A Geographic Routing Oriented Sleep Scheduling Algorithm in Duty-Cycled Sensor Networks

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***Abstract*—Geographic routing is assumed to be the most potential routing scheme in wireless sensor networks (WSNs) due to its scalability and efficiency. Recently more and more research work about geographic routing pay attention to its application scenarios in duty-cycled WSNs because of the natural advantage of saving energy consumption with duty-cycling. However, it may cause significant latency issue when applying geographic routing in duty-cycled WSNs and almost all current researches try to handle the latency problem from the point of changing the geographic forwarding mechanism, apart from the connected-k neighborhood (CKN) algorithm which focuses on sleep scheduling. In this paper, we discuss and analyze the first transmission path's performance of the two-phase geographic forwarding (TPGF) in a CKN based WSN and further propose a geographic routing oriented sleep scheduling (GSS) algorithm to shorten the first transmission path of TPGF in duty-cycled WSNs. Further theoretical and simulation results show that GSS can achieve a good tradeoff between the length of the first transmission path explored by TPGF and the total energy consumption to transmit data with the explored first transmission path, compared with the CKN sleep scheduling algorithm.**

***Index Terms*—Geographic Routing; WSNs; Duty-Cycle; CKN; TPGF**

I. Introduction

Geographic routing (e.g., [1] [2] [3]) which determines the routing path from the source to destination by selecting the forwarding node according to their positions, is the most promising routing scheme in wireless sensor networks (WSNs) [4]. In such a scheme, it can scale better as the routing state maintained per node lies only on the local network density and it can own better efficiency as geographic routing can be done even in the presence of irregular radio ranges and localization errors. Recently, geographic routing pays more and more attention to sensor networks with duty-cycle, as sensors in duty-cycled networks can go to sleep to save energy consumption, which is a very important design factor in practical WSN application scenarios [5]. However, with duty-cycling, nodes are dynamically awake or asleep in each time epoch according to some sleep scheduling algorithm (e.g., [6] [7]) and it will make the networks highly dynamic in terms of global connectivity and the number of awake neighbors per node. This may raise significant latency issue which is shown in Fig. 1.

In order to deal with the latency issue imposed by duty-cycling on geographic routing, a lot of research work (e.g., [8] [9] [10]) center on changing the geographic forwarding mechanism at the intermediate forwarding node or proposing some models and theories to analyze the latency when applying geographic routing in duty-cycled sensor networks (e.g., [11] [12]). For example, [8] tries to make each node wait for the appearance of the expected forwarding successor node first then select a backup node to avoid a dead wait if the first mechanism does not work. [11] derives the expressions for the average latency of a wait-and-forward routing scheme in one-dimensional and two-dimensional lattice topologies as a function of the slot-wake-up probability and the size of the network. But little research work focus on the sleep scheduling algorithm of duty-cycled networks to deal with the latency problem, except the connected-k neighborhood (CKN) sleep scheduling algorithm in [13].

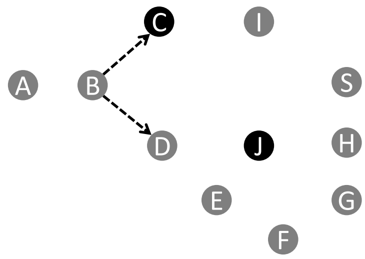


Fig. 1. Latency issue when applying geographic routing in duty-cycled WSNs. Gray nodes are awake nodes and black nodes are asleep nodes. Enroute from A to S, node B should decide waiting for C to wake up or routing from D, E, F, G, H to S. For either decision, the latency may increase significantly.

In this paper, focusing on the geographic routing performance of the two-phase geographic greedy forwarding (TPGF) [14], we evaluate the performance of the first transmission path of TPGF in a CKN based WSN as TPGF can be executed repeatedly to find multiple paths and nodes in any path explored by TPGF cannot be reused, which makes the first transmission path of TPGF have access to all neighbor nodes thus tend to be the shortest and most likely utilized path compared with other paths. Motivated by this goal, we propose a geographic routing oriented sleep scheduling (GSS) algorithm for improving the first transmission path's performance of TPGF in duty-cycled WSNs. By theoretical analysis and simulation, we show that the GSS algorithm can obtain a good tradeoff between the length of the first transmission path explored by TPGF and the total energy consumption to transmit data with the explored first transmission path, compared with the CKN sleep scheduling algorithm.

The rest part of this paper is organized as follows. Section II introduces CKN, TPGF and analyzes the first transmission path's performance of TPGF in a CKN based WSN. Section III presents the design of our proposed geographic routing oriented sleep scheduling (GSS) algorithm and analyzes the performance of the GSS algorithm. Section IV shows the performance of our GSS algorithm compared with the original CKN algorithm in terms of the length of the first transmission path and the total energy consumption to transmit data with that path. And this paper is concluded in section V.

II. TPGF and CKN

A. TPGF

The two-phase geographic greedy forwarding (TPGF) is proposed by Shu *et al.* in [14] for facilitating data transmission in always-on WSNs and it focuses on exploring the maximum number of optimal node-disjoint routing paths with respect to minimize the path length and the end-to-end transmission delay. Specially, the first phase of TPGF is to explore the possible routing path and the second phase of TPGF is to optimize the explored routing path with the least number of hops. By theoretical analysis and simulations in [14], TPGF occupies the following three kinds of transmission characteristics: multi-path transmission, hole-bypassing and shortest path transmission. And TPGF has the following three unique prosperities. First, it is a pure geographic greedy forwarding routing algorithm, which does not include the face routing concept. Second, it has a natural advantage to explore more node-disjoint routing paths as it does not require the computation and preservation of the planar graph [1] in WSNs. Third, it does not have the well-known local minimum problem [1], which may make a node cannot find the next-hop node that is closer to the sink than itself. One example of the first transmission path explored by TPGF is in Fig. 2.

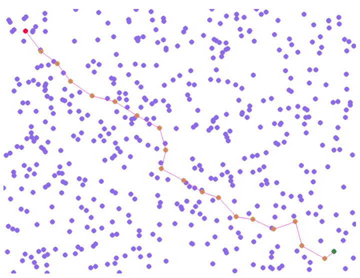


Fig. 2. One example of the first transmission path from a source node (red color) to the sink node (green color) explored by TPGF in an always-on WSN. There are total 500 sensor nodes and they are all awake.

B. CKN

The connected-k neighborhood (CKN) sleep scheduling algorithm is proposed by Nath *et al.* in [13] to reduce the number of awake nodes in a WSN to save energy consumption while making the whole network still connected by the awake nodes. Specially, the CKN algorithm determines the asleep or awake state of a node locally by the number and connectivity status of the node's currently awake neighbor nodes to create a connected network while trying to keep every node have some certain number (k) awake neighbor nodes. Moreover, the number of asleep nodes in a CKN based WSN can be decreased by increasing the k in CKN. One example of a CKN based WSN with different k is shown in Fig. 3.

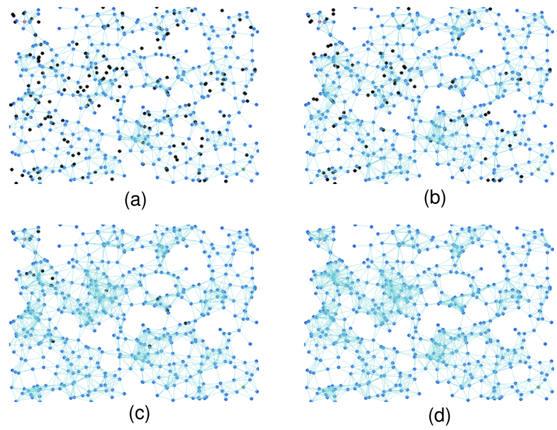


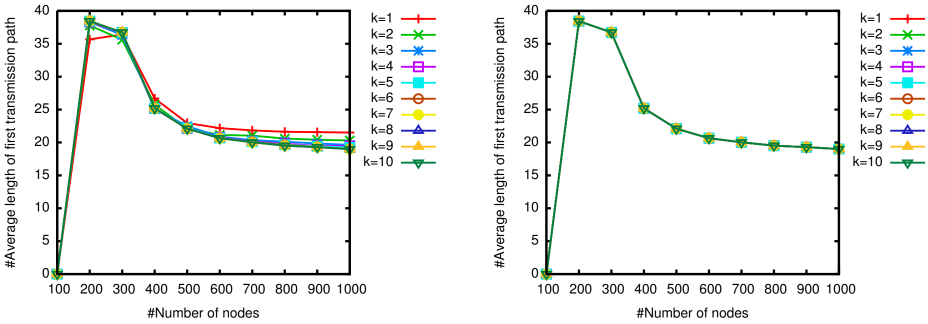
Fig. 3. One example of a CKN based WSN with different k. There are total 500 nodes and the k in CKN is 1, 2, 4, 8 in (a) (b) (c) (d), respectively. The red node is the source node and the green node is the sink node. The black nodes are asleep nodes and the blue nodes are awake nodes. The line between two nodes means they are neighbors. When the k in CKN increases, the number of asleep nodes decreases.

C. TPGF on a CKN based WSN

In order to check the first transmission path's performance of TPGF when there is duty-cycling, we implement TPGF and CKN in NetTopo[1] [15] and compare the length of the first transmission path explored by TPGF in a CKN based WSN and an always-on WSN. The studied WSN has the network size: 800×600 m^2. The number of deployed sensor nodes ranges from 100 to 1000 (each time increased by 100). And the value of k in CKN is changed from 1 to 10 (each time increased by 1). For every number of deployed sensor nodes, 100 different network topologies are generated using 100 different seeds. A source node is deployed at the location (50, 50) and a sink node is deployed at the location (750, 550) and the transmission radius of each node is 60 m.

Fig. 4(a) and Fig. 4(b) show the simulation results. From the two figures, we can clearly see that the average length of the first transmission path explored by TPGF in an always-on WSN is almost always shorter than that in a CKN based WSN. This demonstrates that sleeping nodes in CKN can seriously decrease the length of the first transmission path explored by TPGF although CKN based WSNs can save more energy consumption which has been demonstrated in [13].

[1] NetTopo (available online at http://sourceforge.net/projects/nettopo/) is an open source software on SourceForge for simulating and visualizing WSNs.



(a) (b)

Fig. 4. Average length of the first transmission path explored by TPGF in a CKN based WSN (a) and in an always-on WSN (b).

III. GSS ALGORITHM

A. *GSS algorithm*

Our GSS algorithm aims at shortening the length of the first transmission path explored by TPGF while still considering the energy saving. As CKN already obtains good energy saving, we incorporate both the connectivity and geographic routing requirement while designing the new sleep scheduling algorithm based on the original CKN. Specially, considering (1) the network should be connected by the awake nodes so that data can be transmitted and (2) sensor nodes will choose the neighbor node which is closest to the sink among all neighbor nodes to transmit data during geographic routing, we strategically take account of the geographic information of sensor nodes and make the potential nearest neighbor nodes to sink continue to be awake, although the original CKN already decides the node to be asleep without impairing the network connectivity.

We define our new method as geographic routing oriented sleep scheduling algorithm (GSS) and the pseudocode of GSS is shown below. During the first part of GSS, the geographic location (e.g., g_u) of each node u is got (Step 1 of first part) and the potential nearest neighbor to sink for each node is identified (Step 3 of first part). In the second part of GSS, a random rank $rank_u$ of each node u is picked (Step 1 of second part) and the subset C_u of u's currently awake neighbors having rank $< rank_u$ is computed (Step 5 of second part). Before u can go to sleep, it needs to ensure that (1) all nodes in C_u are connected by nodes with rank $< rank_u$ (2) each of its neighbors has at least k neighbors from C_u and (3) it is not the potential nearest neighbor node for other nodes (Step 6 of second part). The pseudocode without the underline are the original CKN algorithm.

Pseudocode of GSS algorithm

First: Run the following at each node u.

1. Get its geographic location g_u.
2. Broadcast g_u and receive the geographic locations of its all neighbors A_u. Let G_u be the set of these geographic locations.
3. Unicast a flag to w, $w \in A_u$ and g_w is the closest to sink in G_u.

Second: Run the following at each node u.

1. Pick a random rank $rank_u$.
2. Broadcast $rank_u$ and receive the ranks of its currently awake neighbors N_u. Let R_u be the set of these ranks.
3. Broadcast R_u and receive R_v from each $v \in N_u$.
4. If $|N_u| < k$ or $|N_v| < k$ for any $v \in N_u$, remain awake. Return.
5. Compute $C_u = \{v | v \in N_u$ and $rank_v < rank_u\}$.
6. Go to sleep if both the following conditions hold. Remain awake otherwise.
   - Any two nodes in C_u are connected either directly themselves or indirectly through nodes within u's 2-hop neighborhood that have $rank$ less than $rank_u$.
   - Any node in N_u has at least k neighbors from C_u.
   - It does not receive a flag.
7. Return.

B. *Analysis of GSS algorithm*

Theorem 1: A node u will have at least min(k, o_u) awake neighbors after running the GSS algorithm, if it has o_u neighbors in the original network.

Proof: If $o_u < k$, all of u's neighbors should keep awake (Step 4 of the second part of GSS) and node will have o_u awake neighbors.

Otherwise when $o_u \geq k$, we prove it by contradiction. We suppose that a node u will not have at least k awake neighbors after running the GSS algorithm, i.e., we can assume that the i'th lowest ranked neighbor v of u, $i \leq k$, decides to sleep. Then C_u will have at most $i-1$ nodes that are neighbors of u. But since $i-1 < k$, v cannot go to sleep according to the Step 6 of the second part of GSS. This is a contradiction. In other words, the k lowest ranked neighbors of u will all remain awake after running the algorithm, and hence, u will have at least k awake neighbors. ■

Theorem 2: Running the GSS algorithm produces a connected-network if the original network is connected.

Proof: We prove this theorem by contradiction. Assuming that the output network after running the GSS is not connected. Then we put the deleted nodes (asleep nodes determined by GSS) back in the network in ascending order of their ranks, and let u bet the first node that makes the network connected again. Note that by the time we put u back, all the members of C_u are already present and nodes in C_u are already connected since they are connected by nodes with rank $< rank_u$. Let v be a node that was disconnected from C_u but now gets connected to C_u by u. But this contradicts the fact that u can sleep only if all its neighbors (including v) are connected to $\geq k$ nodes in C_u (Step 6 of the second part of GSS). ■

Theorem 3: In terms of the same network topology, running the TPGF algorithm in a GSS based WSN will have shorter first transmission path compared with running that in a CKN based WSN. And the total energy consumption to transmit data with the explored first transmission path of TPGF will mainly depend on data traffic.

Proof: Regarding the same network topology, from the algorithm descriptions, we can get that generally GSS will have more awake nodes than CKN (unless all nodes are awake determined either by GSS or CKN). Note that, all nodes that are closest to the sink for all its neighbor nodes are among the awake nodes in GSS but this generally will not happen for CKN. As the principle of geographic forwarding of TPGF is that a forwarding node always chooses the next-hop node that is closest to the sink among all its neighbor nodes (shown in [14]), it is obvious that the length of the first transmission path explored by TPGF in a GSS based WSN will generally be much shorter than that in a CKN based WSN.

Moreover, about the total energy consumption of transmitting data in a GSS based WSN and a CKN based WSN with the explored first transmission path, although there are extra algorithm execution energy consumption of GSS (Step 1, 2 and 3 of the first part of GSS) and there are more idle energy consumption of being awake but not available by the first transmission path of GSS (there are generally more awake nodes of GSS than that of CKN and the length of first transmission path explored by TPGF in a GSS based WSN is shorter than that in a CKN based WSN), these energy consumption are compromisable as usually the energy consumption to transmit data takes most part. We can further deduce that under a low data traffic, the total energy consumption of GSS may be higher than that of CKN, but with the growth of data traffic, the total energy consumption of GSS may be less than CKN, due to that the reduce length of the transmission path of GSS can reduce energy consumption. In other words, the total energy consumption to transmit data with the explored first transmission path are mostly dependent of data traffic. ■

IV. Evaluation

To further demonstrate the effectiveness of our GSS compared with CKN, we conduct extensive simulations in NetTopo [15] regarding the length of the first transmission path explored by TPGF and the total energy consumption to transmit data with that path. The network configuration here is the same as the network configuration in section II. Moreover, we assume the energy consumption of a sensor by transmitting, transmitting amplifier, receiving one byte packet and being idle are 0.0144 mJ [16], 0.0288 nJ/m^2, 0.00576 mJ [16] and 0.00576 mJ. Each packet is represented by 12 bytes [16] and the source node will transmit 1000, 10000 and 100000 packets to the sink node respectively to simulate the performance under different data traffic.

From Fig. 5(a) and Fig. 5(b), we can clearly see that the average length of the first explored transmission path of TPGF in GSS based WSNs is nearly always shorter than that in CKN based WSNs. It is because there are more awake nodes (especially the potential nodes closest to sink) in GSS based WSNs than that in CKN based WSNs. Moreover, in terms of the same number of nodes, the length of the first explored transmission path of TPGF in Fig. 5(a) and Fig. 5(b) decreases when the value of k in both algorithms increases, as growing k in both algorithms can make more nodes be awake.

Furthermore, from Fig. 6(a) and Fig. 6(b), we can see the total energy consumption of GSS is higher than that of CKN when there are 1000 packets to be transmitted. But when there are 10000 packets to be transmitted, the average total energy consumption of GSS is overall just slightly higher than that of CKN, which are shown in Fig. 6(c) and Fig. 6(d). At some points, the average total energy consumption of GSS is even lower than that of CKN as the reduced length of the first transmission path can greatly decrease the energy consumption to transmit data. And when transmitting 100000 packets, the average total energy consumption of GSS is almost always lower than that of CKN from Fig. 6(e) and Fig. 6(f).

V. Conclusion

The scalability and efficiency of geographic routing algorithms make geographic routing algorithms have the great potential to become the most promising routing scheme in wireless sensor networks (WSNs). With duty-cycling, geographic routing algorithms are supposed to have one more advantage, which is saving energy consumption. However, duty-cycled WSNs may raise significant latency issues and most research work try to handle this problem by adjusting the geographic forwarding method except the connected-k neighborhood (CKN) sleep scheduling. In this paper, we identify the first transmission path's performance of the two-phase geographic greedy forwarding (TPGF) in a CKN based WSN and propose another sleep scheduling algorithm named geographic routing oriented sleep scheduling (GSS) to decrease the length of the first transmission path searched by TPGF in duty-cycled WSNs. Theoretical and simulation analysis about the GSS algorithm are presented and they reveal that: the GSS algorithm can own a better first transmission path in contrast with the original CKN and the total energy consumption to transmit data with the explored path of GSS may even be less than that of CKN under high data traffic.

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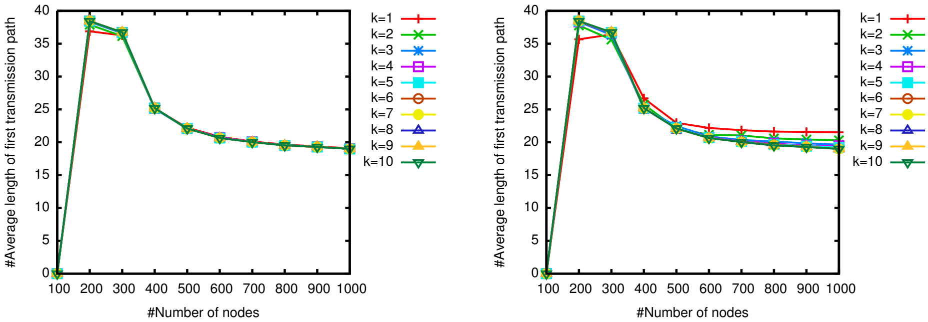
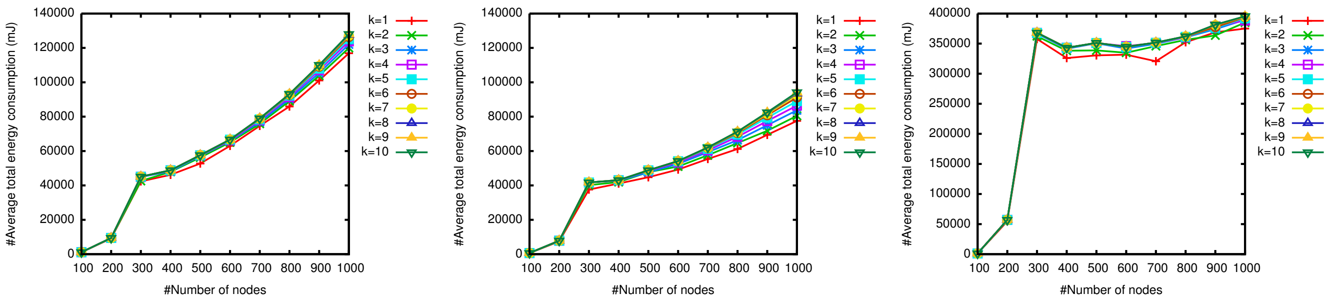
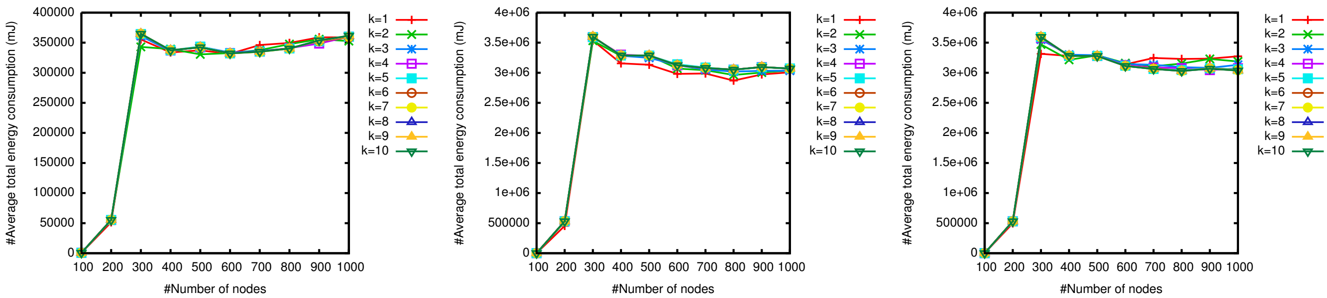


(a) (b)

Fig. 5. Average length of the first transmission path explored by TPGF in GSS based WSNs (a) and CKN based WSNs (b).



(a) (b) (c)



(d) (e) (f)

Fig. 6. Average total energy consumption to transmit data in GSS based WSNs (a) (c) (e) and CKN based WSNs (b) (d) (f). The packets to be transmitted are 1000 in Fig. 6 (a) (b), 10000 in Fig. 6 (c) (d) and 100000 in Fig. 6 (e) (f).

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