# GAF&Co: Connectivity Aware Topology Management for Sensor Networks

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***Abstract*— In order to achieve energy conservation in WSNs, most topology management protocols use a subset of sensor nodes for global routing. Using fewer nodes results in a reduced connectivity of the network, which eventually increases the number of routing holes. Holes in networks often cause failures in message routing due to the local minimum problem. Therefore, traditional geographic routing protocols cannot be applied with such topology management protocols.**

**In this paper, we propose a novel topology management protocol derived from the Geographical Adaptive Fidelity (GAF) protocol, called GAF with COnnectivity-awareness (GAF&Co). Instead of using virtual grids in GAF, our approach employs hierarchical hexagonal cells to avoid local minimums in WSNs. The purpose is to schedule redundant nodes into energy-saving mode, while maintaining the connectivity of a network for simple geographic routing protocols. Comparing to GAF, the number of cells as well as the overall energy consumption of a WSN also drops dramatically with the proposed protocol.**

***Key words*— topology management, geographic routing, routing hole, wireless sensor network.**

## I. INTRODUCTION

Wireless Sensor Networks (WSNs) are composed of sensor nodes, which are capable of sensing environmental parameters, processing data and communicating with each other wirelessly [1]. Sensor nodes are usually battery powered and left unattended after deployment. Therefore, energy efficiency remains a critical design issue for WSNs. Radio communication among sensor nodes is the main drain of energy in WSNs. Various routing protocols have been proposed (see [2]). On-demand routing protocols such as AODV [7] are popular, although their flooding-based route discovery often incur high control overhead [8]. In contrast, geographic routing (georouting) with *greedy forwarding* [6] is attractive for WSNs. With such a geographic routing protocol, a node communicates only with its direct neighbors. The neighboring node which can further minimize the remaining distance of a packet to its destination will be selected as the next hop. In contrast to on-demand routing protocols, geographic routing protocols save energy by avoiding the flooding-based route discovery [4] [5]. Geographic routing protocols find the next hop using localized methods. Therefore, they are also scalable and adaptive to changes in WSNs [13].

As more and more sensor nodes are employed in modern WSNs, redundancy of sensor nodes can be utilized to conserve energy. Many topology management protocols (such as GAF [9], SPAN [11], and ASCENT [10]) divide nodes into equivalence classes according to their geographic properties. For each class, some node is selected as the representative of the class. Such protocols turn only the representative nodes on and reduce energy dissipation by turning the redundant nodes of each class into energy-saving mode [9]. Routing activities are carried out only by the representative nodes.

However, we notice that the connectivity of a network is reduced as only a subset of nodes is active. When applying sleeping strategy together with a generic geographic routing protocol, it is more likely to encounter the *routing hole* problem [3] as illustrated in Fig. 1. Before applying sleeping strategy, all sensor nodes are available in routing activities (Fig. 1(a)). According to the rule of *greedy forwarding*, node *A* selects node *C* as the next-hop, because node *C* is the neighbor that is the nearest to the sink. While after applying sleeping strategy (Fig. 1(b)), fewer nodes (solid) are active. Packets get stuck at node *A* since there is no direct neighbor closer to the destination (sink) than node *A* itself. Here, node *A* is called a *local*

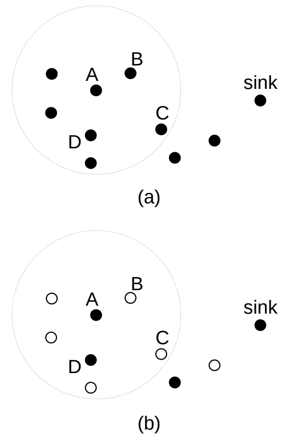


Fig. 1. Sample *local minimum* caused by random sleeping strategy.

This work is partially financed by the German Research Foundation (DFG) (post graduate program MuSAMA, GRK 1424).

*minimum*, which often cause traditional geographic routing protocols to fail. Many topology management protocols consider the general degree of connectivity of a network, but none of them addresses the routing hole problem associated with geographic routing after applying sleeping strategy.

In this paper, we present a novel topology management protocol called GAF with COnnectivity-awareness (GAF&Co). Our protocol targets not only on energy conservation in WSNs, but also on the resulted connectivity for geographic routing protocols. GAF&Co is derived from the topology management protocol Geographic Adaptive Fidelity (GAF) [9], as well as its enhanced version Hierarchical GAF (HGAF) [12]. The objective is to schedule redundant nodes into energy-saving mode, while avoiding the above-mentioned *routing hole* problem in geographic routing protocols. To the best of our knowledge, the *routing hole* problem is not addressed in prior topology management protocols. The proposed GAF&Co protocol yields a connected backbone of active nodes, where efficient geographic routing with *greedy forwarding* can be simply applied.

## II. Related Work

The topology management protocol GAF [9] is based on the energy model, where energy is not only consumed when sending and receiving packets, but also in idle time. According to [9], energy optimization can be achieved only by turning off radio on sensor nodes. GAF forms virtual grids in the network, and associates nodes to the grids according to their location information. The size of virtual grids is defined that any 2 nodes in adjacent grids can reach each other. As in Fig. 2, the communication range of sensor nodes $R_{com}$ satisfies:

$$R_{com} \geq L_0 \tag{1}$$

Or the edge of the virtual grids $r_{GAF}$ satisfies:

$$r_{GAF} \leq R_{com} / \sqrt{5} \tag{2}$$

Nodes in the same virtual grid are considered equivalent in terms of packet routing. Three modes are defined for nodes in GAF: *active*, for participating in routing; *discovery*, for electing an active node in a grid; and *sleeping* when the radio is turned off. Nodes in the *active* mode cost much more energy than in the other 2 modes. GAF aims to extend the lifetime of the network by turning redundant nodes of each grid into the later 2 energy-saving modes.

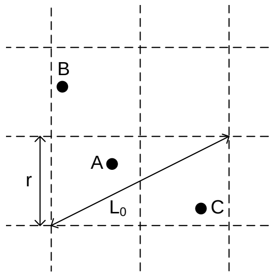


Fig. 2. An example of the GAF protocol.

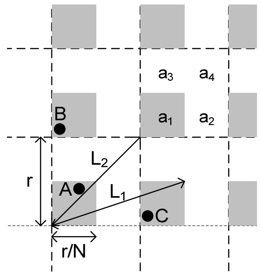


Fig. 3. An example of the HGAF (N=2) protocol.

Inagaki et al. [12] proposed the HGAF algorithm to expand the grid size of GAF. HGAF synchronizes the relative position of active nodes in each virtual grid using the idea of *sub-grid*. $N^2$ *sub-grid* can be defined in each virtual grid. Fig. 3 illustrates the layout of a HGAF network when $N$ is 2. Each virtual grid has 4 *sub-grids* (e.g. $a_1$, $a_2$, $a_3$, and $a_4$,). One set of *sub-grids* with the same relative position in each virtual grid is kept as *active* for a predefined period. The authors suggested using HGAF as a clustering algorithm, where a node in each *active sub-grid* is selected as the cluster head for the corresponding virtual grid. As in Fig. 3, the communication range of sensor nodes $R_{com}$ satisfies:

$$R_{com} \geq \max\left(L_1, L_2\right) \tag{3}$$

Where the edge of the virtual grids $r_{HGAF}$ can be expanded as:

$$r_{HGAF} \leq R_{com} / \max\left(\sqrt{\left((N+1)/N\right)^2 + (1/N)^2}, \sqrt{2}\right) \tag{4}$$

In recent years, many ideas [3] have been proposed to address the *routing hole* problem in WSNs. The main objective of those protocols is to navigate routing paths around holes. To indicate the *routing holes* in WSNs, Fang et al. [14] proposed the TENT rule to exam whether a node can be a *local minimum*. A node is marked as a *stuck node* if an angle between its 2 angular adjacent neighbors is greater than $2\pi/3$. As illustrated in Fig. 4(a), node $A$ is marked as a *stuck node* since the angle

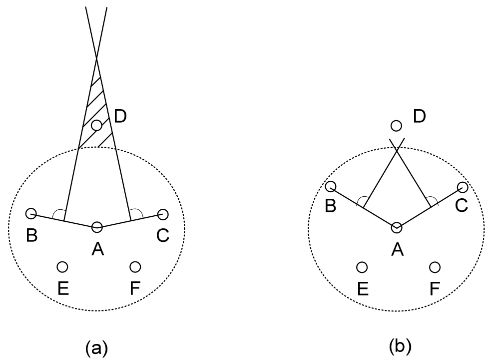


Fig. 4. Description of TENT rule.

$\angle BAC$ is greater than $2\pi/3$. The perpendicular bisector of *BA* and *CA*, together with the communication bounder of node *A*, forms an area (shadowed) outside the transmission range of node *A*, where a point is closer to node *A* than to node *B* or node *C*. When a packet with a destination (e.g. node *D*) in the shadowed area (Fig. 4(a)) arrives, node *A* becomes a *local minimum* since there is no neighbor closer to the destination than node *A* itself. In Fig. 4(b), when the minimal angle formed by 2 angular adjacent neighbors of node *A* is not greater than $2\pi/3$, the shadowed area disappears and node *A* can always find a neighbor which is nearer to any point outside its transmission range.

## III. Protocol Design

In our scenario, we assume a WSN where sensor nodes of the same type are static after deployment. The sensor nodes are aware of their geometrical location as well as the location of their one-hop neighbors. The proposed protocol is designed to avoid *routing holes* between an arbitrary pair of source and destination addresses. Namely, GAF&Co can be applied with the common "many-to-one", "one-to-one" and "many-to-many" communication models in WSNs. GAF&Co can be used as a scheduling algorithm for sleeping strategies, also as an algorithm for clustering. Besides, the idea of the *hierarchical hexagonal cell* can be used as a testing method of *routing holes* before applying geographic routing protocols to a network.

### A. Basic Idea

In the proposed GAF&Co protocol, we utilize the TENT rule to prevent *routing holes* caused by sleeping strategies in GAF-like protocols. As proved in the TENT rule, a nodes is not a *local minimum*, as long as there is no angle spanned by a pair of its angularly adjacent neighbors greater than $2\pi/3$. Therefore, we use the idea of *hierarchical hexagonal cell* instead of rectangular cells in GAF-like protocols. For each *hexagonal cell*, one node is kept active to carry out the sensing and routing activities of the cell at every time.

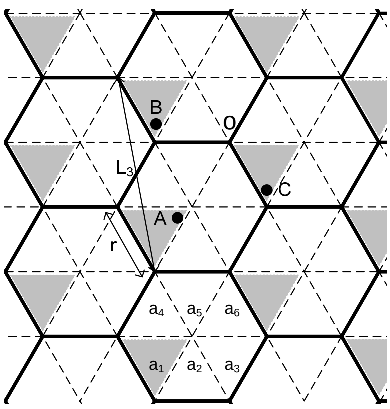


Fig. 5. An example of the GAF&Co protocol. The maximal angle spanned by node A and its 2 angular adjacent neighbors (node B and node C) is not greater than $2\pi/3$.

As in Fig. 5, a hexagonal cell of GAF&Co is composed of 6 triangular *sub-cells* (e.g. $a_1$, $a_2$, $a_3$, $a_4$, $a_5$, and $a_6$,). A set of triangular *sub-cells* with the same relative position in each hexagonal cell are set to be the *active sub-cells* (gray areas in Fig. 5). Each *active sub-cell* has an active node chosen with the same algorithm in GAF. According to the geometrical property of regular hexagon, the maximal internal angle formed by node *A* and its 2 angular adjacent neighbors (node *B* and node *C*) is not greater than $2\pi/3$. According to the TENT rule, node *A* is not a l*ocal minimum* for packets with arbitrary destination addresses.

To ensure the connectivity between an *active sub-cell* and its 6 adjacent *active sub-cells*, the communication range of sensor nodes ($R_{com}$) in GAF&Co satisfies:

$$R_{com} \geq L_3 = \sqrt{(1/2)^2 + \left(3\left(\sqrt{3}/2\right)\right)^2} \cdot r_{GAF\ \&Co} \qquad (5)$$

Or the edge of the hexagonal cells *r* satisfies:

$$r_{GAF\ \&Co} \leq R_{com} / \sqrt{7} \qquad (6)$$

***Lemma 3.1.*** Any point in the GAF&Co network is connected as long as there is one active node in each *active sub-cell*.

***Proof:*** As in Fig. 5, a point (e.g. node *A*) inside an *active sub-cell* can communicate with any points in the 6 neighboring *active sub-cells*. The communication range of sensor nodes $R_{com}$ satisfies equation (5), which implies that node *A* can also reach any point inside its own hexagonal cell. Thus, any 2 points inside the network can be connected through the overlay of the active nodes of the *active sub-cells*.

***Lemma 3.2.*** For any point inside an *active sub-cell*, the angle spanned by a pair of its angularly adjacent neighbors (active nodes in *active sub-cells*) is not greater than $2\pi/3$.

***Proof:*** As in Fig. 5, $\angle BAC$ is the sum of $\angle BAO$ and $\angle OAC$, where O is the joint point of the 3 hexagonal cells containing node *A*, node *B* and node *C*. Both $\angle BAO$ and $\angle OAC$ are not greater than the internal angle of a regular triangle ($\pi/3$). Thus, Angle $\angle BAC$ is not greater than $2\pi/3$. The *active sub-cells* are regular placed. Therefore, the relative position of an *active sub-cell* and its 2 neighboring *active sub-cells* (angular adjacent) is identical with rotation and displacement. Thus, the above proof is true for any point in Lemma (3.2).

### B. Scheduling & Synchronization

Similar to the HGAF protocol, scheduling of *active sub-cells* is required in our GAF&Co. We divide all *sub-cells* in the network into 6 groups according to their relative position in the hexagonal cells. At any time, only one group of *sub-cells* with the same relative position is active. Fig. 5 shows an example where the *sub-cells* on the lower left corner of the hexagons are active. In each *active sub-cell*, a node is kept active to carry out the sensing and routing activities for each hexagonal cell.

Two levels of scheduling are considered in GAF&Co: the selection of the *active sub-cell* group and the selection of the active nodes within each *active sub-cell.* Based on the estimated life time of sensor nodes, an interval $T_{duty}$ is defined where each group of *sub-cells* serves a time period of $T_{duty}$ and passes the active mode to the next group. In our example, the role of *active sub-cell* rotates in the order of $a_1$-$a_2$-$a_3$-$a_4$-$a_5$-$a_6$-$a_1$. In each *active sub-cell*, the node with the most energy capacity is selected to be active. Since the *sub-cells* of a hexagonal cell are considered equivalent, we suggest the strategy that exhausts all the nodes in the current *active sub-cells* before changing to the next group of *active sub-cells*. Ideally, only 6 global synchronizations are needed throughout the lifetime of a WSN. Therefore, we avoid periodical changing of the set of *active sub-cells* as in HGAF, and reduce the cost of control message overhead.

### C. Analytic Analysis

In contrast to AODV-like routing protocols, geographic routing protocols have better performance in terms of energy efficiency and success rate [8]. The main objective of GAF&Co is to avoid *routing holes* based on the TENT rule. GAF&Co avoids *local minimums* caused by sleeping strategies. As a result, geographic routing protocol with *greedy forwarding* can be simply applied with high success rates.

Besides, GAF&Co aims to achieve energy efficiency by expanding the size of the cells. There is only one *active sub-cell* in each hexagonal cell. Therefore, only one node is required to be active for each hexagonal cell, where the rest can be turned in to energy-saving mode as in GAF.

Based on equation (6), the size of hexagonal cells in GAF&Co is:

$$\begin{aligned} S_{GAF\,\&Co} &= 6\left(\sqrt{3}/4\right)\cdot r_{GAF\,\&Co}{}^2 \\ &\le \left(3\sqrt{3}/14\right)\cdot R_{com}{}^2 \approx 0.37\cdot R_{com}{}^2 \end{aligned} \quad (7)$$

In contrast, based on equation (2), the size of virtual grids in GAF is:

$$S_{GAF} = r_{GAF}{}^2 \le 0.2\cdot R_{com}{}^2 \quad (8)$$

Based on equation (4), the size of virtual grids in HGAF ($N$=2) is:

$$S_{HGAF} = r_{HGAF}{}^2 \le 0.4\cdot R_{com}{}^2 \quad (9)$$

According to equation (7), equation (8) and equation (9), the size of cells in GAF &Co is similar with HGAF ($N$=2), which is nearly double the size compared to GAF. As mentioned earlier, the number of active nodes in a network is in inversely proportional to the size of cells. Therefore, the energy consumption in the network is reduced when the size of cells increases. Notice that GAF&Co and HGAF require at least one node in each *sub-cell*. For such protocols, dense deployment is preferred, which also corresponds to the trend of modern WSNs.

## IV. Simulation Results

We simulated the GAF&Co protocol with Matlab [15]. The simulated network was a 500 m × 500 m square plane, where 5000 sensor nodes were randomly deployed. We used a simple *disc-communication model*: sensor nodes in the transmission range can receive signals from a transmitter without loss. The lossy model of wireless signal is out of the scope of this paper, and therefore not considered. For the random simulation, 95% confidence interval is applied to compute the mean values.

The objective of the experiment is to demonstrate the advantage of using *hierarchical hexagonal cells* on the algorithm level. The results of GAF&Co were compared with GAF and HGAF ($N$=2), regarding energy consumption and number of possible local minimums during geographic routing. We used the following metrics to evaluate the performance of the simulated protocols:

*Number of cells (static energy consumption)*: Defined as the number of cells after applying the topology management protocols. At any time, each cell has one node in active mode. The rest of the nodes are in *sleeping* or *discovery* mode as in GAF. According to the energy model in GAF [9], the active nodes consume most energy in a WSN. Therefore, the energy consumption of a network is almost proportional to the number of active nodes. This metric reflects the performance of the simulated protocols in terms of energy conservation.

Fig. 6 shows the number of cells formed by the simulated protocols. The number of hexagonal cells in GAF&Co is similar to the number of grids in HGAF, which is only half the amount comparing to the number of grids in GAF. The simulation results support the analytic analysis of equation (7), equation (8) and equation (9). When applied with the same communication range of sensor nodes, cells of GAF&Co and HGAF are of bigger size than cells of GAF. Therefore, fewer cells are needed to cover the simulated area. This also implies less number of active nodes since only one node is required to be active in each cell.

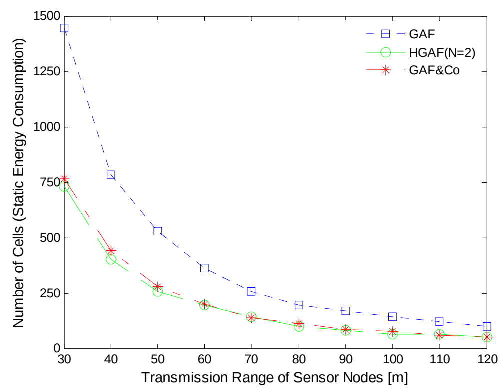


Fig. 6. Number of cells versus communication range.

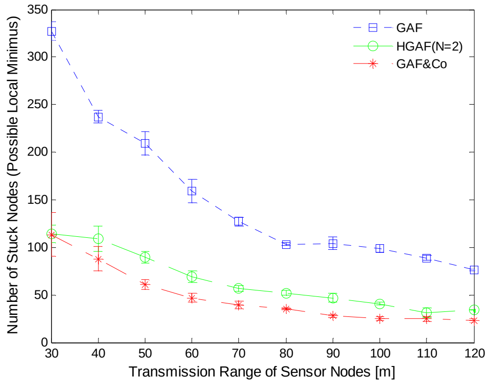


Fig. 7. Number of stuck nodes (possible local minimums) versus communication range.

*Number of struck nodes*: Defined as the number of *stuck nodes* according to the TENT rule. Each active node is tested with its neighboring active nodes by the TENT rule (a node is a *stuck node* if the maximal angle spanned by its 2 angular adjacent neighbors is greater than $2\pi/3$). A node is also recognized as a *stuck node* when its neighboring cells (GAF) or neighboring *active sub-cells* (HGAF, GAF&Co) are empty. This metric reflects the possibility to encounter *routing holes* when using geographic routing with *greedy forwarding*.

As illustrated in Fig. 7, the number of *stuck nodes* in HGAF is smaller than in GAF, since using *sub-grids* in HGAF already restricts the angle spanned by angular adjacent neighbors (as illustrated in Fig. 3). By involving the idea of the TENT rule, GAF&Co achieves significant advantage in reducing the number of *stuck nodes*, as the *hierarchical hexagonal cell* method promises. Therefore, the success rate of *greedy forwarding* can be improved after applying GAF&Co. Such topology management benefits both routing and energy efficiency of the network.

## V. Conclusions and Future Work

In this paper, we proposed a novel topology management protocol called GAF with COnnectivity-awareness (GAF&Co). The proposed protocol divides a network into *hierarchical hexagonal cells*. Each hexagonal cell has 6 triangular *sub-cells*. One set of the *sub-cells* with the same relative position in the hexagonal cells are set to be the *active sub-cells*, where one sensor node is kept active for routing activities. The rest of sensor nodes are switched to energy-saving mode. The number of active nodes is reduced using the hierarchal *sub-cells* to expand the size of the cells.

The main objective of GAF&Co is the avoidance of *routing holes* caused by existing sleeping strategies. The maximal angle formed by points in an active *sub-cell* and its 2 neighboring *active sub-cells* (angular adjacent) is not greater than $2\pi/3$. According to the *routing hole* detecting algorithm called the TENT rule, *local minimums* can be eliminated as long as every *sub-cell* has at least one sensor node. Therefore, efficient geographic routing with *greedy forwarding* can be applied together with GAF&Co.

In future work, we will analyze the impact of deployment density of WSNs (relative to the transmission range of sensor nodes) on the performace of GAF&Co. As such topology management requires accurate location information of sensors, the impact of localization errors will be investigated. The proposed protocol is currently applicable to WSNs with sensors with equal transmission range. In future, WSNs with heterogeneous sensor nodes will also be studied for GAF&Co.

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