Ferry-Based Data Gathering in Wireless Sensor Networks with Path Selection

Mariam Alnuaimi\textsuperscript{a,*}, Khaled Shuaib\textsuperscript{a}, Klaithem Alnuaimi\textsuperscript{a} and Mohammed Abdel-Hafez \textsuperscript{b}

\textsuperscript{a}College of Information Technology, UAEU
P.O. Box 15551 Al Ain, UAE

\textsuperscript{b}College of Engineering, Electrical Engineering Department, UAEU
P.O. Box 15551, Al Ain, UAE

Abstract

Depending on the application, mobile ferries can be used for collecting data in a WSN especially those at a large-scale with delay tolerant applications. Unlike data collection via multi-hop forwarding among the sensing nodes, ferries travel across the sensing field to collect data. A ferry based approach eliminates or minimizes the need for multi-hop forwarding of data, and as a result energy consumption at the nodes will be significantly reduced especially nodes that are near the base station as they are used by other nodes to forward data to the base station. However, this increases data delivery latency and as such might not be suitable for all applications. In this paper an efficient data collection scheme using a ferry node is proposed with emphasis of the effect of ferry’s path. In this scheme the decision of selecting cluster heads is based on their residual energy and their distance from the ferry path. We simulated the proposed scheme in MATLAB using different scenarios to show their performance in terms of the network lifetime and total energy consumption in the network. We found that the centered and the diagonal fitted paths performed better than the diagonal path in terms of the network lifetime and energy consumed. We also found that increasing the check points increases the lifetime of the network.

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* Corresponding author: Mariam Alnuaimi
E-mail address: mariam.alnuaimi@uaeu.ac.ae
1. Introduction

Recent improvement in hardware electronics technology enabled manufacturers to develop low cost, low power and small size sensors. Hundreds and thousands of these sensors are deployed as wireless sensor networks (WSN) serving many applications based on the specific requirements of each one. Nowadays, there are many applications of sensor networks covering different fields such as agriculture, medicine, military, environment monitoring, intrusion detection, motion tracking, machine malfunction, and many others. Sensors can be deployed to continuously report environmental data for long periods of time.

In general, a wireless sensor network is a collection of static nodes with sensing, computation, and wireless communication capabilities. However, due to the nature of some applications, mobile nodes, ferries, are needed. Using mobile nodes to collect data from sensors in WSNs can improve the performance by prolonging the life time of a WSN and maintaining a better coverage area. Ferries are mobile elements that are used to carry data over distance to the base stations or to a data center. They are also used to connect isolated islands of WSNs. In addition, ferries can be used to resolve issues related to isolated nodes and coverage holes in a WSN resulting from the need for replacing deployed fixed sensor nodes which have being out of energy. Mobile elements can be attached to people, animals, vehicles, robots, unmanned aerial vehicles or any movable object.

In this paper, we propose a mobile ferry improved algorithm based on our previous published work, Node Ranking Clustering Algorithm (NRCA). Using NRCA algorithm, the decision of selecting cluster heads is based on their residual energy and their distance from the base station where an energy threshold technique is used to replace cluster-heads. In this paper, the decision of selecting cluster heads is based on their residual energy and their distance from the planned ferry’s path check points. In addition, data is collected by the ferry instead of flooding the network with multi-hopping. The network is divided into several clusters by the base station based on NRCA. Each cluster head collects data and sends it to the mobile ferry based on certain criteria.

The rest of the paper is organized as follows. In section 2 a survey on related work is summarized. Our proposed data collecting algorithm is described in Section 3. In Section 4, the performance evaluation in terms of the network lifetime is shown using different criteria. Finally Section 5 concludes the paper.

2. Background work

Using mobile ferries in WSNs is relatively a new area of research which is gaining the attention of many researchers. Incorporating ferries in WSNs helps in eliminating the need for multi-hop forwarding of data. It also reduces the energy consumption at the nodes. However, using ferries might add delay in collecting, disseminating and processing data and thus might not be suitable for all applications.

The path that the ferry takes to collect sensed data from sensors can be classified into two categories, random path and planned path. Usually in case of the random path the ferry is attached to people or animals moving randomly to collect sensed data whenever they are in the communication range of the static sensor nodes. In mobile entities called mules were deployed in the environment. Mules picked up data from sensors when they were in close range, buffered it, and dropped it off within a communication range of wired access points. They used two-dimensional random walk to model the mobility of mules. Both mules and sensors required to have memory capacities as they were buffering data. In mobile nodes were used in the sensor field as forwarding agents. When a mobile node moved in close proximity to sensors, data is transferred to the mobile node for later depositing at the destination. They used analytical models to understand key performance metrics such as data transfer, latency to the destination, and power consumption. Due to the random mobility of the ferry it is difficult to gather sensed data from all deployed nodes. Unlike the random path approach, in the planned path approach a path is determined before the dispatching of the ferry and thus the ferry is sent to cover a certain area of deployed sensors to collect data. The authors in used a single ferry to collect data from a circular dense sensors network. They showed that the optimal mobility strategy of the ferry is achieved when moving at the border of the sensing area. They divided the area into circles starting from the source. The inner circles forward the data to the outer ones; until the border is reached where the ferry is used to collect the sensed data.

The scheduling of when exactly to send the ferry to collect sensed data from nodes is a quite complicated task. In authors studied the scheduling problem where the path of a mobile sink was optimized to visit each node in the
WSN before its buffer gets full. In \(^1\) the authors suggested the mobile sink to visit exact locations (rendezvous points) based-on a predetermined schedule to collect data. The rendezvous points buffer and aggregate data originated from the source nodes through multi-hopping and transfer it to the mobile sink upon its arrival. In \(^1\) the authors considered on demand data collection where sensor nodes broadcast data collection requests when their buffers are about to be full. On receiving such requests, the ferry moves toward the sensor nodes to collect data, and transfer the data to the sink. In \(^1\) a mobile node was used to help in disseminating data to the sink. It was used to move back and forth along the linear network, and collect data from the individual sensors when it comes within their communication range. The mobile node will then transfer the collected data to a base station. The mobile node was also used to perform other functions, such as data processing and aggregation, and can also transport messages from the sink to the sensor nodes.

3. Ferry Node Ranking Clustering algorithm (FNRCA)

Since data transmission can account for up to 70% of the power consumed in typical sensor nodes \(^2\), substantial energy can be reduced by reducing the distance travelled and the amount of data transmitted to the base station. Distance of the nodes from the base station and inter-node distances can have a high impact on saving nodes’ energy and thus prolonging the network life time which can be defined either as the time for the first node to die, the time for the last node to die or the time for a certain percentage of nodes in the WSN to die \(^2\). Moreover, in dense deployments of sensor nodes in a WSN, nodes can cooperate to send data and therefore distribute the consumption of energy between them.

In this paper we propose a ferry-based node ranking clustering algorithm (FNRCA) to collect data from nodes. The difference between this algorithm and other algorithms is that this algorithm uses a more efficient mechanism to select cluster heads. This is done by measuring the distances, the current energy levels of nodes and calculating the number of rounds that each can be cluster heads for, to maximize the network life time and decrease excessive communication overheads used for electing new cluster heads. In this algorithm, nodes are ranked based on their current energy level (\(E_n\)) and their positions (\(D_n\)) with reference to the predetermined checkpoints on ferry’s trajectory. This ranking is used for choosing cluster heads which are also ranked into levels based on their position, Euclidean distance, from the checkpoints on ferry’s trajectory. Therefore, each node is assigned a rank \(R_n (E_n, D_n)\) reflecting its candidacy for being elected as a cluster head.

The proposed algorithm is shown to be energy efficient because it minimizes the energy used by cluster-heads to reach the BS by using a ferry. In the next subsection we introduce the proposed algorithm in more details.

3.1. Assumptions:

In the proposed algorithm, the Base Station (BS) is placed in a fixed position and has unlimited energy. Thus no constraints are assumed with regards to power consumption due to data processing and communication. Also, it is assumed that the ferry dispatches from the base station and go back to it. In addition to that, it is assumed that there are no energy constraints on the ferry. Nodes are distributed randomly based on uniform distribution. Through the initial step of the below algorithm, the BS becomes aware of the locations of all sensor nodes either via collecting their GPS coordinates or any other mechanism \(^2\).

3.2. Description of the algorithm:

The proposed algorithm is an extension based on our previously published work \(^7,\ 8\) with node ranking being based on the planned path of the ferry. The following steps give a description of the algorithm and cluster heads’ selection process:

- Similar to the initial step done in \(^21,\ 22\), each node at the set up phase broadcasts a message of its energy level and location to its neighbors. Therefore, each node sets up a neighbor information table recording the energy levels and positions of its neighbors and broadcast this information to its neighbors. This is conducted by all
nodes in the network until information about all nodes in the network is received by the BS. This will provide the BS with a global knowledge of the network.

- The BS divides the area into smaller partitions called clusters based on the assumed communication range of the nodes.
- The path of the ferry and checkpoints where the ferry will stop to collect data on its planned trajectory are predetermined by the BS and sent to cluster-heads.
- Nodes with the highest energy level (En) and least distance (Dn) from the closest checkpoint on the ferry’s trajectory in each cluster become a Cluster Head (CH) after the first round is completed where cluster heads were chosen in reference to the BS using the NRCA.
- At each checkpoint the ferry stops to collect gathered sensed data from cluster heads associated with the checkpoint. Gathered data is collected either directly from sensing nodes within these cluster heads communication range or through multi hop forwarding through other cluster heads for out of communication sensing nodes.
- Dissemination of data from cluster heads to the ferry is triggered by a control message communicated by the ferry to the cluster heads associated with each check point. The time the ferry will stay for at each check point is determined based on several parameters as will be shown later.
- Cluster heads, which are located closer to the path of the ferry, are referred to as the first level cluster heads. The cluster heads that are located at more distant positions from the path are considered as second level, third level...etc. Higher cluster heads’ levels transmit to lower cluster heads level in order to reach the ferry with the least energy consumption.
- The used energy model for sensing and dissemination of data in our simulation is the same used by 23, 19.

3.3. Cluster head selection process

After the initial forming of clusters, the BS assigns a cluster head for each cluster based on NRCA. Nodes in each cluster are ranked based on how far they are from the path of the ferry and on their current energy level. Nodes with the maximum residual energy and minimum distance will be chosen as a cluster head based on NodeRanking (En, Dn) where

\[
(\text{Dn}(i)) = \min(\text{D}(i, \text{Ferry\_path\_CP})), (\text{En}(i)) = \max(\text{ResidualEnergy}(i))
\]  

\[
|\text{D}(i, \text{Ferry\_path\_CP})| = \sqrt{(X_i - X_{cp})^2 + (Y_i - Y_{cp})^2}
\]

ResidualEnergy (En (i)) is the current energy level of the node i, D(i, Ferry\_path\_CP) is the Euclidean distance of node i to the closest checkpoint on the ferry’s path. Given a particular deployment region of interest, X_i and Y_i are the X and Y positions of node i. X_{cp} and Y_{cp} are the X and Y positions of the closest checkpoint on the ferry’s path.

A cluster head in each cluster will be changed when its energy level reaches a pre-defined threshold or a calculated value and not every round. This will make it possible for a node, i, to continuously play the role of a cluster head for multiple rounds and thus save any wasted energy for control and exchanged messages used in replacing it.
3.4. Ferry’s Stopping time at each checkpoint

The stopping time (ST) is the time period the ferry will stay at each checkpoint, $j$, to allow the associated cluster heads to send gathered data to the ferry. This time period depends on the number of associated cluster heads, their buffer sizes and the transmission time of a bit.

$$\text{ST}(j) = \text{BufSize}(j) \times \text{numberOfAttachedCHs} \times \text{timeToTransmitAbit} + T$$

where BufSize is the cluster head memory size in bits, the numberOfAttachedCHs is the number of cluster heads associated with the checkpoint $j$, timeToTransmitAbit is the time needed to transmit a bit of information to the checkpoint and $T$ is an assumed constant delay added to account for propagation delay.

3.5. Problem formulation

Given a set of cluster-heads, $n$, in a multi-hop based WSN, our aim is to use a ferry to collect gathered data from the cluster heads based on a predefined path while satisfying minimizing the overall energy consumed during such a process to prolong the network life time. We formulated our problem such that the ferry will take two paths. In the first one will be a diagonal line in the middle of the field. The diagonal line can be fitted to move closer to the cluster-heads with lower values of energy. The second path, the ferry will move along a line in the center of the field as shown in orange color in Fig. 1. Along both paths, there will be checkpoints where the ferry will stop to collect data from cluster-heads.

Table 1 Parameters used in the simulation, values for the various energy parameters are per the energy model used by $^{19,21,23}$

<table>
<thead>
<tr>
<th>Notation</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>N = 400</td>
<td>Total number of sensor nodes</td>
</tr>
<tr>
<td>Eo = 0.5J / node</td>
<td>Initial energy of each node</td>
</tr>
<tr>
<td>Eelec = 50nJ / bit</td>
<td>Per bit energy consumption</td>
</tr>
<tr>
<td>EDA = 5nJ / bit</td>
<td>Energy for data aggregation</td>
</tr>
<tr>
<td>Eamp = 100 pJ/bit/m²</td>
<td>Amplifier transmitting energy</td>
</tr>
<tr>
<td>Area = 200 x 200</td>
<td>Area used in the simulation in meters</td>
</tr>
<tr>
<td># of cluster heads/ # Checkpoints = 10</td>
<td>Ratio of checkpoints to cluster-heads</td>
</tr>
<tr>
<td>Packet size</td>
<td>256 bits</td>
</tr>
<tr>
<td>Data Rate</td>
<td>256 Kbps</td>
</tr>
<tr>
<td>Cluster Radius, coverage Radius</td>
<td>30 m</td>
</tr>
<tr>
<td>Sensing Radius</td>
<td>30 m</td>
</tr>
<tr>
<td>Buffer size</td>
<td>256 K Bytes</td>
</tr>
</tbody>
</table>

4. Performance Evaluation

To evaluate the performance of the proposed FNRCA algorithm we used MATLAB to simulate four scenarios on a 200 meters x 200 meters sensing field. In the first scenario we set the trajectory of the ferry to be diagonal while in the second scenario we fit the diagonal trajectory using curve fitting based on a one degree polynomial function to move closer to cluster-heads with lower energy values. In the third scenario we set the trajectory of the ferry to be along the center of the sensing field, while the fourth scenario represent our previous work, NRCA algorithm, without using a ferry node for comparison. The base station was placed three different locations: at the center of the field (x= 100, y =100), at (0,0) and at (0,100). The ferry was dispatched from the base station along the planned trajectory path. Table 1 shows the parameters used in this simulation environment which are a standard parameters used by all researcher in this field. Every node was given an initial energy of 5 J. The energy for data aggregation is 5 nJ/bit. The energy to run the radio is 50 nJ/bit. The amplifier transmitting energy is 100 nJ/bit/m². Using simulation, we considered the network lifetime metric to evaluate the performance of the four mentioned scenarios.
4.1. Simulated scenarios

As shown in Fig. 1, the ferry will move along a diagonal path of the sensing field. It will move back and forth on this path while stopping at the checkpoints to collect the data from cluster-heads then disseminate it to the BS. The second scenario the ferry will move back and forth on the path where the diagonal line is fitted to move closer to the cluster-heads with lower values of energy. Curve fitting using a one degree polynomial function was used to fit the line by assigning cluster heads residual energy values as a weight. The fitted line will move closer to cluster heads with less energy. In the third scenario the ferry will move on the horizontal line crossing the middle of the field. The fourth scenario is based on our previous NRCA algorithm without using any ferry nodes. When using a ferry, checkpoints are distributed along the path with a ratio in reference to the number of cluster heads i.e. areas with more cluster heads will have more number of checkpoints.

![Fig. 1. Paths of the ferry with checkpoints](image)

4.2. Network lifetime

Network Lifetime is defined here as the time interval from the time the sensor network starts its operation until the death of the last node in the network. From Table 2, we can see that the last node died in NRCA is at round 3300 making it the least achiever with the shortest network life time among the other scenarios. On the other hand, we can see that the centered and the diagonal fitted paths had longer network life time as their last nodes died at rounds 3860 and 3837, respectively. This can be justified because cluster-heads on the opposite diagonal direction corners will be far from the path and their multi-hopping chain to reach the path will be longer. Also in the fitted diagonal, it can be justified because the path will be closer to the cluster-heads with less energy which will make them consume less energy to reach the check points. The placement of the base station did not affect the result as we got the same result for the different placements of the base station.

<table>
<thead>
<tr>
<th>Protocols</th>
<th>Round first node died</th>
<th>Round last node died</th>
</tr>
</thead>
<tbody>
<tr>
<td>Diagonal path</td>
<td>1479</td>
<td>3556</td>
</tr>
<tr>
<td>Fitted diagonal path</td>
<td>1760</td>
<td>3837</td>
</tr>
<tr>
<td>Center line</td>
<td>1810</td>
<td>3860</td>
</tr>
<tr>
<td>NRCA</td>
<td>1300</td>
<td>3300</td>
</tr>
</tbody>
</table>
4.3. Energy consumed

As shown in Fig. 2 the energy consumed per round in fitted path is less than the diagonal unfitted one. Allowing the ferry to move closer to the cluster heads with lower energy values help in reducing the energy consumption in these cluster heads and as a result prolonging the life time of these cluster heads and preserve the overall energy of the whole network.

![Fig. 2 Energy consumption in the network](image)

4.4. Changing the number of checkpoints

We also simulated the second scenario while changing the ratio of the checkpoints to be one checkpoint for every 20 cluster heads, one checkpoint every 10 cluster heads one checkpoint for every 5 cluster heads. Table.3 shows the network performance of changing the number of checkpoints. From Table.3 we can see that the network lifetime increases as the number of the checkpoints increases. This because the more the checkpoints, the less distance the data will travel which saves the energy of the cluster heads and the overall energy of the network.

<table>
<thead>
<tr>
<th># checkpoints</th>
<th>Measurements</th>
</tr>
</thead>
<tbody>
<tr>
<td># of cluster heads/ # Checkpoints = 15</td>
<td>Round first node died 1560</td>
</tr>
<tr>
<td># of cluster heads/ # Checkpoints = 10</td>
<td>1760</td>
</tr>
<tr>
<td># of cluster heads/ # Checkpoints = 5</td>
<td>1913</td>
</tr>
</tbody>
</table>

5. Conclusions and future work

In this paper we proposed new efficient data collection algorithm using ferry node to collect data from nodes of WSN based on ferry’s path selection. In this algorithm the decision of selecting cluster heads is based on their residual energy and their distance from the ferry path. We also surveyed the recent progress of using mobile ferry nodes for data gathering in WSNs. We showed through simulation the performance of the proposed algorithm in term of network lifetime and overall energy consumption of the network per rounds using different scenarios of the ferry path and changing the number of checkpoints. In future, we plan to use nonlinear trajectory to achieve a better optimization.
References


