A Ring-based Bidirectional Routing Protocol for Wireless Sensor Network with Mobile Sinks

Dezhong Shang[1], Xiulian Liu[2], Yan Yan[1], Cheng Li[3], Baoxian Zhang[1,4]

[1] Research Center of Ubiquitous Sensor Networks, University of Chinese Academy of Sciences, Beijing 100049, China
[2] Astronaut Center of China, Beijing 100094, China
[3] Faculty of Engineering and Applied Science, Memorial University, St. John's, NL A1B 3X5, Canada
[4] Jiangsu Internet-of-Things Research and Development Center, Wuxi, Jiangsu 214135, China

***Abstract*—Recently, research on wireless sensor networks with mobile sinks (mWSN) has attracted a lot of attention. The mobility of such sinks often results in unpredictable changes of network topology, and brings big challenge to the design of efficient routing protocols for such networks. In this paper, we focus on design of an energy efficient distributed routing protocol for mWSNs. For this purpose, we propose a lightweight ring-based bidirectional routing protocol, referred to as BI-LRRP. BI-LRRP does not need location information and it performs ring-based routing on multi-ring based network structure for packet delivery. To reduce the transmission cost and also prolong the network lifetime, BI-LRRP uses bidirectional search for finding a mobile sink before actual packet delivery. Simulations results show that the proposed protocol can achieve high performance as compared with existing work.**

***Index Terms*—Wireless sensor network, mobile sinks, routing protocol.**

I. Introduction

In a wireless sensor network (WSN), sink nodes can be mobile as well as static. A WSN with one or multiple mobile sinks (MS) is often referred to as mWSN. Much existing research shows that mobile sinks can improve the performance of a WSN [1][2]. However, the mobility of the sinks often result in unpredictable changes of network topology, which brings much challenges to the design of efficient routing protocol for such a network. Moreover, how the routing protocol utilizes the mobility of the sinks while suppressing the protocol overhead has great influence on the performance of an mWSN [3].

Existing routing protocols for mWSNs can be divided into the following three categories: location-based protocols, topology-based protocols, and reactive based protocols, based on the routing information required in their implementation [4]. In location based protocols, location information of nodes is used for assisting geographical forwarding. Typical location-based protocols include Line-Based Data Dissemination (LBDD) protocol [5]), Adaptive Location Update-based Routing Protocol (ALURP) [6], and Elastic Routing (ER) protocol [7]. All these protocols focus on how to suppress the protocol overhead for learning the up-to-date location information of mobile sinks while maintaining good path quality as mobile sinks move. The advantages of location based protocols include their simplicity and high scalability. However, acquiring location information often requires extra hardware, which is not always practical in reality. Topology-based protocols work to discover and then maintain topological information for identifying good paths from sensor nodes to mobile sinks [8]. Typical topology based protocols include Anchor-based Voronoi Routing Protocol (AVRP) [9], Multistage Data Routing Protocol MDRP [10], and λ-flooding protocol [11]. The former two protocols are based on the well-known Voronoi scoping concept. The third protocol can achieve worst case path stretch ratio via partial updating in the presence of sink movement. The difficulty in designing efficient topology based protocols lies in how to keep a good balance between the quality of the routes from sensor nodes to mobile sinks and the protocol overhead consumed for such routing operations in the presence of network dynamics. Reactive based protocols work in a reactive/passive way for route learning and updating. It in general has low protocol overhead but has long initial route acquisition latency and also long data path length. A typical example protocol in this aspect is the TRAIL protocol [9], which utilizes the trails left by mobile sinks for facilitating packet delivery. However, when no fresh trail is available, random walk routing has to be used, which can lead to high protocol overhead and low packet delivery ratio.

In [12], Yu et al. designed a lightweight ring based routing protocol (LRRP) for data gathering in mWSNs. LRRP is a hybrid protocol and it is purely a distributed routing protocol in which each network node only needs to keep limited routing information. It integrates ring-based forwarding and trail-based forwarding. Specifically, each packet is forwarded by using ring-based forwarding until the packet encounters a mobile sink or can be forwarded along a fresh trail to reaching a mobile sink. To enable efficient ring-based packet forwarding, a multi-ring-based

978-1-4799-6664-6/16/$31.00 ©2016 IEEE

infrastructure is built on top of a multihop wireless sensor network, which is used for packet forwarding on such a network. One big problem in LRRP is that it only considers the use of unidirectional search on the ring-based network structure for mobile sink discovery, which can lead to unnecessarily long data path and accordingly degraded network lifetime performance.

In this paper, we are aimed to enhancing the performance of LRRP and accordingly propose a lightweight ring-based bidirectional routing protocol (referred to as BI-LRRP). The design objectives include prolonging the network lifetime and also shortening the data path length. For this purpose, BI-LRRP uses bidirectional search to find nearby mobile sinks in the multi-ring based structure built by [12] for packet delivery. Detailed protocol design description is provided. Simulation results show that BI-LRRP can achieve high delivery ratio performance and it can largely reduce the per-packet transmission cost and also prolong the network lifetime as compared with existing work.

The remainder of this paper is organized as follows. In Section II, we model the network under study, and then present the design details of the proposed protocol. In Section III, we conduct extensive simulations for performance evaluation. In Section IV, we conclude the paper.

II. Proposed Protocol

In this section, we design a lightweight ring-based bidirectional routing protocol for mWSNs, which is aimed to achieve the following design objectives: (1) high packet delivery ratio, (2) reduced per-packet transmission cost, and (3) prolonged network lifetime. Our protocol is targeted for mWSNs with continuous traffic streaming applications.

Next, we will first formulate the network under study, then give a brief overview of the LRRP protocol, on top of which our new protocol is designed, and finally present the detailed design description of the proposed protocol.

A. Network Model

In this paper, we study a multi-hop wireless network, which can be modeled by $G(V, E)$, where $V(G)$ represents the set of nodes (including both sensor nodes and mobile sink nodes) and $E(G)$ represents the set of links in the network. All the nodes in the network are assumed to have the same communication range and the transmission power of nodes is fixed. A link $(u,v) \in E(G)$ means node u and v can communicate with each other directly. Specifically, if $d(u,v) \le R$, then a link exists between node u and node v, where $d(u,v)$ represents the geometrical distance between u and v, and R represents the uniform communication range of nodes in the network. Sensor nodes are randomly deployed in a two-dimensional sensing field and each node is assigned a network-wide unique id number. Sink nodes can freely move in the network deployment field. Moreover, nodes do not know their location information.

B. Brief Review of LRRP

LRRP [12] is purely a distributed routing protocol in which each network node only needs to keep very limited routing information. It integrates ring-based forwarding and trail-based forwarding. Specifically, each data packet is forwarded using ring-based forwarding until it reaches a mobile sink or can be forwarded along a fresh trail to reaching a mobile sink. To support efficient ring-based forwarding, LRRP builds a multi-ring-based infrastructure on top of a multihop wireless sensor network when the network is initially deployed. For creating such a multi-ring-based structure, LRRP first builds a shortest cycled path (in hop count), which tightly embraces a *virtual* topological hole that is artificially created in the central area of the network, as the *base ring*. Each remaining (outer) ring is formed by those nodes having the same hop distance to the base ring. When performing ring-based forwarding, data packets are forwarded along nodes on a selected ring in a pre-determined direction (either anticlockwise or clockwise). To make data packets to keep moving in the same direction along a particular ring and also shorten the path distance, virtual angle is assigned to each node in the ring structure in the following way: Nodes on the base ring are first assigned with virtual angles based on their respective positions (more exactly, hop distances to a preselected reference node on the base ring, all in the same direction) on the cycled path and the virtual angles for nodes on non-base-rings are iteratively computed based on the virtual angles of their father nodes on the shortest paths to the base ring. In this sense, we say polar coordinates are assigned to nodes on the multi-ring based network structure, which can ease the ring based packet forwarding. In this process, each node say n_x on the ring based structure will be assigned a ring ID and a virtual angle, which are denoted by $n_x.ringId$ and $n_x.va$, respectively. Fig. 1

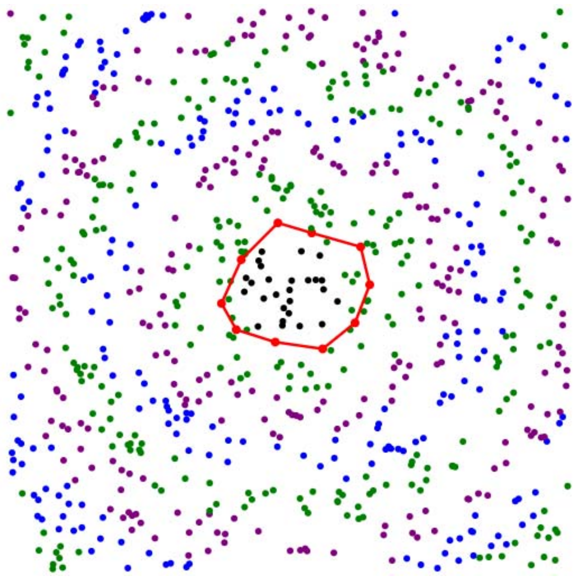

Figure 1 Example illustrating a multi-ring based network structure built by LRRP.

gives an example illustrating the multi-ring based network structure built by LRRP. In Fig. 1, the red cycle represents the identified base ring and nodes in different colors represent different outer rings: i.e., green, brown, blue, green, brown, …, and etc. In LRRP, to hide short movement of mobile sinks, each mobile sink chooses a close sensor node as its anchor node, which will be responsible for relaying received data packet(s), if any, to the mobile sink. Moreover, each anchor node will further recruit agent nodes for the mobile sink, one on each ring in the network, in order to increase the probability for receiving data packets in the context of ring-based forwarding. Note that agent nodes are also regular sensor nodes.

One big problem in LRRP is that it uses unidirectional packet forwarding. That is, when performing ring based forwarding, it chooses to use either clockwise or anticlockwise direction and will keep forwarding packets along the pre-selected direction. However, in a two-dimensional polar coordinate system, such a way of packet forwarding may lead to unnecessarily long paths because the closest mobile sink may be quickly reached if reverse direction was used for packet forwarding. This motivates us to design a new protocol by using bidirectional search.

C. *Detailed Design of BI-LRRP*

In this subsection, we present the detailed design description of our proposed protocol BI-LRRP, which is designed to enhance the LRRP protocol [12]. To achieve prolonged network lifetime and also shortened data path length, BI-LRRP uses bidirectional search for mobile sink discovery on top of the multi-ring based network structure built by LRRP.

1) *Bidirectional Search*

Upon receiving a data packet, a node *i* checks the target ring data segment in the packet first. If the target ring of the data packet is different from the ring where node *i* is located, node *i* will continue forwarding the packet to its target ring by selecting a neighbor node on a ring closer to the target ring; otherwise, node *i* will try forwarding the packet along the current ring by using ring-based forwarding (see later). To increase the data delivery ratio, shorten the path length, and also prolong the network lifetime, BI-LRRP uses bidirectional search to find a closer mobile sink (or its agent node) on the current ring before performing actual packet forwarding, if no such mobile sink or agent node is known. Details are as follows.

When the first node on the target ring (also called bidirectional search initiator) receives a data packet, it will first send two signaling packets in two different directions (one in clockwise direction and another in counterclockwise direction) to find an MS or an agent node of an MS on the ring. An agent node can be detected more quickly by using such bidirectional search than unidirectional search, and then determine which direction is closer to reach an MS based on the returned results. After the direction is determined, the packet will be forwarded in the chosen direction. This can quickly find an MS (or its agent node), shorten the data path length, which will bring larger gain in network lifetime, especially for continuous data streaming services.

The details of bidirectional search are as follows. The bidirectional search initiating node sends one SEARCH packet to its farthest neighbor node (measured by virtual angle progress) on the same ring in the clockwise direction and also another SEARCH packet to its farthest neighbor node on the same ring but in the counterclockwise direction. Such SEARCH packets carry "*detect*" tag, "*direction*" segment, and "*dist_so_far*" segment that records the length of the path already taken by the packet. *dist_so_far* is initially set to be 0. After a node receives the SEARCH packet, the value of *dist_so_far* will be updated by adding the virtual angle difference between the predecessor node and the current node. Then, the node checks the value of *dist_so_far*. If it is greater than π, which means the SEARCH packet has traveled half circle without finding an MS (or an agent node), then the search in this direction will be terminated. If the value is smaller than π, the node will check whether it itself is an agent node or a neighbor node of an agent node.

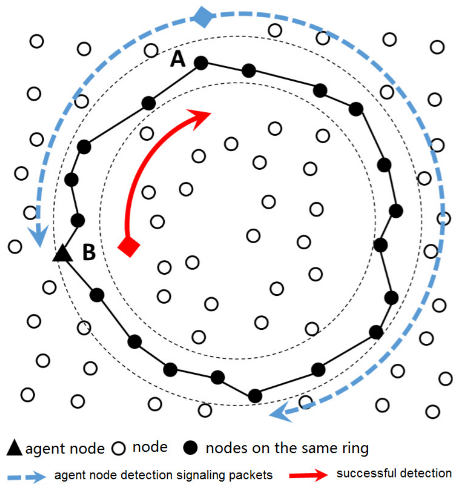

Figure 2 Example illustrating how bidirectional search works.

When the SEARCH packet reaches an agent node or agent node's neighbor, the search is said to be successful. A REPLY packet will be sent back to the search initiating node along the reverse path that it took earlier, which carries the position information (more exactly, its virtual angle information and search direction) of the discovered agent node. In an mWSN with multiple sinks, searches in both directions may be successful and in this case the search initiating node will receive two REPLY packets. In this case, we use the first received REPLY packet and ignore the other. If searches in both directions failed, the search initiating node will change the target ring in the data packet and sends it to an inner ring. The process will be repeated until the search succeeds. Note that the existence of certain broken point(s) on some ring(s) can also be well handled by using the above strategy for mobile sink discovery.

```
Input:  s: The current node;
        N_s: Neighbor set of node s
Output: NextHopSet_{s,clk}; Next hop candidate set of node s in
            the clockwise direction on the same ring;
        NextHopSet_{s,anti_clk}; Next hop candidate set of node s
            in the anticlockwise direction on the same ring;
1.  NextHopSet_{s,clk} ← NextHopSet_{s,anti_clk} ←∅
2.  for each neighbor n_i ∈ N_s  // clockwise direction
3.      do if (n_i.ringId ≠ s.ringId) then CONTINUE; end if
4.         va_prog(n_i)← n_i.va - s.va
5.         if (va_prog(n_i)<0)
6.            then va_prog(n_i)← va_prog(n_i)+2π
7.         if va_prog(n_i)∈ (0, π)
8.            then NextHopSet_{s,clk} ← NextHopSet_{s,clk} ∪ n_i
9.  for each neighbor n_i ∈ N_s // anticlockwise direction
10.     do if (n_i.ringId ≠ s.ringId)  then CONTINUE; end if
11.        va_prog(n_i) ← s.va - n_i.va
12.        if va_prog(n_i)<0
13.           then va_prog(n_i)← va_prog(n_i)+2π
14.        if va_prog(n_i)∈ (0, π)
15.           then NextHopSet_{s,anti_clk} ← NextHopSet_{s,anti_clk} ∪ n_i
16. return
```

Figure 3 Pseudo code for a node s to determine its next hop candidate set for performing ring based forwarding in clockwise and anticlockwise directions.

Fig. 2 illustrates the process of the bidirectional search in an mWSN with single sink. Node A which is the search initiating node, sends two SEARCH packets, one in clockwise direction and another in counterclockwise direction. In Fig. 2, there is only one agent node B on the target ring. The SEARCH packet in the counterclockwise direction arrives at the node B, and find the agent node successfully. Then node B sends a REPLY packet back to node A, which is shown by red solid arrow in the figure. The SEARCH packet in the other direction is finally discarded after finishing its journey with virtual angle distance of π and node A receives nothing in this direction. In this way, node A can determine counterclockwise direction as the appropriate direction to forward data packets towards mobile sink.

2) Ring-based Packet Forwarding

Upon finding a nearby agent node (or an MS), ring based forwarding will be performed. First, the forwarding node needs to use virtual angle information of neighbor nodes to determine next hop node candidate set, which contains all possible next hop nodes in either clockwise or anticlockwise direction based on which direction is chosen for packet forwarding.

Fig. 3 shows the pseudo code for determining the next hop candidate node set in either direction. In Fig. 3, we check two different directions separately. Lines 2-8 are for clockwise direction and lines 9-15 are for anticlockwise direction. If the direction is clockwise, node s goes through all its neighbor nodes and find those neighbors on the same ring with virtual angle progress in this direction and put them into the set $NextHopSet_{s,clk}$. For a neighbor node n_i, the value of $va\_prog(n_i)$ can tell whether node n_i is in the clockwise direction of node s or not. All the nodes that meet the condition form s's next hop candidate set $NextHopSet_{s,clk}$ in the clockwise direction. It is similar if the direction is counterclockwise. In particular, it must be noted that the right hand in line 4 and that in line 11 are different. The pseudocode in Fig. 3 can be executed offline during the network initialization phase.

Once the forwarding direction is determined based on the result returned by the bidirectional search, it is critical to choose appropriate metric to determine which is the best one as the next hop node for packet forwarding. For this purpose, we consider both progress in virtual angle and energy usage balancing. Suppose the forwarding direction is CLOCKWISE and the corresponding next hop candidate set is $NextHopSet$, for a node i, the weight associated with its next hop candidate c_i can be calculated as follows.

$$w_{c_i} = \beta \frac{va\_prog(c_i)}{\max_{x \in NextHopSet} va\_prog(x)} + (1-\beta)\frac{e_{c_i}}{E} \quad (1)$$

e_{c_i} represents the remaining energy of the node c_i, E represents the maximum nodal energy, and β is a coefficient, $0 \leq \beta \leq 1$, $\max_{x \in NextHopSet} va\_prog(x)$ returns the maximum virtual angle progress value among all the next hop candidates in $NextHopSet$. To determine the appropriate value for β, we conducted extensive simulations and the results show that when $\beta = 1$, the total number of transmissions per data packet is the lowest; when $\beta =$ 0,5, the protocol can achieve the longest network lifetime. In (1), $va\_prog(.)$ is virtual angle progress in pre-determined direction by a selected next hop.

Once the next hop node is chosen, the current packet holder will send its packet to the selected next hop. The node receiving the packet will continue this process until an MS or agent node of an MS is met. For the latter case, the agent node will forward the packet to its associated anchor node and then to the associated MS.

III. SIMULATION RESULTS

In this section, we conduct computer simulations to evaluate the performance of BI-LRRP by comparing it with LRRP and TRAIL. All these three protocols work in a reactive way for mobile sink discovery and has very low protocol overhead when the traffic load in the network is light. The simulator was written in C++. In the simulations, sensor nodes are uniformly distributed in a disk area. The diameter of the disk area is 180m. The transmission range of all nodes are all 30m. The MAC layer is considered to be ideal. Each mobile sink moves randomly at a constant velocity of 1 m/s. The TTL (time-to-live) of all data packets is 64 hops. That is, after traveling 64 hops without meeting an MS, a data packet

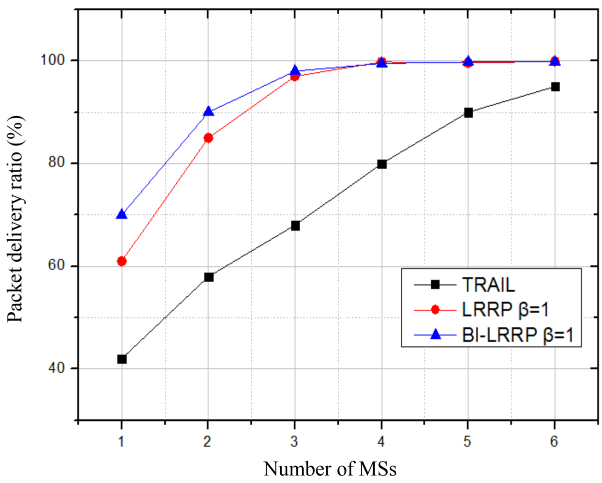

Figure 4 Comparison of packet delivery ratio performance by different protocols.

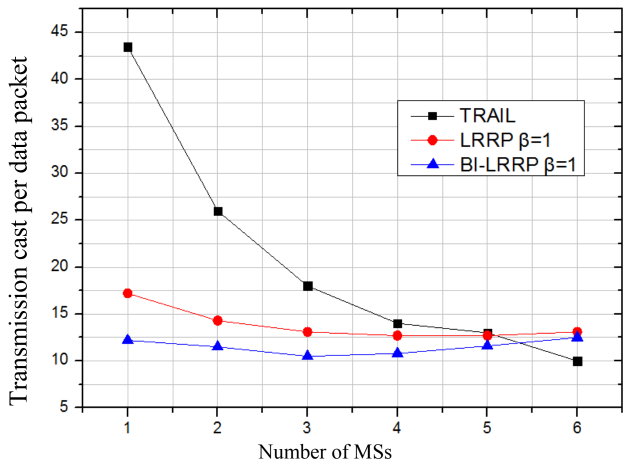

Figure 5 Comparison of transmission cost per data packet by different protocols.

will be discarded. We only consider the energy consumed for sending and receiving packets. The powers for these two operations are 80mW and 25mW, respectively. The data rate is set to be 19.2kb/s and the length of all the packets are 50 bytes. The initial energy of all sensor nodes are 5J.

There are always 10 data connection requests in the network, and each connection's source node and destination node are randomly selected. The data packet rate of a connection is 4 packets per second. The duration of a connection is randomly chosen in the range [2, 5] seconds. Once a connection is finished, another random connection will be generated.

Fig. 4 compares the delivery ratio performance of TRAIL, LRRP and BI-LRRP. In Fig. 4, it is seen that the delivery rates for all the three protocols increase as the number of mobile sinks increases. It can also be seen that BI-LRRP performs the best among the three protocols. Fig. 4 shows that when the number of mobile sink is one, the gap between LRRP and BI-LRRP is obvious. This is because nodes just forward the data packets towards a fixed direction in LRRP. In many cases, the agent node may be closer in the counterclockwise direction. In this case, LRRP has to take a long path to transfer data packets, which may lead to TTL timeouts, resulting in a lot of packet drops. BI-LRRP takes bidirectional search, which can shorten the data path length, which leads to higher packet delivery ratio. The simulation results also show that both LRRP and BI-LRRP achieve the highest delivery ration when $\beta = 1$. Packet delivery ratio performance by other settings of β is not shown here.

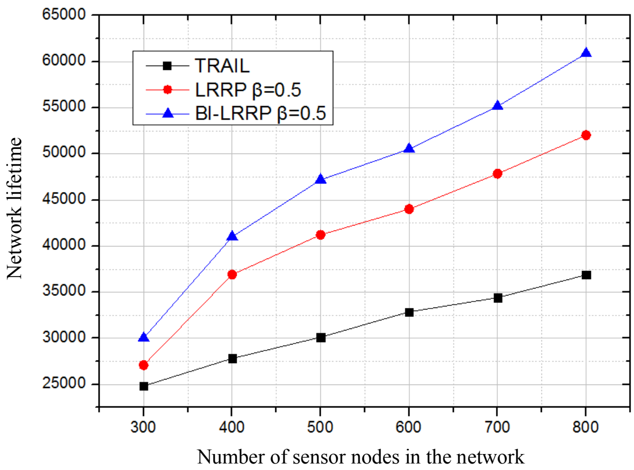

Figure 6 Comparison of network lifetime by different protocols.

Fig. 5 compares the per-packet transmission cost by different protocols. In Fig. 5, it is seen that BI-LRRP has the lowest per-packet transmission cost among the three protocols. Moreover, the per-packet transmission cost by both LRRP and BI-LRRP do change insignificantly with MS number.

Fig. 6 compares the network lifetime by different protocols for two-mobile-sink WSNs with network size ranging from 300 to 800 nodes. Moreover, the setting of $\beta = 0.5$ leads to the longest network lifetime for both LRRP and BI-LRRP based on extensive simulation results. In Fig. 6, BI-LRRP performs the best in prolonging network lifetime. This is because the bidirectional search strategy in BI-LRRP can not only shorten the path length but also reduce the energy consumed for packet delivery.

IV. CONCLUSION

In this paper, we proposed a lightweight energy efficient distributed routing protocol for wireless sensor networks with mobile sinks. To achieve high data delivery ratio, low transfer cost per data packet, and prolonged network lifetime, bidirectional search is introduced to enhance ring based packet forwarding. We conducted extensive simulations and the results shows that the proposed protocol BI-LRRP achieves high routing performance as compared with existing protocols.

ACKNOWLEDGEMENT

This work was supported in part by the NSF of China under Grant Nos. 61531006, 61471339 and 61173158, and National Science & Technology R&D Program of China under Grant No. 2014BAK06B03, and Natural Sciences and Engineering Research Council (NSERC) of Canada (Discovery Grant 293264-12 and Strategic Project Grant STPGP 397491-10).

REFERENCES

[1] Francesco, M. D.; Das, S. K.; Anastasi, G.; "Data Collection in Wireless Sensor Networks with Mobile Elements: A Survey," *ACM Transactions on Sensor Networks*, vol. 8, no. 1, pp.108-108, Aug. 2011.

[2] Akkaya, K.; Younis, M.; "A survey on routing protocols for wireless sensor networks." *Ad Hoc Networks*, vol. 3, no. 3, pp. 325-349, 2005.

[3] Tunca, C.; Isik, S.; Donmez, M. Y.; Ersoy, C.; "Distributed mobile sink routing for wireless sensor networks: A survey." *IEEE Communications Surveys & Tutorials,* vol. 16, no. 2, pp.877-897, 2014.

[4] Hamida, E. B.; Chelius, G.; "A line-based data dissemination protocol for wireless sensor networks with mobile sink," in *Proc. IEEE ICC 2008*, pp. 2201-2205, May 2008.

[5] Wang, G.; Wang, T.; Jia, W. J.; Guo, M.; Li, J.; "Adaptive location updates for mobile sinks in wireless sensor networks," The Journal of Supercomputing, vol. 47, no. 2, pp. 127–145, Feb. 2009.

[6] Yu, F.; Park, S.; Lee, E.; Kim, S.-H.; "Elastic routing: a novel geographic routing for mobile sinks in wireless sensor networks," *IET Communications*, vol. 4, no. 6, pp. 716-727, June 2010.

[7] Chong, C.-Y.; Srikanta, P. K.; "Sensor networks: evolution, opportunities, and challenges." *Proceedings of the IEEE,* vol. 91, no. 8, pp.1247-1256, 2003.

[8] Tian, K.; Zhang, B.; Huang, K.; Ma, J.; "Data Gathering Protocols for Wireless Sensor Networks with Mobile Sinks," in *Proc. IEEE GLOBECOM 2010,* pp.1-6, Dec. 2010.

[9] Shi, L.; Zhang, B.; Huang, K.; and Ma, J.; "An efficient data-driven routing protocol for wireless sensor networks with mobile sinks," in *Proc. IEEE ICC 2011*, pp.1-5, June 2011.

[10] Li, Z.; Li, M.; Wang, J.; Cao, Z.; "Ubiquitous data collection for mobile users in wireless sensor networks," in *Proc. IEEE INFOCOM 2011*, pp. 2246-2254, Apr. 2011.

[11] Yu, S.; Shang, D.; Yao, Z.; Zhang, B.; Li, C.; "A lightweight ring-based routing protocol for wireless sensor networks with mobile sinks," in *Proc. IEEE GLOBECOM 2014,* pp. 4580 – 4585, Dec. 2014.

[12] Yu, S.; Zhang, B.; Li, C.; Mouftah, H.; "Routing Protocols for Wireless Sensor Networks with Mobile Sinks: A Survey," *IEEE Communications Magazine*, vol. 52, no. 7, pp.150-157, July 2014.