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EFFICIENT DATA GATHERING USING SPEED-CONTROLLED PATH-FIXED MOBILE DATA SINK IN WIRELESS SENSOR NETWORKS

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ABSTRACT

In this article, we consider data gathering in large-scale wireless sensor networks (WSNs) with a mobile data sink, where a mobile data sink moves on a constrained (or fixed) trajectory path to collect time-sensitive sensed data from sensors within a given time bound. As the sensors are being heavily energy constrained due to limited battery power and poorer speed of the mobile data sink pose a great challenge in designing efficient data gathering in the network within the given time bound. Therefore, time-sensitive data gathering through exploiting a path-fixed mobile data sink in WSN has increased attention among WSNs researchers. In this article, we devise a novelized data gathering improvement problem that copes with the speed-controlling of the mobile data sink along a given path at the specified time. We focus on determining a sequence of the speeds of the mobile data sink along that path so that, the mobile data sink will collect an improved amount of data from sensors within the given time. The proposed algorithm is called improved data gathering movement planning of a mobile data sink at a given deadline (IDMPMS). IDMPMS is a deterministic algorithm. It's running-time is polynomial. Furthermore, the performance of the IDMPMS algorithm is demonstrated through simulation (using MATLAB).

Keywords: *Time-sensitive, Data gathering, Mobile data sink, Controlling speed, Wireless sensor networks*

I. INTRODUCTION

Nowadays, mobile data sink based data gathering is be-coming more popular in a wireless sensor network (WSN) [2]–[13]. An extensive study has shown that the mobile data sink can significantly improve the performances of the network including, energy efficiency, connectivity, coverage, network reliability, throughput, etc.

However, exploiting mobile data sink for sensory data collection in the network would decrease the data collection rate as well as increase the data delivery delay owing to its slower speed [2]. Thus, in practice, considering the delivery latency, it would be difficult to optimize the data collection for the mobile data sink approach. Besides, some time-sensitive applications such as fire detection system, crisis detection system, and intrusion detection system, etc. have a strict requirement to meet time deadline on data collection using path-constrained mobile data sink(s). The main challenge, therefore, is to collect an improved amount of data using a path-constrained mobile data sink from the sensors within the specified time. Addressing this issue, a viable solution is to control the traversing-speed of the mobile data sink, so that the data collecting performance of the network can be increased.

There are some existing studies based on data collected using a path-constrained mobile data sink [7]–[13]. They considered the movement problem of the mobile data sink for efficient data gathering from sensors in the network. In addition, they divided the movement problem of mobile data sink into simpler sub-problems. But, the formulations made from them could not provide optimum solutions. As, their solutions designs are for the same problem with the specific scenario, which is very difficult or almost impossible for comparing with others for the same problem in the dissimilar scenario.

In this work, the traversal-path of the mobile data sink is given and fixed. But, its speed on that path is adjustable. Therefore, we will only focus on controlling the traversing-speed of the mobile data sink to enhance data gathering performance. We refer a sequence of the traversing-speeds of the mobile data sink along the path within the specified time period as a speed-schedule of the mobile data sink. Thus, our goal is determining a speed-schedule of a mobile data sink that will give the improved data collection at a given time bound. The most similar work is [12].

However, in [12], a constant speed mobile data sink is used for data collection from sensors with the same application set-up. Another work similar to our proposed work is [13]. In [13], sub-sinks have assumed some amount of data randomly. As illustrated in figure 1, in this article, a mobile data sink MDS moves along a path P and collects sensed data from the near by sensors which are under its communication range along the path P . Those near by sensors are called sub-sinks (SS_1, SS_2, SS_3, SS_4). It is taken into account that, The MDS can receive data from the sub-sinks only when it is in the communication ranges of them. Therefore, sub-sinks deliver their cached data to the MDS directly, while the MDS comes into their communication regions. Remaining other far away sensors (S_1, S_2, . . . , S_{11}) deliver their pre-cached data to near by sub-sinks. Later on, sub-sinks deliver those received data together with its sensed data to the mobile data sink. Thereafter, the mobile data sink finally sends the cached data to the base station. Our major contributions of the proposed work are as follows.

We devise a data collection problem using a constraint-path mobile data sink with adjustable speed within the given time deadline.

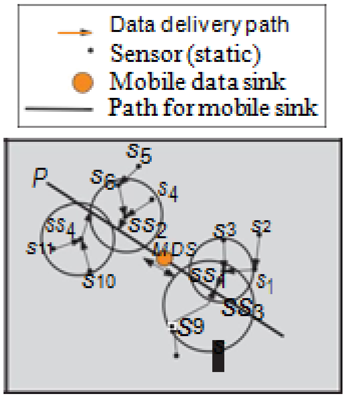


Figure 1. An example of sensor network with a Path-fixed mobile data sink.

A polynomial time solution for a large-scale sensor network is proposed for collecting an improved amount of sensed data from the WSN within the specified time bound.

Our proposed algorithm is called improved data gather-ing movement planning of a mobile data sink at a given deadline(IDMPMS).

The efficiency of the IDMPMS algorithm is evaluated by comparing with fixed-speed movement of mobile data sink technique with the same parameter.

The rest are organized as follows: Related works is de-scribed in section II. Section III formulates the system model and the proposed data gathering problem. The proposed IDMPMS algorithm's design and its theoretical analysis are introduced in section IV. Moreover, the simulation experimen-tal results are evaluated in sections V. Finally, we conclude our proposed work and outlines our future work VI.

II. RELATED WORKS

As already stated in the previous section, controlling the speeds of the mobile data sink(s) can reduce the overall data gathering delay in the wireless sensor network. In article [7], [8], [9], [10] and [11], a mobile data sink moves on a constrained path for data collection from sensors. In general, it moves at the maximum speed. But, it's speed becomes slow or even stops according to the network condition to enhance the data gathering performance of the network. Therefore, in this way, the mobile data sink learns the data transfer technique to control its moving speed based on history.

In [7], a mobile data sink with very poor speed (up to 1mps) is used in the network. Which is consequently not feasible for the large-scale network. Therefore, to address this issue, the article [8] uses more than one mobile data sinks in its speed control algorithm. Somasundara et al. [9] analyzed the motion states of the mobile data sink in depth. They showed the effect of the design of trajectory on the sensors' buffer requirements. In addition, they also showed that buffer overflow is not the direct reason for data loss. In [10], a single-hop communication-based clustering technique is used to collect sensed data by a mobile data sink on a straight-line path. The overall target of this article is to enhance data gathering performance at a given delay bound. Thus, the algorithm proposed in [10] is particularly applicable for large scale, disconnected heterogeneous sensor networks. Huang et al. [11] proposed a novel data collection scheme to collect sensory data from the sensing field, grouped into regions through a mobile data sink. Where each region may have varying importance level.

Although, the above mentioned approaches try to improve the amount of data collected. But, their speed control algo-rithms are reactive due to the adaptive nature of speed learning. Besides, these algorithms don't have any particular solutions for the speed-optimizing of the mobile data sink to improve the data collection rate and to reduce delays in WSNs.

In our proposed work, a mobile data sink is also used on a path-fixed network for collecting sensory data from the sensors. And, our proposed algorithm is proactive.

Some existing literatures [3]–[6] aslo solved the movement planning problem of the mobile data sink. In those literatures, the primary target is to design the path for the mobile data sink. In addition, they also wanted to control the mobility speed along that path. In [3], an efficient path was determined for a mobile data sink to send data between sensors in the sparse network to ensure the minimization of average data delivery latency and sensors' bandwidth requirements can be met. However, Zhao et al. [3] did not employed the speed adjustment method for enabling the improved data gathering performance. In [4], mobile data sink (data mule) scheduling problem is devised to balance the data gathering delay. The data mule scheduling (DMS) problem consists of various sub-problems such as selection of an optimal trajectory path, speed control mechanism, and job-scheduling. The article [4] also focused on various models of movement planning of mobile data sink. Such as single mobile data sink with periodic or non-periodic data generation case and multiple mobile data sinks cases. Furthermore, Mohandes et al proposed a movement planning and control scheme in [6] by controlling the mobile data sinks (unmanned aerial vehicles) in order to minimize the data uncertainty. Though, the path designed by Mohandes et al. may not be straight in nature. But in these articles, the trajectory of the mobile data sink is controllable not constrained. Our proposed algorithm is proactive and for speed adjustable mobile sink network.

The most similar work to the one presented in this article is MDSP algorithms [12]. In the MDSP algorithm, a path-constrained mobile data sink with a fixed speed is utilized to collect sensed data from the sensor nodes, which are directly reachable from it along the given path. Those directly reachable sensor nodes have pre-assumed the amount of data availability randomly. In addition, sensory data of all sensors except neighboring close sensors to the mobile data sink are unused. Therefore, the mobile data sink is not been able to gather actual sensed data of the network.
Our proposed work, the IDMPMS algorithm, differs from MDSP algorithms [12] in that it will use a speed-adjustable mobile data sink to gather sensed data of the network in an energy efficient way. In addition, our proposed IDMPMS scheme is a deterministic one.

III. SYSTEM MODEL

In this article, a wireless sensor network is modeled as

A communication topology graph $G(N, E)$, where $N = \{S_1, S_2, . . . , S_n\}$ denotes a set of static sensors with E no. of communication links between them. A set $R = \{R_1, R_2, . . . , R_n\}$ represents communication radii or ranges of the corresponding sensors. It is assumed that the mobile data sink (or $M\ DS$) knows the location of every sensor very well and it has sufficient energy and sufficient memory capacity. $M\ DS$ can move upto the maximum speed (V) on a given path P. Though, the mobile data sink can reduce its moving speed, when neighboring sensors have more data to be delivered to it. The $M\ DS$ gathers cached data from the neighboring sensors while entering into their communication regions on path P . Based on the movement of $M\ DS$ along P , the sensors which are close to P ,are called as sub-sinks. They can directly send their cached data to the $M\ DS$. Remaining sensors send their data to the selected sub-sinks through multi-hop communication method. Subsequently, the sub-sinks deliver their received data together with its sensed data to the mobile data sink. After that $M\ DS$ finally send the received data to the fixed base station. This available data (received and own sensed data) of the sub-sink subjective to the final delivery to the mobile data sink is referred as data availability of the sub-sink. In our proposed network model, the mobile data sink is allowed to collect sensory data from multiple overlapped communication regions of sub-sinks simultaneously. Let a set

$SS = \{SS_1, SS_2, \ldots, SS_{nss}\}$ represents a set of chosen sub-sinks from a set N of sensors. The proposed problem is defined

as follows.

Problem Statement: For a given a set $SS = \{SS_1, SS_2, \ldots, SS_{nss}\}$ of sub-sinks, and their communication ranges $R = \{r_{ss1}, r_{ss2}, \ldots, r_{ssnss}\}$ and a mobile data sink $M\ DS$ moving on a given path P with maximum speed V for gathering data, our goal is to compute a speed-schedule SP of the mobile data sink $M\ DS$, which will return an improved data collection from the sub-sinks in t time period.

IV. SOLUTION DESCRIPTION

The proposed algorithm focuses on collecting an improved amount of data through controlling the mobile data sink's speed on P in time t. Considering the maximum speed V , a naive approach would be for the mobile data sink to move at speed V . However, even within the given time deadline t, the moving speed of the mobile data sink can be controlled according to the amount of data availability of the sub-sinks. For instance, a mobile data sink can move at slow speed in the communication region of the sub-sink, which has large data availability. Furthermore, It can move at high speed in the communication region of the sub-sink, which has less or no amount of data availability. It can be noted that the moving speed of the mobile data sink must between 0 and V . In this way, there can be a sequence of the speeds on P in time t called as speed-schedule of the mobile data sink within time t.

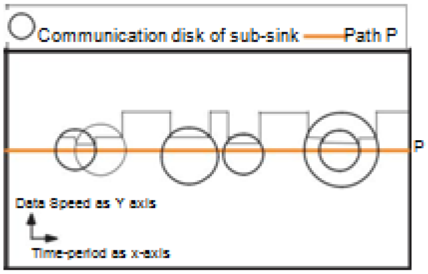


Figure 2. A possible speed sequence of a mobile data sink in the sensor network

Therefore, in this paper, our objective is to determine a speed-schedule SP of the $M\ DS$ along P , such that, the $M\ DS$ can collect the improved amount of data using SP on P in time t. A possible speed-schedule is illustrated in figure 2. Among all schedules of the speeds, we have to select a speed-schedule that provides the improved amount of data collected. Owing to given traversal time t and the fixed path P , the traversed part of path P affects the set of sub-sinks.

Definition 1 (Secant line(SL_i)). *is a sub-path on path P that intersects the communication disk SS_i at exactly two points (Secant start-point (SS_i^s) and Secant end-point (SS_i^e)) along P . In other words, the part of path P bounded by these two points SS_i^s and SS_i^e is known as secant SL_i of the communication disk of sub-sink SS_i.*

Definition 2 (Data delivery time(DT_i)). *DT_i is a time taken to deliver the DA_i amount of data availability of sub-sink SS_i is $DT_i = \frac{DA_i}{dtr}$, where dtr denotes a data transfer rate of SS_i.*

Definition 3 (Data speed(DS_i)). *The speed at which the mobile data sink receives data from the sub-sink SS_i under its communication region based on its data availability DA_i is $DS_i = \frac{|SLi|}{DT_i}$.*

A. Solution design of IDMPMS schme

Our algorithm provides a solution of improved data gather-ing through utilizing a mobile data sink $M\ DS$ on P within time t in n_{ss} rounds. At every i^{th} round, a secant start point SS_i^s is set as a beginning position to start traversing along the path P with regard to sub-sink SS_i, where i is ranging from 1 to n_{ss}. It is done only if $SS_i^s \exists SS_i$ comes at or after than start-point of path P , otherwise; start-point of the path is set as beginning position for i^{th} traversal.Similarly, we find the ending position of i^{th} traversal. Therefore, the start position and the end position of the mobile data sink change at every round of traversal. Thereafter, we find a speed-schedule SP_i and compute the amount of data gathering with respect to it,

$\forall i = 1$ to n_{ss}. Finally, the speed-schedule with the improved amount of data among n_{ss} rounds is selected as an optimal solution.

We briefly explain about the step of IDMPMS Algorithm as follows:

Determine all secants start-points and secants end-points (SS_i^s, SS_i^e), $\forall i$ is ranging from 1 to nss. Arrange these points into an ascending order into a vector sbx. Determine data availability DA_i corresponding to each sub-sink SS_i using shortest path tree (SPT) technique, $\forall i = 1$ to n_{ss}. Compute data transfer time DT_i and data speed DS_i of mobile sink concerning with each sub-sink SS_i, $\forall i = 1$ to n_{ss}. Take a temporary vector $T\ Data$ initialized to zero to store data collected by a mobile data sink in nss rounds. In each i^{th} round, the initial speed for mobile data sink is set to the data speed DA_i of the i^{th} selected sub-sink SS_i, whose communication disk's secant start-point SS_i^s is made as a source point to start the i^{th} traversal round movement.

The mobile data sink may change its speed until i^{th} selected sub-sink disk's end-point SS_i^e is not visited or communication region of another sub-sink begins SS_j^s, where $j = i$ within the given time period. The speed of the mobile data sink is set to data speed of the non-overlapped sub-sink, if it is moving under the communication region of that sub-sink and data gathered from that sub-sink will be data availability of that sub-sink until the time period is elapsed or remaining all secants' start-points and end-points are visited. In case of overlapped regions of sub-sinks, the speed of mobile data sink is set to the minimum value in data speeds of all overlapped sub-sinks until the time period is over or data delivery of each sub-sink is completed. Let the overlapped region is denoted by L and the minimum value in data speeds of the sub-sinks in region L is represented by d. Then, the amount of data collected from all overlapped sub-sinks will be the sum of min (min (remaining time t, $\frac{L}{d}$) * dtr), remaining data availability of the of the sub-sinks in that overlapped region. The mobile data sink will move at speed V , if the sink is not under the communication region of any sub-sink within given time period or remaining all secants' start-points and secants' end-points are not visited. The mobile data sink will stop if the time is elapsed or remaining all secants' start-points and secants' end-points are visited.

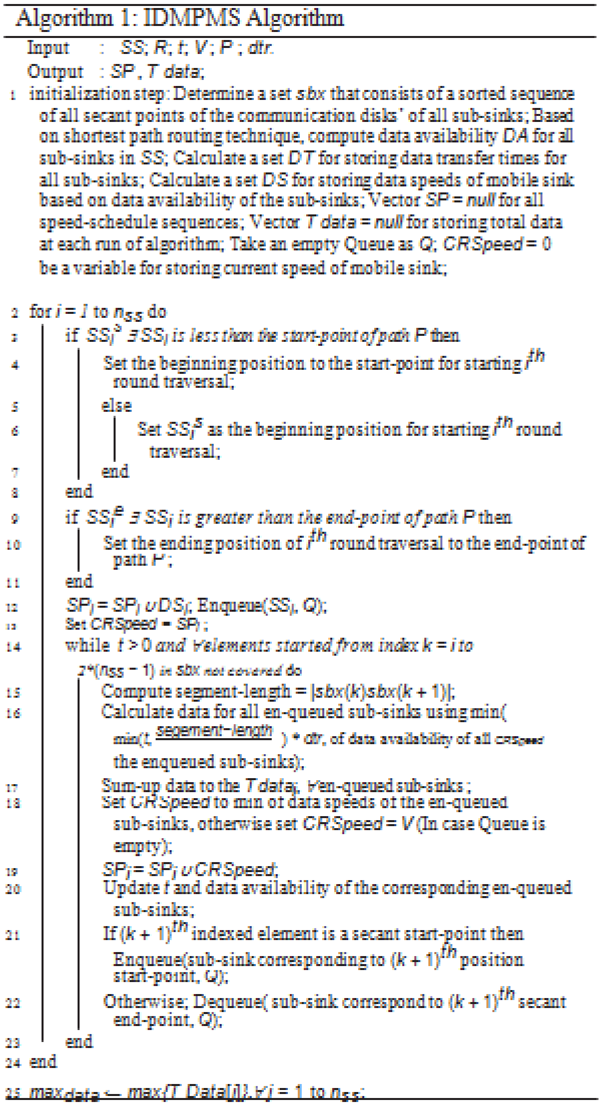
In this fashion, we determine a speed-schedule SP_i and compute the $T\ data_i$ amount of gathered data accordingly at each i^{th} round, where i is ranging from $i = 1$ to nss. Thereafter, we select a round which returns maximum

value among data collected in all rounds. Let J denote the round among nss rounds in which amount of data for a speed-schedule SPJ is maximum (T Dataj = Max{ $T\ Data_1, T\ Data_2, \ldots, T\ Data_{nss}$ }). This is the optimal speed schedule SP_J against which improved amount of data is gathered by our algorithm.

The algorithm is detailed in IV-B.

B. IDMPMS Algorithm

The following parameters are used as inputs for IDMPMS algorithm: A set $SS = \{SS_1, \ldots, SS_{nss}\}$ of sub-sinks Communication radius $R = \{R_1, \ldots, R_{nss}\}$; Data gathering time t; Maximum speed of mobile data sink V; Path $P(x_p,y_p)$; Data transfer rate of a sub-sink dtr.



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Algorithm 1: IDMPMS Algorithm
  Input    :  SS; R; t; V; P ; dtr.
  Output   : SP , T data;
initialization step: Determine a set sbx that consists of a sorted sequence
  of all secant points of the communication disks' of all sub-sinks; Based
  on shortest path routing technique, compute data availability DA for all
  sub-sinks in SS; Calculate a set DT for storing data transfer times for
  all sub-sinks; Calculate a set DS for storing data speeds of mobile sink
  based on data availability of the sub-sinks; Vector SP = null for all
  speed-schedule sequences; Vector T data = null for storing total data
  at each run of algorithm; Take an empty Queue as Q; CRSpeed = 0
  be a variable for storing current speed of mobile sink;

for i = 1 to n_SS do
    if SS_i^s ∃ SS_i is less than the start-point of path P then
        Set the beginning position to the start-point for starting i^th
          round traversal;
        else
            Set SS_i^s as the beginning position for starting i^th round
              traversal;
        end
    end
    if SS_i^e ∃ SS_i is greater than the end-point of path P then
        Set the ending position of i^th round traversal to the end-point of
          path P;
    end
    SP_i = SP_i ∪ DS_i; Enqueue(SS_i, Q);
    Set CRSpeed = SP_i ;
    while t > 0 and ∀elements started from index k = i to
      2*(n_SS − 1) in sbx not covered do
        Compute segment-length = |sbx(k)sbx(k + 1)|;
        Calculate data for all en-queued sub-sinks using min(
          min(t, segement-length / CRSpeed) * dtr, of data availability of all
          the enqueued sub-sinks);
        Sum-up data to the T data_i, ∀en-queued sub-sinks ;
        Set CRSpeed to min of data speeds of the en-queued
          sub-sinks, otherwise set CRSpeed = V (In case Queue is
          empty);
        SP_i = SP_i ∪ CRSpeed;
        Update t and data availability of the corresponding en-queued
          sub-sinks;
        If (k + 1)^th indexed element is a secant start-point then
          Enqueue(sub-sink corresponding to (k + 1)^th position
          start-point, Q);
        Otherwise; Dequeue( sub-sink correspond to (k + 1)^th secant
          end-point, Q);
    end
end
max_data ← max{T Data[i]}, ∀i = 1 to n_SS;
```

C. Time complexity analysis

Theorem 1. *The IDMPMS algorithm has* $O(n^3)$ *time com-plexity.*

Proof. In IDMPMS algorithm, Determining the start-point and the end-point of a secant of each selected sub-sink takes O(n) time complexity. Sorting these points requires $O(n\log n)$ time. The computation required for calculating data availabilities of all sub-sinks has $O(n^3)$ time complexity. Determining the speed-schedule and correspondingly data collection at each round of traversal require $O(n^2)$ time complexity. So, the analyzed time complexity is $O(n^3)$ from the defined Step 2 to defined Step 24. In step 25, finding the maximum value among all data collected takes $O(n)$ time complexity. Hence, overall IDMPMS algorithm will be $O(n^3)$ time complexity. □

V. SIMULATION EXPERIMENT

Now, we come for evaluating the data gathering perfor-mance of IDMPMS protocol using extensive simulations. We simulate a sensor network of sensor nodes 50, 100, 150, 200, 250, & 300 with different communication radii (between 52 m and 60 m) randomly in the monitoring area of 400 m x 600 m for different time periods ranging from 20 Sec to 120 sec at an interval of 20 sec respectively. A mobile data sink can move at maximum speed 5 m/s along the mid vertical path of the network. The data transmission rate of each sub-sink is taken as 20 Kbps. After that, we study the impact of various time bounds and the various sizes of the network over the amount of data collection.

A. Data Gathering Performance of IDMPMS protocol

Now, we analyze & evaluate data collection performance of IDMPMS protocol with fixed speed movement based mobile data sink technique. In figure 3, we analyze that the extent of the data collected is greatly dependent on the network size and given time t. Furthermore, the degree of the amount of gathered data is proportional to the size of the network in term of no. of uniformly deployed sensors as well as time t. However, the incremental rate of data gathering is relatively fast for larger networks comparing with smaller networks, as shown in figure 3. Also from figures 4, we find that the proposed IDMPMS protocol had better data collection ability as compared to the fixed speed mobile data sink based data gathering approach for the small network as well as large network also. In IDMPMS protocol, we find that the mobile data sink travels a longer path-segment in a larger time. However, the determined displacement value and avg. segment length is decreased as the mobile data sink moves from smaller network to larger network based on the given time bound.

VI. CONCLUSION

In this article, we studied the movement problem of a mobile data sink for time-sensitive data gathering applications. In which a mobile data sink can adjust its moving speed to gather sensory data from sub-sinks on a predetermined path in the network. Though, the speed of the mobile data sink cannot go beyond its given maximum speed. To address the movement planning problem, we have presented an IDMPMS protocol. In IDMPMS protocol, for the given set of sub-sinks, a speed-schedule is selected among all determined schedules which provide an improved amount of data in data gathering time t. Furthermore, IDMPMS scheme is deterministic one. In addition, it run-time complexity is polynomial in nature. We have used MATLAB for simulation. The simulations results prove that IDMPMS provides potential data gathering performance for the different size networks in different data gathering periods as compared to the fixed speed mobile data.

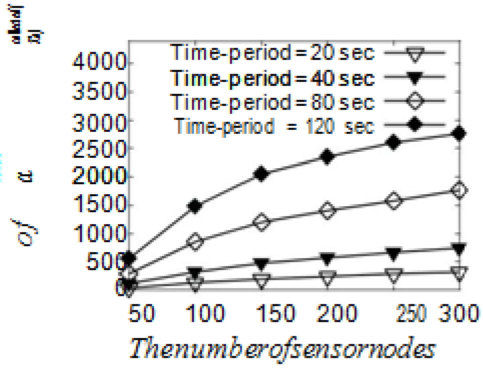

Figure 3. Amount of data collected for different time periods in one round

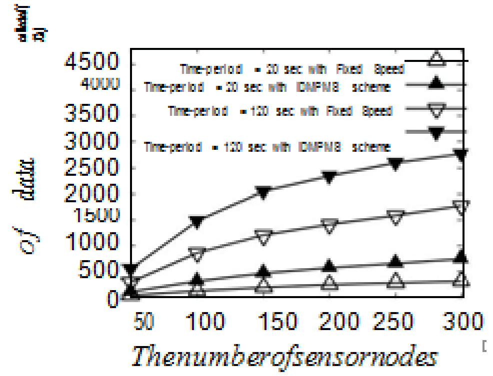

Figure 4. Comparision of amount of data collected between fixed speed mobile data sink technique & and IDMPMS scheme

sink technique. the results show that using a mobile data sink with controlled speed significantly improves the data collecting performance compared to the case when the mobile data sink moves at fixed speed. Determining a path for a mobile data sink across the network that will provide maximized network lifetime within the specified time as our future work.

VII. ACKNOWLEDGEMENT

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