulation time after 700 seconds.

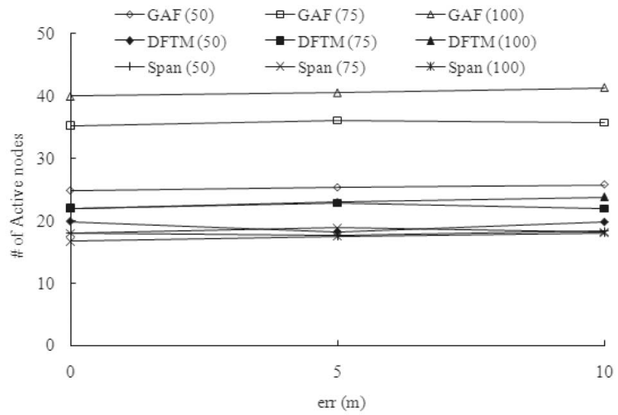


Fig. 22. Number of mean active nodes comparison.

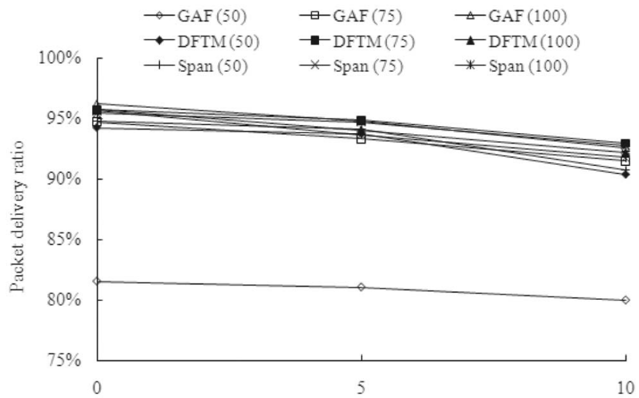


Fig. 23. Packet delivery ratio comparison.

7.2.2 *Impact of Position Error*

GPS (and other position determination schemes) may not always provide precise location information. A series of simulations were performed to assess the impact of node positional errors on the performance of GAF, Span, and DFTM. To simplify, the value of α was set to 0.6 in DFTM. To model the positional inaccuracy of the sensor nodes, the mean errors for each node's x- and y-axes coordinates were set to err with a normal distribution. As shown in Fig. 22, when the nodes' positions are not precisely known, there is no more than a slight increase in the total number of active nodes required in DFTM and Span. Furthermore, it is apparent that DFTM and Span were not sensitive to node density. Fig. 23 illustrates the effect of node positional errors on the packet delivery ratios obtained under GAF, Span, and DFTM in topologies of different densities. In three schemes, the delivery ratio decreased slightly as the positional error increased. When the topology has more than 75 nodes, the difference between the three schemes was marginal (i.e., less than two percent). However, in the sparser network (i.e.,

TABLE 3
Comparison for Dead-End Occurrence

	Mean number of dead-ends					
err (m)	GAF (50)	Span (50)	DFTM (50)	GAF (100)	Span (100)	DFTM (100)
0	72.1	40.9	15.8	0	17.2	0
5	88.0	48.4	19.7	1.1	37.5	9.7
10	104.5	52.3	25.2	2.5	58.3	12.9

50 nodes), many of the nodes became exhausted during the simulation time after 700 seconds in the GAF scheme, and hence, the average delivery ratio fell to approximately 78 percent. Table 3 illustrates the effect of positional errors on the number of dead-end events in the DFTM, Span, and GAF schemes. For a topology containing 50 nodes, the average number of dead-end events in GAF, Span, and DFTM was approximately 88.2, 47.2, and 20.2, respectively. For the network containing 100 nodes, the topology constructed by DFTM is dead-end free when the nodes' positional locations were accurately known. Furthermore, even when *err* was specified as 10 m, the average number of dead-ends in DFTM was just 12.9. It is apparent that DFTM has a robust dead-end free topology construction capability. Fig. 24 compares the average path length for the three schemes for different magnitudes of positional errors and topologies of different densities. Since positional errors may cause data packets to be retransmitted, the path length in hop count increased as the magnitude of the positional error increased. In Span, the path length was longer than DFTM due to the frequently occurred dead-end events. On average, Span forwarded packets along paths with approximately seven percent longer length compared to DFTM.

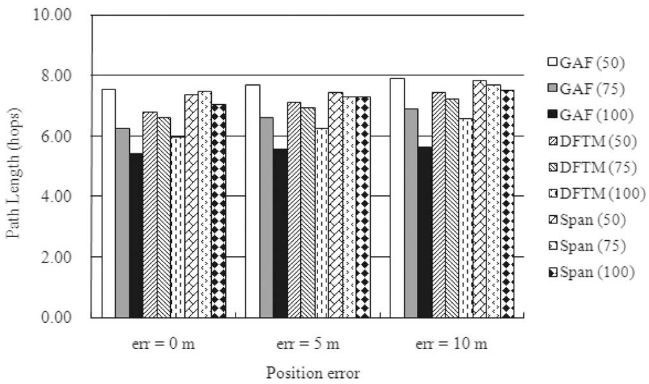


Fig. 24. Average path length.

8 Conclusion

This paper has presented a distributed dead-end free topology maintenance protocol, designated as DFTM, for the construction of dead-end free topologies for wireless sensor networks using a minimum number of active nodes. We have shown how the dead-end free topologies can be constructed according to the proposed conditions and heuristic algorithms. DFTM can be integrated with any MFR-based geographic forwarding algorithm to achieve a packet forwarding capability with low energy consumption and a minimum number of dead-end events. The performance of DFTM has been benchmarked against that of GAF and Span in a series of simulations conducted using the ns2 simulator. The analytical and simulation results have shown that DFTM achieves a significant reduction in the total number of active nodes and therefore extends the overall network life considerably compared to that attainable using the GAF scheme. The results have also shown that the topology constructed by DFTM is dead-end free in most of the simulated scenarios. Furthermore, even when positional errors exist, DFTM ensures that only a limited number of dead-end events take place.

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Chih-Hsun Anthony Chou received the BS degree in information and computer engineering from Chung Yuan Christian University and the PhD degree in electrical engineering from National Cheng Kung University. He is currently the associate section manager of the Emerging Smart Technology Institute at the Institute for Information Industry, Taipei, Taiwan. He has recently led the research team in developing DSRC-based vehicular safety applications and algorithms. His research interests include vehicular ad hoc networks, mobile computing, dependable systems, and wireless communication. He is a member of the Phi Tau Phi Scholastic Honor Society and the IEEE.

Kuo-Feng Ssu received the BS degree in computer science and information engineering from National Chiao Tung University and the PhD degree in computer science from the University of Illinois, Urbana-Champaign. He is currently a professor in the Department of Electrical Engineering, National Cheng Kung University, Tainan, Taiwan. He was a visiting associate professor in the School of Electrical and Computer Engineering, Cornell University, Ithaca, New York. His research interests include mobile computing, distributed systems, and dependable computing. His research awards include the Ta-You Wu Memorial Award, the K.T. Li Research Award, and the Lam Research Thesis Award. He is a member of the IEEE, the IEEE Computer Society, the ACM, and the Phi Tau Phi Honor Scholastic Society.

Hewijin Christine Jiau received the BS degree in electrical engineering from National Cheng Kung University, Tainan, Taiwan, the MS degree in electrical engineering and computer science from Northwestern University, Evanston, Illinois, and the PhD degree in computer science from the University of Illinois, Urbana-Champaign. She is currently a professor in the Department of Electrical Engineering, National Cheng Kung University. She was a visiting associate professor in the School of Electrical and Computer Engineering, Cornell University, Ithaca, New York. Her research interests include software reuse, object technologies, information integration, data mining, and database applications. She is a member of the IEEE, the IEEE Computer Society, and the ACM.

Wei-Tong Wang received the BS degree in computer science and information engineering from National Chung Cheng University and the PhD degree in electrical engineering from National Cheng Kung University. He is currently fulfilling the compulsory military service. His research interests include mobile ad hoc networks and wireless sensor networks.

Chao Wang received the BS degree in electrical engineering from National Cheng Kung University, Taiwan, R.O.C., and the MS degree from the Institute of Computer and Communication Engineering, National Cheng Kung University, Taiwan, R.O.C. He is currently fulfilling the compulsory military service. His research interests include wireless sensor networks, mobile ad hoc networks, and graph theory.