VGDRA: A Virtual Grid-Based Dynamic Routes Adjustment Scheme for Mobile Sink-Based Wireless Sensor Networks

Abdul Waheed Khan, Abdul Hanan Abdullah, *Member, IEEE*, Mohammad Abdur Razzaque, *Member, IEEE*, and Javed Iqbal Bangash

***Abstract*— In wireless sensor networks, exploiting the sink mobility has been considered as a good strategy to balance the nodes energy dissipation. Despite its numerous advantages, the data dissemination to the mobile sink is a challenging task for the resource constrained sensor nodes due to the dynamic network topology caused by the sink mobility. For efficient data delivery, nodes need to reconstruct their routes toward the latest location of the mobile sink, which undermines the energy conservation goal. In this paper, we present a virtual grid-based dynamic routes adjustment (VGDRA) scheme that aims to minimize the routes reconstruction cost of the sensor nodes while maintaining nearly optimal routes to the latest location of the mobile sink. We propose a set of communication rules that governs the routes reconstruction process thereby requiring only a limited number of nodes to readjust their data delivery routes toward the mobile sink. Simulation results demonstrate reduced routes reconstruction cost and improved network lifetime of the VGDRA scheme when compared with existing work.**

***Index Terms*— Routes reconstruction, energy efficiency, mobile sink, wireless sensor networks.**

I. Introduction

WIRELESS Sensor Network (WSN) – a self-organized network of tiny computing and communication devices (nodes) has been widely used in several un-attended and dangerous environments. In a typical deployment of WSN, nodes are battery operated where they cooperatively monitor and report some phenomenon of interest to a central node called sink or base-station for further processing and analysis. Traditional static nodes deployment where nodes exhibit n-to-1 communication in reporting their observed data to a single static sink, gives rise to energy-hole phenomenon in the vicinity of sink. Sink mobility introduced in [1] not only helps to balance the nodes' energy dissipation but can also link isolated network segments in problematic areas [2]. In addition, several application environments naturally require sink mobility in the sensor field [3] e.g., in a disaster management system, a rescuer equipped with a PDA can move around the disaster area to look for any survivor. Similarly, in a battlefield environment, a commander can obtain real-time information about any intrusion of enemies, scale of attack, suspicious activities etc via field sensors while on the move. In an Intelligent Transport System (ITS), sensor nodes deployed at various points of interest - junctions, car parks, areas susceptible to falling rocks, can provide early warnings to drivers (mobile sink) well ahead of their physical approach.

Exploiting the sink's mobility helps to prolong the network lifetime thereby alleviating energy-hole problem; however, it brings new challenges for the data dissemination process. Unlike static sink scenarios, the network topology becomes dynamic as the sink keeps on changing its location [4]. To cope with the dynamic network topology, nodes need to keep track of the latest location of the mobile sink for efficient data delivery. Some data dissemination protocols e.g., Directed Diffusion [5], propose periodic flooding of sink's topological updates in the entire sensor field which gives rise to more collisions and thus more retransmissions. Taking into consideration the scarce energy resource of nodes, frequent propagation of sink's mobility updates should be avoided as it greatly undermines the energy conservation goal. In this regard, to enable sensor nodes to maintain fresh routes towards the mobile sink while incurring minimal communication cost, overlaying based virtual infrastructure over the physical network is considered as an efficient approach [6]. In the virtual infrastructure based data dissemination schemes, only a set of designated nodes scattered in the sensor field are responsible to keep track of sink's location. Such designated nodes gather the observed data from the nodes in their vicinity during the absence of the sink and then proactively or reactively report data to the mobile sink.

In this paper, a novel scheme called Virtual Grid based Dynamic Routes Adjustment (VGDRA) is proposed for periodic data collection from WSN. Unlike the existing solutions, which improve data delivery performance either by employing multiple mobile sinks or by deploying super nodes at strategically important points in the sensor field, the proposed scheme does not impose any such constraints. It aims to optimize the trade-off between nodes energy consumption and data delivery

Manuscript received June 2, 2014; revised July 27, 2014; accepted July 27, 2014. Date of publication August 12, 2014; date of current version November 11, 2014. This work was supported by the Universiti Teknologi Malaysia, Malaysia, under Grant PY/2012/00306 (Vote No: 4F205). The associate editor coordinating the review of this paper and approving it for publication was Dr. Nitaigour P. Mahalik.

The authors are with the Department of Computer Science, Faculty of Computing, Universiti Teknologi Malaysia, Johor Bahru 81310, Malaysia (e-mail: wkabdul2@live.utm.my; hanan@utm.my; marazzaque@utm.my; ibjaved2@live.utm.my).

Color versions of one or more of the figures in this paper are available online at http://ieeexplore.ieee.org.

Digital Object Identifier 10.1109/JSEN.2014.2347137

performance using a single mobile sink while adhering to the low-cost theme of WSN. The proposed scheme enables sensor nodes to maintain nearly optimal routes to the latest location of a mobile sink with minimal network overhead. It partitions the sensor field into a virtual grid of K equal sized cells and constructs a virtual backbone network comprised of all the cell-headers. Nodes close to the centre of the cells are appointed as cell-headers, which are responsible for data collection from member nodes within the cell and delivering the data to the mobile sink using the virtual backbone network. The goal behind such virtual structure construction is to minimize the routes re-adjustment cost due to sink mobility so that the observed data is delivered to the mobile sink in an energy efficient way. In addition, VGDRA also sets up communication routes such that the end-to-end delay and energy cost is minimized in the data delivery phase to the mobile sink. The mobile sink moves along the periphery of the sensor field and communicates with the border cell-headers for data collection. The routes re-adjustment process is governed by a set of rules to dynamically cope with the sink mobility. Using VGDRA, only a subset of the cell-headers needs to take part in re-adjusting their routes to the latest location of the mobile sink thereby reducing the communication cost. Simulation results reveal decreased energy consumption and faster convergence of VGDRA compared to other state-of-the art.

The rest of this paper is organized as follows: Section II describes the related work encompassing the various approaches in literature that deal with data delivery to a mobile sink in WSN. Section III presents our VGDRA scheme in detail. To evaluate the performance of the VGDRA scheme, simulation setup and results are presented in Section IV. Finally, Section V concludes the paper.

II. Related Work

Several virtual infrastructure based data dissemination protocols have been proposed for mobile sink based WSN in the last decade. Based on the mobility pattern exhibited by the sink in the sensor field, the data collection or dissemination schemes can be classified into controlled and uncontrolled sink mobility schemes. In controlled sink mobility schemes [7]-[10], the mobility (speed and/or direction) of the sink is manipulated and controlled either by an external observer or in accordance with the network dynamics. The uncontrolled sink mobility based schemes are characterized by the fact that the sink makes its next move autonomously in terms of speed and direction. This paper considers the uncontrolled sink mobility environments and in the following lines, we briefly describe the related works in this context including their methodology and the relative strengths and weaknesses.

Chen et al. [11] presented a converge-cast tree algorithm called Virtual Circle Combined Straight Routing (VCCSR) that constructs a virtual structure comprised of virtual circles and straight lines. A set of nodes are appointed as cluster-heads along these virtual circles and straight lines. Together the set of cluster-heads form a virtual backbone network. The sink circulates the sensor field and maintains communication with the border cluster-heads for data collection. The cluster-heads in VCCSR follow a set of communication rules to minimize the routes re-adjustment cost in propagating the sink's latest location information. VCCSR scheme although reduces the routes reconstruction cost in handling the sink mobility, however, the cluster-head at the centre of the sensor field being the focal point in routes re-adjustment process, depletes its energy much earlier.

Hexagonal cell-based Data Dissemination (HexDD) proposed in [12] constructs a hexagonal grid structure to address real-time data delivery while taking into consideration the dynamic conditions of multiple mobile sinks and event sources. Based on the six directions of a hexagon, HexDD defines query and data rendezvous lines to avoid redundant propagation of sink's data queries. Nodes send their data to nearest border line which is then propagated towards the centre cell. Nodes along the border line store and replicate the data. Sink's data queries are forwarded towards the centre cell and as soon as it approaches a border line node with the relevant data stored, data delivery to the mobile sink starts using the reverse path. To cope with sink mobility, whenever the sink moves from one cell to another, it informs the centre nodes as well as the border nodes along the route about the new cell where the sink is currently stationed. This results in high energy consumption especially at higher sink's speeds. Nodes along the border line cells and especially at the centre cell are vulnerable to high energy consumption thereby causing early hot-spot problem.

Oh et al. proposed a data dissemination scheme called Backbone-based Virtual Infrastructure (BVI) in [13] that makes use of single-level multi-hop clustering. It aims to minimize the total number of clusters and thus the scale of network overhead associated with informing all the CH nodes about the sink's location information. For clustering it employs HEED [14] where priority is given to residual energy level of nodes in electing the CH nodes. To keep track of sink location information, it assumes that the network operator appoints a certain CH node as root of the tree. Whenever, the mobile sink joins the sensor field, it registers itself with the closest CH via an agent node. The host CH node accordingly updates other CH nodes along the route to the root CH about the sink's location information. Furthermore, when a mobile sink moves within a cluster, the respective CH node only takes care of connection with the sink within the cluster and avoids propagation of sink location updates to the root. However, when the sink joins another cluster, it selects another agent node and registers itself to the new CH node which accordingly shares this information with the root and the other CH nodes along the BVI segment to the root. The multi-hop clustering although appears a good strategy to minimize the number of clusters and thus the network control overhead, however, the root node being the focal point in routes adjustments triggers early energy depletion and thus reduces the network lifetime.

Multiple Enhanced Specified-deployed Sub-sinks (MESS) in [15], creates a virtual strip in the middle of sensor field thereby placing enhanced wireless nodes (sub-sinks) having more storage capacity at equal distances. The set of sub-sink nodes along the accessible path serve as rendezvous points for

TABLE I

SUMMARY AND COMPARISON OF VIRTUAL STRUCTURE BASED DATA DISSEMINATION PROTOCOLS

Scheme	Location Awareness	Cost of Network Control Overhead	Convergence Time	Applicability
VCCSR [12]	Yes	Moderate	Medium	Widespread
HexDD [13]	Yes	Moderate	Slow	Widespread
BVI [14]	No	Moderate	Slow	Widespread
MESS [16]	Yes	Low	Slow	Limited
LBDD [17]	Yes	Low	Slow	Limited
RailRoad [18]	Yes	Low	Slow	Limited
QDD [19]	Yes	High	Slow	Widespread
TTDD [20]	Yes	High	Slow	Widespread
GCA [21]	Yes	Low	Slow	Widespread
HCDD [22]	No	Low	Slow	Widespread

the mobile sink and collect and store data from sensor nodes. In data delivery phase, mobile sink floods the query along the virtual strip till it reaches to the sub-sink node owning the data. Upon receiving the query from mobile sink, the sub-sinks route their deposited data to the mobile sink using geographical forwarding approach. A similar approach has also been proposed in Line-Based Data Dissemination (LBDD) [16] which constructs a vertical line by dividing the sensor field into two equal sized blocks. Yet another similar approach can be found in [17], which places a virtual rail (called RailRoad) in the middle of the sensor field where nodes inside the virtual rail's premises serve as rendezvous points. The main limitation of MESS, LBDD, and RailRoad is the early energy depletion of nodes close to the virtual structure as the same nodes are repeatedly chosen as relays for the farther nodes. In addition, MESS also imposes placement of enhanced nodes along the virtual strip which limits its applicability.

In Quadtree-based Data Dissemination (QDD) proposed by Mir and Ko in [18], a node upon detecting an event calculates a set of rendezvous points (RPs) by successively partitioning the physical network space into four quadrants of uniform sizes. After partitioning the network, QDD routes the observed data to those nodes which are close to the centroid of each partition. The mobile sink disseminates the query packet using the same strategy by querying the node at closest RP first, followed by the subsequent RP nodes till it reaches the required data report. In static nodes deployments, the same set of nodes become RPs repeatedly which results in early energy depletion of those nodes and thus decreases the overall network lifetime.

Virtual grid based Two-Tier Data Dissemination (TTDD) in [19] proactively constructs a uniform per source node virtual grid structure spanning the entire sensor field. For data collection, the mobile sink floods its local grid cell where the query packet makes use of all the disseminating points along the virtual grid till it gets to the source node. During query dissemination process, a reverse path is also established for data reporting to the mobile sink. TTDD although avoids the flooding of the sink's topological updates, however, the per source virtual grid construction undermines the network lifetime.

Geographical Cellular-like Architecture (GCA) in [20] proactively constructs a cellular-like hierarchical hexagonal virtual structure for handling sink mobility. GCA just like home-agent in cellular networks appoints the node close to the centre of the cell as the *header* node and remark the rest of the nodes as *member* nodes. For data collection, the mobile sink sends its query to nearest *header* which then propagates the query to all the *headers*. To handle sink mobility, when the sink joins another cell, it informs the old cell's *header* about the new *header* which re-route the packets accordingly. GCA although avoids flooding of sink's location information, however, the non-optimal data delivery paths results in increased latency and packet loss ratio due to the expiry of time-to-live value of packets.

Hierarchical Cluster-based Data Dissemination (HCDD) in [21] proposes a hierarchical cluster architecture where the second level cluster-heads of the mobile sink are appointed as routing agents. The routing agents are responsible to keep track of sink's latest location information and all the cluster-heads route their collected data to the nearby routing agents. When sink moves from one point to another, it informs the nearest routing agent via the closest cluster-head. The routing agent upon sink discovery broadcasts the sink's latest location information to all the other routing agents. In high sink mobility, nodes using HCDD suffer from high energy consumption. In addition, due to the restricted propagation of sink's location information, the data delivery paths are not optimal which results in high latency.

Table 1 presents a summary and comparison of the variously discussed schemes. We evaluate each scheme in terms of parameters such as location awareness, cost of network control overhead, convergence time and applicability. The location awareness specifies whether the considered scheme requires the nodes to be aware of their physical/relative coordinates. This feature is quite helpful in constructing the virtual infrastructure as well as routing of the query and response packets [22], [23]; however it incurs some additional energy cost. The second parameter provides an estimate of the overhead cost involved in establishing and maintaining data delivery routes to the latest location of the mobile sink. For prompt delivery of data packets to the mobile sink, nodes need to be informed of the latest location of the mobile sink. Similarly, the convergence time is an estimate of how promptly the sensor nodes come to know about some significant position change of the mobile sink and indirectly reflects the efficiency of the subsequent data delivery phase. Finally, the applicability parameter represents the scope of each scheme where if the considered scheme imposes too many constraints and/or violates the self-organized nature of the low cost sensor nodes, it limits its widespread applicability.

Based on the study of literature, it is observed that improved data delivery performance can be achieved at the expense of more energy consumption in the form of frequent propagation of sink's location updates. The main contribution of this paper is to optimize the trade-off between nodes' energy consumption and improved data delivery performance thereby proposing a virtual grid based dynamic routes adjustment scheme. It offers a light weight solution for the resource constrained real motes which neither requires any specialized set of resources on part of the sensor nodes nor imposes too many constraints for network operation. These features together with the dynamic routes adjustments in an energy-efficient manner make it a viable choice in a range of WSN's applications as compared to existing schemes.

III. The VGDRA Scheme

In this section, we give detailed description of our VGDRA scheme, including how to construct the virtual infrastructure and how to maintain fresh routes towards the latest location of the mobile sink. We design a virtual infrastructure by partitioning the sensor field into a virtual grid of uniform sized cells where the total number of cells is a function of the number of sensor nodes. A set of nodes close to centre of the cells are appointed as cell-headers which are responsible for keeping track of the latest location of the mobile sink and relieve the rest of member nodes from taking part in routes re-adjustment. Nodes other than the cell-headers associate themselves with the closest cell-headers and report the observed data to their cell-headers. Adjacent cell-headers communicate with each other via gateway nodes. The set of cell-headers nodes together with the gateway nodes constructs the virtual backbone structure.

A. Network Characteristics

Before describing the methodology of VGDRA scheme, it is worthwhile to highlight the various assumptions of the sensor networks. We assume the following network characteristics:

- Nodes are randomly deployed and throughout remain static.
- All the nodes are of homogeneous architecture and know their location information.
- Nodes adapt their transmission power based on the distance to the destination nodes.
- The mobile sink does not have any resources constraints.
- The mobile sink performs periodic data collection from sensor nodes while moving along the periphery of the sensor field and maintains communication with the closest border-line cell-headers for data collection.

B. The Virtual Structure Construction

The VGDRA scheme constructs the virtual grid structure by first partitioning the sensor field into several uniform sized

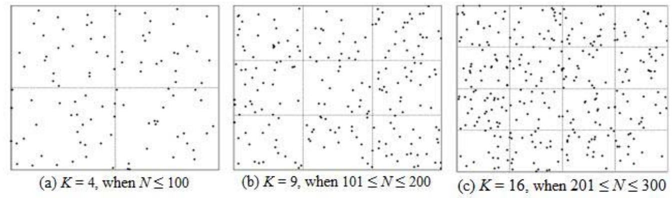


Fig. 1. Example of different virtual grid based structures for different number of nodes

cells based on the number of nodes in the sensor field. The rationale behind such portioning is to uniformly distribute the work-load on part of cell-header nodes which consequently results in prolonged network lifetime.

To determine the optimal number of cells and thus the cluster-heads, we adopt the heuristics used in LEACH [24], TEEN [25], and APTEEN [26] which consider 5% of the total number of sensor nodes. Given N number of nodes, the VGDRA scheme partitions the sensor field into K uniform sized cells using Equation 1, where K is a squared number. Fig. 1 (a), (b) and (c) shows network partitioning into various uniform sized cells for $N = 100, 200, 300$ respectively.

$$K = \begin{cases} 4 & N \times 0.05 \leq 6 \\ 9 & 6 < N \times 0.05 \leq 12 \\ 16 & 12 < N \times 0.05 \leq 20 \\ \vdots & \vdots \end{cases} \tag{1}$$

After the network partitioning, next VGDRA scheme appoints a set of nodes as cell-headers. Initially in every cell, the node closest to the mid-point of the cell is elected as the cell-header. Nodes using the knowledge of sensor field's dimension and the total number of nodes compute the mid-points of all the cells. In order to reduce the communication cost in the cell-header election, only those nodes take part in the election whose distance to the mid-point of the cell is less than a certain threshold. The threshold distance to the mid-point is gradually increased if no node can be found within the threshold distance around the mid-point of the cell. This threshold based cell-header election strategy not only helps in energy conservation but also elects the cell-header at the most appropriate position within the cell. After the initial cell-header election, each cell-header notifies its status not only to the surrounding nodes within its cell but also to the nodes which are slightly beyond the cell boundary. Nodes might receive cell-header notifications from more than one cell-header and associate themselves to the closest one. Nodes that receive notifications from multiple cell-headers also share the information of the secondary cell-header with their primary cell-header. In this way, each cell-header form adjacencies with neighboring cell-headers using gateway nodes. The maximum number of adjacent cell-headers for a border-line cell-header is 3 whereas for an inside cell-header is 4. The set of cell-header nodes together with the gateway nodes constructs a chain like virtual backbone structure as shown in Fig. 2.

After the cell-header election and establishing the adjacencies, communication routes are setup considering the mobile

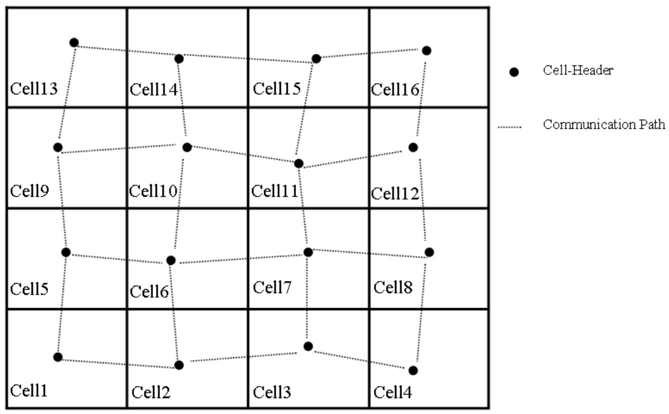


Fig. 2. An example of virtual backbone structure after establishing adjacencies.

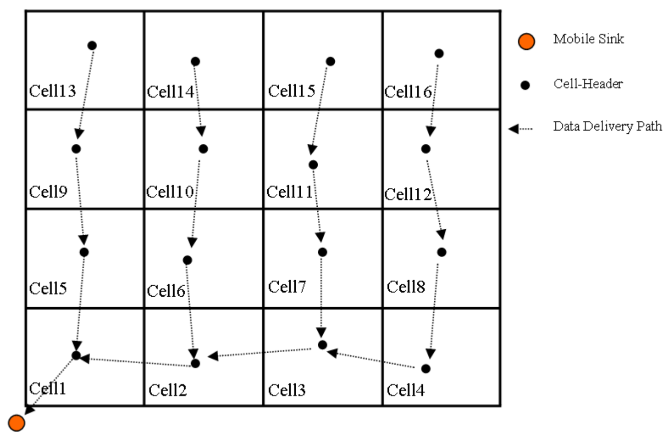


Fig. 3. An example of virtual backbone structure after initial routes setup.

sink is located at coordinates (0, 0). As a result of the initial routes setup, all the cell-headers adjust their routes to the initial position of the mobile sink. Fig. 3 shows the virtual backbone structure after the initial routes setup when the sensor field is partitioned into 16 cells.

C. Dynamic Routes Adjustment

In order to cope with dynamic network topology caused by sink mobility, nodes need to setup their data delivery routes in accordance with the latest location of the mobile sink. Flooding the sink's latest location to the entire sensor field is the most naive approach in this regard but greatly undermines the energy conservation goal and is therefore avoided. Using our VGDRA scheme, only the set of cell-headers that constitute the virtual backbone structure are responsible for maintaining fresh routes to the latest location of mobile sink. For periodic data collection from the sensor field, the mobile sink moves around the sensor field and collects data via the closest border-line cell-header. The closest border-line cell-header (originating cell-header) upon discovering the sink's presence, shares this information with the rest of the cell-headers in a controlled manner. The VGDRA scheme defines a set of propagation rules so that only those cell-headers take part in the routes re-adjustment process that really require

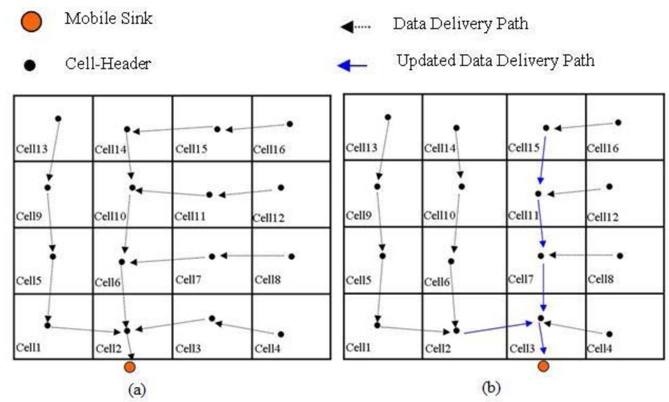


Fig. 4. An example of routes re-adjustments when sink moves from cell 2 to cell 3.

to adjust their routes. The propagation rules are described as follows:

Rule 1: The originating cell-header upon sink discovery first verifies whether its next-hop is already set to the mobile sink or not. If the mobile sink was previously being setup as its next-hop, the originating cell-header does not propagate sink's location update. However, if the next-hop entry of the originating cell-header is other than the mobile sink, it exercises rule 2.

Rule 2: The originating cell-header being one-hop from the mobile sink sets the mobile sink as its next-hop and shares this information with the previous originating cell-header and its downstream adjacent cell-header.

Rule 3: The previous originating cell-header upon receiving the sink's location update from the current originating cell-header, adjusts its data delivery route by setting the current originating cell-header as its next-hop towards the sink.

Rule 4: The downstream cell-header upon receiving the sink's location update checks whether the sender cell-header is the same as its previous next-hop or different. If it is the same, the downstream cell-header drops the sink's location update packet and does not propagate it further to the next downstream cell-header. In the case when it is different, the downstream cell-header updates its next-hop entry to the new sender cell-header and further propagates the sink's location update to the next downstream cell-header. This procedure is repeated till all the downstream cell-headers adjust their data delivery routes towards the latest location of the mobile sink.

Fig. 4(a) shows an example of the data delivery paths when the sink is located in the cell 2 premises. When the mobile sink moves from cell 2 to cell 3, the cell-header at cell 3 exercises rule 2 and rule 3 to update the cell-header at cell 2, followed by rule 4 to update its downstream cell-headers i.e., 7, 11 and 15 as shown in Fig. 4(b). In this way, only a limited number of cell-headers take part in the routes re-adjustment process thereby reducing the overall routes re-adjustment cost of the network.

Similarly, Fig. 5 demonstrates when the mobile sink moves from position a to b within the same cell, the cell-header at cell 4 exercises rule 1 and refrains itself from propagating sink's location information. This strategy helps to minimize the

Algorithm 1 Routes Re-Adjustment Using VGDRA Scheme

```
Mobile Sink (MS) updates its location to the closest
  Cell-Header (CH).
The closest CH becomes Originating Cell-Header
  (OCH).
if the previous Next_Hop of OCH is not the MS
{
  set Next_Hop of OCH ← MS
  OCH sends route update packet to the previous OCH
  set Next_Hop of previous OCH ← OCH
  OCH sends route update packet to its immediate
    downstream CH
  for each downstream CH receives route update packet
  {
    if the previous Next_Hop of CH is not the current
      sender
    {
      set Next_Hop of CH ← current sender
      if next downstream CH is not NULL
      {
        set sender ← current CH
        Current CH sends route update packet to its
          immediate downstream CH
      }
      else
        drop the packet
    }
    else
      drop the packet
  }
}
else
  drop the packet
```

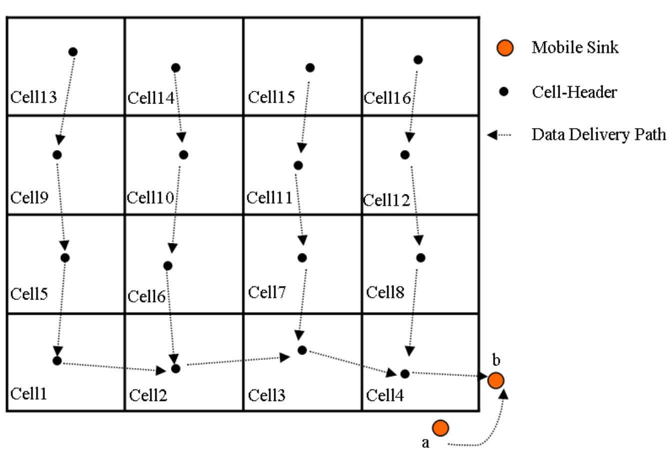


Fig. 5. An example of preventing the undesired propagation of sink location updates.

routes reconstruction cost to a great extent and thus improves the network lifetime.

The VGDRA algorithm that governs the routes adjustment process along the sink mobility is described in detail as shown in top of the page.

D. Cell-Header Rotation

An integral part of the proposed VGDRA scheme is rotating the role of the cell-header in every cell. The cell-header being the local data collector is vulnerable to high energy dissipation and therefore to prolong the network lifetime, the cell-header role needs to be distributed among the nodes within the cell. In order to achieve uniform energy dissipation, the VGDRA scheme keeps track of the residual energy level of the current cell-header, where if it gets below a certain threshold, the new cell-header election is initiated by the current cell-header. In the re-election process, the node that is relatively more close to the mid-point of the cell and has a higher energy level compared to other candidates is elected as the new cell-header. Also in the re-election process, the search zone around the mid-point in every cell is slightly increased or the energy threshold level is decreased progressively if no suitable node can be found. In order to preserve the virtual backbone structure, the current cell-header before stepping down, shares the information of the new cell-header not only with all its member nodes but also with the adjacent cell-headers in its neighborhood.

IV. Simulation and Results

In this section, we present the simulation results using NS-2. We varied the total number of sensor nodes from 100 to 400 which are randomly deployed in a sensor field of 200 × 200 dimension. A mobile sink moves around the sensor field counterclockwise and periodically broadcasts hello packets. Initially all the sensor nodes have uniform energy reserve of 1 mJ. We considered the energy model being used in [27] and assumed free space radio propagation model (d^2, d is the distance between sender and receiver). Furthermore, we considered nodes energy consumption in transmission (Tx) and receiving (Rx) modes only which are computed using Equation 2 and 3 respectively.

$$T_x = (E_{\text{elect}} \times K) + \left(E_{\text{amp}} \times K \times d^2\right) \tag{2}$$

$$R_x = E_{elect} \times K \tag{3}$$

In Equation 2 and 3, K is the message length, E_{elect} is the node's energy dissipation in order to run its radio electronic circuitry and E_{amp} is the energy dissipation by the transmitter amplifier to suppress the channel noise. In our experiment, we took $E_{elect} = 50$ nJ, and $E_{amp} = 10$ nJ/bit/m^2 and $K = 8$ bits. We considered the nodes communication cost in adjusting the data delivery routes only, whereas the actual data delivery is beyond the scope of this paper.

We compared our VGDRA scheme with VCCSR, HexDD, and BVI where a common feature among them is the use of a virtual infrastructure for network operation. We used four different criteria to evaluate the performance of the VGDRA against the other schemes under the same network dynamics: virtual backbone structure construction cost, per round routes reconstruction cost, average network lifetime, and network convergence time.

A. The Virtual Backbone Structure Construction Cost

The virtual structure construction cost is an estimate of the nodes energy consumption in electing the cell-headers

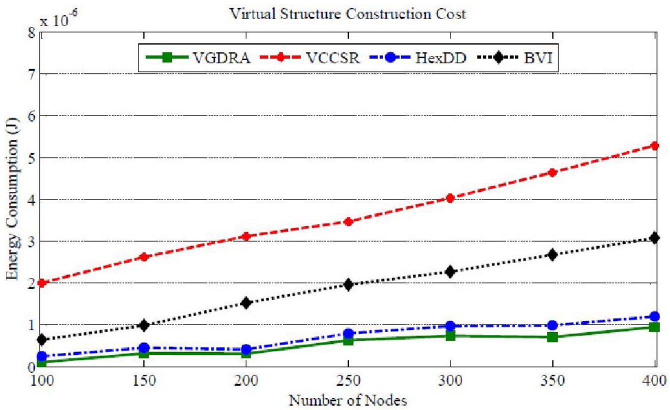


Fig. 6. Comparing the virtual structure construction cost for different network sizes.

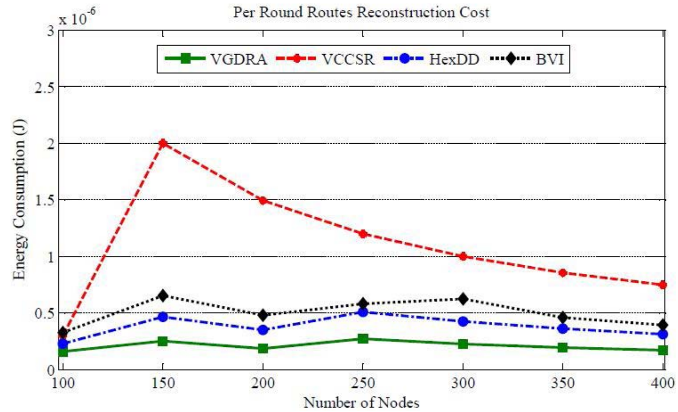


Fig. 7. Comparing the per round routes reconstruction cost for different network sizes.

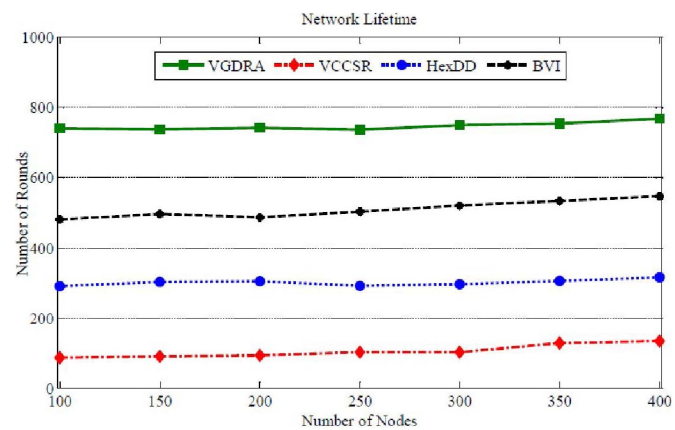


Fig. 8. Comparing the network lifetime in terms of number of rounds around the sensor field.

and then forming the virtual backbone network. Fig. 6 compares the average nodes' energy consumption of our VGDRA scheme with the other schemes in constructing the virtual backbone network for different network sizes.

As demonstrated in Fig. 6, nodes using VGDRA scheme incur least cost compared to other schemes in constructing the virtual structure. The VCCSR considers fixed number of cluster-head nodes irrespective of the network size e.g., it considers 81 cluster-head nodes under the considered network dynamics and thus as a result, a high population of the sensor nodes take part in the cluster-head election. Similarly, the BVI incurs considerable communication cost in clustering the network where all the nodes exchange residual energy level information. Compared to VCCSR and BVI, nodes using HexDD perform local processing thereby causing less communication overhead. On contrary, using our VGDRA scheme, the total number of cells and thus the cell-headers is a function of the total number of nodes e.g., the number of cell-headers varies from 4 to 16 when N varies from 100 to 400 nodes. In addition, only the nodes within short distance to the mid-point of the cell take part in cell-header election thereby reducing the communication cost.

B. The Per Round Routes Reconstruction Cost

The per round routes reconstruction cost represents the nodes energy expenditure in re-adjusting the data delivery routes as the sink moves around the sensor field and completes one round of the sensor field. As shown in Fig. 7, using the VGDRA scheme, the average nodes' energy consumption in reconstructing the data delivery routes to the latest location of the mobile sink is significantly less compared to the other schemes. This is mainly attributed to the least propagation of sink's location updates by following the set of communication rules of the VGDRA while preserving nearly optimal routes towards the latest location of the mobile sink. Using our VGDRA scheme, only a partial sub-set of cell-header nodes takes part in the routes reconstruction process thereby reducing the overall routes reconstruction cost as the mobile sink completes one round of the sensor field.

C. The Network Lifetime

The network lifetime is defined as the time elapsed since the nodes deployment till the first node dies due to energy depletion. In our experiments, we estimated the network lifetime in terms of the number of rounds of the mobile sink around the sensor field till the first node in the network dies due to energy depletion. As presented in Fig. 8, our VGDRA scheme outperforms the other schemes in terms of network lifetime at different network sizes. In VCCSR, the cluster-head at the central-point of the sensor field suffers from more work-load for taking part in every single reconstruction phase and thus depletes its energy much earlier compared to others. Similar behavior is exhibited by the centre and border nodes in HexDD thereby decreasing the overall network lifetime. Unlike the VCCSR and HexDD, the proposed VGDRA and BVI schemes keep track of the residual energy of cell-header nodes and progressively elect new header nodes thereby prolonging the network lifetime. Furthermore, compared to BVI, the proposed VGDRA scheme incurs least network control overhead. The results presented in Fig. 8 also demonstrates nearly uniform network lifetime at different network sizes using our VGDRA scheme which justifies our approach of partitioning the sensor field into different number of cells on the basis of the total number of nodes.

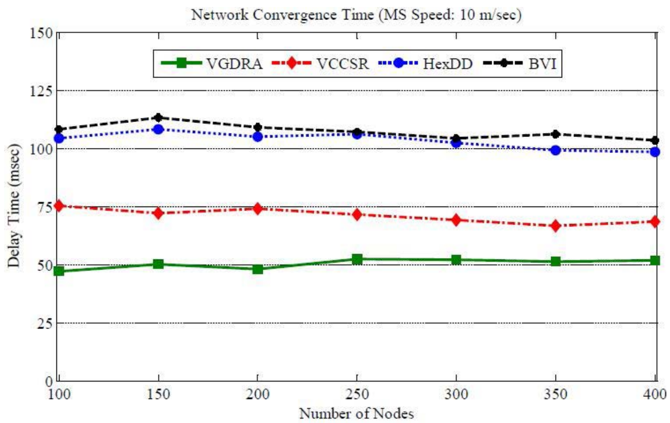


Fig. 9. Comparing the network convergence time for different network sizes.

D. The Network Convergence Time

The network convergence time is an indirect reflection of the data delivery efficiency as the more promptly the nodes come to know about the latest location of a mobile sink, the more efficient routes they can select in disseminating the sensed data. It is an estimation of the elapsed time that a significant position change of the mobile sink is recorded by the nodes constituting the virtual infrastructure. In terms of convergence time, the faster the nodes converge to latest location of a mobile sink, the better they perform in data dissemination phase. As shown in Fig. 9, the convergence time of the proposed VGDRA scheme is very fast compared to VCCSR, HexDD, and BVI when the sink is moving at a speed of 10 m/sec. Using the set of communication rules, our VGDRA scheme intelligently picks a small subset of cell-headers in the routes re-adjustment process and then greedily shares the latest location information of the mobile sink with them. This partial re-adjustment greatly reduces the network overhead and leads to faster convergence of nodes to the latest location of the mobile sink.

V. Conclusion and Future Work

In this paper, we proposed a novel Virtual Grid based Dynamic Routes Adjustment (VGDRA) scheme that incurs least communication cost while maintaining nearly optimal routes to the latest location of the mobile sink. Our VGDRA scheme partitions the sensor field into a virtual grid and constructs a virtual backbone structure comprised of the cell-header nodes. A mobile sink while moving around the sensor field keeps on changing its location and interacts with the closest border-line cell-header for data collection. Using a set of communication rules, only a limited number of the cell-headers take part in the routes reconstruction process thereby reducing the overall communication cost. In terms of nodes energy consumption, the simulation results reveal improved performance of our VGDRA scheme for different network sizes.

Considering the scope of this paper, we have not included the actual data delivery model. In future work, we will analyze the performance of our VGDRA scheme at different sink's speeds and different data generation rates of the sensor nodes. The proposed VGDRA scheme though offers a light weight solution and does not impose many constraints on part of the resource constrained sensor motes, yet its practical implementation on real hardware needs to be confirmed. We also aim to develop a small test bed for the practical implementation of the proposed VGDRA scheme on real hardware (motes) and evaluate its results.

References

[1] R. C. Shah, S. Roy, S. Jain, and W. Brunette, "Data MULEs: Modeling and analysis of a three-tier architecture for sparse sensor networks," in *Ad Hoc Netw.*, vol. 1. 2003, pp. 215–233.

[2] S. R. Gandham, M. Dawande, R. Prakash, and S. Venkatesan, "Energy efficient schemes for wireless sensor networks with multiple mobile base stations," in *Proc. IEEE Global Telecommun. Conf. (GLOBECOM)*, vol. 1. Dec. 2003, pp. 377–381.

[3] A. W. Khan, A. H. Abdullah, M. H. Anisi, and J. I. Bangash, "A comprehensive study of data collection schemes using mobile sinks in wireless sensor networks," *Sensors*, vol. 14, no. 2, pp. 2510–2548, 2014.

[4] M. Di Francesco, S. K. Das, and G. Anastasi, "Data collection in wireless sensor networks with mobile elements," *ACM Trans. Sensor Netw.*, vol. 8, no. 1, pp. 1–31, Aug. 2011.

[5] I. Chalermek, R. Govindan, and D. Estrin, "Directed diffusion: A scalable and robust communication paradigm for sensor networks," in *Proc. ACM SIGMOBILE Int. Conf. Mobile Comput. Netw. (MOBICOM)*, 2000, pp. 56–67.

[6] E. B. Hamida and G. Chelius, "Strategies for data dissemination to mobile sinks in wireless sensor networks," *IEEE Wireless Commun.*, vol. 15, no. 6, pp. 31–37, Dec. 2008.

[7] A. Kinalis, S. Nikoletseas, D. Patroumpa, and J. Rolim, "Biased sink mobility with adaptive stop times for low latency data collection in sensor networks," *Inf. Fusion*, vol. 15, pp. 56–63, Jan. 2014.

[8] W. M. Aioffi, C. A. Valle, G. R. Mateus, and A. S. da Cunha, "Balancing message delivery latency and network lifetime through an integrated model for clustering and routing in wireless sensor networks," *Comput. Netw.*, vol. 55, no. 13, pp. 2803–2820, Sep. 2011.

[9] B. Nazir and H. Hasbullah, "Mobile sink based routing protocol (MSRP) for prolonging network lifetime in clustered wireless sensor network," in *Proc. Int. Conf. Comput. Appl. Ind. Electron. (ICCAIE)*, Dec. 2010, pp. 624–629.

[10] T. Banerjee, B. Xie, J. H. Jun, and D. P. Agrawal, "Increasing lifetime of wireless sensor networks using controllable mobile cluster heads," *Wireless Commun. Mobile Comput.*, vol. 10, no. 3, pp. 313–336, Mar. 2010.

[11] T.-S. Chen, H.-W. Tsai, Y.-H. Chang, and T.-C. Chen, "Geographic convergecast using mobile sink in wireless sensor networks," *Comput. Commun.*, vol. 36, no. 4, pp. 445–458, Feb. 2013.

[12] A. Erman, A. Dilo, and P. Havinga, "A virtual infrastructure based on honeycomb tessellation for data dissemination in multi-sink mobile wireless sensor networks," *EURASIP J. Wireless Commun. Netw.*, vol. 2012, no. 17, pp. 1–54, 2012.

[13] S. Oh, E. Lee, S. Park, J. Jung, and S.-H. Kim, "Communication scheme to support sink mobility in multi-hop clustered wireless sensor networks," in *Proc. 24th IEEE Int. Conf. Adv. Inf. Netw. Appl.*, Apr. 2010, pp. 866–872.

[14] O. Younis and S. Fahmy, "HEED: A hybrid, energy-efficient, distributed clustering approach for ad hoc sensor networks," *IEEE Trans. Mobile Comput.*, vol. 3, no. 4, pp. 366–379, Oct. 2004.

[15] B. Tang, J. Wang, X. Geng, Y. Zheng, and J.-U. Kim, "A novel data retrieving mechanism in wireless sensor networks with path-limited mobile sink," *nt. J. Grid Distrib. Comput.*, vol. 5, no. 3, pp. 133–140, 2012.

[16] E. B. Hamida and G. Chelius, "A line-based data dissemination protocol for wireless sensor networks with mobile sink," in *Proc. IEEE Int. Conf. Commun.*, May 2008, pp. 2201–2205.

[17] J.-H. Shin and D. Park, "A virtual infrastructure for large-scale wireless sensor networks," *Comput. Commun.*, vol. 30, nos. 14–15, pp. 2853–2866, Oct. 2007.

[18] Z. H. Mir and Y.-B. Ko, "A quadtree-based data dissemination protocol for wireless sensor networks with mobile sinks," in *Proc. Personal Wireless Commun.*, 2006, pp. 447–458.

[19] H. Luo, F. Ye, J. Cheng, S. Lu, and L. Zhang, "TTDD: Two-tier data dissemination in large-scale wireless sensor networks," *Wireless Netw.*, vol. 11, nos. 1–2, pp. 161–175, Jan. 2005.

[20] X. Chen and M. Xu, "A geographical cellular-like architecture for wireless sensor networks," in *Proc. Mobile Ad-Hoc Sensor Netw.*, 2003, pp. 249–258.

[21] L. Buttyán and P. Schaffer, "Position-based aggregator node election in wireless sensor networks," *Int. J. Distrib. Sensor Netw.*, vol. 2010, pp. 1–15, 2010.

[22] L. Buttyán and P. Schaffer, "Position-based aggregator node election in wireless sensor networks," *Int. J. Distrib. Sensor Netw.*, vol. 2010, pp. 1–15, Jan. 2010.

[23] M. Eslaminejad and S. A. Razak, "Fundamental lifetime mechanisms in routing protocols for wireless sensor networks: A survey and open issues," *Sensors*, vol. 12, no. 10, pp. 13508–13544, Jan. 2012.

[24] W. B. Heinzelman, A. P. Chandrakasan, S. Member, and H. Balakrishnan, "An application-specific protocol architecture for wireless microsensor networks," *IEEE Trans. Wireless Commun.*, vol. 1, no. 4, pp. 660–670, Oct. 2002.

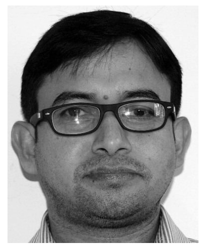
[25] A. Manjeshwar and D. P. Agrawal, "TEEN: A routing protocol for enhanced efficiency in wireless sensor networks," in *Proc. 15th Int. Parallel Distrib. Process. Symp. (IPDPS)*, vol. 1. Apr. 2000, pp. 2009–2015.

[26] A. Manjeshwar and D. P. Agrawal, "APTEEN: A hybrid protocol for efficient routing and comprehensive information retrieval in wireless," in *Proc. 16th Int. Parallel Distrib. Process. Symp.*, 2002, p. 48.

[27] W. R. Heinzelman, A. Chandrakasan, and H. Balakrishnan, "Energy-efficient communication protocol for wireless microsensor networks," in *Proc. 33rd Annu. Hawaii Int. Conf. Syst. Sci.*, Jan. 2000.

Abdul Waheed Khan received the Degree from the Department of Computer Science, University of Peshawar, Peshawar, Pakistan, in 2005, and the M.Sc. (Hons.) degree in digital communications networks from London Metropolitan University, London, U.K., in 2008. He is currently pursuing the Ph.D. degree at the Faculty of Computing, University of Technology Malaysia, Johor Bahru, Malaysia. From 2009 to 2012, he was a Lecturer with the Faculty of Computing and Information Technology in Rabigh, King Abdulaziz University, Jeddah, Saudi Arabia. His research areas include wireless sensor networks, ad hoc networks, and next-generation networks.

Abdul Hanan Abdullah received the Ph.D. degree from Aston University, Birmingham, U.K., in 1995. He is currently a Professor with the University of Technology Malaysia (UTM), Johor Bahru, Malaysia. From 2004 to 2011, he was the Dean of the Faculty of Computer Science and Information Systems. He is currently heading the Pervasive Computing Research Group under K-Economy Research Alliances, UTM. His research interests include wireless sensor networks, mobile ad hoc networks, network security, and next-generation networks.



Mohammad Abdur Razzaque (M'12) received the B.Sc. degree in applied physics, the M.Sc. degree in electronics and communication engineering, and the Ph.D. degree in computer science. He is currently a Senior Lecturer with the Faculty of Computing, University of Technology Malaysia, Johor Bahru, Malaysia. His research interests include wireless and mobile computing and communications, cloud computing, and big data analytics. He has authored several peer-reviewed publications and has served as a regular reviewer for various international reputed journals and conferences. He is a member of the IEEE Vehicular Technology Society, the IEEE Computer Society, and the Association for Computing Machinery.

Javed Iqbal Bangash received the B.E. degree in computer information systems engineering from the University of Engineering and Technology, Peshawar, Pakistan, in 2005, and the M.Sc. (Hons.) degree in digital communications networks from London Metropolitan University, London, U.K., in 2008. He is currently pursuing the Ph.D. degree at the Faculty of Computing, University of Technology Malaysia, Johor Bahru, Malaysia. He was a Lecturer at the College of Engineering, Majmaah University, Al Majma'ah, Saudi Arabia. His research areas include wireless body sensor networks, wireless sensor networks, and ad hoc networks.