Distributed Wirelss Sensor Network Architecture: Fuzzy Logic based Sensor Fusion

Garimella Rama Murthy
IIIT-Hyderabad, India
rammurthy@iiit.ac.in

Vasanth Iyer
IIIT-Hyderabad, India
vasanth@research.iiit.ac.in

Abstract

In this research paper, power aware distributed wireless sensor network architecture proposed by us (in the context of design of routing algorithm) is summarized. An approach to combined routing and fusion algorithm is discussed. Fuzzy logic based approach to wireless sensor fusion is discussed. The need for modeling sensor readings using fuzzy uncertainty is discussed. Novel overlap function for sensor fusion is presented. Concept of fuzzy overlap function is proposed. Method of distributed computation of means is proposed.

Keywords: Sensor Fusion, Fuzzy Logic, Network Architecture.

1 Introduction

Traditionally sensors were used to monitor natural or artificial phenomena. For instance, in the case of manufacturing process, the temperature and pressure in a set of boilers is monitored by sensors. The sensor readings are communicated to a centralized control center. Thus, conventionally the sensors are connected to one another through wires. These wired sensor based systems were utilized in many practical applications.

Motivation for Wireless Sensors:

Advances in VLSI (Very Large Scale Integration) as well as MEMS (Micro-Electro-Mechanical Systems) facilitated the manufacture of tiny sensors (say sensor motes). These tiny sensors have multiple functionalities such as sensing, processing/computing and communication. Thus, each sensor is typically equipped with a sensor (sensing unit), a processor (computing unit), a transmitter/receiver(transceiver for communication), memory, small battery etc. It is demonstrated by companies like Crossbow that these tiny sensors are commercially viable.

Wireless Sensor Networks:

Advances in sensor technology and computer networks have enabled distributed sensor networks (DSNs) to evolve from small clusters of large sensors to large swarms of micro-sensors, from fixed sensor nodes to mobile nodes, from wired communication to wireless communication, from static network topology to dynamically changing topology [5]. However, these technological advances have also brought new challenges to processing large amount of data in a bandwidth-limited, power constrained, unstable and dynamic environment [5]. To be effective, a wireless sensor network must implement the following procedures:

(a) Neighbor Discovery and Self Organization, (b) Distributed Computation Algorithms, (c) Capacity Optimization, (d) Localization, (e) Routing, (f) Sensor Fusion etc. Details related to these procedures can be found in [2].

Let us consider the routing problem/procedure. It is easy to see that most wireless sensor networks monitoring a phenomenon are data-centric. The goal is to communicate an event from a certain region of sensor field to the base station. In such data-centric networks absolute addressing of sensor nodes is not necessary. Our research group proposed two routing algorithms in wireless sensor networks. Details of these algorithms are described in Section 2. Now let us consider the sensor fusion problem.

Sensor Fusion Problem:

We illustrate this problem using an application. Consider the problem of monitoring fires in a forest. Utilizing a helicopter/air-craft temperature sensors are deployed over a certain terrain. In the deployment phase, some sensors could become faulty. Some more sensors could malfunction due to various reasons after deployment. These faulty as well as functioning wireless sensors monitor the temperature and transmit the information to a base station (using various routing procedures).

At the base station, the temperature information (raw data) coming from various sensors has to be aggregated to detect an event such as fire. Thus we are naturally led to the problem of designing a fusion/aggregation algorithm. Suppose the average value of raw temperature readings is computed it is easy to see that the temperature readings coming from faulty sensors influence the aggregated value and thus leading to a wrong aggregated value. In the worst case, it might so happen that an event such as forest fire is not properly detected. Hence it is necessary to design a robust/fault tolerant sensor fusion algorithms.

In the remaining portion of the research paper, we often refer to a wireless sensor network deployed to monitor the temperature in a forest region and report events such as a forest fire.

2 Power Aware, Distributed Network Architecture

In the case of wireless sensor network, the sensors are deployed over the sensor field. The performance of sensor fusion algorithm depends on the network architecture. Also, sensors should be coordinated using a distributed architecture so that an efficient routing algorithm can be designed. Thus, in the following we summarize the routing algorithms designed by us and the associated network architecture.

The sensor network lifetime is limited due to constrained power requirements of sensor motes. The network lifetime is defined as period of network reliability till the first sensor drains out of power as shown in figures 7, 8, 9&10. To maximize the sensor network life-time the architecture relies on using power-aware routing and data aggregation algorithms. As the need to minimize network traffic only on-demand protocols are considered for power-aware routing. As seen from simulation results the power-aware LEACH algorithm does 40% better than the standard LEACH in terms of number of rounds before the first sensor fails. The remaining Life-time of the sensor network gives the residual power, from the simulation results the standard LEACH increases by 12% when the number of cluster heads is increased gradually up to 50% of the total sensors deployed. The main reason of better efficiency with higher cluster head count is due to evenly distributing the number of sensors per cluster head. In the case of power-aware LEACH the remaining life-time is evenly spread so as to maximize the number of rounds by better balancing the selection of cluster heads. At lower percentage of cluster heads the power balancing algorithm performs best so to not fail a single sensor till the last sensor has no more power. When the percentage of cluster head is gradually increased up to 50% the power balancing algorithm selection is suboptimal due to the increased need to find more optimal cluster heads. Due to this some of the cluster heads have less resource than average remaining residual power causing earlier failure of sensor nodes. The protocols considered can be categorized in the following ways-- flooding, multi-hoping, clustering and our own distributed algorithms like Control Radius Flooding [4], Hierarchical Leveling, Power-aware routing using dual-cluster members.

2.1 Conventional Routing Algorithms

Flooding is a conventional routing algorithm as shown in Figure 1 which allows discovering the topology and the destination path. Due to the nature of the flooding process it generates many duplicates causing collision in the network. The variants of this type of protocol allow a transmission probability to be sent with the message header which can be used to forward or not to forward the current message to its neighbor. Such protocols are classified as gossip and regional flooding. The problem of power-awareness is partially addressed in these types of protocols as these could be deployed on an on-demand or reactive type network without using any prior information of the topology or any other network protocol discovery overheads.

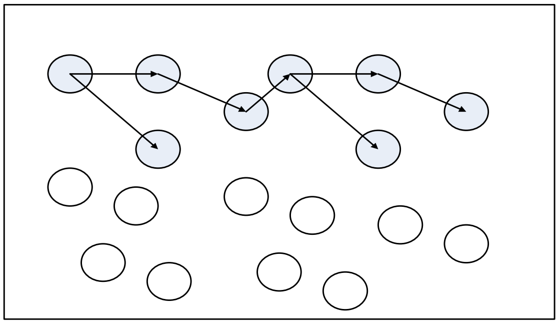

Figure 1: Example of flooding.

Multi-hopping as shown in Figure 2 is an enhancement of the earlier routing protocol by introducing a hop-count in the protocol. This allows forwarding the messages discretely by checking the least hop count to the destination. The overhead in this is to maintain the routing information for the underlying network. The problem of power-awareness is addressed as the total power dissipated by the network is minimized due to multi-hopping. Hence the power dissipated during forwarding a message to its nearest neighbor is the least compared to sending it to the base station directly, enhancing the total life-time of the network.

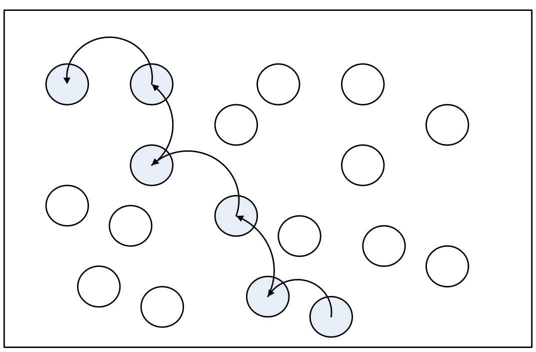

Figure 2: Example of multi-hoping.

2.2 Distributed power-aware architectures

Clustering is a technique in which a cluster head is elected using a power-aware cost factor and its entire neighbors join the cluster dividing the network as shown in Figure 3 into many different regions. This further reduces the power dissipation compared to multi-hopping. The clustering algorithms like LEACH [9] (Low Energy Adaptive Clustering Hierarchy) and HEED (Hybrid, Energy-Efficient, Distributed clustering) help to find suitable cluster heads using localized optimizations or finding optimizations using a distributed parameter. As in the case of sensor networks periodic data is gathered and sent to the base station. Clustering aggregates data to a single cluster head further reducing the energy constraints and enhancing the total lifetime of the network.

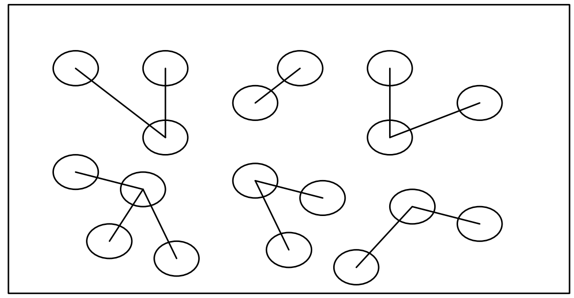

Figure 3: Example of clustering.

2.3 Our Routing approaches

A zone based protocol called CRF (Control Radius/Radio Flooding) is proposed by our group which partitions the sensor network mainly into three hierarchically functional zones as shown in figure 4 using sensor’s variable transmit power, the zone farthest from the base station does the data collection and the middle zone does the routing using a route cache and the zone closest to the base station does multi-hopping of data to the base station and enhancing the lifetime of the sensor network. The route cache maintains a use count which is checked against a residual cost factor and if it reaches or exceeds that threshold the cluster head is rotated with one which has a lower use count.

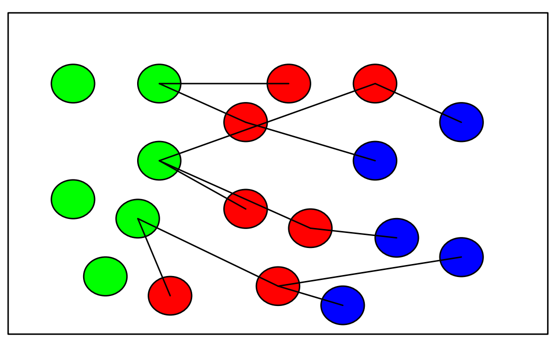

Figure 4: Example of Control Radius/Radio Flooding.

- Leveling Algorithm

Hierarchical Leveling is a frame work as shown in figure 5 in which base station divides the network using proximity of the sensor distance from itself using the power to reach a segment of the network. By this all the nodes have a specific level number and eventually at the end of the division of the network all nodes farthest away from the base station have a large number compared to the nodes closer to the base station making the base station at zero. When an event is detected in the outmost level the message is embedded with its current level and broadcasted, the listening neighbors check if the level is lower than the source of the message if so they are re-broadcasted over the network by which propelling the message to the base station and avoiding collisions generated by the same levels. The problem of power-awareness is addressed by minimizing re-broadcast of unnecessary packets as in the case of conventional flooding.

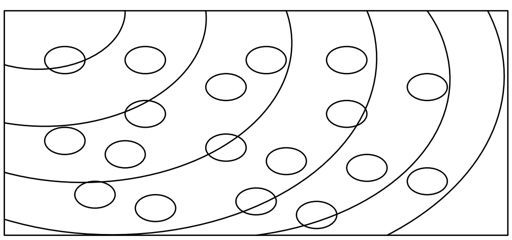

Figure 5: Example of Hierarchical Leveling

- Clustering Algorithm

The new algorithm proposes dual-membership clustering as shown in Figure 6, which is very useful to minimize the use of epidemic algorithms of any sort, thereby saving a lot of resources and also making route discovery more deterministic. This novel technique uses selection of cluster heads and also keeps track of the most recently used path for using the off-line cluster head. The problem of power-awareness is addressed by combining clustering and multi-hopping during transmission and also uses a dual membership of clusters which minimizes the overhead of route discovery.

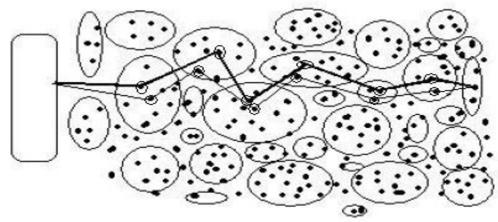

Figure 6: Example of dual membership cluster and recent path usage

2.4 Intuitive betterness of our algorithms

Intuitively, we reason that our routing algorithms are better than various known variants of flooding algorithms from the point of view of minimizing duplicate packets in the network and thus power.

Our first routing algorithm effectively achieves hierarchical partitioning of the network into levels [1]. The data packets are propelled in the direction of base station using a controlled flooding algorithm (also called gossip routing algorithm). The algorithm prevents propagation of packets in the opposite direction of the base station. Thus the algorithm ensures that duplicates packets that are generated (due to broadcast nature of transmission) are prevented from being transmitted repeatedly. The idea of our algorithm has some resemblance to the regional gossip algorithm proposed in [7]. This regional gossip algorithm makes the strong assumption of location awareness.

Traditionally clustering algorithms such as LEACH, HEED are proposed to minimize energy consumption. We proposed a dual membership clustering algorithm [3]. This algorithm also proposed the innovative idea of forming data highways on the sensor field and utilizing them for routing. Thus, in this algorithm, the overhead associated with route discovery is minimized.

- Leveling plus clustering algorithm

We also proposed a hybrid algorithm which combines the advantages of leveling algorithm and clustering algorithm. Detailed performance study is reported in [8]. Thus we expect this hybrid algorithm to be a good power aware algorithm of utility in wireless sensor networks. In the following section, we propose a combined routing and fusion algorithm.

3. Traditional Wireless Sensor Fusion Approaches

Decision/Information fusion problems have been investigated since few centuries. For instance, the works of Condorcet on democracy models in 1786 and Laplace on composite methods studied the fusion problem. In engineering, the investigations of Von Neumann showed that a reliable system can be built using unreliable components by employing simple majority fusers [5].

Wireless sensor fusion is one among numerous application areas in which information/decision fusion methods have been employed. Sensor fusion techniques must be robust and fault tolerant so that uncertainty and faultiness in sensor readings can be handled. Naturally redundancy in sensor readings are used to provide error tolerance in fusion [5].

- Fault Tolerant Fusion Algorithms: Overlap Functions

An abstract sensor is defined as a sensor that reads a physical parameter and gives out an abstract interval estimate which is bounded and connected subset of the real line. Abstract sensors can be classified into correct sensors and faulty sensors. A correct sensor is an abstract sensor whose interval estimate contains the actual value of the parameter being measured. Otherwise, it is a faulty sensor. A faulty sensor is tamely faulty if it overlaps with a correct sensor, and is wildly faulty if it is does not overlap with any correct sensor [5].

Several overlap functions are defined that process the readouts from abstract sensors. Four such functions are discussed in [5] in the references. For instance Marzullo defined the M function. Let n be the number of sensor readouts, f be the number of faulty sensors. $M([I_1, I_2, \ldots\ldots, I_n])$ is defined to be the smallest interval that contains all the intersections of n-f intervals. It is guaranteed to contain the true value provided the number of faulty sensors is at most f. The disadvantages of such a function are discussed in [5].

- Also, there are efforts to model the sensor readings using probabilistic uncertainty. In the following, we reason that in the case of a wireless sensor network monitoring a phenomenon (such as forest fire), the sensor measurements and/or cluster head measurements should be modeled using fuzzy uncertainty

- Combined Routing and Fusion:

In all wireless sensor networks, the sensors monitoring a phenomenon collect raw data. In pure routing algorithms (epidemic algorithms) such as flooding and its variants (controlled flooding: gossip, regional gossip), the collected raw data is propagated to the base station without any processing.

We propose an approach in which the routing decisions as well as aggregation/fusion decisions are combined. For instance the leveling and clustering algorithm described in Section 2 enables combined routing and fusion.

4. Wireless Sensor Fusion: Fuzzy Logic Based Approach

Limitation of Traditional Fusion Approaches:

In the case of conventional, wireless sensor fusion algorithms, the raw temperature (for example) readings are transmitted to the cluster head. The cluster head can transmit all the raw/unprocessed values to the base station. Alternatively, the cluster head processes the raw values and produces a fused estimate. Typically the fusion measure employed at the cluster head is mean, medium, mode etc. The cluster heads propagate the fused values to the Base Station (in a cooperative manner).

From the point of view of natural/artificial phenomenon being monitored (e.g. Forest Fire), the actual sensor readings (or processed estimate, say mean) are only of limited utility. *To take any control action (say to control forest fire), we want to decide whether the temperature is LOW, MEDIUM, HIGH etc.*

Thus the linguistic variable corresponding to the monitored variable (say temperature) is characterized by fuzzy uncertainty. The linguistic variable (say temperature) assumes values in the fuzzy sets, “LOW”, “MEDIUM”, “HIGH” etc. To emphasize the point, it should be understood that the uncertainty cannot be modeled using probabilistic uncertainty, but requires fuzzy uncertainty

Fuzzy Sensor Fusion:

There are two possible approaches to fusion of measurements collected at sensor nodes

Approach—1:

Crisp measurements at the sensor nodes are aggregated using crisp fusion measures such as median, mode, mean etc (It should be seen that using median leads to a robust estimate as in the case of median filtering).Using the crisp estimates, fuzzification is done at the cluster heads. These fuzzified values at the cluster heads are propagated to the base station. At the base station, different aggregation measures are employed. After proper de-fuzzification, fire control decisions are taken.

Approach—2:

In contrast to approach-1, the monitored variables (temperature) at the sensors are treated as being fuzzy i.e. they assume values in the fuzzy sets LOW, MEDIUM, HIGH (temperature). The crisp measurements are fuzzified. Using fuzzy arithmetic rules, median, mode type measures are computed at the cluster head. The fused values at various cluster heads are composed using FUZZY IF THEN ELSE rules. As in the case of a Fuzzy control system [page 635, 6], fuzzy rule base, fuzzy inference engine, defuzzification interface are utilized to take a control action for monitoring temperature in a forest (Specifically, in case of forest fire event, appropriate control action is taken).

Let temperature at the i-th sensor node/i-th cluster head be denoted by TEMP-i. Typical fuzzy IF, THEN, ELSE rules are:

(1) IF TEMP-1 is LOW, TEMP-2 is LOW, …., TEMP-N is LOW,

THEN FIRE CONTROL IS (NOT REQUIRED)

(2) IF MAJORITY OF (TEMP-1, TEMP-2, …, TEMP-N) is HIGH,

THEN FIRE CONTROL is (REQUIRED).

5. Distributed Sensor Fusion: Mean Computation

In traditional sensor arrays, measurements are simply sent to a central signal processor for computation. In contrast a wireless sensor network should be able to provide some useful inferences based on measurements at the sensors [2]. Anurag et.al proposed distributed computation of maximum and reasoned that the communication complexity is reduced.

We propose distributed computation of mean. For 'n' sensors placed in one dimension, if the average value of measurements is needed, then the method of sending all individual values to a central operator would be extremely inefficient in communication complexity ($0(n^2)$ for 'n' sensors placed in one dimension , with the operator node at one end). Mean can be recursively computed in the network as the sensors exchange their measured values. The distributed computation of mean is illustrated below:

Let the lower case letters denote raw measurements i.e. $\{ x_0, x_1, x_2, \ldots\ldots x_n \}$. As shown below, the mean values are computed in a distributed manner:

$X(0) = x_0$, $X(1) = \frac{X(0) + x_1}{2}$, $X(2) = \frac{2X(1) + x_2}{3}$, $X(3) = \frac{3X(2) + x_3}{4}$ and so on. This distributed computation based approach leads to minimal delay in determination of average temperature at the base station.

Now we return to some innovative ideas related to fuzzy sensor fusion.

6. Negative membership function: Modeling need

It is well accepted that a linguistic variable is modeled using fuzzy uncertainty. Now we reason the need for allowing the membership function to assume negative values i.e. membership function assumes values in the set [-1, 1].

Consider a "linguistic variable" such as temperature. Let the associated sets be "COLD", "HOT" and "MEDIUM" (to capture the degree of heat). The following situation directs our attention towards negative membership function values. Consider a linguistic variable such as "Temperature". Let the temperature be -20°C. The degree of membership of that observation in the fuzzy set "HOT TEMPRATURE" is not zero but SRICTLY NEGATIVE. Suppose these is a common "UNIVERSE OF DISCOURSE" (for the elements of Fuzzy sets). It seems that using the current framework of fuzzy sets, it is possible to make into account the "negative membership" value and the need for it. We are thus BROADENING the scope of fuzzy sets.

It may be possible to convert the above situation in such a way that the traditional fuzzy set idea (with only positive membership function values) is sufficient. But we feel that there is loss of information in such an approach. One might conceive of situations where the membership function assumes complex values and not necessarily real values.

7. Novel Overlap Functions

• In [5], Qi et.al proposed Ώ(.) overlap function. We propose a novel overlap function based on the prior Ώ(.)

Dual of Ώ – Function θ(x): It gives the number of intervals non-overlapping at 'x'. This function is more natural under the assumption that "most of the sensors" are non-faculty.

θ(x) = *N* – Ώ(x), where *N* is the total number of sensors.

• θ(x) Associated overlap function β(x), Just as *N* function is associated with θ(x). β(x) gives the interval with the θ(x) Є [0,f]

Novel Idea: Associate a measure with the fused interval specified by the overlap function. This measure quantifies the agreement/disagreement among sensors.

8. Fuzzy overlap function

Suppose we model the sensed value to be a linguistic variable which assumes the values in an interval with associated membership function.

- Arrive at a "fused" interval estimate using one of the various overlap functions.
- Using the membership functions (corresponding to different sensors) over the "fused" interval, associate/compute the resulting membership function as follows:

(i) Compute the Maximum/Minimum of the membership values.

(ii) Compute the average/median other measure of the membership values.

9. Conclusions

In this research paper, design of wireless sensor networks is addressed. Specifically, the problem of wireless sensor fusion is considered.

To address the fusion problem, the distributed network architecture proposed by us is discussed. This architecture was utilized for designing routing algorithms. We propose a combined routing and fusion algorithm. Traditional approach to wireless sensor fusion is summarized. Fuzzy logic based approach to sensor fusion is proposed as a novel solution. The problem of distributed sensor fusion is discussed in the context of computation of average/mean value of the sensor readings.

10. Acknowledgement

Authors are grateful to DST, Govt. of India, for supporting the work with a grant. Also will like to acknowledge the faculty Dr. Rama Murthy department of Communication Research Centre and Dr. Srinivas of VLSI and Embedded systems who had constantly advised on the project since it began a year back.

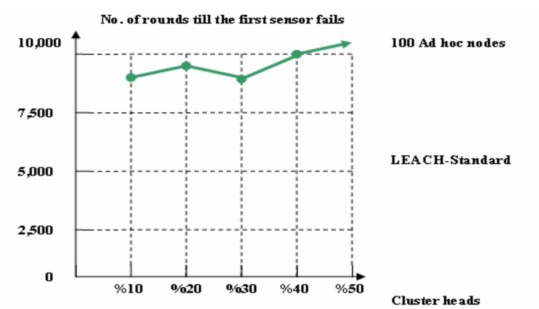

Figure 7: Plot of no. of rounds using LEACH standard with different number of cluster heads.

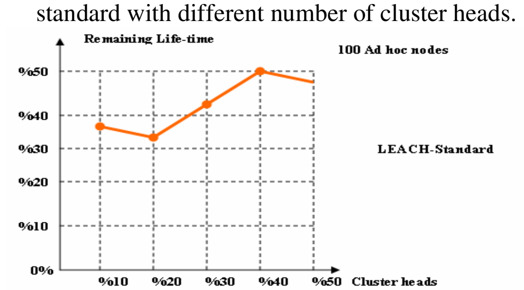

Figure 8: Plot of remaining life-time residual power using LEACH standard with different number of cluster heads.

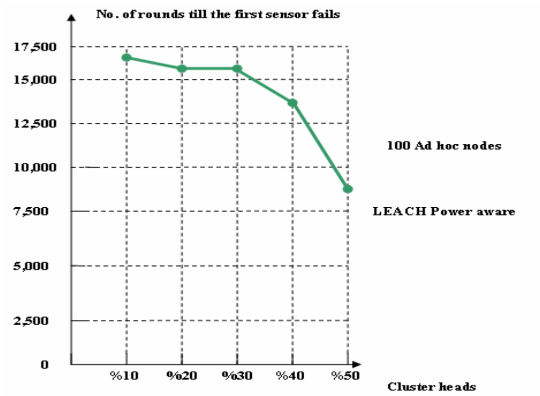

Figure 9: Plot of no. of rounds using LEACH power-aware with different number of cluster heads.

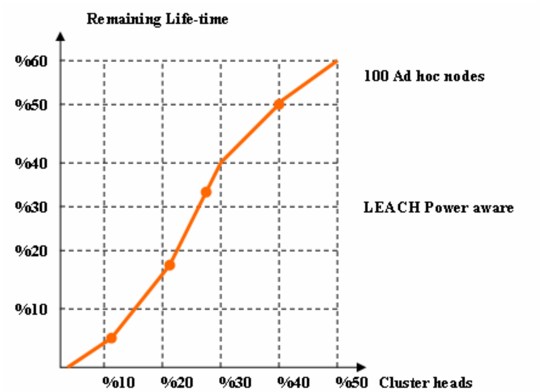

Figure 10: Plot of remaining life-time residual power using LEACH power-aware with different number of cluster heads.

References

[1] S. Arora, S. Chaudhary, M. B. Srinivas and G. Rama Murthy, "Power Aware, Probabilistic and Adaptable Routing Algorithm for Wireless Sensor Networks," Proceedings of 10th National Communications Conference (NCC), January 2004, Organized by IISc, Bangalore. Submitted to SADHANA.

[2] Anurag Kumar, D. Manjunath and Joy Kuri, "Communication Networking: An Analytical Approach," Morgan Kaufmann Publisher, 2005.

[3] N. Bharat Varma, M. Pratyush, G.Rama Murthy and M.B.Srinivas, "Energy-Aware Routing in Sensor Networks using Dual Membership Clusters and Data Highways," Proceedings of IEEE TENCON, Bangkok, 2004. GESTS International Transactions on Computer Science and Engineering, Vol.25, #1, December 2005, Pages. 196-208, ISSN 1738-6438.

[4] Vasanth Iyer, Rama Murthy, M.B. Srinivas "Information Processing of Wireless Sensor Networked Motes by Harvesting Residual Power", The Second IEEE International Workshop on Next Generation Wireless Networks 2006 (IEEE WoNGeN '06).

[5] H. Qi, S.S. Iyengar and K.Chakrabarty, "Distributed Sensor Networks---a Review of Recent Research, " Journal of the Franklin Institute 338 (2001), Pages 655-668.

[6] Satish Kumar, "Neural Networks: A Classroom Approach," Tata McGraw Hill Publishing Company Limited, New Delhi.

[7] Regional Gossip Routing for Wireless Ad Hoc Networks Xiang-Yang Li Kousha Moaveninejad Ophir Frieder.

[8] Amit Kumar, Rumeet Singh, G. Rama Murthy, M.B. Srinivas, "Energy Effcient Layer and cluster formation in Wireless Sensor Networks" B.Tech final year project, IIIT, Hyderabad.

[9] LEACH (Low Energy Adaptive Clustering Hierarchy) Wendi Heinzelman,Hari Balakrishnan,Anantha Chandrakasan.