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

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***Abstract*—In Wireless Sensor Networks (WSNs), exploitation of sink mobility has been considered as a good strategy to balance nodes energy dissipation. Despite of its numerous advantages, data dissemination to mobile sink is a challenging task for resource constrained sensor nodes due to dynamic network topology caused by sink mobility. For efficient data delivery, nodes need to reconstruct their routes towards 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 re-adjust their data delivery routes towards the mobile sink. Simulation results demonstrate reduced routes reconstruction cost and improved network lifetime of the VGDRA scheme when compared to existing work.**

***Index Terms*—Routes Reconstruction, Energy Efficiency, Mobile Sink, Wireless Sensor Networks**

I. INTRODUCTION

Wireless Sensor Network (WSN) - a self-organizing 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], [2] not only helps to balance the nodes' energy dissipation but can also interconnect the isolated network segments in problematic areas [3]. In addition, several application environments naturally require sink mobility in the sensor field [4] 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.

Sink mobility although improves network lifetime thereby alleviating energy-hole phenomenon; however, it brings new challenges when reporting sensed data to a mobile sink. Unlike static sink scenarios, the network topology becomes dynamic as the sink keeps on changing its location. 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 resources 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, a set of designated nodes scattered in the sensor field are only 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. The proposed scheme 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 center 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

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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 need to take part in re-adjusting their routes to the latest location of the mobile sink thereby reducing the routes reconstruction cost. Simulation results reveal decreased energy consumption in routes re-adjustment of VGDRA compared to VCCSR algorithm [7].

Section 2 describes the related work encompassing the various approaches in literature that deal with data delivery to a mobile sink in WSN. Section 3 presents the proposed VGDRA scheme in detail. To evaluate the performance of the VGDRA scheme, simulation setup and results are presented in Section 4. Finally section 5 concludes the work and points to direction of potential future work.

II. RELATED WORK

Several virtual infrastructure based data dissemination protocols have been proposed for mobile sink based WSN in the last decade. In this section, we briefly describe the related works in this context including their methodology and the relative strengths and weaknesses.

Chen et al. [7] 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 move around the sensor field and maintains communication with the border cluster-heads for data collection. 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. Although reduces the routes reconstruction cost in handling the sink mobility, however, the cluster-head at the center 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 [8] 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 center cell. Nodes along the border line store and replicate the data. Sink's data queries are forwarded towards the center 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. The main limitation of HexDD is the formation of energy holes near the border lines and especially at the center cell as nodes at these positions dissipate their energy quickly due to high load.

Multiple Enhanced Specified-deployed Sub-sinks (MESS) in [9], creates a virtual strip in the middle of sensor field thereby placing enhanced or powerful 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 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) [10] which constructs a vertical line by dividing the sensor field into two equal sized blocks. Another similar approach can be found in [11], which places a virtual rail in the middle of the sensor field where nodes inside the virtual rail 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 [12], a node after detecting an event calculates a set of rendezvous points (RPs) by successively partitioning the physical network space into four quadrants of uniform sizes. After portioning the network, QDD report the observed data to the 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 [13] 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 flooding sink's topological updates, however, the per source virtual grid construction undermines the network lifetime.

Geographical Cellular-like Architecture (GCA) in [14] 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 center 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 cells 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 (DCDD) in [15] 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, DCDD suffers 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.

From the analysis of the existing works 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. This work aims to optimize the trade-off between these two, especially minimizing the cost of frequent location updates and route readjustments.

III. THE VGDRA SCHEME

In this section, we give detail 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 based on the number of sensor nodes. A set of nodes close to center 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 nearest 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.
- Nodes are homogeneous in capacity and capability 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 all the sensor nodes while moving along periphery of sensor field and maintains communication with the nearest 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 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 cell-headers, we adopt the heuristics used in LEACH [16], TEEN [17], and APTEEN [18] 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. Figure 1 (a), (b) and (c) shows network partitioning into various uniform sized cells for N = 100, 200, 300 respectively.

$$K = \begin{cases} 4 & N \times .005 \leq 6 \\ 9 & 6 < N \times .005 \leq 12 \\ 16 & 12 < N \times .005 \leq 20 \\ . & . \\ . & . \end{cases} \tag{1}$$

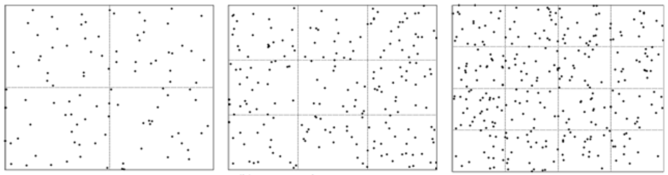
(a) $K = 4$, when $N \leq 100$ (b) $K = 9$, when $101 \leq N \leq 200$ (c) $K = 16$, when $201 \leq N \leq 300$

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

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-headers 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 forms 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

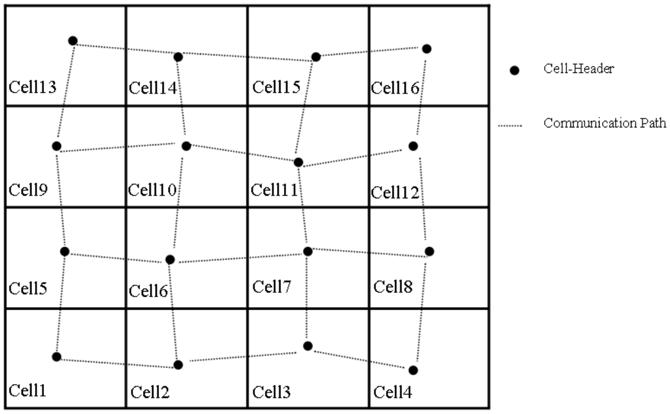

Fig. 2: An example of virtual backbone structure after establishing adjacencies.

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.

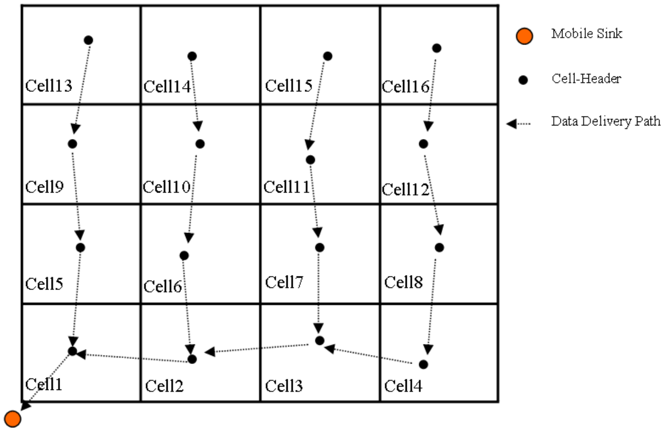

Fig. 3: An example of virtual backbone structure after initial routes setup.

C. Dynamic Routes Adjustment

In order to cope with the 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 communication rules so that only those cell-headers take part in the routes re-adjustment process that really require to adjust their routes. The communication 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.

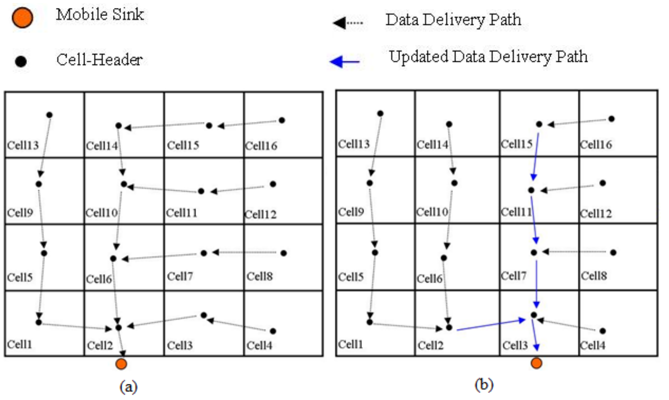

Fig. 4: An example of routes re-adjustments when sink moves from cell 2 to cell 3.

Figure 4(a) shows an example of the data delivery paths when the sink is located near 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 Figure 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, Figure 5 demonstrates when the mobile sink moves from position a to b, the cell-header at cell 4 exercises rule 1 and refrains itself from propagating sink's location

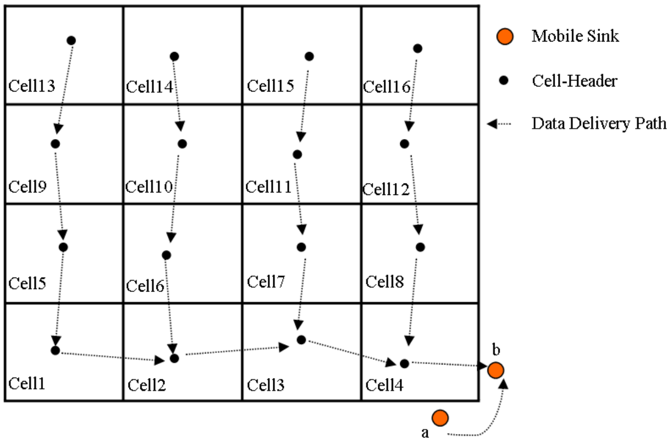

Fig. 5: An example of preventing the undesired propagation of sink location updates.

information. This strategy helps to minimize the routes reconstruction cost to a great extent and thus improves the network lifetime.

Algorithm 1 Routes re-adjustment using VGDRA scheme.

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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 then
    set $Next\_Hop$ of OCH $\leftarrow$ MS
    OCH sends route update packet to the previous OCH
    set $Next\_Hop$ of previous OCH $\leftarrow$ OCH
    for each downstream CH receives route update packet do
        if the previous $Next\_Hop$ of CH is not the current sender then
            set $Next\_Hop$ of CH $\leftarrow$ current sender
            if next downstream CH is not NULL then
                set sender $\leftarrow$ current CH
            else
                drop the packet
            end if
        else
            drop the packet
        end if
    end for
else
    drop the packet
end if
```

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 closer 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 [19]. We varied the total number of sensor nodes from 100 to 400 which are randomly deployed in a sensor field of 200 × 200 meter 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 consider the energy model being used in [20] and assume free space radio propagation model (d^2, d is the distance between sender and receiver). Furthermore, we consider nodes energy consumption in transmission (Tx) and receiving (Rx) modes only which are computed using Equation 2 and 3 respectively.

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

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

Where 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 $E_{amp} = 10\ nJ/bit/m2$ and $K = 8\ bits$. We consider the nodes communication cost in reconstructing the data delivery routes only, whereas the actual data delivery is beyond the scope of this paper.

We compare our VGDRA scheme with the VCCSR as both the schemes make use of virtual infrastructure and consider periodic data collection from sensor field by moving the sink around the sensor field. We used three different parameters to evaluate the performance of the VGDRA against the VCCSR using the same network dynamics: the virtual backbone structure construction cost, the per round routes reconstruction cost, and the average network lifetime.

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

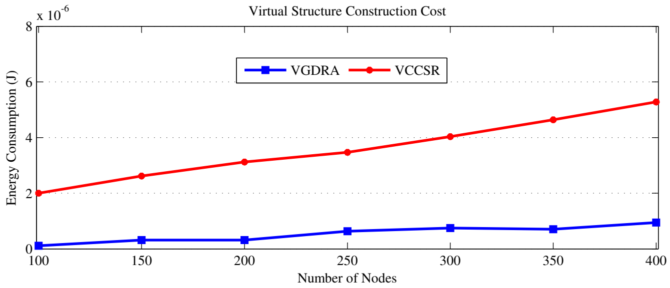

Fig. 6: Comparing the virtual structure construction cost of VGDRA with VCCSR.

As demonstrated in Figure 6, nodes using VGDRA scheme incur significantly lower cost compared to VCCSR 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. 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 300 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 Figure 7, using the VGDRA scheme, the average nodes' energy consumption in reconstructing the data delivery routes towards the mobile sink is significantly less compared to the VCCSR algorithm. This is mainly attributed to less 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.

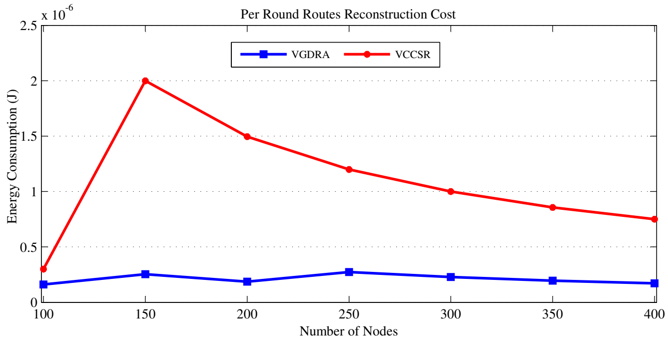

Fig. 7: Per round routes reconstruction cost at different network sizes.

C. The Network Lifetime

For the network lifetime estimation, different metrics can be found in the literature like the time elapsed since the nodes deployment till the first node dies due to energy depletion [21], or the elapsed time before 50% of the nodes die due to energy depletion [9]. We adopt the first definition and estimate 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. In terms of the network lifetime, we compare the performance of our VGDRA scheme with the VCCSR by considering our VGDRA with cell-header rotation (VGDRA-R) and without. As presented in Figure 8, our VGDRA scheme outperforms the VCCSR scheme in terms of network lifetime at different network sizes. In VCCSR, the cluster-head at the central-point of the sensor field suffers from high work-load for taking part in every single reconstruction phase and thus depletes its energy much earlier compared to others. Unlike the VCCSR algorithm, we gradually rotate the cell-header role among other member nodes within the cell which prolongs the network lifetime several times more compared to the VCCSR algorithm. The results presented in Figure 8 also demonstrates nearly uniform network lifetime at different network sizes using our VGDRA-R scheme which justifies our approach of partitioning the sensor field into different number of cells on the basis of the total number of nodes.

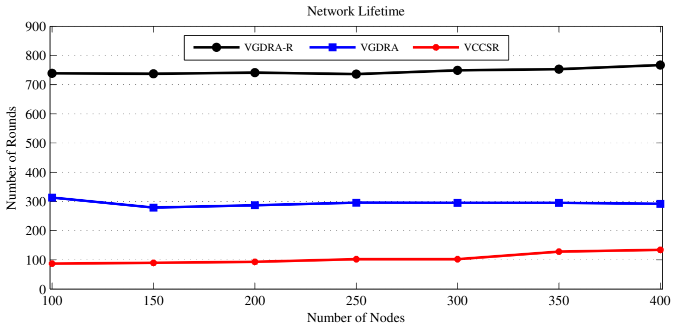

Fig. 8: Network Lifetime for different network sizes.

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. The proposed 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 at 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 at different data generation rates of the sensor nodes.

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