KCN: Guaranteed Delivery via K-Cooperative-Nodes in Duty-Cycled Sensor Networks

[1]Min Chen, [2]Xianbin Wang, [1]Junfeng Wang, [3] Di Wu, [4] Yong Li
[1] School of Computer Science and Technology, Huazhong University of Science and Technology, China (minchen@ieee.org)
[2] Department of Electrical and Computer Engineering, The University of Western Ontario, Canada (xianbin.wang@uwo.ca)
[3] School of Information Science & Technology, Sun Yat-Sen University, China (wudi27@mail.sysu.edu.cn)
[4] Department of Electronic Engineering, Tsinghua University, Beijing, China (e-mail: liyong07@tsinghua.edu.cn)

***Abstract*—Performance of multihop cooperative sensor networks depends on relaying candidate selection, optimal relay assignment, and cooperative communication. In this paper, we first propose a novel relaying candidate selection scheme (KCN-selection) to choose k-cooperative nodes (KCN) at each hop based on geographic information, while the certain number of k is initially determined based on an on-demand end-to-end (ETE) reliability in the presence of unreliable communication links. However, the pre-assigned KCN cannot ensure an optimal performance due to wireless channel dynamics. To prolong the lifetime of wireless sensor network (WSN), we schedule some part of KCN to sleep while the on-demand ETE reliability still can be guaranteed with wireless channel variations. A probabilistic ETE reliability model is built to compute optimal duty cycle for KCN in an online manner. Furthermore, a KCN based optimal relay assignment and cooperative data delivery (KCN-delivery) scheme is presented, which can provide fully stateless, energy-efficient sensor-to-sink data delivery at a low communication overhead without the help of prior neighborhood knowledge. Simulation results show that our scheme significantly outperforms existing protocols in wireless sensor networks with highly dynamic wireless channel.**

I. Introduction

Performance of multihop cooperative wireless networks depends on relaying candidate selection, optimal relay assignment, and cooperative communication [1]. In this paper, we first propose a novel relaying candidate selection scheme (KCN-selection) to choose k-cooperative nodes (KCN) at each hop based on geographic information, while the certain number of k is initially determined based on an on-demand end-to-end (ETE) reliability in the presence of unreliable communication links. However, the pre-assigned KCN cannot ensure an optimal performance due to wireless channel dynamics. To prolong the lifetime of wireless sensor network (WSN), we schedule some part of KCN to sleep while the on-demand ETE reliability still can be guaranteed with wireless channel variations. A probabilistic ETE reliability model is built to compute optimal duty cycle for KCN in an online manner. Furthermore, a KCN based optimal relay assignment and cooperative data delivery (KCN-delivery) scheme is presented, which can provide fully stateless, energy-efficient sensor-to-sink data delivery at a low communication overhead without the help of prior neighborhood knowledge.

In KCN-selection, the source node initiates the construction by transmitting a prob message. Among the cooperative nodes at each hop, a reference node (RN) will decide k-cooperative neighborhoods (KCN) and the next RN. Then, the probe message will be forwarded to the next RN. The construction will terminate when the sink receives the probe message.

In KCN-delivery, RN allocates a backoff delay to each cooperative node in KCN, such that the higher energy level will be assigned with a time slot with higher priority. Since the time slots are predetermined, during the data dissemination phase, the data is broadcast by a packet holder. On the reception of a data packet, each cooperative node fires its timers with the predetermined backoff delay. The one whose timer expires first will continuously broadcast the data packet. And the other cooperative nodes snooping the data message notice that another node has forwarded the data packet and quit the contention process.

Compared to the selection of potential forwarders (PFs) in conventional beaconless geographic routing, KCN-selection has the following advantages:

- In beaconless geo-routing, the selection of PFs is based on the shape and size of the forwarding area. Thus, the number of PFs is fluctuated hop by hop. Though some hops with a large number of PFs can reach high reliability, the ETE reliability cannot be predicted and guaranteed considering some “bottleneck” hop has only very few PFs. By comparison, KCN-selection always ensure k cooperative nodes at each hop, which makes ETE reliability predictable in this paper.

Compared to the forwarding strategy of the conventional beaconless geographic routing, KCN-delivery has the following advantages:

- The time slots of KCN are allocated by reference node (RN) in a centralized fashion before data dissemination, which is similar with TDMA-like approach. In practice, the value of each time slot should be as small as possible, yet it should be long enough that a PF can hear the data packet from another PF with higher priority before its

978-1-4673-9101-6/15 $31.00 © 2015 IEEE
DOI 10.1109/MASS.2015.29

timer expires. In other words, each time slot should be long enough to accommodate the hop delay, the elapsed time from the instance when a sensor node sends a data packet to its farthest neighbor node to the instance when the neighbor node receives it. By comparison, beaconless geo-routing needs three hand-shaking mechanism to avoid collision. Thus, KCN-delivery exhibits lower delay while guaranteeing the same packet delivery ratio.

- In beaconless geo-routing, packet holder typically broadcast a probe message, and waits for the first reply from PHs. After confirming the next packet holder, the current packet holder releases data packet by unicast. Comparing to such high cost data forwarding, in KCN-delivery, packet holder is not involved in the determination which PH will be the next packet holder. It is because the collision ratio of KCN-delivery can be ignored due to centralized allocation of forwarding delay among KCN.
- The priority assignment is performed in RN according to the PFs' residual energy information, in order to achieve load balancing among KCN. By comparison, most of beaconless geo-routing schemes do not consider energy efficiency.
- Since it dynamically schedule cooperative nodes' duty cycles, KCN-delivery can achieve energy efficiency while guaranteeing on-demand ETE reliability. By comparison, most existing beaconless geo-routing schemes cannot guarantee energy efficiency since all of the PFs should be awake to attend the election.

WSNs are normally powered by batteries with limited energy, which are difficult or impossible to be recharged or replaced. A common approach for saving the sensor nodes' energy is to select only a subset of nodes to remain active and let others to go to sleep. In KCN-delivery, we try to optimize network performance by reducing the number of active cooperative nodes efficiently while keeping the on-demand ETE reliability. Thus, in this paper, we build an ETE reliability model to investigate the following problems: (i) Given duty cycle, link failure ratio, and average node density, how is the relationship between the on-demand ETE reliability and the number of cooperative nodes at each hop; (ii) Given k number of cooperative nodes at each hop, how is the relationship between the on-demand ETE reliability and the duty cycle of cooperative nodes. Given a duty cycle, we further design a sleep scheduling algorithm that can balance the energy consumption of cooperative nodes to prolong network lifetime further, such that cooperative nodes with less residual energy have more chance to enter sleeping status.

II. KCN-SELECTION

Each sensor node is location-aware. All sensor nodes are equipped with the same radio transceiver and the transmission range R between $(0, R_{max}]$, where R_{max} is the maximum transmission range. Each node knows its own location as well as the location of the sink. The topology of sensor networks may dynamically change during operation, due to 1) energy

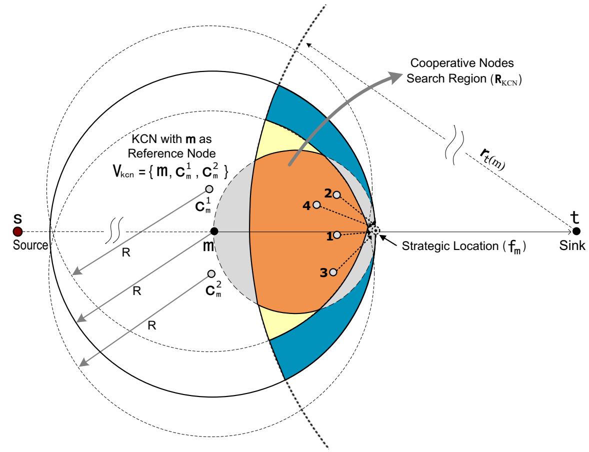


Fig. 1. Illustration of Cooperative Nodes Search Region

conservation (sensor nodes may periodically switch to sleep mode);[1] 2) unreliable links and node failures.

A multihop WSN with area size S is modeled by a graph $G = (V, E)$, where the vertices $V = \{v1, v2, \cdots, v_N\}$ denote the set of $N = |V|$ sensor nodes in the network, and a directed link $(u, v) \in E$ if $|uv| \le R$, where $|uv|$ is the euclidean distance between nodes u and v which can communicate with each other directly without relaying.

Definition 1 (Cooperative Nodes Search Region)**.** *Given a reference node m, let $C_m = \{c_m^1, c_m^2, \cdots, c_m^{k-1}\}$ denotes its associated $k-1$ cooperative nodes of m. The next-hop cooperative nodes search region, denoted by $\boldsymbol{R}_{KCN}$, is defined as the overlapping area of the k disks centered at m, c_m^1, c_m^2, $\cdots$, c_m^{k-1}, with radius R, the disk centered at sink t with radius $r_t(m)$ where $|mt| - R < r_t(m) < |mt|$, and the disk centered at the middle node between m and f_m with radius $\frac{R}{2}$.*

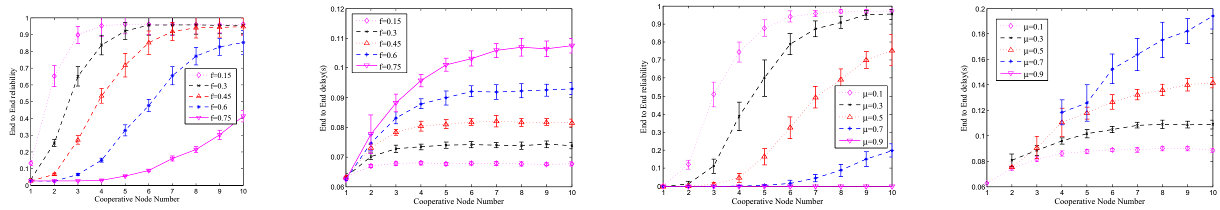
Let V_{kcn} denote the set of KCN. Then, V_{kcn} is equivalent to the combination of m and C_m, i.e., $V_{kcn} = \{m, c_m^1, c_m^2, \cdots, c_m^{k-1}\}$. For case of consistency, we also denote the reference node m as c_m^0.

Within the cooperative nodes search region, k nodes will be selected as the KCN for next hop. In our study, the ideal next-hop location for reference node m to select KCN is defined as follows:

Definition 2 (Strategic Location for KCN-selection)**.** *Given a reference node m, the strategic location for the selection of its next-hop KCN, denoted by f_m, is defined as the point on the straight line from m to the sink t, where $|mf_m| = R$.*

In the pure location-based selection criterion, the nodes, which are located in the cooperative search region and their distance to the strategic location is among the first k shortest value, will be selected as KCN.

[1] In WSNs, there are generally two kinds of networks: always-on WSNs in which sensors always keep awake and duty-cycled WSNs in which sensors dynamically sleep and wake.



(a) The impact of f and K on reliability.

(b) The impact of f and K on ETE delay.

(c) The impact of f and μ on reliability.

(d) The impact of f and μ on ETE delay.

Fig. 2. The impact of f, μ and K on reliability and ETE delay in KCN

Considering load balancing, the residual energy levels of the nodes are considered. We assume that every node starts with the same energy level corresponding to full battery capacity. And the current energy levels (remaining battery capacities) of the sensor nodes are discretized into integer-valued quantized-energy-levels (L_{QE}). The joint distance- and energy-level-based criterion is defined as:

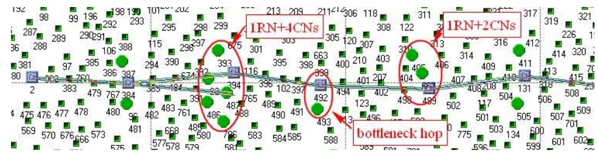
Definition 3. *Given a node u in the cooperative nodes search region, let $L_{QE}(u)$ be the quantized-energy-level, and let $|uf_m|$ be the distance from u to the strategic location. Its eligibility (or priority) as the cooperative node for next hop, denoted by Q_u, is defined as $Q_u = \sqrt{(1-\frac{|uf_m|}{R})^2 + (\frac{L_{QE}(u)}{L_{max}})^2}$ where L_{max} is the full battery level.*

The closer distance to f_m, the larger Q_i becomes, whereas the higher $L_{\mathrm{QE}}(u)$ is, the Q_i becomes. The nodes with the first k largest Q_i will be selected as KCN under this criterion.

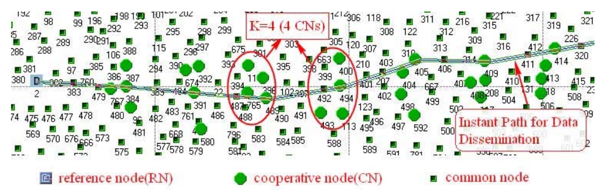
Among the KCN, the cooperative node with the least distance to the strategic location will be selected as the reference node for next-hop. Time is divided into epoches, and each epoch is T. In each epoch, the source node will initiate KCN-selection by transmitting a probe message. Then, KCN will be updated at each hop based on the residual energy and the location of neighborhood nodes.

III. Performance Evaluation

We implement our KCN along with three compared schemes, i.e., BLR [2], REER [3] and GPSR using OPNET Modeler, and perform extensive simulations. We choose a network where nodes are randomly deployed within a 1000m $\times$ 500m field. To verify the scaling property of our algorithms, we select a large-scale network with 800 nodes. Let f denote link failure rate. Let μ denote duty cycle of sensors. Let K represent the total number of cooperative nodes at each hop. Let R denote transmission range. By default, we set f to 0.3; μ is 1; K is 5; R is 75m; τ is 0.025s. We set hop count to be 14 and μ is equal to 0. K is changed from 1 to 10, and f is varied from 0.15 to 0.75. Fig. 2(a) shows the Impact of K and f on reliability. Fig. 2(b) shows the Impact of K and f on ETE delay. The larger f is, ETE delay is longer. Under a certain f, the ETE delay will converge to a stable value with the increase of K. Next, let f be fixed to 0.3. K is changed from 1 to 10. We vary μ from 0.1 to 0.9 with step of 0.2. Fig. 2(c) shows the impact of f and μ on reliability. Fig. 2(d) shows the impact of f and μ on ETE delay. The larger μ is, the ETE delay is longer. Once μ is fixed, with the increase of K, ETE delay converges to a certain value. Fig. 3 shows the comparison of the snapshot in OPNET. As shown in Fig. 3, KCN selects application-specific number of cooperative nodes while REER is not.



(a) Selection of cooperative nodes in REER.



(b) Selection of cooperative nodes in KCN

Fig. 3. Comparison of cooperative node-selection in the simulation of REER and KCN.

In this paper, a novel KCN scheme is proposed to choose k-cooperative nodes at each hop, while K is strategically determined to meet specific requirement on ETE reliability. After the construction of KCN structure at each hop, all of the non-cooperative nodes will remain in sleep state. Practically, an optimal duty cycle value can be calculated according to network dynamics, which enables part of cooperative nodes to switch into idle status for further saving energy consumption. Simulation results show that the proposed KCN scheme significantly outperforms existing protocols in terms of energy saving and QoS guarantees in terms of ETE reliability.

References

[1] D. Li, Y. Xu, X. Wang, and M. Guizani, "Coalitional game theoretic approach for secondary spectrum access in cooperative cognitive radio networks," *IEEE Transactions on Wireless Communications*, vol. 10, no. 3, pp. 844-856, March 2011.

[2] M. Heissenbuttel, T. Braun, T. Bernoulli, and M. Walchli, "BLR: Beacon-Less Routing Algorithm for Mobile Ad Hoc Networks," Computer Comm., vol. 11, pp. 1076-1086, 2004.

[3] M. Chen, T. Kwon, S. Mao, and Y. Yuan, "Reliable and energy-efficient routing protocol in dense wireless sensor networks," *International Journal of Sensor Networks*, vol. 4, no. 1, pp. 104–117, 2008.