Grid routing: an energy-efficient routing protocol for WSNs with single mobile sink

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Abstract: In a traditional wireless sensor network (WSN) with static sinks, sensor nodes close to the sink run out of their batteries quicker than other nodes due to the increased data traffic towards the sink. These nodes with huge data traffic are easy to become hotspots. Therefore, such networks may prematurely collapse since the sink is unreachable for other remote nodes. To mitigate this problem, sink mobility is proposed, which provides load-balanced data delivery and uniform energy dissipation by shifting the hotspots. However, the latest location update of the mobile sink within the network introduces a high communication overhead. In this paper, we propose Grid Routing, an energy-efficient mobile sink routing protocol, which aims to decrease the advertisement overhead of the sink's position and balance local energy dissipation in a non-uniform network. Simulation results indicate that the Grid Routing shows better performance compared with existing work.

Keywords: hotspots; hierarchical structure; sink mobility; virtual infrastructure; non-uniform network.

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1 Introduction

Recent advances in wireless sensor networks (WSNs) have drawn attention of a large number of researchers since they can be applied into a wide range of application domains, such as environmental monitoring and protection (Shen et al., 2015), medical care (Chen et al., 2011), intrusion detection (Xiao et al., 2009), home automation and forest fire detection (Yick et al., 2008), due to the advantages of cheapness, easy implementation, reliability and small footprint. Traditional WSNs are composed of lots of low-cost, dime-size, multifunctional sensor nodes. These sensor nodes, which consists of the sensing unit, processing unit, communication unit and power supply unit, are randomly deployed in a self-organised manner (Akyildiz et al., 2002). However, sensor nodes are usually deployed in a harsh area that is inaccessible to humans, and the battery capacity of sensor devices is limited. These constraints make sensor nodes for one-time use. If a sensor node runs out of its battery power, then it cannot get power supply and will no longer work (Peng et al., 2009). Hence, energy efficiency is always a challenge for WSNs (Tunca et al., 2014).

In a static sink scenario, sensor nodes in the vicinity of the sink suffer from a large number of data forwarding tasks towards the sink, which makes these nodes consume more battery power than other nodes. These nodes are easy to become hotspots and will run out of their battery power quickly (Rao and Biswas, 2008). If no node within the communication range of the sink can work normally, monitoring data generated from sources nodes will not be transmitted to the sink, leading to network failure.

Owing to mobility property of the sink, mobile sinks can shifting the hotspots by changing the sojourning position used for data collection, thus alleviating the hotspot problem, which helps balancing the overall energy consumption to extend the network lifetime (Bi et al., 2009). Mobile sinks also implicitly provide load-balancing by distributing extra workload over other nodes. During the WSN operation, it is highly possible to form isolated sensor islands due to non-uniform node distribution or hotspot effect. In order to make full use of network resources, one way is changing the sensing coverage of sensor nodes to guarantee the network connectivity (Liu et al., 2006). However, this method may increase the node energy consumption. Mobile sinks can use their mobility property to address this problem perfectly by accessing sensor islands one by one to collect data, which might not be realised while using a static sink.

Although mobile sinks bring lots of benefits to WSNs, a series of new problems also comes with them, e.g., the advertisement of the latest sink's position and dynamic routes adjustment. Unlike static sink scenarios, the network topology becomes dynamic as the sink moves. Frequent location updates will cause frequent unpredictable topology changes. So exploring mobile sinks, how to maintain the fresh routes towards mobile sinks is a core problem. Flooding the location update packets of mobile sinks within the network is the simplest approach, whereas this method needs frequent broadcast communications, which will introduces a high communication overhead.

In order to minimise this overhead, the approach of determining a multitier hierarchy of roles among the nodes has been proposed (Khan et al., 2015). Only a limited set of nodes which is high-tier nodes in the hierarchical architecture need to trace the latest location of mobile sinks. Low-tier nodes query them to retrieve the sink's position, thus facilitating data delivery. Such an approach limits high communication cost to a subset of nodes, which significantly decreases the advertisement overhead of the sink's position.

It is obvious that the hierarchical architecture decreases the overall energy consumption. However, the increased traffic of high-tier nodes will lead to a new problem for WSNs that the batteries of high-tier nodes deplete quicker than other regular nodes. Deaths of high-tier nodes will destroy the hierarchical structure, which thereby causes the premature collapse of the network (Wang and Xiao, 2006). So in order to keep the network running smoothly, a high-tier structure maintenance mechanism is necessary to distribute extra communication overhead over a set of regular nodes. Local replacement of high-tier nodes with low-tier nodes during the WSN operation and resetting the hierarchical structure are two main approaches to address this problem.

In this paper, we propose grid routing, an energy-efficient virtual infrastructure-based routing protocol, suitable for time-sensitive applications. We highlight some key features and the contributions of Grid Routing as follows:

- Grid routing is a hierarchical mobile sink routing protocol targeted for periodic data reporting in a large-scale networks.
- Grid routing initially constructs a virtual grid structure that allows the latest location information of the mobile sink to be easily delivered to each cell with minimal communication cost.
- Grid routing adopts a grid maintenance mechanism to prevent the virtual grid structure from being destroyed. When the residual energy level of high-tier nodes drop to a certain energy threshold, grid routing enables them to switch roles with regular nodes.
- Grid routing provides efficient data delivery, in that each high-tier node only needs to maintain a simple forwarder candidate set, which allows the protocol to be used for a time-sensitive periodic data reporting application scenario.

The rest of this paper is organised as follows: Section 2 introduces the related work about virtual infrastructure-based routing protocols using mobile sinks in WSNs. Section 3 describes a proposed Grid Routing protocol, including network characteristics, grid construction, a dynamic routes adjustment scheme and grid maintenance. Section 4 shows simulation scenarios and results. Finally, the paper is concluded in Section 5.

2 Related work

2.1 Virtual infrastructure-based routing protocols

There have been many solutions to be proposed to cope with the problem of data dissemination in a mobile-sink-based WSN (Tunca et al., 2015). The most widely adopted approach is to overlay a virtual infrastructure over the physical network, which not only enhances the data transmission efficiency but also decreases node's energy dissipation. In such virtual infrastructure-based scenarios, a set of high-tier nodes are designated to obtain the observed data from low-tier nodes in the vicinity and then forward it to mobile sinks. A successful hierarchy can enable the latest location of mobile sinks to be easily forwarded to the hierarchical structure and regular nodes to acquire the sink's position from the virtual high-tier infrastructure. In the remainder of this subsection, we will explore several hierarchical mobile sink routing protocols and analyse their respective relative merits.

A distributed load balanced clustering and dual data uploading (LBC-DDU) is a cluster-based hierarchical routing protocol (Zhao et al., 2015), which is proposed for sensors to self-organise themselves into clusters and realise DDU by imposing multiuser multi-input and multi-output (MU-MIMO) technique. The network is partitioned into several separate clusters with two cluster-heads of each cluster. LBC-DDU employs a mobile collector (called SenCar) to access each polling points selected in each cluster to collect data within a tolerable delay. The SenCar can determine the sequence to visit each polling points and find the optimal trajectory for the data collection tour. Even so, it is clear that LBC-DDU is not suitable for time-sensitive applications. Moreover, data packets will be dropped after a certain period of time if the SenCar does not reach each polling points on time.

Cluster-based structure is the most popular hierarchical structure but not the only choice for a hierarchical structure. Two-tier data dissemination (TTDD) is a virtual grid-based hierarchical routing protocol (Luo et al., 2005). Every source node proactively constructs a virtual grid-based network structure while existing sensory data and itself becomes a crossing point of this grid. The mobile sink floods a query locally where this query packet will be relay to the source nodes via the crossing points. And data packets generated by the source node will be then forwarded to the sink along the opposite direction of the originating path taken by the query packet. Although the TTDD decreases the overall energy consumption by limiting the flooding overhead within a local grid, grid construction cost for every source node is immense.

Obviously, the TTDD is not suitable for the network where events occur frequently. In order to overcome the TTDD's shortcoming of grid construction, a grid-based energy-efficient routing (GBEER) from multiple sources to multiple mobile sinks is presented (Kweon et al., 2009), which constructs only one grid structure for all the source nodes using global location information. Data request packets are sent from the sink along the horizontal direction while the source node sends data announcement packets along the vertical direction, ensuring that there must be a header to receive both two data packets. Data request packets will be forwarded to the source node along the reverse of the path taken by data announcement packets. Although the GBEER significantly decreases grid construction cost and enables high overhead to be limited in a separate cell, headers which process data request and announcement are easy to become hotspots and deplete their energy quicker than other nodes.

Similar to the GBEER and TTDD, a virtual grid-based dynamic routes adjustment (VGDRA) scheme is put forward (Khan et al., 2015), aiming to reduce the routes reconstruction cost to extend the network lifetime. Initially, VGDRA establishes a virtual grid-based infrastructure over the physical network for all source nodes and this grid structure will exist until the network fails. In addition, the VGDRA adopts four communication rules to dynamically readjusting routes towards the mobile sink, thereby addressing the problem of the sink's location update within the virtual high-tier infrastructure. Moreover, high-tier nodes can easily spread extra load to other nodes of every cell via a cell-header rotation mechanism. Even though dynamic routes adjustment scheme is a good solution for the problem of the sink's location update, the VGDRA has no good performance in a non-uniform network.

Area-based approaches are also adapted to the problem of the sink's position advertisement in a hierarchical mobile sink routing protocol. Line-based data dissemination (LBDD; Hamida and Chelius, 2008) and Railroad are typical area-based routing protocols.

The LBDD defines a vertical virtual line, where in-line nodes belong to high-tier nodes. Source nodes forward the data to the nearest in-line nodes while generating some new data. The sink sends a query to the line and in-line nodes share this query until the destination node is reached. The data are then directly forwarded to the sink. However, the LBDD suffers from the hotspot problem. Especially for large-scale networks, the line has to be wide enough to alleviate the hotspot problem since sharing queries on the line will introduce a high communication overhead.

Virtual LBDD (VLDD) is also a VLDD protocol (Mo et al., 2013). The process of data collection from the virtual line structure is similar to the LBDD, whereas the VLDD exploits both individual and group mobility schemes for supporting mobility of group sinks, which helps enhancing lower energy consumption and higher data delivery than the LBDD.

Railroad (Shin et al., 2005) constructs a virtual rail structure, which is a closed loop of a strip of nodes. When a source node generates data, it sends an event notification message to the nearest rail node. This rail node constructs a new station and floods this notification message in the station. The sink sends a query to the nearest rail node and shares this query in two directions until this query reaches the station. Nodes upon receiving the query within the station inform the source node of the sink's position. The source node forwards sensory data directly to the sink. However, Railroad may introduce a high data delivery delay due to a much longer structure travelled by the query and a long distance between the rail node and the source node.

Ring routing is a typical virtual infrastructure-based routing protocol (Tunca et al., 2015). The sink's position is stored at the ring nodes and source nodes send a query packet to the ring and retrieve it. Ring Routing also supports dynamic change of the ring in case that the ring structure fails. Comparing with the VGDRA, one key difference is that source nodes should query the ring nodes to get the latest position information of the mobile sink at regular intervals, whereas the VGDRA avoids this process. Data packets from source nodes are directly sent to high-tier nodes and then forwarded to the sink via these high-tier nodes, which makes the VGDRA relatively energy-efficient.

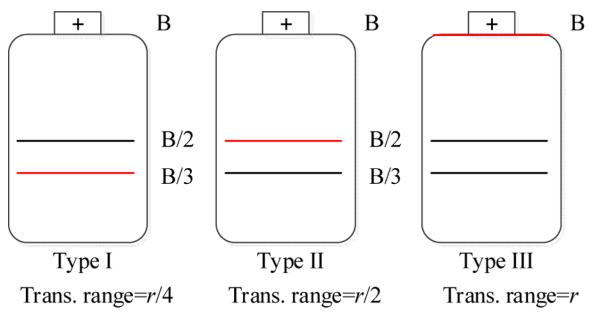
To achieve efficient data delivery and uniform energy consumption, the Grid Routing establishes a virtual grid structure that imposes dynamic routes adjustment scheme to make the latest location of mobile sinks to be easily forwarded to cell-headers (high-tier nodes) with minimal communication overhead (Keskin et al., 2016). On the other hand, grid routing improves the grid maintenance mechanism to enable the cell-headers to distribute more reasonably, which helps decreasing the overall energy consumption of every cell.

2.2 *Energy-aware transmission range adjusting*

A node with a large communication range will have amounts of neighbours. This means this node will suffer from a large number of data forwarding tasks. If a sensor node keeps the same transmission range of a 'healthy' node all the time during the WSN operation, then it will run out of its battery resource quickly.

Wang et al. (2014) proposed an energy-aware transmission range adjusting scheme to enable a sensor node to adjust its communication range based on their current residual energy. Assuming that the total battery capacity of a 'healthy' sensor node is B and its transmission range is r, the battery capacity of a sensor node can be classified into three types as described in Figure 1. Grid Routing adopts this method to enable a sensor node to adaptively control its own transmission range, thereby prolonging the lifetime of a single node.

Figure 1 The energy-aware transmission range adjusting mechanism (see online version for colours)



3 Grid routing

In this section, we give a detailed description of Grid Routing, mainly including how to construct a virtual grid structure in a 2D sensor field and how to make the latest location information of mobile sinks to be easily delivered to source nodes. Initially, the sensor field is partitioned into K same-sized cells based on the total number of sensor nodes. A set of nodes closest to the mid-point of each cell are elected as cell-headers. These cell-headers actually act as a regional static sink to collect data from a smaller sensor field, and then send it to mobile sinks which moves at the periphery of the network. When the sink's location has changed, following a few communication rules, only a limited fraction of cell-headers need to readjust routes thereby reducing the network control overhead as well as keeping the optimal routes towards mobile sinks.

3.1 Network characteristics

Before describing the methodology of the Grid Routing, following basic assumptions need making about network characteristics.

- Nodes are randomly deployed throughout the sensor field and all remain static after deployed successfully.
- All nodes are equipped with a global position system (GPS) device and are aware of their own locations.
- All sensor nodes have the same limited initial energy level, whereas the battery power of the mobile sink is rechargeable, which means it has no resource constraints.
- The transmission power of all sensor nodes can be adjusted based on the distance between the sender and receiver.
- There is no communication obstacle between any two nodes.

3.2 Grid construction

Initially, the grid routing establishes a virtual grid-based network structure by partitioning the sensor field into several uniform-size cells. The number of cells is determined by the total number of sensor nodes in the sensor field. The purpose of such deployment is to uniformly distribute the work-load to prolong the network lifetime and improve data delivery performance.

As described in Figure 2, in practical sensor network deployment, the number of cell-headers introduces an interesting trade-off due to different network coverage intensities (Xiao et al., 2010):

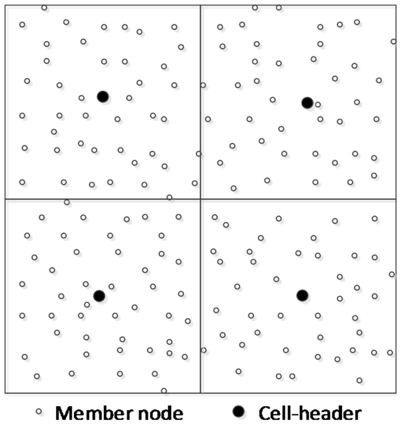
- A small number of cell-headers with high total number of sensor nodes implies that each cell-header is associated with a large group of sensor nodes. Every cell-header needs to forward huge amounts of data packets to destination nodes, thereby leading to the rapid depletion of batteries.
- A large number of cell-headers with low total number of sensor nodes implies that the effect of the virtual structure is weakened and more energy will be consumed to facilitate the latest location updates of mobile sinks.

To determine the optional number of cell-headers, we adopt a heuristic method used in LEACH (Heinzelman et al., 2002) to approximate the optimal number of cell-headers, which considers 5% of the total number of sensor nodes. Considering load-balancing, equation (1) is adopted to partition the sensor field with N sensor nodes into K same-sized cells, where K is a square number. K is calculated by the following:

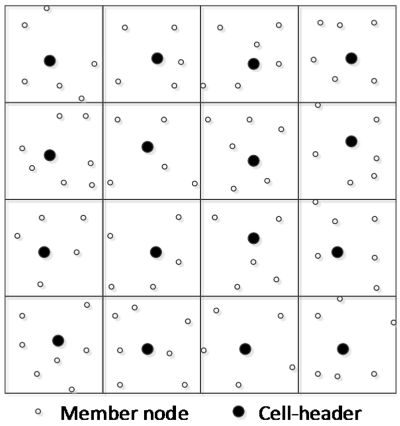
$$K = \begin{cases} 4 & N \times 0.05 \le 6; \\ 9 & 6 < N \times 0.05 \le 12; \\ 16 & 12 < N \times 0.05 \le 20; \\ \vdots & \vdots \end{cases} \tag{1}$$

After completing the network partition, a unique serial number will be assigned to each cell, which can be seen in Figure 3, and each node in the sensor field will be aware of which cell it belongs to.

Figure 2 Different deployment scenarios: (a) example of a small number of cell-headers with high total number of sensor nodes and (b) example of a large number of cell-headers with low total number of sensor nodes

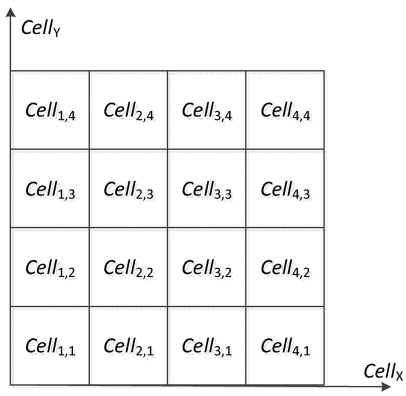


(a)



(b)

Figure 3 Sketch map of virtual grid structure



Based on the optimal number of cells which has been calculated using equation (1), we can get the side length of cells as $L/\sqrt{K}$, where L is the side length of the virtual grid. Then each node can get its own serial number, $\text{Cell}_{X,Y}$ using equation (2).

$$\text{Cell}_X = \left\lceil \frac{x}{L/\sqrt{K}} \right\rceil = \left\lceil \frac{x\sqrt{K}}{L} \right\rceil, \quad \text{Cell}_Y = \left\lceil \frac{y}{L/\sqrt{K}} \right\rceil = \left\lceil \frac{y\sqrt{K}}{L} \right\rceil \tag{2}$$

$$\text{Mid}_X = \frac{L}{\sqrt{K}}\left(\text{Cell}_X - \frac{1}{2}\right), \quad \text{Mid}_Y = \frac{L}{\sqrt{K}}\left(\text{Cell}_Y - \frac{1}{2}\right), \tag{3}$$

where (x, y) is the location coordinates of nodes. Meanwhile, nodes can calculate the coordinates of their own cell's mid-point $\text{Mid}_{X,\,Y}$ according to equation (3). Then nodes can get the Euclidean distance to the mid-point of their respective cells.

Initially, nodes within the same cells broadcast a status share packet containing their IDs, Cell-IDs they belong to, location information and distance to the mid-point. Nodes closest to the mid-point of cells are determined as first cell-headers, which are responsible for storing and keeping track of the location information of the mobile sink. Only those nodes whose distance to the mid-point of cells is below a certain distance threshold will be qualified to be a cell-header candidate. Each elected cell-header informs their member nodes and adjacent cell-headers of its role using a cell-header announcement packet containing its ID, role, location information and Cell-ID it belongs to. The adjacent cell-headers communicate with each other via gateway nodes.

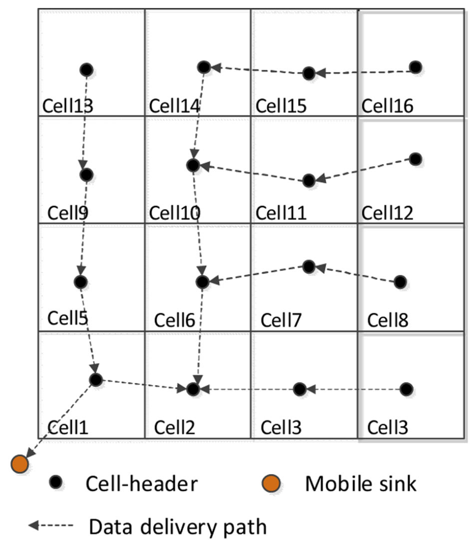
After the virtual grid structure is constructed, all cell-headers set up their corresponding initial routes towards the latest location of the mobile sink which first sojourns at coordinates (0, 0). The mobile sink moves counter-clockwise around the periphery of the sensor field at a constant speed. Figure 4 is an example of a virtual grid-based structure when the sensor field is partitioned into 16 cells.

3.3 *The sink's position update mechanism*

The mobile sink moves counter-clockwise to broadcast beacon messages to nodes in the vicinity periodically. Nodes upon receiving beacon messages determine whether the mobile sink has moved to another cell. If the mobile sink changes its location, routes towards the mobile sink should be reset. Flooding the location update packets within the network is the most efficient way, however, the significant communication overhead will cause a short network lifetime.

To minimise network control overhead, a dynamic local routes adjustment scheme is used that only follows a set of communication rules to update the sink's location information. The grid routing potentially shortens the data delivery routes of partial cell-headers, and that only these partial cell-headers participate in routes adjustment process, thus significantly decreasing node energy consumption.

Figure 4 The backbone of virtual grid structure (see online version for colours)



The specific process is as follows:

- *Rule 1*: The mobile sink sends a location update packet to its immediate cell. Then nodes upon receiving this packet will forward it to their cell-header. If the current cell-header (CH) is the originating cell-header (OCH), which communicates directly with the mobile sink, the current CH informs the mobile sink to transmit data directly. Otherwise, Rule 2 will be executed.
- *Rule 2*: The current CH becomes OCH, and forwards this location update packet to its immediate downstream cell-header. The next downstream cell-header upon receiving the update packet checks whether its next-hop is the sender node. If not, this cell-header set its next-hop as the sender node, and continues to relay this update packet to its downstream cell-header. If the downstream cell-header is NULL, the update packet is discarded.
- *Rule 3*: The current OCH also shares the sink's position update to the previous OCH. The previous OCH upon receiving the update packet adjusts its route setting the current OCH as its next-hop towards the mobile sink.

In order to well describe the sink's location, we give a unique number to every cell. As illustrated in Figure 5, a mobile sink is located at Cell 2. The cell-header in Cell 2 is the current OCH. After a short tour, the following cases are possible.

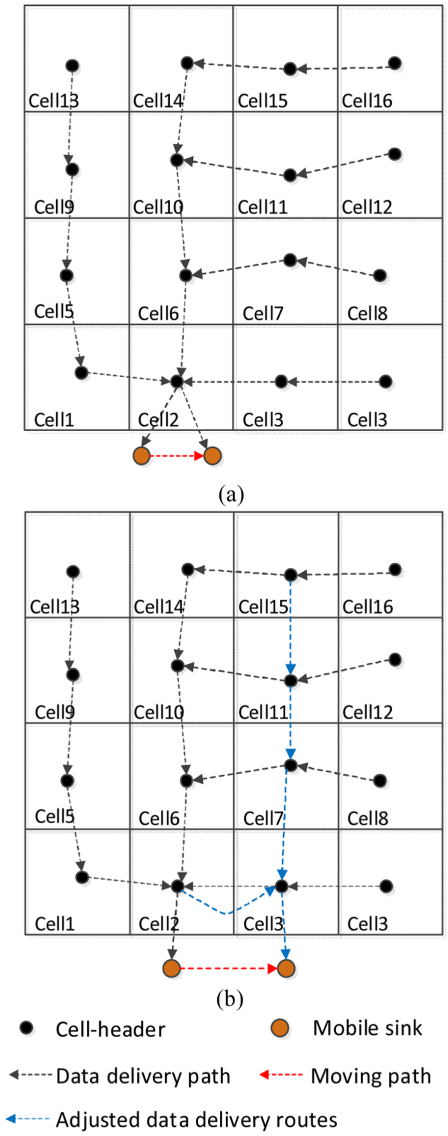
3.3.1 *Slow speed*

If the mobile sink moves at a slow speed, then it might be the case that the mobile sink has not moved to another cell. As described in Figure 5(a), the mobile sink is still at Cell 2 after a short tour and the latest sink's location updates can be easily achieved just by executing Rule 1. Therefore, routes towards the sink remain the same as before.

3.3.2 Fast speed

If the mobile sink moves at a fast speed, then it might be the case that the mobile sink moves to next cell. Considering network load-balancing and uniform energy consumption, the speed of the mobile sink is controlled that it can only move from Cell 2 to Cell 3 as illustrated in Figure 5(b).

Figure 5 Dynamic routes adjustment scheme: (a) the mobile sink moves from Cell 2 to Cell 2 at a slow speed and (b) the mobile sink moves from Cell 2 to Cell 3 at a fast speed (see online version for colours)



When the mobile sink moves to Cell 3, the cell-header in Cell 3 becomes a new OCH and execute Rule 2 to update the routes from downstream cell-headers to the current OCH. The downstream cell-header means cell-headers, i.e., 7, 11 and 15. Furthermore, the current cell-header executes Rule 3 to update the routes from the previous OCH to the current OCH. Blue arrows represent adjusted data delivery routes. The specific algorithm is also shown in Algorithm 1.

Algorithm 1 Data dissemination using grid routing

The mobile sink (MS) broadcasts a location update packet to nodes in the vicinity.
The node upon receiving this update packet forward it to its CH.
if (CH upon receiving this update packet is already set to OCH)
  if (MS can be reached directly)
    drop the packet;
    send data to MS directly;
  else
    send data to MS along with the opposite direction of the original path taken by the update packet;
  end if
else
  CH upon receiving this update packet becomes new OCH;
  readjust routes towards the mobile sink using VGDRA algorithm;
  if (MS can be reached directly)
    drop the packet;
    send data to MS directly;
  else
    send data to MS along with the opposite direction of the original path taken by the update packet directly;
  end if
end if

3.4 Grid maintenance

In our proposed grid routing, the cell-header is similar to a local data collector and takes charge of keeping track of the sink's location information. Member nodes retrieve their own cell-header and then forward generated data packets to the destination. These processes make the cell-header vulnerable to high energy dissipation. A cell-header will die quickly due to the depletion of its battery power. To ensure a long network lifetime, this grid structure should be kept during the WSN operation. Hence, a grid maintenance mechanism is necessary to virtual infrastructure-based routing protocols. The approach of re-electing cell-headers to replace current cell-headers with the low energy level in every cell aims to employ the optimal cell-headers to handle high-tier huge data traffic.

We define a certain energy threshold to trigger the cell-header re-election process. When the current residual energy level of a cell-header fails to this threshold, a cell-header re-election process occurs among nodes whose distance to the mid-point of cells is below a distance threshold.

The cell-header process is divided into four phases:

Phase 1: The cell-header broadcasts a cell-header request packet in its own cell, which contains ID of the current cell-header, role, Cell-ID it belongs to and distance threshold.

Phase 2: Nodes within the same cell calculate the distance to the mid-point of its cell. If a member node meets the requirement for the distance and energy, then it will return a reply packet to the current cell-header. The current cell-header upon receiving the reply packet will add this node into the cell-header candidate list.

Phase 3: The current cell-header selects the new cell-header from the cell-header candidate list based on a weight function and informs the new cell-header that it has been elected as the new cell-header.

Phase 4: The current cell-headers share information of new cell-headers with their respective member nodes and adjacent cell-headers before retiring from the current position.

The weight function in Phase 3 is calculated on the basic of node density and their current residual energy levels. If the cell-header is determined in a denser area, more nodes within the cell will have a short distance to the cell-header thereby reducing node energy consumption used for data delivery. We use the number of neighbours to approximately represent node density, and so the node with a higher energy level and more neighbour nodes compared with other candidates is more likely to be elected as the new cell-header. The weight function W can be obtain by

$$W = w \times \frac{E_{\text{residual}}}{E_{\text{total}}} + (1-w) \times \frac{N_{\text{neighbours}}}{N_{\text{total\_node\_cell}}}, w \in (0,1). \quad (4)$$

In equation (4), E_{residual} and E_{total} represent the current residual energy and battery capacity of a sensor node respectively. $N_{\text{neighbours}}$ is the total number of neighbour nodes of a node. $N_{\text{total\_node\_cell}}$ is the total number of nodes in every cell. w is a value between 0 and 1.

Nodes that have been elected as cell-headers will not take part in the cell-header re-election in the next round of re-election process. Also in the cell-header re-election process, if no node is suitable to be a cell-header in the search zone, the distance threshold will be slightly increased and the re-election process will be repeated until a new cell-header is elected. The specific re-election process is governed by Algorithm 2.

Algorithm 2 Cell-header re-election

```
if (residual energy of the current CH < E_threshold)
    current CH initiates re-election process bybroadcasting a
    request packets;
end if
foreach node upon receiving CH request packets
do
   if (node's Cell-ID == CH's Cell-ID)
          if (distance to the mid-point of cells > D_threshold ||
          current residual energy < E_threshold)
                 drop the packet;
          else
                 send response (residual energy and the total
                 number of neighbours) directly;
           end if
   else
          drop the packet;
   end if
end for
/* After collecting nodes information, select appropriate
new cell-header.*/
Let the response is obtained from M number of nodes.
if (M = 0)
   D_threshold = D_threshold + D_threshold /10;
   return Step 1;
else
   K = 0;
   S = 0;
   foreach node i ∈ [1: M]
   do
      W = weight value calculated using Equation 4.
      if (W > K)
         K = W;
         S = node.ID;
      end if
   end for
   New-CH = S;
end if
```

4 Performance evaluation

This section presents the simulation environment and results analysis. We used NS-2.34 to evaluate the performance of our proposed Grid Routing protocol in Ubuntu 10.10. We compared our grid routing protocol with the VGDRA from the performance of end-to-end delay, energy consumption and network lifetime.

4.1 Simulation environment

A successful virtual infrastructure-based routing protocol with mobile sinks can provide low data delivery delay and uniform energy consumption. We choose a time-sensitive data reporting application scenario such as a forest fire monitoring system (sensor data consisting of temperature, humidity, etc.) for the performance evaluation.

In our experiment, we consider a square sensor field of 200×200 m^2 dimension where 300 nodes are randomly deployed. As shown in Figure 4, the mobile sink is initially placed at Cell 1 and then moves counterclockwise around the sensor field to broadcast location update packets every one second at a constant speed. Nodes upon receiving location update packets forward this update packet to its cell-header. The cell-header only receives the first arrived location update packet. If more location update packets with the same sequence reach the cell-header, they will be discarded. grid routing adopts the first-order radio energy model as energy consumption model (Heinzelman et al., 2002) and we assumed the two-ray ground propagation model (d^4 path loss, d is the distance between senders and receivers) which represents a relatively practically channel model. Therefore, when a sensor node transmit l-bit length data packet at distance d, node energy consumption in transmission (E_{Tx}) and receiving (E_{Rx}) modes can be computed using the following equations (5) and (6), respectively.

$$E_{Tx} = (E_{\text{elec}} \times l) + (E_{\text{two\_ray\_amp}} \times l \times d^4) \quad (5)$$

$$E_{Rx} = E_{elec} \times l, \tag{6}$$

where l is message length, E_{elec} represents the energy consumed to transmit or receive one-bit length data and $E_{two\_ray\_amp}$ is the energy dissipation by the transmitter amplifier. Based on equation (1), the sensor field can be partitioned into 16 cells. Specific simulation parameters are listed in Table 1.

Table 1 Simulation parameters

Parameter	*Value*
Simulation area	200×200 m^2
Data packet size	512 bytes
Number of nodes	100, 150, 200, 250, 300
Sink speed	5 m/s
CSThresh	1 nw
RXThresh	6 nw
E_{elec}	50 nJ/bit
$E_{two\_ray\_amp}$	0.0013 pJ/bit/m^4
Simulation time	1000 s

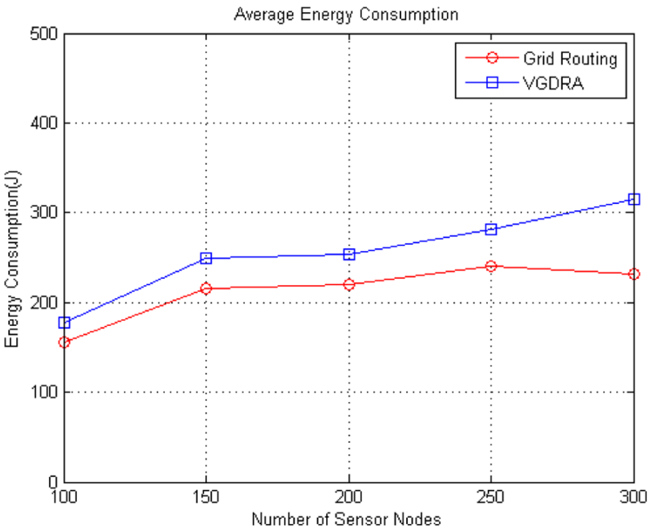
4.2 Results analysis

4.2.1 Average energy consumption

This subsection evaluates the average energy consumption of grid routing when exposed to different network sizes. The total numbers of nodes are varied from 100 to 300.

In terms of overall energy consumption at different network sizes, the grid routing shows better performance than VGDRA, as demonstrated in Figure 6. Unlike VGDRA, the grid routing adopts an energy-aware transmission range adjusting scheme to adaptively change the communication range of a sensor node. After a node consumes most energy, it will decrease its communication rang, thereby reducing some work load, e.g., huge neighbour discoveries.

Figure 6 Energy consumption changes with time (see online version for colours)

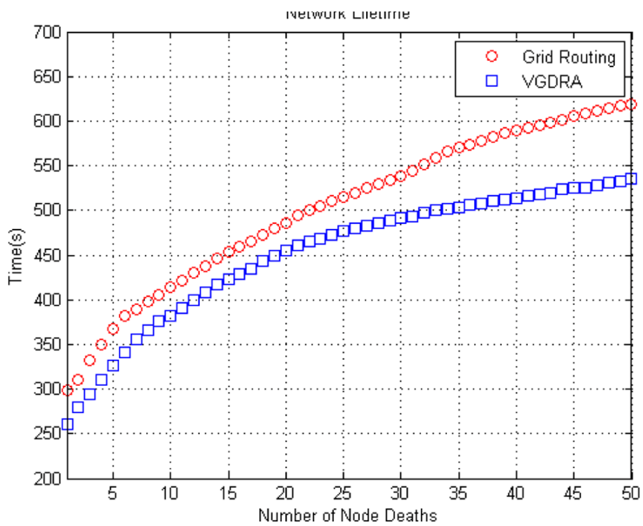


Furthermore, we improve the cell-header re-election process to select the optimal node as the new cell-header in every cell. The VGDRA also considers local replacement of high-tier nodes with low-tier nodes. However, the VGDRA ignores the impact of node density. Using the VGDRA scheme, more nodes will experience a long distance data delivery to forward data to the cell-header if the cell-header is located at a place with low node density. This means partial nodes in the cell will suffer from more energy dissipation due to uneven node distribution. On the contrary, if a cell-header is located at a high-density area, this cell-header will own more neighbour nodes, thus shortening hops for data delivery. Therefore, in a given period of time, grid routing can save more energy theoretically since nodes using grid routing share work load with other nodes.

4.2.2 Network lifetime

For WSNs, a long network lifetime is significantly important because WSNs work in an unattended manner and sensor devices in WSNs can be used only once. Hence, we should extend the network lifetime as far as possible. As described in Figure 7, within the same time, the number of death nodes using grid routing is less than that using VGDRA. Grid routing considers the impact of node density on the node energy consumption, which makes grid routing perform better in a randomly deployed network.

Figure 7 Death time for first 50 nodes (see online version for colours)



4.2.3 End-to-end delay

For a time-sensitive application, delay for data delivery is an important indicator to evaluate the performance of a routing protocol. We set the speed of the sink as 5 m/s. Figure 8 illustrates the data delivery latency of two protocols at different network sizes. It is clear that the data delivery latency of grid routing at different network sizes is relatively stable and obviously lower than that of VGDRA. Similar to VGDRA, grid routing utilises a location update packet to decrease the communication traffic on the grid structure, whereas grid routing improves dynamic routes adjustment scheme, which enables the node to converge faster to the latest location of the mobile sink.

In our experiment, the mobile sink circles the sensor field. Figure 9 shows the moving trajectory. We compare the performance of protocols at different speeds when the total number of sensor nodes is 300. From Figure 10, we can learn that data delivery latency of protocols are both high if the mobile sink moves at a faster speed, since data packets has expired during the period of data delivery, thereby leading to high packet loss rate and end-to-end delay. Moreover, grid routing can enables the node to converge faster to the latest location of the mobile sink. Hence, from the general trend, grid routing has better performance in terms of the data delivery latency at different speeds.

Figure 8 End-to-end delay at different total numbers of sensor nodes (see online version for colours)

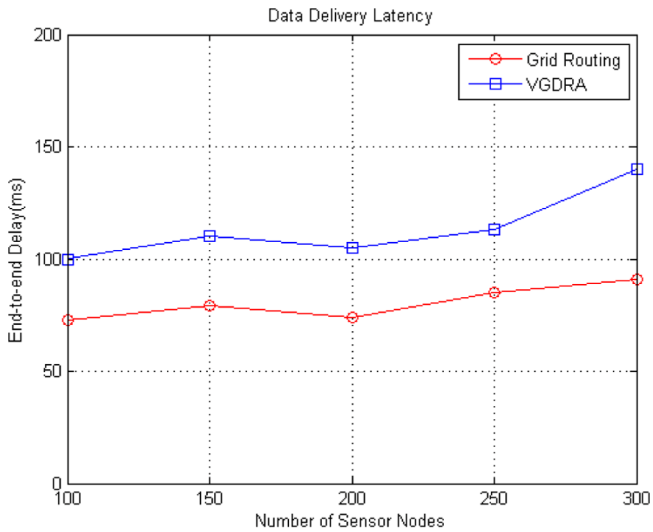


Figure 9 The moving trajectory that the mobile sink circles the sensor field (see online version for colours)

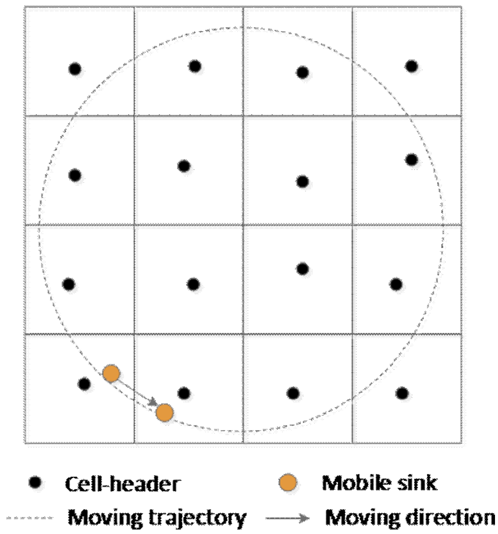
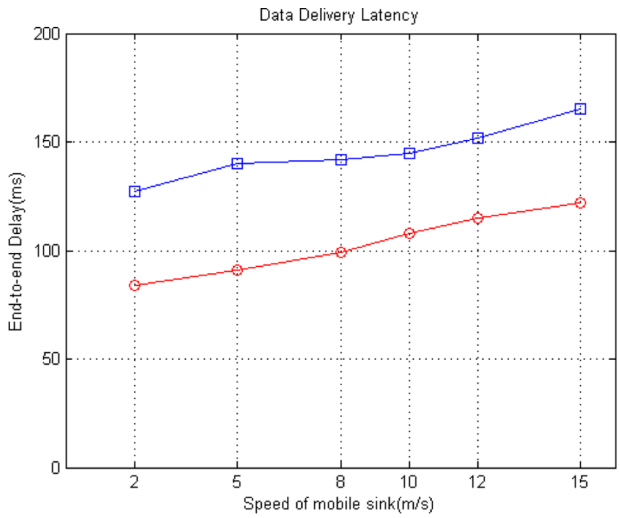


Figure 10 End-to-end delay at different speeds (see online version for colours)



5 Conclusions and future work

In this paper, we proposed an energy-efficient hierarchical mobile sink routing protocol, called grid routing, which partitions the sensor field into several same-sized cells and constructs a virtual infrastructure over the physical network. A mobile sink is employed to move counter-clockwise around the sensor field to collect data periodically. The mobile sink keeps on changing its position to shift the hotspots, thereby avoiding rapid death of individual nodes. Using a limited set of communication rules, grid routing successfully maintains the fresh routes towards the mobile sink with minimal communication cost and improves the cell-header re-election process to select the optimal node as high-tier nodes as well as protect the high-tier virtual infrastructure from failing.

The performance of grid routing is evaluated by simulations conducted in NS2.34. Simulation results demonstrate improved network performance at delay, energy consumption and network lifetime when compared with existing work.

Even simulation results show good performance of grid routing, this does not mean that grid routing is a good routing protocol. In the next stage, we will analyse the performance of grid routing at different moving trajectories. Furthermore, we also want to modify grid routing to support multiple mobile sinks or partition the sensor field into several different-sized cells, thereby reducing the overall energy consumption.

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