Novel Framework for Data Collection in Wireless Sensor Networks Using Flying Sensors

Mathur, Prateek; Nielsen, Rasmus Hjorth; Prasad, Neeli R.; Prasad, Ramjee

Published in:
2014 Eighth IEEE International Conference on Advanced Networks and Telecommunications Systems

DOI (link to publication from Publisher):
10.1109/ANTS.2014.7057237

Publication date:
2014

Document Version
Accepted author manuscript, peer reviewed version

Novel Framework for Data Collection in Wireless Sensor Networks Using Flying Sensors

Prateek Mathur*, Rasmus H. Nielsen†, Neeli R. Prasad*, Ramjee Prasad*
*Center for TeleInFrastruktur (CTIF), Department of Electronic Systems
Aalborg University, Aalborg 9220, Denmark
{in_pm,np,prasad}@es.aau.com
†Cisco Systems, San Jose, USA
{rhnielsen}@ieee.org

***Abstract*—This paper proposes a novel framework for data collection from a sensor network using flying sensor nodes. Efficient data communication within the network is a necessity as sensor nodes are usually energy constrained. The proposed framework utilizes the various entities forming the network for a different utility compared to their usual role in sensor networks. Use of flying sensor nodes is usually considered for conventional purpose of sensing and monitoring. Flying sensing nodes are usually utilized collectively in the form of an aerial sensor network, they are not expected to function as a data collection entity, as proposed in this framework. Similarly, cluster heads (CHs) are usually expected to transfer the aggregated data to an adjoining CH or to the base station (BS) directly. In the proposed framework the CH transfers data directly to the flying sensor node, averting the need for energy intensive multi-hop inter-cluster communication to relay information to the BS. The flying sensor node is referred as *sensor fly*. The limitations of a conventional sensor network deployed on ground surface, in respect to the near ground path loss, and communication hindrance due to undulating terrain are avoided in this framework. The proposed framework is therefore highly suitable for sensor network deployment in inhabitable harsh terrain. Fuzzy logic based inference of the clusters (referred as *cluster-hops*) that could be covered by the sensor fly, governed by the input parameters has been presented.**

***Keywords*—Miniature aerial vehicles, wireless sensor networks, compressed sensing, mobile nodes, clustering**

I. Introduction

Wireless sensor networks (WSNs) are energy constrained due to limited availability of battery resources on the sensor nodes. Data is often relayed within the network in a multi-hop manner from the source node to the base station (BS). Due to this, nodes relaying data for other source nodes are likely to drain out their battery much earlier compared to nodes not relaying significant traffic. This in turn influences the lifetime of the network [1], [2]. Two ways in which this could be addressed, broadly, include clustering of nodes, wherein the data is aggregated at the cluster head (CH) and only aggregated information is communicated to the BS. Alternatively, utilizing mobile nodes as mobile BS, data mules and mobile relays have also been proposed to help in reducing the total data communicated in a multi-hop manner by visiting certain nodes in the network, collecting data from collection points (nodes collecting data on behalf of some other nodes) or assisting nodes in relaying traffic [2], [3]. Apart from the aforesaid use of mobile nodes their other significant functionality in sensor networks is coverage improvement (sensing operations). Various types of actuation mechanisms to move the mobile nodes between two given locations have been proposed in the literature and include: wheels, springs and wings [4]. Flying sensing nodes in the form of miniature aerial vehicles (MAVs) capable of sensing a given area, aerially, have been discussed in the literature [6].

In this paper we propose a novel framework for data collection using flying sensor nodes in WSNs instead of their conventional utility to function as an active sensor. To the best of the authors' knowledge, no work has been undertaken in which use of such sensor MAVs as data collection entities (data mules) has been proposed. This framework is suited for applications wherein the BS is expected to be far from the deployment region (distance atleast greater than the communication range of CHs and sensor nodes) and transfer of data in a multi-hop manner could be infeasible, or consumes excessive amount of energy.

The related work relevant to the various prominent facets comprising this framework are discussed in Section II. The framework is discussed in Section III, and the fuzzy logic based inference of sensor fly's operational capacity has been presented in Section IV. The paper is concluded in Section V.

II. Related Work

Clustering of nodes to form a hierarchical network for efficient transfer of data to the BS has been discussed extensively in the literature. Several protocols for electing the CH have been stated with diverse parameters governing the election such as remaining energy of a node, location of a node in respect to other nodes and the adjoining clusters, as well as node importance in respect to amount of data transferred by it to the BS. Similarly, data aggregation at a CH could be based on different aggregation operations such as sum, maximum or average of the readings received from the nodes. The CH communicates the aggregated data to the next CH in the direction of the BS, or it communicates directly with the BS [5]. In our proposed framework, the CHs would not be required to communicate with adjoining CHs or the BS. A mobile BS could collect data visiting certain nodes / regions in the network. Similar is the role performed by the data mule. While a mobile relay could reposition itself in proximity to certain node(s) that are generating higher traffic and thereby

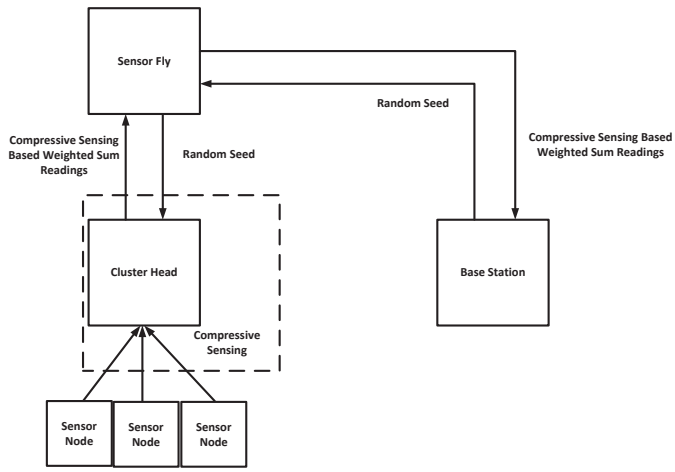

Fig. 1. Data collection - system model

assist them in multi-hop traffic relaying [3]. Mobile sensor nodes in the form of MAVs referred as *sensor fly* have been proposed by the authors in [6]. They are expected to perform a collective sensing function flying as a *swarm of nodes* for applications such as crowd surveillance and disaster recovery [7]. It is also stated that for these flying sensor nodes it is the actuation which consumes the maximum amount of energy as is the case for other types of mobile nodes [6]. The research focus has been on making the sensor MAV more intelligent in sensing operations, thereby increasing the possible applications addressable by them. In a deployment region, due to undulating terrain, nodes could be at different heights relative to each other and moreover subjected to path loss due to near ground communication [8]. Packet loss and additional communication cost would be incurred to overcome this constraint. This could be a major constraint especially for WSN applications in harsh terrain. Utilizing jumping sensor nodes to improve coverage by avoiding the near ground path loss due to foliage and compensate for undulating terrain has been presented in [9]. In the proposed framework, data collection would be carried out by the sensor fly aerially, and relative height differences between the nodes would not impact the communication. Generally, it is considered that the BS would be located at the periphery or at the center of the deployment region. This would be unrealistic for the applications in inhabitable harsh terrain. In the proposed framework the BS could be at a significant distance away from the deployment region.

The authors of [10] present the first design for compressive sampling based data gathering in WSNs as a good alternative for collecting the correlated data from WSNs. Compressed sensing with the network partitioned in cells with data gathering carried out by a cell head, and transferred to the next cell head merging the data and sending forward to the BS is presented in [11]. In the proposed framework the data would be collected by the sensor fly from the CHs directly, therefore energy saving is not just with compressive sensing implementation but also in avoidance of multi-hop data transmission that would have been necessitated to deliver data at BS.

III. Proposed Framework

The relevant work in regard to the various facets forming the framework has been discussed in the previous section. This section presents the system model and detailed description of the framework.

A. System Model

The data collection from the network through the proposed framework relies on the following entities: cluster head; compressive sensing; sensor fly; BS and sensor nodes. The system model detailing the operational relation between the various entities is elaborated in the Fig. 1. The various aspects comprising this system model have been discussed in following sub-sections.

B. Compressive Sensing

Compressive sampling theory allows recovery of a signal from a few random projections of the actual signal. The signal is however required to be sparse and compressible in a certain known domain. Data from sensor nodes fulfils this condition as there is a high correlation between the readings of sensor nodes deployed in a region. The difference between compressive sensing based data gathering, and conventional multi-hop gathering is shown in Fig. 2. The node S_1 multiplies its reading e_1 with a random coefficient ϕ_{i1}, S_2 does the same with its reading e_2 multiplying it with random coefficient ϕ_{i2} and so on towards the BS. In the random coefficient notation ϕ_{i1}, 'i' refers to the ith weighted round of data collection. This way the BS receives a few sets of weighted readings represented as [10]:

$$\sum_{j=1}^{N} \phi_{ij} e_j \tag{1}$$

The authors of the paper [11] extend this concept, instead of a node to node multi-hop transmission of the measurements, cell heads for partitioned cells carry out the multi-hop communication. The cell head computes the random coefficients for all the node readings and forms weighted sum sets by multiplying the random coefficients with the readings, summing them all together. The random coefficient is generated by the CH using random seed supplied by the BS through sensor fly. BS being aware of the random seed supplied to a given CH is able to reorder the reading of the individual nodes comprising that cluster. The readers are directed to papers [10], [12] for further information about the conditions for successful recovery of the signal from the weighted sums received as given in (1), and the relevant compressive sensing theory steps involved. Compressive sensing based weighted sum readings from CHs reduce the total data transfer requirement in comparison to a multi-hop stream as shown in Fig. 2, especially for data from all nodes in the network. It should be noted that instead of collecting compressed data (based on compressive sensing) from the CHs, sensor fly could also collect aggregated data (based on certain data aggregation function). However, the utility of using compressive sensing with aerial data collection with the sensor fly is that with a single round the BS is able to reorder the actual values of individual nodes, in comparison for aggregated data multiple rounds would be necessitated if individual sensor readings are to be collected at the BS.

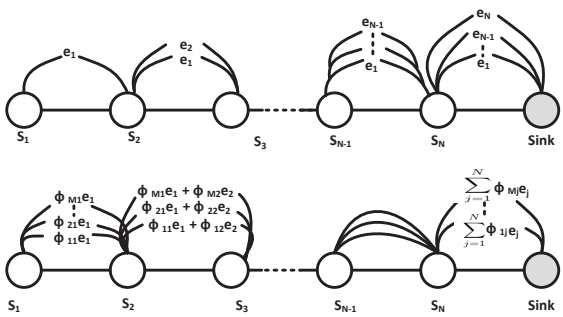

Fig. 2. Difference common data collection (top) and compressive data collection on a multi-hop route(bottom) [10]

C. Cluster Head

A cluster can be represented with a circle, with the CH at the center of that circle. Radius of this circle would then be represented as [13]:

$$(A/\pi k_{opt})^{\frac{1}{2}} \tag{2}$$

Here A represents the area of the deployment region and k_{opt} the optimal number of clusters that are expected in the deployment region. k_{opt} is dependent on the distance to BS, dimensions of the sensing region, amongst others as stated in [13]. In the proposed framework there would be a limit on communication hops permitted between the farthest node in the cluster to the CH, so as to maintain an appropriate cluster size. As this in turn influences the total number of clusters in the deployment region. This is necessitated, as the appropriate number of clusters would be equal to the number of cluster-hops that the sensor fly would be required to cover for collecting the data. The sensor fly would stop (hop) at individual clusters to collect data and this would be referred as *cluster-hops* from here on for ease of understanding, as shown in Fig. 3. The authors also state that the number of optimal clusters within the sensing region is inversely related with the distance to the BS from the sensing region. If the BS is located very far from the sensing region only one large cluster spanning across the whole sensing region would be feasible. This implies in a way that if the BS is located far from the sensing region the hierarchical structure of the network cannot be maintained. This imposed limitation of placing the BS close to the sensing region for having multiple clusters, could be unrealistic to implement for WSNs deployed in inaccessible harsh terrain. In the proposed framework, the data would be collected by the sensor fly and delivered to the BS, therefore the BS could be placed at a far distance from the sensing region (distance atleast greater than the communication range of CHs and sensor nodes) while maintaining the cluster based hierarchical structure. In the proposed framework the operational parameters of the sensor fly would also have to be taken into consideration for determining the optimal number of clusters in the sensing region.

Forest monitoring as an application utilizing the proposed framework is shown in Fig. 3. A three dimensional operational view with the sensor fly on the tree canopy above the cluster is shown in Fig. 4, and the view of the complete deployment region from top with optimal number of clusters (circled) for sensing region shown in Fig. 5. There is time division multiple access (TDMA) based scheduling for nodes to transfer their data to the CH. The CH would multiply the received reading from the node with a random coefficient using the random seed provided by the BS. The random coefficients are generated taking into account the node IDs. Subsequently, the CH would add all the values obtained to form a weighted sum of readings. Instead of transferring this weighted sum reading set to the next CH as in [11], in the proposed framework CH retains it. The CH repeats the process to generate a few more sets in a similar manner with the same readings received from the nodes, as per requirement of compressive sensing theory for successful reordering of data at the BS. Subsequently, merging these sets, the CH forms a master weighted sum reading set. This would be transferred to the sensor fly when it visits a given cluster.

With this approach the BS would receive the master weighted sum readings sets for all clusters from one round of the sensor fly. This way the multi-hop CH - CH communication to send each weighted sum reading set generated by the respective CHs is avoided. After delivering the data to the sensor fly the CH accepts the new readings from the nodes. The CH would repeat the process generating random coefficients

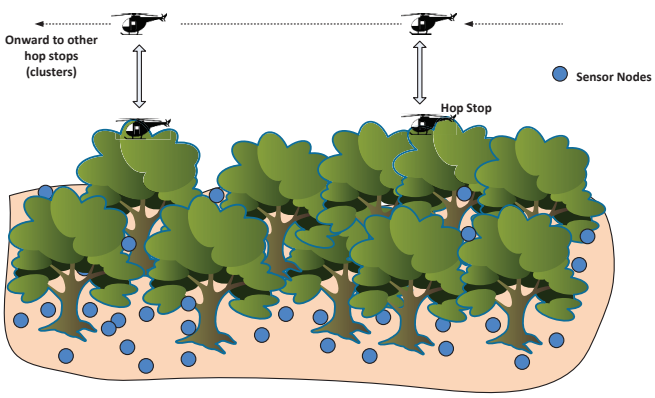

Fig. 3. Front view of three dimensional data gathering operation by sensor fly

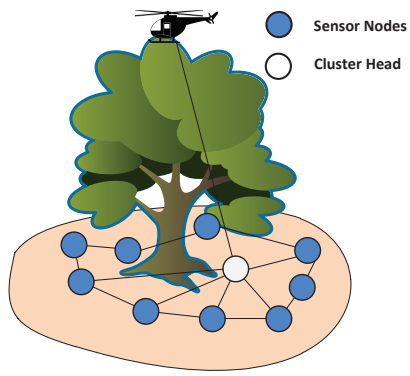

Fig. 4. Cluster-hop - (vertical landing on tree canopy) sensor fly collecting data from the CH

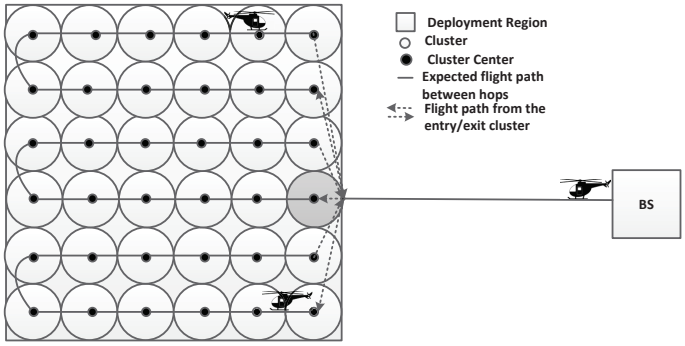

Fig. 5. Top view of data collection by sensor fly

using a new random seed issued by the BS. Specific network conditions under which this data collection framework is expected to operate are as follows:

1) The framework can only be utilized for a delay tolerant application.
2) All nodes have unique IDs and CHs have access to the IDs of the nodes in their respective clusters.
3) The sensor fly can navigate the complete flight path in the deployment region with a uniform speed. The sensor fly is not impacted by factors such as wind while traversing the sensing region.
4) The sensing region is square in shape, such that the total region could be divided into an even number of rows.
5) The nodes and the sensor fly are unaware of their location, and there is no access to localization services such as GPS. The sensor fly would be assisted by the CHs in the first column from the entry/exit cluster to navigate to the rows assigned to it.
6) The sensor fly has sufficient memory for storing the random seeds to be provided to the the CHs, and collect the previous round data from the CHs.

D. Sensor Fly

As elaborated earlier, the use of flying sensors (sensor fly) in WSNs has been an active area of research and the focus has been how their sensing capabilities could be improved, while in our framework the sensor flies would only perform data collection from the clusters. Since no sensing activity has to be undertaken, additional energy resources are freed up for actuation. In this framework we consider the BS is located significantly distant from the periphery of the deployment region in comparison to the conventional distance of the BS - sensing region considered in state of the art. The deployment region is expected to be divided in even number of rows and columns so as to achieve equal distribution amongst the sensor flies. Each sensor fly would cover a pair of rows in the clusters as shown in Fig. 5. At the commencement of the network operation, the sensor fly would deliver the random seed to the CHs from the BS. The sensor fly would be assisted from the entry/exit cluster to the assigned rows by the clusters in the first column. Therefore, the multi-hop communication in

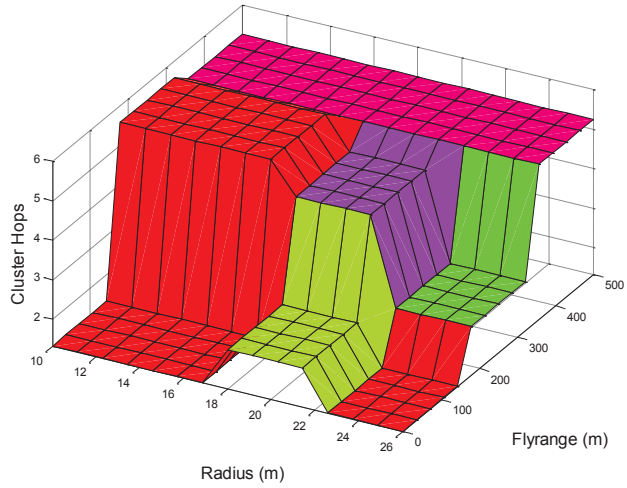

Fig. 6. FIS Relation between input parameters radius and flyrange, with cluster-hops

the network to support inter-cluster interaction and relaying of information to the BS is totally avoided. The sensor fly considered in the framework is expected to be capable of performing a vertical take - off and landing (VTOL). It would also be capable of performing hovering flight operation. In the forest monitoring application focused here, as shown in Fig. 3, the sensor fly flies at a constant height higher than the tree canopy height. On reaching a cluster, the sensor fly performs a cluster-hop landing on the tree canopy, above the cluster region on ground as shown in Fig. 4. The distance between two consecutive hops is derived as twice of the value given by (2). Before the collection round, the sensor fly is updated with the flight duration between two hops (based on inter-cluster distance and flying speed). This way the sensor fly would successfully reach a new cluster with every cluster-hop. The sensor fly is also aware of the number of clusters (cluster-hops) in a row as on the last cluster-hop in a row, the sensor fly would fly sidewards to the adjoining row, and subsequently fly back towards the entry/exit cluster (reverse direction) as shown in Fig. 5. The direction that sensor fly turns to switch between the rows would be the opposite direction it took while reaching the initial row from the entry/exit cluster in the deployment region. It is intended the sensor fly commences with a row farther away from entry/exit cluster and completes data gathering from a row closer to entrance/exit cluster. On completing this row the sensor fly would fly to the entrance/exit point cluster of the deployment region and then fly onward to the BS. As stated earlier, first column clusters would assist the sensor flies in reaching the entrance/exit cluster shown with a grey circle in Fig. 5. We consider that there would be no added delay for this path guiding in the overall time for the sensor fly to complete its data gathering round. It is also considered that exiting from the deployment region, the BS lies at a straight line and the sensor fly can navigate this without any additional assistance.

TABLE I. INPUT AND OUTPUT PARAMETERS AND MEMBERSHIP FUNCTIONS

Radius (m)		Flyrange (m)		Deadline (min)		Cluster-hops	
$1.5R_c$	9.5 - 17.2	Low	0 - 185	Minimum	0 - 4.8	Group 1	0 - 2.4
$2R_c$	17 - 22.5	Medium	182 - 344	Medium	4.7 - 9.8	Group 2	2.15 - 4.9
$2.5R_c$	22 - 26	High	342.1 - 510	Moderate	9.7 - 15.2	Group 3	4.4 - 6.6
				High	15 - 20	Group 4	6.5 - 8.6

IV. OPERATIONAL CAPACITY OF SENSOR FLY

Based on the previous sections it can be inferred that the operational capacity of the sensor fly to collect data from the deployed network would be governed by three major parameters, that are:

1) Radius of the cluster
2) Maximum flying range
3) Data delivery deadline at BS

Considering the clusters to be organized in circles as shown in Fig. 5, the radius of the cluster would influence the cluster size which in turn would influence the number of cluster - hops. Similarly, the sensor fly (MAV) would have a certain maximum flying limit. It has been stated earlier that data collection using the sensor fly would be feasible only for a delay tolerant network, accordingly, the operational capacity of the sensor fly would have to adhere with the delivery deadline imposed at the BS. The three parameters (referred as radius, flyrange and deadline) are inter-related, and influence operational capacity of the sensor fly. Since, definitive values for the input and the output are not determinable, *fuzzy* values are considered, and accordingly fuzzy logic is utilized to infer the relation between the inputs and their influence on output. It has has been implemented using MATLAB fuzzy logic toolbox based on Mamdani Fuzzy Inference System (FIS), and defuzzification using centroid method. For the evaluation sensing radius (R_s) is considered as 5 m and communication radius (R_c) as twice the sensing radius *i.e.* 10 m. Input parameters and their respective membership functions, and their values have been presented in Table I. Instead of a definite value a range broadly around multiples of (R_c) is considered as fuzzy logic supports non definite values.

As stated earlier, for making a cluster-hop to collect data, sensor fly would switch from forward flight to aerial flight to reach in aerial proximity of the cluster. As this is an energy intensive operation the effective flying range as stated in table is considered to be halved while determining the fuzzy logic rules. A large radius of the cluster would favour the sensor fly (less hops) but would be detrimental for nodes to communicate with the CH. The delivery deadline is significant as a short deadline would limit the possible cluster-hops that the sensor fly could cover. Therefore, favourable condition for sensor fly would be a mid-range cluster radius, a high flying range and a high delivery deadline. Rules for fuzzy inference based on the membership functions of the input parameters have been based on these inherent conditions. A total of 34 fuzzy rules have been formed based on the membership functions, and FIS surface output have been shown in Fig. 6, 7, and 8. The inherent conditions governing the cluster-hops that could be covered is evident from the figures. The membership functions for the input parameters were of trapezoidal shape (trapmf), as the input values are non continuous. This is also the reason for non smoothness of the output surface. Certain observations

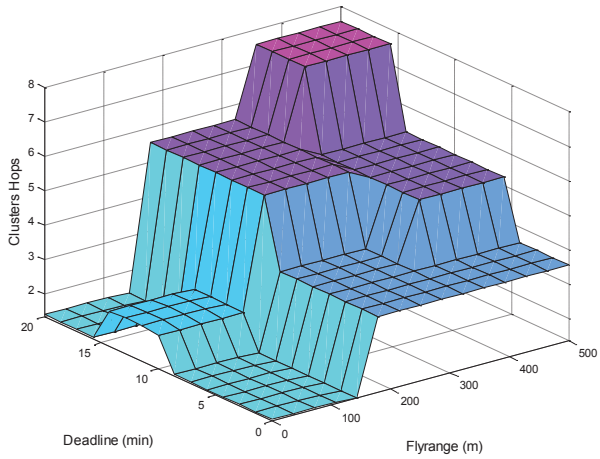

Fig. 7. FIS Relation between input parameters deadline and flyrange, with cluster-hops

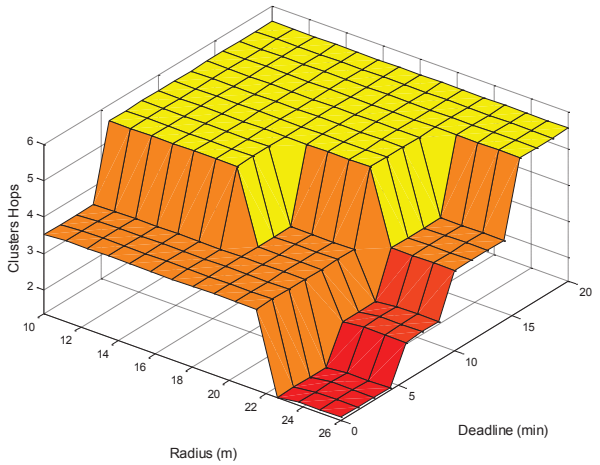

Fig. 8. FIS Relation between input parameters radius and deadline, with cluster-hops

based on the surface plots are as follow in Fig. 6 maximum number of cluster-hops is observable for radius less than 1.5 R_c. Based on the Fig. 7 the cluster-hops governed solely on deadline and flyrange would be when both would be maximum permissible. Collectively from the figures the extreme significance of radius being around around 1.5 R_c is evident. As stated earlier multi-hop inter-cluster communication is avoided in the proposed framework. If the cluster size is fixed equal to R_c then multi-hop intra-cluster could also be avoided, thereby no multi-hop communication in the whole network at all. Even for the favourable cluster size of 1.5 R_c, only certain nodes would need multi-hop communication to deliver data to CH.

V. Conclusions

Proposed framework would prolong the lifetime of the network due to energy savings with avoidance of inter-cluster multi-hop communication. Data gathering using sensor flies and delivery to the BS would be beneficial especially in WSN applications in inhabitable harsh terrain. The proposed framework is well designed to address the various concerns that would hamper sensor network deployment under such conditions. This framework also offers a new perspective for flying sensor nodes. Normally the research on flying sensors would focus on both aspects to achieve efficient actuation and sensing capabilities. With this framework all attention could be centred only on achieving efficient actuation for the sensor fly. Fuzzy inference of the cluster-hops that could be covered by sensor fly based on the three input parameters has been presented. Actual results for determining the capacity of the sensor fly based on these parameters would form an optimization problem and is expected to be taken as further work of the proposed framework. The optimization problem for determining the number of clusters would require definite values for the input parameters and a mathematical formulation defining their inter-relation. The number of sensor flies required to cover area of interest can be determined before the commencement of the network operations based on the solution of the optimization problem. Additionally, with mathematical formulation the proposed framework's effective utility could be compared in respect to energy saved per round in comparison with data aggregation based data collection, and multi-hop compressive sensing based data collection. Effective energy saving with avoidance of possible packet loss in inter-cluster communication due to near ground path loss in comparison with aforesaid two data collection methods would also be evaluated as further work.

References

[1] J. Yick, B. Mukherjee, and D. Ghosal, "Wireless sensor network survey," *Computer Networks*, vol. 52, no. 12, pp. 2292 – 2330, 2008.

[2] W. Liu, K. Lu, J. Wang, L. Huang, and D. Wu, "On the throughput capacity of wireless sensor networks with mobile relays," *Vehicular Technology, IEEE Transactions on*, vol. 61, pp. 1801–1809, 2012.

[3] F. El-Moukaddem, E. Torng, G. Xing, E. Torng, G. Xing, and G. Xing, "Mobile relay configuration in data-intensive wireless sensor networks," *Mobile Computing, IEEE Transactions on*, vol. 12, pp. 261–273, 2013.

[4] S. Chellappan, X. Bai, B. Ma, D. Xuan, and C. Xu, "Mobility limited flip-based sensor networks deployment," *Parallel and Distributed Systems, IEEE Transactions on*, vol. 18, pp. 199–211, 2007.

[5] A. A. Abbasi and M. Younis, "A survey on clustering algorithms for wireless sensor networks," *Computer Communications*, vol. 30, pp. 2826 – 2841, 2007.

[6] K. Dantu, B. Kate, J. Waterman, P. Bailis, and M. Welsh, "Programming micro-aerial vehicle swarms with karma," in *Proceedings of the 9th ACM Conference on Embedded Networked Sensor Systems*, 2011.

[7] J. Ratti and G. Vachtsevanos, "Inventing a biologically inspired, energy efficient micro aerial vehicle," *Journal of Intelligent & Robotic Systems*, vol. 65, no. 1-4, pp. 437–455, 2012. [Online]. Available: http://dx.doi.org/10.1007/s10846-011-9615-z

[8] D. Wang, L. Song, X. Kong, and Z. Zhang, "Near-ground path loss measurements and modeling for wireless sensor networks at $2.4ghz$," *International Journal of Distributed Sensor Networks*, p. 10, 2012.

[9] F. Cintron, K. Pongaliur, M. W. Mutka, L. Xiao, J. Zhao, and N. Xi, "Leveraging height in a jumping sensor network to extend network coverage," *Wireless Communications, IEEE Transactions on*, vol. 11, pp. 1840–1849, 2012.

[10] C. Luo, F. Wu, J. Sun, and C. W. Chen, "Compressive data gathering for large-scale wireless sensor networks," in *Proceedings of the 15th Annual International Conference on Mobile Computing and Networking*, ser. MobiCom '09. New York, NY, USA: ACM, 2009, pp. 145–156. [Online]. Available: http://doi.acm.org/10.1145/1614320.1614337

[11] H. Zheng, S. Xiao, X. Wang, and X. Tian, "Energy and latency analysis for in-network computation with compressive sensing in wireless sensor networks," in *INFOCOM, 2012 Proceedings IEEE*, 2012.

[12] E. Candes and M. Wakin, "An introduction to compressive sampling," *Signal Processing Magazine, IEEE*, vol. 25, pp. 21–30, 2008.

[13] N. Amini, A. Vahdatpour, W. Xu, M. Gerla, and M. Sarrafzadeh, "Cluster size optimization in sensor networks with decentralized cluster-based protocols," *Computer Communications*, vol. 35, no. 2, pp. 207 – 220, 2012.