Plane Sweep Algorithms for Data Collection in Wireless Sensor Network using Mobile Sink

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Abstract—Usage of mobile sink(s) for data gathering in wireless sensor networks(WSNs) improves the performance of WSNs in many respects such as power consumption, lifetime, etc. In some applications, the mobile sink MS travels along a predefined path to collect data from the nearby sensors, which are referred as subsinks. Due to the slow speed of the MS, the data delivery latency is high. However, optimizing the data gathering schedule, i.e. optimizing the transmission schedule of the sub-sinks to the MSand the movement speed of the MS can reduce data gathering latency. We formulate two novel optimization problems for data gathering in minimum time. The first problem determines an optimal data gathering schedule of the MS by controlling data transmission schedule and the speed of the MS, where the data availabilities of the sub-sinks are given. The second problem generalizes the first, where the data availabilities of the subsinks are unknown. Plane sweep algorithms are proposed for finding optimal data gathering schedule and data availabilities of the sub-sinks. The performances of the proposed algorithms are evaluated through simulations. The simulation results reveal that the optimal distribution of data among the sub-sinks together with optimal data gathering schedule improves the data gathering time.

Index Terms—Mobile sink, Data gathering protocol, Wireless Sensor network, Plane Sweep Algorithm

I. INTRODUCTION

In WSNs, data generated at the sensor nodes are either transmitted through multi-hop transmission to a base station [8], [3], or a mobile sink (MS) moves through the communication regions of the sensors and collects data from sensors directly/indirectly and brings them to a base station [9], [14]. In multi-hop transmission, sensors located near the base station are overloaded for relaying data from other sensors to the base station and are therefore prone to deplete their energy faster than other far away sensors.

Recently, mobile sink based data gathering has been gaining popularity significantly in wireless sensor networks (WSNs). In some applications, the MS periodically patrols the sensors, collects their data, returns to the base station and dumps the collected data at the base station. The problem of determining the tour of the MS has been studied rigorously in [9], [14], [4]. Mobile sink based data gathering improves the performance of WSNs in terms of energy consumption and lifetime of the sensors. However, introducing MS as a data carrier in the network increases the data delivery latency due to the slow speed of the MS. Reducing the data delivery latency is a critical issue for the MS based data gathering. Ren and Liang et al. [17] have shown that the volume of data collection

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is proportional to the data delivery latency. Time-sensitive applications such as forest fire detection, intrusion detection etc., demand time bound data delivery. Thus, improving data collection with minimum delivery latency is one of the most challenging issues in MS based data gathering.

Several data gathering algorithms are proposed to improve the data gathering time using mobile sink by shortening the tour length of the MS [9], [14], [4]. The data gathering time depends on the speed of the MS and the length of the tour. There are some studies in [18], [10] on the adaptive speed planning of MS along a predefined path. The MS adjust its speed to maximize network utility and minimize energy consumption. Data gathering problems for rechargeable sensor networks are formulated in [22], [?], [?] by jointly optimizing mobile data gathering and energy provisioning. Gao et. al. [6], [7] propose novel data collection scheme, where a MSis moving along a predefined path with a fixed speed. But, the MS gets limited communication time to collect data from its nearby sensor nodes, referred as sub-sinks. Besides, a metaheuristic (genetic) algorithm is proposed to find data forwarding paths to improve the network throughput as well as to conserve energy. Due to the non-deterministic nature of the algorithm, the solution may vary each time you run the algorithm on the same instance. Therefore, the existing data gathering techniques using MS find optimal tour of MS or find data forwarding paths to MS to improve the network performance, but there is a lack of studies on how to maximize data collection and minimize the data gathering time by controlling the data transmission schedule and speed of the MS. The data transmission schedule of the sub-sinks to the MS together with the speed schedule of the MS is called as data gathering schedule of MS. To further improve the total data gathering time, we consider the above two factors and find an optimal distribution of the data generated within sensors among the sub-sinks. In addition, our algorithms are based on the geometric characteristics of the problem and are deterministic. Their correctnesses are also shown.

An example of such type of network is illustrated in Figure 1. A mobile sink MS moves along a given path P. It collects pre-cached data from a few sensors which are directly reachable from the trajectory path P. Those directly reachable sensors are referred as sub-sinks $(ss_1, ss_2, ss_3, ss_4, ss_5)$. The MS may collect data from a sub-sink whenever the MS comes under the communication range of the sub-sink. Thus, the sub-sinks send their data to the MS directly. The MS may be within multiple sub-sinks' communication regions, and it receives data from any one of them at a time. Therefore, proper data transmission schedule of the sub-sinks are also required. The remaining sensors, which are not directly reachable to

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Fig. 1. Example of Path-constrained mobile sink based sensor network.

MS (e.g. s_1, s_2, \ldots, s_{11}) send their data to the MS through the sub-sinks using multi-hop communication. The major challenges are to find the optimal data transmission schedule of the sub-sinks to the MS for their data delivery and speed variation of MS along P. Moreover, since a sensor can send data to MS through multiple sub-sinks, finding the optimal data distribution among the sub-sinks is another challenging issue in MS based data gathering. Our major contributions in this article are summarized as follows.

- 1) Introduce a time-sensitive data gathering problem using a speed adjustable mobile sink to collect data from sensor networks.
- Linear programming formulation of the problem is discussed, where the initial data availabilities of the subsinks are given.
- 3) Plane sweep based data gathering algorithm is proposed to collect data from the sub-sinks by controlling the data transmission schedule of sub-sinks and speed of the MS.
- 4) It is further generalized, where data availabilities of the sub-sinks are optimized by controlling sensors' data distribution among the sub-sinks to improve the data gathering time.

The rest of the article is organized as follows. Section II discusses some related works on data gathering problems. Section III presents system model and problem statement. Background and related terminologies are defined in section IV. Section V describes a plane sweep algorithm for data gathering in minimum time, where data availabilities of the sub-sinks are given. Section VI presents a plane sweep algorithm to improve the data gathering time by optimizing the data availability values of the sub-sinks so that the total data gathering time can be reduced. Section VII measures the performance of our proposed solutions. Finally, section VIII concludes the article.

II. RELATED WORKS

Several data gathering algorithms have been proposed in the literature using mobile sink MS where the path of the MS is controllable or fixed. Depending on applications, different objectives are attained such as maximizing network lifetime, minimizing the total energy consumption, reducing total tour length, etc. In this section, we classify the literature based on whether the path of the MS is controllable or fixed.

Somasundara et. al. [19] claim that the sensors with higher variation in sensed data demand more frequent data collection than others. They proposed a solution based on optimizing travelling path of the MS that allows the MS to visit sensor with a different frequency to reduce buffer overflow. They prove that the decision version of the problem is NP-complete and two heuristic algorithms are proposed. The authors in [20] analyze various models of motion planning of mobile sink to solve mobile sink scheduling problem in order to minimize the data delivery latency of the network. He et. al. formulate the data gathering problem using MS as a travelling salesman problem (TSP) with neighborhoods [9]. They schedule MSthrough the deployed region to improve the tour length of the MS and consider multi-rate wireless communication for data transmission. In [14], a periodic data gathering protocol is proposed for a disconnected sensor network. The MStraverses the entire sensor network, polls sensors and gathers sensed data from sensors. It improves the scalability issue of large-scale sensor networks. Sayyed et al. in [18] investigate the utility of speed control mobile sink for collecting data in WSN. Single-hop clustering technique is used to increase the data collection rate as well as to decrease the data collection latency.

To overcome the delay due to the slow speed of the MS, a subset of sensors are selected as rendezvous nodes. These nodes are used to buffer the data temporarily from the nearby sensors. When the MS visits these rendezvous nodes, then they transfer their data to the mobile sink. In [1], sensors are grouped into single hop clusters, and the mobile sink visits the centroids of these clusters. If the tour length of the set of centroids is greater than a given upper bound, then some of the clusters are removed until the tour length is less than the upper bound. In [2], a shortest path tree rooted at the initial position of the mobile sink is built, and then a sensor node having sufficient energy as well as many nearby sensors within its vicinity is chosen as the next rendezvous node. In this way, a set of rendezvous nodes are selected and then a travelling salesman tour is obtained over the selected rendezvous nodes. In [11], k-means clustering with a weight function is used for finding the rendezvous points and an efficient tour among the rendezvous points is determined for the MS. In addition, an efficient data gathering scheme is also proposed to reduce the total packet drop. In [21], rendezvous nodes are selected using set covering problem. The MS tour is scheduled to pass through those rendezvous points. They introduce novel rendezvous node rotation scheme for fair utilization of all the nodes. Konstantopoulos et. al. in [12] use multiple mobile

sinks to ensure timely delivery of data to the base station. Mobile sinks visit only a subset of rendezvous points while the remaining sensors forward their data to the rendezvous points through multi-hop communication. The proposed approach increases network lifetime by finding tour passing through energy-rich zones as well as through regions where energy consumption is high.

In some scenarios, the trajectory of the MS is predefined to a fixed path. Efficient data collection algorithms are proposed to improve network performance. In [6], [7], data gathering algorithms are proposed for such cases to improve network performance. Data forwarding paths from the sensors to the sub-sinks are determined to maximize the data collection and balance the energy consumption. Huang et. al. in [10] consider a scenario where a label of importance is assigned to each sensing region. A path-constrained ground vehicle with adaptive speed is used to collect data from the sensing field. Although the approach tries to improve the data collection throughput, their speed control algorithms are reactive due to the adaptive nature of speed learning characteristics of the MS. Besides, these algorithms don't have any specific solution for controlling or optimizing the speed of the MS to improve the data collection rate and minimize delay. In article [?], a deterministic algorithm is proposed for maximization of data collection using fixed speed mobile sink. However, it may not provide quality data collection due to the mismatch between the data available to the gateways and the data communication time between the gateways and MS. Maximizing the data collection throughput in rechargeable sensor networks is addressed in [15]. Zhang et. al. [22] maximize data collection while maintaining the fairness of the network in rechargeable sensor networks. In [5], [13], data gathering protocols are proposed from path-constrained mobile sensors. The major drawback of the MS based system is its slow speed, which causes long data gathering delay. Since sensors have limited memory, it causes buffer overflow in the sensors. To avoid buffer overflow, multiple mobile sinks are deployed and they periodically collect data from the mobile sensors and deliver the collected data to the base station.

It can be noted that several data gathering techniques have been proposed which focus on reducing the data gathering time of the mobile sink. The existing literature on path constrained mobile sink mostly consider efficient data forwarding mechanism from the sensors to the mobile sink through the subsinks to improve the network performances. But, no existing works consider controlling the data transmission schedule of the sub-sinks to the MS along with the speed of the MS and the sensor's data distribution among sub-sinks to improve the total data collection and the total data gathering time of the mobile sink.

III. SYSTEM MODEL AND PROBLEM FORMULATION

We consider a wireless sensor network (WSN) which consists of a set of sensors $N = \{s_1, s_2, \ldots, s_n\}$. Sensor s_i generates/senses $DG(s_i)$ amount of data from its environment. The communication topology of the network is modelled as an undirected graph G(N, E). The communication regions of

the sensors are modelled as disks. There is a mobile sink MS moving on a given path P. We assume that the path P is approximated as piecewise straight line segments. The MS can move with a given maximum speed value V to collect data from the sub-sinks. However, the MS can change its speed depending upon the data availabilities of the sub-sinks. The MS can collect data from sensors whose communication disks intersect the path P. Based on the relative position of the sensors with respect to P, sensors are divided into two groups, sub-sinks and far-away sensors. Sensors which can directly communicate with MS on P are referred as *sub-sinks* and rest of the sensors are referred as *far-away* sensors. The far-away sensors send their data to MS through the sub-sinks. Let $SS = \{ss_1, ss_2, \ldots, ss_m\}$ represent a set of sub-sinks which is a subset of N.

Furthermore, we also assume that the MS and the sensors have sufficient energy and memory to collect and store all the sensed/relayed data temporarily. The data delivery capacity of a sub-sink is the amount of data that can be delivered by the sub-sink to the MS. The data delivery capacity of a sub-sink ss_i depends on the time t^i the MS allocates to ss_i for its data delivery within the communication region of ss_i and the data transmission rate dtr. We assume that the MS can receive data from one sub-sink at a time. We also assume that there is no data aggregation in the network. Then, our problems are stated as follows.

Problem 1: Let the data availabilities of the sub-sinks be $DA = \{DA(ss_1), DA(ss_2), \dots, DA(ss_m)\}$. Our objective is to find data transmission schedule of the sub-sinks to the MS and a speed-schedule of the MS through P such that the MS can collect complete data from all the sub-sinks in minimum time.

Our second problem generalizes the previous one, where data gathering time is further improved by optimizing the data availabilities of the sub-sinks.

Problem 2: Find an optimal data availabilities of the subsinks $DA = \{DA(ss_1), DA(ss_2), \ldots, DA(ss_m)\}$ by distributing the sensors' data among the sub-sinks along with their data transmission schedule to the MS and the speedschedule of the MS through P such that the MS can collect complete data from all the sub-sinks in minimum time.

IV. BACKGROUND AND TERMINOLOGIES

The far-away sensors send their data to the MS through the sub-sinks. A sub-sink generates its data and receives data from other sensors and store them temporarily in its local buffer. This buffered data is delivered by the sub-sink to the MS when it passes through the sub-sink's communication region. We refer this buffered data as *data availability* of the sub-sink.

Since the maximum speed V of the MS is given, a naive approach for the MS is to move at this maximum speed V on P and visit all the sub-sinks and collect their data. But it may not collect complete data from all the sub-sinks. However, if the speed of the MS can be varied according to the data availabilities of the sub-sinks, then it may improve the amount of data collection.

For instance, the MS should move at slow speed within the communication range of a sub-sink, which has more



Fig. 2. Speed-schedule of mobile sink in sensor network

data, whereas it should move at a faster speed within the communication range of a sub-sink which has less or no data. Furthermore, the MS should move with its maximum speed of V, when it is not under the communication range of any subsink or the sub-sinks do not have data to deliver. Determining the speed of the MS at different position on P is referred as speed-schedule of MS. Note that the speed of the MScan vary between 0 to V. It may happen that the MS is within multiple sub-sinks communication regions then one of the sub-sinks can transmit data to the MS. Therefore, proper time sharing among the sub-sinks is also required. We refer it as data transmission schedule of the sub-sinks. The data transmission schedule of the sub-sinks to the MS together with the speed schedule of the MS is called as data gathering schedule of MS. Our objectives are to find optimal data gathering schedule of the MS through the communication regions of the sub-sinks along the path P to collect complete data from the sub-sinks in minimum time.

A possible speed-schedule for MS is shown in Figure 2. Figure 2(a) shows the path P of the MS with dashed line and circles denote the communication disks of the sub-sinks. Let the MS start from S and end at E while travelling through the path P. Figure 2(b) shows the speed-schedule of the mobile-sink at different position on P. It shows that the speed of MS is slow within the communication disks of the sub-sinks whereas it runs with its maximum speed V outside the communication disks.

We introduce some terminologies to describe our algorithm, which are as follows.

Definition 1. Start-point (p_i^s) : It is a first point on P from which a sub-sink ss_i can communicate or start delivering data to the MS.

Definition 2. End-point (p_i^e) : It is a last point on P after which a sub-sink ss_i cannot communicate or ends delivering data to the MS.

Definition 3. Data availability $(DA(ss_i))$: It is the amount of data available at a sub-sink ss_i .

Definition 4. Data delivery time $(DT(ss_i))$: It is the minimum time requirement to transmit the data available at a sub-sink ss_i to the MS.

Data delivery time is determined using $DT(ss_i) = \frac{DA(ss_i)}{dtr}$



Fig. 3. Start-point and end-point of sub-sinks on path P

formula, where dtr denotes the data transmission rate between ss_i and MS.

V. DATA GATHERING IN MINIMUM TIME (DATA AVAILABILITY OF SUB-SINKS ARE KNOWN APRIORI)

In this section, we first discuss linear programming problem (LPP) formulation of the proposed problem, thereafter we discuss a plane sweep based algorithm. The mobile sink MS travels through the path P and collects complete data from all the sub-sinks. The data availability values of the sub-sinks are given. The MS receives data from one sub-sink at a time. The objective is to collect the complete data from all the sub-sinks in minimum time. We control the *data gathering schedule* of the MS. In other words, the time allocation of the MS to the sub-sinks and the time spent by the MS within their communication regions are determined based on their data availability values to minimize the data gathering process.

A. LPP Formulation

The ordering of the start-points and end-points of the subsinks partition the path P into disjoint segments/intervals. An example of partitioning the path P into segments is shown in Figure 3. In Figure 3(a), a set of sub-sinks $SS = \{ss_1, ss_2...ss_5\}$ and their start-points and end-points are shown on the path P. The ordering of the start-points and end-points of the sub-sinks partition the path P into disjoint segments, which are shown in Figure 3(b). Zero or more subsinks are reachable to the MS from a particular segment. The idea of the solution is that the data gathering time within each segment is shared properly among the sub-sinks such that the MS can collect complete data from all the sub-sinks through the segments and total data gathering time from the starting position S to the ending position E is minimum. Also, the MS maintains the maximum speed limit constraint.

The start-points and end-points of the sub-sinks partition the path P into disjoint segments/intervals. The m sub-sinks have 2m end-points. This will partition the path P into at most 2m + 1 disjoint segments $\{I_1, I_2, \ldots, I_{2m+1}\}$. For each segment, we use a set of variables for the set of sub-sinks reachable from the segment. Within a particular segment I_j , the set of sub-sinks reachable to the MS remains unchanged. Let $SS(I_j)$ denote the sub-sinks in SS reachable to the MSwithin the segment I_j . Let t_j^i denote the time allocated to sub-sink $ss_i \in SS(I_j)$ for transferring its data to the MS on the segment I_j . If a segment I_j is not reachable to any sub-sink, then we assume that it is reachable from a virtual sub-sink ss_0 which has no data, i.e. $DA(ss_0) = 0$, and the time the MS spends to cross the segment I_j is denoted by $T(I_j) = t_j^0 \ge \frac{|I_j|}{V}$. Similarly, if from segment I_j two subsinks ss_i and ss_k are reachable, i.e. $SS(I_j) = \{ss_i, ss_k\}$, then there are two variables t_j^i and t_j^k corresponding to two sub-sinks for the segment I_j . Each variable value denotes the amount of time allocated to the corresponding sub-sink for data delivery when the MS travels through the segment I_j .

There are two types of constraints (i) time spent on each segment I_j by the MS is at least the travelling time $\frac{|I_j|}{V}$, and (ii) total time $t^i = \sum_{j=1}^{2m+1} t_j^i : ss_i \in SS(I_j)$, allocated by the MS to a sub-sink ss_i for its data delivery, must be greater than or equal to the sub-sink's data delivery time $DT(ss_i)$. The LPP formulation of the said problem is shown in Equation 1.

$$\begin{aligned} \text{Minimize} &: \sum_{j=1}^{2m+1} \sum_{i:ss_i \in SS(I_j)} t_j^i \\ \text{Subject to} &: \sum_{i:ss_i \in SS(I_j)} t_j^i \geq \frac{|I_j|}{V}, \quad j = 1 \dots (2m+1) \\ &\sum_{j:ss_i \in SS(I_j)} t_j^i \geq DT(ss_i), \quad i = 1 \dots m \\ &t_j^i \geq 0, \quad i = 0 \dots m, \quad j = 1 \dots (2m+1) \end{aligned}$$

After solving the LPP in Equation 1, t_j^i , $i = 0 \dots m, j = 1 \dots (2m+1)$ are known, which denote the data transmission schedule of the sub-sinks. The lengths of the segments I_i , $i = 1 \dots (2m+1)$ are already derived from the start-points and end-points. Hence, the speed of the MS at different segments can be determined easily. The following subsection discusses a plane sweep based algorithm for the problem.

B. Plane Sweep Algorithm

The mobile sink MS moves through the path P. When the MS is within the multiple sub-sinks' communication range, then the MS receives data from only one of them by prioritizing them according to their end-points positions on P. The sub-sink whose end-point appears first on P has higher priority than that sub-sink whose end-point appears later. Let $PR(ss_i)$ denote the priority of a sub-sink ss_i .

In the plane sweep algorithm, it is simulated by moving a sweep line through the path P. We consider a horizontal data gathering path P for the MS and a virtual vertical line perpendicular to P, called *sweep line* moves (sweeps) through the path P from S to E. While sweeping the sweep line intersects the sub-sinks' communication disks. We have defined two types of events : start-point event and end-point event for every sub-sink. Start-points and end-points of the sub-sinks are stored in an event queue Q according to their appearance on P from left to right. At a particular position of the sweep line on P, we maintain a list of sub-sinks in a *status line* data structure L. The sub-sinks whose communication disks intersect the sweep line on P are in L. At a particular position on P, if multiple sub-sinks' communication disks intersect the sweep line on P and they have data, then a subsink ss_i in L with maximum priority gets the preference to deliver data to MS.

Initially, all the start-points and end-points of the subsinks are added to the event queue Q. We are calling three methods to perform different operations on the event queue Q. InsertInQ() method is used for inserting an event, RemoveFromQ() method removes the leftmost event on P, and PeekFromQ() method retrieves the leftmost event but does not remove it from the queue. Similarly, three methods InsertInL(), RemoveFromL(), and PeekFromL() areused to perform three different operations on the status line data structure L. Events are processed one by one from the event queue Q, as the sweep line moves through the path P. The top event is removed from Q and is referred as current event CE. A sub-sink ss_i is inserted into L, whenever the sweep line processes its start-point p_i^s . If the sweep line is processing an end-point p_i^e of sub-sink ss_i and the complete data of ss_i is not yet delivered, then the MS waits at the end-point p_i^e and receives the remaining data from ss_i . Subsequently, the sub-sink ss_i is removed from L. Thereafter, the next event point NE is picked from the event queue Q. Travel time TT of the MS between current event CEand the next event NE is determined assuming that the MSmoves with its maximum speed V in between the two events. Thereafter, maximum priority sub-sink ss_j is picked from L. If the data transmission time $DT(ss_i)$ of the sub-sink ss_i is $\leq TT$, then the sub-sink ss_i completes data delivery to the MS between the two events. The sub-sink ss_i is removed from L. Subsequently, the next highest priority sub-sink in L is picked for data delivery. This process continues until the sweep line reaches another event point or the data delivery process is completed. If there is no sub-sink in L having data to deliver then the MS moves with its maximum speed V. The detailed algorithm is presented in Algorithm 1.

In Figure 3(a), the MS starts its journey from S with speed V. As it reaches p_1^s , then the sub-sink ss_1 is inserted into L. Thereafter, MS starts receiving data form ss_1 until it reaches p_2^s . If the data delivery of ss_1 is not over, then there are two sub-sinks ss_1 , ss_2 reachable to MS within segment $[p_2^sp_1^e]$. As the end-point p_1^e appears before p_2^e , therefore, according to our algorithm, sub-sink ss_1 gets the privilege to deliver its remaining data to MS within the segment $[p_2^sp_1^e]$. If the data delivery of ss_1 is still not over within $\frac{|p_1^*p_1^e|}{V}$ time, then the MS waits at point p_1^e for the remaining data delivery time for the duration of $DT(ss_1) - \frac{|p_1^sp_1^e|}{V}$ time. Otherwise, the MS starts receiving data from ss_2 after crossing the start-point p_2^s and allocating $DT(ss_1)$ time to ss_1 . In this way, the MS either moves with its maximum speed or waits at the end-points of the sub-sinks until it reaches the end of the path E.

Corollary 1. Data gathering sub-paths of the mobile sink MS on P from a sub-sink ss_i is confined within $[p_i^s, p_i^e]$ for $i \in \{1 \dots m\}$.

Theorem 1. If the mobile sink MS follows the Algorithm 1 for data gathering, then it receives complete data from all the sub-sinks.

Algorithm 1: Plane sweep algorithm for data gathering using MS

Data: Location(ss_i) and $DA(ss_i) \forall ss_i \in SS, P, V, dtr$ **Result:** Data Transmission Schedule of the sub-sinks, and Speed Schedule of MS $\forall ss_i \in \mathbb{SS}$: Compute start-point (p_i^s) and end-point (p_i^e) with respect to P; $Q = \emptyset, m = |\mathbb{SS}|;$ /* Initialize event queue Q with start-points and end-points */ for i = 1 to m do InsertInQ(p_i^s); InsertInQ(p_i^e); $DT(ss_i) = rac{DA(ss_i)}{dtr};$ /* Data delivery time of ss_i */ end $L = \emptyset;$ /* Initialize status line L*/ The MS moves with its maximum speed V from S to the next end-point event, or until it reaches end of the path E; while $Q \neq \emptyset$ do CE = RemoveFromQ();if $CE = p_i^s$ then $InsertInL(ss_i)$; else if $CE = p_i^e \wedge DT(ss_i) > 0$ then MS stops and receives remaining data of ss_i ; $DT(ss_i) = 0$; RemoveFromL (ss_i) ; /* If $L \neq \emptyset$ then select a sub-sink ss_i with maximum priority from L and MS starts receiving data from ss_i */ NE = PeekFromQ(); /* next event */ $TT = \frac{dist(CE, NE)}{V}$; /* travel time between CE and NE*/ $ss_i = PeekFromL();$ while $L \neq \emptyset \land DT(ss_i) \leq TT$ do MS moves with speed V and receives data from ss_i for $DT(ss_i)$ time; $TT = TT - DT(ss_j) ;$ $DT(ss_j) = 0$; $RemoveFromQ(p_i^e)$; $RemoveFromL(ss_i)$; $ss_i = PeekFromL();$ end if $L \neq \emptyset \land DT(ss_j) > TT$ then $DT(ss_i) = DT(ss_i) - TT$; MS moves with speed V and continue receiving data from ss_i for TT time ; else MS moves with speed V without receiving any data to next event for TT time ; end

Proof. Algorithm 1 selects the highest priority sub-sink in L for data delivery to the MS. A sub-sink $ss_i \in SS$ is removed from L only when the MS finishes receiving its data by allocating $DT(ss_i)$ time to ss_i . The time allocation may be continuous or discontinuous. A sub-sinks ss_i is inserted to L whenever the MS crosses p_i^s . Since all the star-points and endpoints of the sub-sinks are in Q and are processed. Therefore, all the sub-sinks get a chance to be in L. Once the algorithm ends then the event queue Q and the list L become empty. Therefore, all the sub-sinks must have delivered their complete data to the MS.

Theorem 2. The mobile sink MS completes the data gathering process in minimum time by following Algorithm 1.

Proof. Assume for the sake of contradiction that the MS does not complete the data gathering process in minimum time. According to our algorithm, the MS moves with its maximum speed V throughout the path except at some end-points. So, there is an extra delay at some end-points. Extra delay for receiving data from a sub-sink ss_i is possible only when the MS waits at p_i^e , but for some sub-path of $[p_i^s, p_i^e]$, the MS moves without receiving data from any sub-sink or receives data from a sub-sink ss_j , whose end-point p_j^e appears after p_i^e . This is because the sub-sinks, whose end-points appear after p_i^e can deliver data beyond $[p_i^s, p_i^e]$, and may overall reduce the waiting time at p_i^e .

According to Algorithm 1, once the MS enters $[p_i^s, p_i^e]$, it either receives data from ss_i , or any other sub-sink ss_j such that $PR(ss_j) \ge PR(ss_i)$ in L. This implies p_j^e appears before p_i^e . Therefore, there is no sub-path within $[p_i^s, p_i^e]$ where the MS moves/waits without receiving data from any subsink $ss_j \in L$, where $PR(ss_j) \ge PR(ss_i)$ and waits at p_i^e . Hence, the MS does not make extra delay at any end-point and completes the data gathering process in minimum time. \Box

Theorem 3. *Time complexity of the plane sweep algorithm 1 is* $O(m \log m)$.

Proof. Throughout the algorithm, an event point (startpoint/end-point) of a sub-sink is inserted once and removed once in the event queue Q, and in total 2m event points are processed. The events are processed from event queue Qusing a heap data structure. Inserting and then removing the event points require $O(m \log m)$ time. During the processing of an event, some basic operations on the status line data structure L are performed. In the worst case, m sub-sinks are simultaneously in L. Therefore, the time needed to perform an insert or delete operation on the status line is $O(\log m)$ and the peek operation takes O(1) time.

The plane sweep algorithm processes 2m event points for m sub-sinks. In total m insert and m delete operations, and at most 2m peek operations are performed on the status line data structure L, and each such operation takes at most $O(\log m)$ time. Hence, it follows that the total time processing all the events is $O(m \log m)$.

VI. IMPROVING THE DATA GATHERING TIME BY Optimizing The Data Availabilities of the Sub-Sinks

The solution in the previous section finds a *data gathering* schedule of the MS, where the data availability values of the sub-sinks are given. This section generalizes the problem, where data availabilities of the sub-sinks are determined to improve the data gathering time. Proper distribution of the sensors' data among the sub-sinks is carried out to improve the data gathering time. Determining an optimal data distribution among the sub-sinks is another challenging issue in WSN. The data availability values of the sub-sinks are determined using a plane sweep algorithm for the given sensor network. After determining the optimal data availability values of the subsinks, we consider the values as data delivery capacity of the sub-sinks and the sensors' data are pushed to those sub-sinks using network flow algorithm. Thereafter, Algorithm 1 is used to complete the data gathering process in minimum time. In summary, this section discusses the solution for the Problem 2, where our objective is to distribute the sensors' data among the sub-sinks properly so that the MS can collect complete data from all the sub-sinks in minimum time.

A. Determining Data Availabilities of the Sub-Sinks Using Plane Sweep Algorithm

In this subsection, we determine the data availability values of the sub-sinks for a given network topology. We assume that the data generated on the sensors are known, which are denoted as $DG(s_i) : i = 1 : n$. Using a plane sweep algorithm, we determine the data availability values of the sub-sinks $DA(ss_i) : i = 1 : m$. Initially, the sensor network is partitioned into connected components $C = \{c_1, c_2, \ldots c_k\}$ based on its communication topology G. The idea of this algorithm is that the data generated in a component is distributed among its corresponding sub-sinks so that the MS can collect complete data from the component through its sub-sinks in minimum time. The MS moves with its maximum speed V through P, except at a few end-points.

For individual connected component, the total data generated by the sensors in the corresponding component is determined. Let $\{DG(c_1), DG(c_2), \ldots DG(c_k)\}$ denote the data generated in the components. The data availabilities of the sub-sinks are initialized to zero : $DA(ss_1) = 0, DA(ss_2) =$ $0, \ldots DA(ss_m) = 0$. The start-points and end-points of the sub-sinks are determined. The sub-sinks are labelled with their corresponding component identity. Let $C(ss_i)$ denote the component identity of a sub-sink ss_i . The *last sub-sink* of a component c_i denoted by $LSS(c_i)$ is a sub-sink, whose endpoint appears last on P among all the sub-sinks in c_i . For each component c_i , identify its last sub-sink $LSS(c_i)$. The start-points and end-points of the sub-sinks are stored in an event queue Q according to their order on the path P. The status line data structure L is initialized to \emptyset .

A virtual perpendicular sweep line moves through the path P and process the events one after another from the event queue. At a particular position on the path P of the sweep line, it keeps track of all the sub-sinks in a status line L,

whose communication disks intersect the sweep line on the path P. The priority of a sub-sink ss_i in L is based on the two parameters : its corresponding component's last sub-sink's end-point position, i.e. end-point of $LSS(ss_i)$, and its startpoint p_i^s on P. If two sub-sinks ss_i and ss_j belong to same component, i.e. $C(ss_i) = C(ss_j)$, then the sub-sink whose start-point appears first on P, has higher priority than the other sub-sink. If the two sub-sinks belong to different components, i.e. $C(ss_i) \neq C(ss_j)$ and the end-point of $LSS(C(ss_i))$ appears before the end-point of $LSS(C(ss_j))$ on P, then $PR(ss_i) > PR(ss_i)$.

The top event is removed from the queue Q and is referred as the current event CE. If CE is a start-point of ss_i , then ss_i is inserted into L. If CE is an end-point of sub-sink ss_i and it is the last sub-sink of its corresponding component c_j and the component has data $(DA(c_j) > 0)$ then the data availability of ss_i is increased by $DA(c_j)$. Subsequently, the sub-sink ss_i is removed from L. Thereafter, the next event point NEis picked from the event queue Q. Travel time TT of the MS between current event CE and the next event NE is determined assuming that the MS moves with its maximum speed V in between the two events.

Next, the maximum priority sub-sink ss_i is picked from L. Let $C(ss_i)$ denote the component of sub-sink ss_i . If the remaining data availability of the component $C(ss_i)$, which is $DA(C(ss_i)) \leq TT * dtr$ (data transmission capacity of ss_i) between the two event points), then data availability of ss_i is increased by $DA(C(ss_j))$. The sub-sink ss_j is removed from L. The remaining travel time between the two events CE and NE of the MS is updated accordingly. This process continues until the remaining travel time by the MS is exhausted and subsequently process the next event. In other words, if data transfer from a component c_i is over before the sweep line reaches the end-point of its corresponding last sub-sink $LSS(c_i)$, then all the sub-sinks in c_i are removed from L. This process continues until the sweep line reaches the next event point or the data delivery process is completed. The detailed algorithm for finding data availabilities of the subsinks is shown in Algorithm 2.

Theorem 4. *Time complexity of the plane sweep algorithm* 2 *is* $O(n + e + m \log m)$ *, where* n *and* e *denote the number of sensors and number of links in the communication graph* G*.*

Proof. Depth first search is used for partitioning the network into components which can be performed in O(n + e) time. Computing total data generated for each component can be performed in O(n) time. Finding the start-points and endpoints of the sub-sinks can be done in O(m) time. Identifying the last sub-sink for each component can be done in O(n) time. The time complexity analysis for the rest of the algorithm is similar to Algorithm 1. The plane sweep algorithm processes 2m event points. The events are inserted and then removed from the event queue, which takes overall $O(m \log m)$ time. During the processing of an event, some basic operations on the status line data structure are performed. There are at most m sub-sinks intersecting the sweep line on P at any time and therefore, the time needed to perform an insert or delete

Algorithm 2: Plane sweep algorithm for computing data availabilities of the sub-sinks **Data:** Communication topology G, Data generated by the sensors $\{DG(s_1), DG(s_2), \dots DG(s_n)\}, SS, P,$ V, dtrResult: Data availabilities of the sub-sinks $DA = \{DA(ss_1), DA(ss_2), \dots DA(ss_m)\}$ Partition the sensor network into components C = $\{c_1, c_2, \ldots c_k\}$ based on its communication topology; $\forall c_i \in C$: Compute total data generated $DG(c_i)$ by adding all sensors data in the component ; $\forall c_i \in C : DA(c_i) = DG(c_i) ;$ $\forall ss_i \in \mathbb{SS} : DA(ss_i) = 0 ;$ $\forall ss_i \in \mathbb{SS}$: Find start-point (p_i^s) , end-point (p_i^e) and component-id $C(ss_i)$; $\forall c_i \in C$: Find last sub-sink $LSS(c_i)$; $/\star$ Initialize event queue Q with start-point and end-point of the sub-sinks */ $Q = \emptyset, m = |\mathbb{SS}|;$ for i = 1 to m do InsertInQ(p_i^s); InsertInQ(p_i^e); end $L = \emptyset$; /* Initialize status line L */ while $Q \neq \emptyset$ do CE = RemoveFromQ();if $CE = p_i^s$ then InsertInL(ss_i) ; else if $CE = p_i^e$ then if $ss_i \in c_i \wedge ss_i = LSS(c_i) \wedge DA(c_i) > 0$ then $DA(ss_i) = DA(ss_i) + DA(c_i);$ $DA(c_i) = 0$; RemoveFromL (ss_i) ; NE = PeekFromQ();Let dist(CE,NE) = Distance between events CE and NE: $TT = \frac{dist(CE, NE)}{V}$; /* Travel time between CE and NE*/ $ss_i = PeekFromL()$; /* Peek maximum priority sub-sink in L*/ while $L \neq \emptyset \land DA(C(ss_i)) \leq TT * dtr$ do $DA(ss_j) = DA(ss_j) + DA(C(ss_j));$ $DTT = \frac{DA(C(ss_j))}{dtr}$; /* Data transfer time */ TT = TT - DTT ; $DA(C(ss_i)) = 0$; $RemoveFromQ(p_i^e)$; $RemoveFromL(ss_i)$; $ss_i = PeekFromL();$ end if $L \neq \emptyset \land DA(C(ss_i)) > TT * dtr$ then $DA(ss_j) = DA(ss_j) + TT * dtr ;$ $DA(C(ss_i)) = DA(C(ss_i)) - TT * dtr;$ end



Fig. 4. Connected components corresponding to the sensors network

operation on status line is $O(\log m)$ and peek operation can be performed in O(1) time. Through the algorithm, a subsink is inserted once and removed once from the status line data structure. Therefore, the total time spent on accessing the sweep line status data structure is $O(m \log m)$. Hence, it follows that the total time spent processing all the events is $O(m \log m)$. Therefore, the total time complexity of the algorithm is $O(n + e + m \log m)$

B. Distributing Data Among the Sub-Sinks Using Network Flow Algorithm

Once the data availability values of the sub-sinks $DA(ss_1), DA(ss_2) \dots DA(ss_m)$ are determined using Algorithm 2, this phase distributes the sensors' data among the sub-sinks. Data are pushed from the sensors to the sub-sinks based on their calculated data availability values. Sensors use the communication topology network to send data to the sub-sinks. Network flow algorithm is used for finding data flow from the sensors to the sub-sinks. Construction of network flow graph and determining the distribution of data from the sensors to the sub-sinks for a given communication topology is described with an example for the sensor network in Figure 1.

The connected components corresponding to the sensor network of Figure 1 are identified and labelled with c_1 , and c_2 in Figure 4. To determine the data distribution from the sensors to the sub-sinks, a network flow graph is constructed using the communication topology of the sensor network. Thereafter, the sensors' data are distributed among the sub-sinks based on the data availability values of the sub-sinks, the amount of data generated within the sensors, and the communication topology. The network flow graph corresponding to the communication topology in Figure 4 is shown in Figure 5. A virtual source vertex VS and a virtual sink vertex VK are added to the network topology. To maintain the cleanness of the figure, we



Fig. 5. Network flow graph corresponding to the sensors network; Link capacity : $(VS, s_i) = DG(s_i)$; $(VS, ss_i) = DG(ss_i)$; $(ss_i, VK) = DA(ss_i)$; other links capacities are ∞

have drawn four duplicate virtual source vertices, but actually they are a single vertex VS. The virtual source vertex is incident to the sensor nodes including the sub-sinks using virtual links. The capacities of these virtual links are set based on their data generation capacities. Therefore, the capacity of a link between VS and s_i is $DG(s_i)$. Similarly, the link capacity between VS and ss_i is $DG(ss_i)$ because, as these are data generation limits of the sensor s_i /sub-sink ss_i . The sub-sinks are incident to the virtual sink VK through virtual links. The capacity of a virtual link between a sub-sink ss_i and the virtual sink VK is set to $DA(ss_i)$, which is its data availability value determined in the previous phase. Other links represent the communication links among the sensors/sub-sinks, and their capacities are set to infinity because we assume that a sensor can forward the data generated within itself or received from its neighbors.

Thereafter, the network flow algorithm is used for finding the maximum data flow from the VS to VK. The flow value of the links denotes the data flow between the corresponding sensors/sub-sinks. Finally, data is delivered from a sub-sink to virtual sink VK. The flow value between a sub-sink and the virtual sink denotes the actual data delivery by the sub-sink to the MS.

C. Gathering Data Using Algorithm 1

In this subsection, we find an optimal data gathering schedule of the mobile sink (MS) to collect complete data from all the sub-sinks in minimum time. Once the data availabilities of the sub-sinks $DA(ss_1), DA(ss_2) \dots DA(ss_m)$ are determined, and data are pushed from the sensors to the sub-sinks, we use the Algorithm 1 of Section V to find the *data gathering* schedule of the MS. **Theorem 5.** If the data availabilities of the sub-sinks are determined using Algorithm 2 and MS follows the speed-schedule using Algorithm 1, then the mobile sink MS completes the data gathering process in minimum time.

Proof. The data availabilities of the sub-sinks are determined using Algorithm 2 such that the MS is able to receive complete data from a component while moving with its maximum speed V and if required waits only at the last sub-sink's endpoint. The data generated in the sensors are distributed among its sub-sinks based on the data availability values determined using Algorithm 2. According to Algorithm 1, while the MS is moving, it receives data from the highest priority sub-sink having data to deliver. Let the first sub-sink of a component c_i be a sub-sink $ss_j \in c_i$, whose start-point p_j^s appears first on P. Let $c_i^s = p_j^s$ denote the start-point of the first sub-sink of c_i . Similarly, c_i^e denotes the end-point of the sub-sink $LSS(c_i)$.

Algorithm 2 prioritizes the sub-sinks based on their components' last sub-sink's end-point positions and sub-sinks' startpoint positions. The sub-sink whose component's last subsink's end-point appears first on P, gets the highest preference for data delivery. If two sub-sinks are on the same component, then the sub-sink whose start-point appears first has a higher priority than the other. The MS receives data from a sub-sink in L, which has maximum priority and has data to deliver. If there is no data, then it is immediately removed from L.

Similar to the proof of Theorem 2, assume for the sake of contradiction that the MS does not complete the data gathering process in minimum time. It implies that there is a sub-path of $[c_i^s, c_i^e]$ for component c_i , and the sub-path is under the communication disk of a sub-sink $ss_k \in c_i$, where the MSmoves without receiving data from any sub-sink or receives data from a sub-sink ss_l , whose priority $PR(ss_l) < PR(ss_k)$ and the MS waits at c_i^e for receiving data from component c_i . The sub-sink ss_l may belong to (i) same component c_i as of ss_k , or (ii) in a different component c_j , i.e. $c_j \neq c_i$.

In case (i), where sub-sink $ss_l \in c_i$, the MS does not wait at c_i^e . This is because within the communication disk of ss_k , if the MS receives data from sub-sink $ss_l \in c_i$ with $PR(ss_l) < PR(ss_k)$, then all the sub-sinks in c_i with priority $\geq PR(ss_k)$ do not have data to deliver.

In case (ii), where sub-sink $ss_l \in c_j$ and $c_j \neq c_i$, based on the first sub-sink's start-point and last sub-sink's end-point positions of a component, two components c_i and c_j have three different types of overlaps as shown in Figure 6. All other types of overlaps are equivalent to one of them. We will show that extra delay at c_i^e does not hold for any of these three types of overlaps.

In Figure 6(a) type overlap, two components are disjoint. Hence, the MS does not receive data from $ss_l \in c_j$ within $[c_i^s, c_i^e]$ and make an extra delay at c_i^e .

In Figure 6(b) type overlap, the second component starts before the end of first component. In this case, the priority of any sub-sink in component c_i is higher than any sub-sink in component c_j . Hence, the MS receives data from $ss_l \in c_j$ within $[c_i^s, c_i^e]$ only when there is no data in ss_k . If there is no data in ss_k , then all data from c_i is already delivered to the MS and the MS does not wait at c_i^e .



Fig. 6. Overlaps between components

In Figure 6(c) type overlap, the priority of any sub-sink in component c_j is higher than any sub-sink in component c_i . So, $PR(ss_l)$ can not be less than $PR(ss_k)$.

Therefore, in both case (i) and case (ii) our assumption does not hold and hence the theorem is proved. \Box

VII. EXPERIMENT AND PERFORMANCE ANALYSIS

We evaluate the performance of our two proposed algorithms. We have used MATLAB for implementing our algorithms. In this section, we evaluate the performances of our proposed algorithms. We refer the algorithms for data gathering algorithm using speed controllable mobile-sink with known data availability (Algorithm 1) as VS-K-DA. VS-UK-DA refers to the case where data availabilities of the sub-sinks are unknown and optimized using Algorithm 2. Algorithm VS-UK-DA is combined with network flow algorithm for data distribution and with Algorithm 1 to find data gathering schedule. We compare the above two algorithms with a third algorithm FS-K-DA, where data availabilities of the sub-sinks are known apriori as in VS-K-DA and the mobile sink MS is moving with its maximum speed as in [7] for collecting data from the sub-sinks.

A. Simulation environment

During simulation, the number of sensor nodes is varying for 100, 120, 140 and 160. The communication range of sensors is set to 75m. Sensors deployment region is a rectangular area of size 1000m x 400m. The rectangular region is vertically partitioned into four sub-regions of length 250m each. Within each sub-region of length 250m, sensors are randomly deployed within a vertical strip of [75m : 150m]. This is done to ensure that the random communication topology forms at least four connected components and there are gaps between the consecutive components. In the simulation, the MS is moving along a horizontal path P at the centre of the region (y=200m). The maximum speed V of the MS is set to 2 m/s. The MScollects data from one sub-sink at a time, which is within the communication range. The data transfer rate between a sub-sink and the MS is set to 2 Kbps. We assume that the sensors generate data randomly between 0 to 10 packets, and each packet is of size 1Kb. The far-away sensors send their sensed data to the sub-sinks through multi-hop forwarding. Data availabilities of the sub-sinks (for known apriori case) of problem 1 is determined using shortest path routing, where the sensors forward their data to its closest (hop-count) sub-sink. Let e_r and e_t denote energy consumption for receiving and transmitting unit bit data. Let E_i represent the total energy consumption of a sensor s_i for receiving d_r^i bits, and transmitting d_t^i bits. Therefore, E_i can be written as :

$$E_{i} = (e_{r} * d_{r}^{i} + e_{t} * d_{t}^{i})$$
⁽²⁾

Total energy consumption of the network E_{total} is calculated as the summation of energy consumption for forwarding data from the sensors to the MS through their respective subsinks.

$$E_{total} = \sum_{i=1}^{n} E_i \tag{3}$$

Let $DD(ss_i)$ denote data delivered by a sub-sink ss_i to the MS. Hence, total energy consumption E_{total} includes energy consumption for delivering data from the sub-sinks to the MS, which is $\sum_{i=1}^{m} e_t * DD(ss_i)$. This is because the sub-sinks $SS \subseteq N$. Table I summarizes the simulation parameters.

TABLE I Simulation Parameters

Parameter	Value
Rectangular deployment area	$1000m \times 400m$
No. of sensors	100, 120, 140, 160
Maximum speed of MS	2 m/s
Communication range of sensor	75 m
Data transmission rate	2 Kbps
e_r	2 μ Joule/bit
e_t	3 μ Joule/bit

B. Performance analysis of the proposed algorithms

Figure 7 shows the total data collected by the mobile-sink with respect to the number of sensors. From the figure, it is obvious that the amount of data collection is proportional to the number of sensors. Data collection in **VS-K-DA** and **VS-UK-DA** are same because both the algorithms collect complete data from the network, whereas data collection in **FS-K-DA** is lesser than the two proposed algorithms. The difference between fixed speed and variable speed data gathering increases as the number of sensors increases. This is because, in **VS-K-DA** and **VS-UK-DA**, the complete data from the sub-sinks are collected by controlling the speed of the *MS*, whereas in **FS-K-DA**, the *MS* moves with its maximum speed, and the sub-sinks do not get enough time to deliver their data completely.

Figure 8 shows the data gathering time with respect to the number of sensors. It shows that the data gathering time increases proportionally to the number of sensors for the two proposed algorithms VS-K-DA and VS-UK-DA. But data gathering time of FS-K-DA is constant and it does not depend on the number of sensors. This is because in FS-K-DA the *MS* moves with its fixed maximum speed (2m/sec). Data gathering time in VS-UK-DA is lesser than VS-K-DA. The time difference between VS-K-DA and VS-UK-DA increases proportional to the number of sensors present in the network. Because in VS-UK-DA, sensors' data are forwarded to the sub-sinks to reduce the total data gathering



Fig. 7. Data collected (Kb) with respect to no of sensors

time. In algorithm **VS-UK-DA**, sometimes data are forwarded to the sub-sinks at a longer hop count distance. It increases the energy consumption of the network, which is reflected in Figure 12.



Fig. 8. Data gathering time (Sec) with respect to no of sensors

Figure 9 shows the average speed of the MS with respect to the number of sensors. For our two proposed algorithms, the average speed of the MS decreases as the number of sensors increases. This is because as the number of sensors increase, more data are forwarded to the sub-sinks, and it increases the data transmission time from the individual sub-sink to the MS. The average speed of **VS-UK-DA** is little higher than **VS-K-DA**.



Fig. 9. Average speed (m/Sec) of the mobile sink



Fig. 10. Idle time (Sec) of the mobile sink

Idle period of the MS denotes the time the MS moves without receiving data from any sub-sink while moving on the path P. Figure 10 shows the idle period of the MS. The idle period decreases as the number of sensors increases. This is because as the number of sensors increases, more sub-sinks are there and hence, the total data transfer time increases and the idle time decreases. Idle period of **VS-UK-DA** is comparatively lower than the other, and the difference increases as the number of sensors increases.

Throughput measures the amount of data collected by the MS per unit time. Figure 11 shows the throughput of the network with respect to the number of sensors. As the number of sensors increases, the number of sub-sinks and the total data collection by the MS are also increased and hence, improves the throughput of the network. From the result, it is observed that the throughput of **VS-UK-DA** is comparatively higher than the other.



Fig. 11. Throughput with respect to no of sensors

We evaluate the total energy consumption for forwarding data to the *MS*, but the energy consumption of the *MS* is not considered. Figure 12 shows the total energy consumption with respect to the number of sensors. As the number of sensors increases total data generated in the network increases proportionally and hence, total energy consumption increases proportionally. In both **VS-K-DA** and **FS-K-DA** data gathering algorithms, the data generated in the sensors are transferred to the sub-sinks through the shortest path. But, in algorithm **FS-K-DA**, complete data from the sub-sinks are not delivered to the *MS* and hence, energy consumption is little lesser



Fig. 12. Total Energy Consumption (m Joule) with respect to no of sensors

than VS-K-DA. Whereas both VS-K-DA and VS-UK-DA algorithms deliver complete data to the MS, but algorithm VS-UK-DA forwards data to the sub-sinks to optimize total gathering time. Hence, sometimes sensors' data are forwarded to sub-sinks which are at a longer distance, which increases the total energy consumption of VS-UK-DA.

Finally, we study the performance of the algorithms, by varying the maximum speed limit V of the MS and evaluate the total data gathering time of the MS. Figure 13 shows the total data gathering time for different speeds. As the maximum speed limit increases, the data gathering time also decreases. This is because as the speed increases, the idle period of the MS decreases proportionally. Also, the time difference between **VS-K-DA** and **VS-UK-DA** decreases proportionally. For fixed speed data gathering **FS-K-DA**, total data gathering time decreases linearly, which is reflected in the figure.



Fig. 13. Data gathered time (Sec) with respect to maximum speed of the MS

VIII. CONCLUSION

In this article, we have studied two problems for the maximum data gathering using a mobile sink (MS) for timesensitive applications. The MS can adjust its movement speed while moving along a given path in the network. However, the speed of the MS cannot go beyond a given maximum speed limit V. We have presented plane sweep based algorithms to find optimal data gathering schedule of the MS. In the first algorithm, the minimum time data gathering schedule of the mobile-sink is determined by controlling the data transmission schedule of the sub-sinks and speed of the MS, where the data availability values of the sub-sinks are known. The second algorithm improves the data gathering time and the throughput by optimizing the data availability values of the sub-sinks by controlling the data distribution from the sensors to the sub-sinks. It is observed from the experiment results that the data gathering time of Algorithm **VS-UK-DA** is better than the Algorithm **VS-K-DA**. But, energy consumption of **VS-UK-DA** is higher than **VS-K-DA** and **FS-K-DA**. The results also show that both **VS-K-DA** and **VS-UK-DA** have better data gathering capability and throughput than **FS-K-DA**. In future, we plan to find an optimal fixed speed of the MS to improve the total data collection process. In addition, we will find an optimal path for the MS to improve data collection for time-sensitive applications.

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