FUCP: Fuzzy Based Unequal Clustering Protocol for Wireless Sensor Networks

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***Abstract*—This paper presents Fuzzy Based Unequal Clustering Protocol (FUCP) for wireless sensor networks. The cluster head selection mechanism uses fuzzy logic with three node descriptors namely, residual energy, centerness with respect to its neighbor, and quality of communication link with its neighbors for cluster head selection. To avoid *hot spots* and for uniform network traffic distribution, FUCR uses unequal clustering. For this, fuzzy logic is used with node distribution and distance from master station to decide number of cluster heads and cluster head advertisement radius in a given area. A comparative analysis of FUCR, Low Energy Adaptive Clustering Hierarchy, Hybrid Energy Efficient Distributed Clustering, Cluster Head Election mechanism using Fuzzy logic, and Distributed Energy Efficient Hierarchical Clustering shows that FUCP is up to 40% more energy efficient, has 31% more network lifetime, and sends 57% more packets to master station compared to Distributed Energy Efficient Hierarchical Clustering.**

Keywords*— *wireless sensor networks; cluster head selection; clustering; fuzzy logic

I. Introduction

Wireless sensor networks (WSN) applications involve: (i) data gathering where nodes periodically report their data to master station (MS) or (ii) event detection where nodes send data when an event has occurred [1]. The resource constraints in node like limited processing, memory, and power supply capabilities at one end and the design needs of multipurpose applications at the other end calls for a clustering architecture. In a clustering architecture neighboring nodes are prearranged into "clusters" with one node performing as cluster head and rest as cluster members [2][3].

Low Energy Adaptive Clustering Hierarchy (LEACH) is one of the most widely held distributed architecture that elects cluster heads based on probability model. It ensures that a node becomes a cluster head in round r, only if it has not been a cluster head for previous (r-1) rounds to dispense energy depletion amongst the nodes [4]. However, cluster head election is random which leads to cases when selected cluster heads are in close locality of each other or from area with less node density or may be having less residual energy sacrificing the overall performance of the network.

Hybrid, Energy Efficient, and Distributed (HEED) is a distributed clustering procedure that intermittently picks cluster heads based on: residual energy (to probabilistically pick an preliminary set of cluster heads) and node degree [5]. HEED's clustering process requires several iterations and a lot of control packets are broadcast to update neighbor sets in each iteration.

Distributed Energy Efficient Hierarchical Clustering (DWEHC) is a distributed clustering procedure that constructs multi-level clusters with one cluster head and its first level child node, second level child node, and so on [6]. The number of levels inside a cluster is based on cluster radius. TDMA is used for intra-cluster communication and 802.11 based MAC mechanism [7] is used by cluster heads for data transmission to MS. Limiting number of child nodes makes DWEHC scalable and cluster head selection algorithm ensures that nodes inside each other's cluster range will never be cluster heads. Drawback of DWHEC is that cluster heads use 802.11 MAC mechanisms for data transmission to MS which is not an energy efficient solution [8].

Topology and Energy Control Algorithm (TECA) forms node clusters and then includes bridges to interconnect them [9]. The cluster head selection considers residual energy of nodes. The character of cluster head and bridge node is rotated to evenly distribute load amongst nodes and prolong network lifetime. The use of bridge nodes maintains network connectivity. However, bridge nodes are required to remain active along with cluster head till data reaches MS increasing overall energy consumption of the network.

Access Based Energy Efficient Cluster Algorithm (ABEE) uses a first-come-first-serve technique for cluster creation [10]. Cluster head selection is done using simple request-response procedure that takes care that cluster members and cluster heads are in the vicinity of each other to reduce intra-cluster communication cost. The cluster head role is periodically rotated to evenly distribute load amongst nodes of the network. The main drawback of ABEE is that it does not use the residual energy of node for cluster head selection and involves a huge number of control packets to be send for cluster head selection.

Fuzzy logic technique that can adapt to complicated and changing wireless environments have been used for WSN protocol design. For example, clustering protocol by Indrail et. al. uses fuzzy logic with input variables as energy, concentration (number of neighboring nodes), and centrality of node with respect to cluster for cluster head selection [11]. Fuzzy logic selects best cluster head in terms of node's energy and intra-cluster transmission cost. However, each node has to send its present location and outstanding energy to MS in each round which is a significant energy overhead.

Cluster Head Election using fuzzy logic by Junpei Anno et. al. uses fuzzy logic with distance of cluster centroid from MS, outstanding energy of node, and network traffic as input variables for cluster head selection [12]. Probability of node to become cluster head is zero if its residual energy is less than 2 J. Cluster Head Election using Fuzzy logic (CHEF) protocol uses residual energy of node and local distance (sum of distances between particular node and its neighbors in a specified radius) as fuzzy descriptors for cluster head selection [13]. It overcomes the overhead of sending node's parametric information to MS by running fuzzy logic locally at node in a distributed manner.

In protocols based on clustering methods, cluster heads are to do data aggregation and forwarding to MS. Thus, cluster heads close to MS die earlier because dense traffic consisting of their sensor data and that relayed from neighbor cluster heads. This leads to *hot spots* problem [4].

All the above clustering protocols do not suggest inter-cluster routing mechanisms leaving it to the user to choose them from the literature. The selected inter-cluster routing mechanism might not match with proposed cluster head selection techniques and may lead to *hot spots* problems [3].

To this end, this paper introduces Fuzzy Based Unequal Clustering Protocol (FUCP) for WSN that encompasses:

- A novel cluster head selection algorithm that uses fuzzy logic with residual energy, centerness with respect to its neighbor, and quality of communication link with its neighbors as fuzzy descriptors for cluster head selection.
- A novel cluster and relay traffic distribution algorithm that uses fuzzy logic with node distribution and distance from MS to choose number of cluster heads in a given area.

The rest of the paper is organized as below: Section 2 introduces the system model and basic assumptions of FUCP design. Section 3 discusses FUCP operation in detail. Section 4 delivers comparative analysis of FUCP with four well referred clustering protocol configurations. The paper is concluded in Section 5.

II. System Model

A. Nodes

Nodes in network are: stationary; homogenous; have hardwired identification; can vary transmit power; their clocks are synchronized. The MS has good energy, computational, and storage capabilities and can broadcast to all the nodes.

B. Network model

Nodes are arbitrarily dispersed within an M x M square shaped sensing area with MS at center of area at coordinates (0,0). Nodes are then organized into *layered-hexagons* lattice as described next. The first *layered-hexagon* has its center at MS and arm length as R_{max} (maximum transmission range of the node). Second *layered-hexagons* form a ring around the first *layered-hexagon* with one of their side common with the first *layered-hexagon*. The *layered-hexagon* formation is continued till entire sensing field is covered.

C. Energy consumption model:

For energy dissipation a simple model as given in [4] is used. Transmitter's energy dissipation consists of energy for radio and power amplifier, and in receiver it is to run radio.

If distance amongst transmitter and receiver is less $d_{crossover}$, friss free space ε_{fs} model (d^2 power loss) is used or else, multipath fading ε_{mp} model (d^4 power loss) is used. Consequently, to transmit a *l*-bit message at a distance *d*, radio spends,

$$E_{Tx}(l,d) = E_{Tx\text{-}elec}(l) + E_{Tx\text{-}amp}(l,d) \quad (1)$$

$$= \begin{cases} lE_{elec} + l\varepsilon_{fs}d^2, d < d_{crossover} & (2) \\ lE_{elec} + l\varepsilon_{mp}d^4, d \geq d_{crossover} & (3) \end{cases}$$

By equating expressions (2) and (3) at $d=d_{crossover}$,

$$d_{crossover} = \sqrt{\frac{\varepsilon_{fs}}{\varepsilon_{mp}}} = 87.7 \text{ m.} \quad (4)$$

To receive this message, radio spends,

$$E_{Rx}(l) = E_{Rx-elec}(l) = lE_{elec} \quad (5)$$

Electronics energy, E_{elec}, depends on quantity of sensing and actuation action, coding, modulation techniques, filtering, transmission, and reception of signal, and amplifier energy, ε_{fs} or ε_{mp}, depends on distance to receiver and acceptable BER.

III. FUCP Operation

Operation of FUCP involves network setup, neighbor finding, and steady-state phase.

A.Network setup

Step 1. MS transmits BECON_MESG (comprising its ID, location, timing information for synchronization, transmitting power) with signal strength large enough to reach R_{max} m.

Step 2. Each node then uses received signal power to find its distance from MS. Using two-ray ground radio propagation model, distance between MS and node *i* is given by,

$$dist(i) = \sqrt[4]{\frac{P_{MSt}G_{MSt}G_{ir}h^2_{MSt}h^2_{ir}}{P_{ir}L}} \quad (6)$$

where P_{MSt} and P_{ir} is power, G_{MSt} and G_{ir} is gain, h_{MSt} and h_{ir} is height overhead ground for transmitting antenna of MS and receiving antenna of node *i* respectively [14]. *L* is path loss. Based on their distances each node finds its layers.

Next ***Steps 1*** and ***2*** are reiterated with MS increasing its signal strength to reach successive layers. This iteration is carried out to cover entire sensing area. Each node then finds its hexagon by considering first layered-hexagon centered at the MS. At the completion of network setup phase, each node is aware of its hexagon. The resultant layered-hexagon lattice network model formed is shown in the Fig. 1 where L1 to L4 are hexagon layers from layer 1 to layer 4.

B.Neighbor finding:

To gather neighborhood information each node broadcasts NODE_INFO_MESG (containing its ID, hexagon ID and

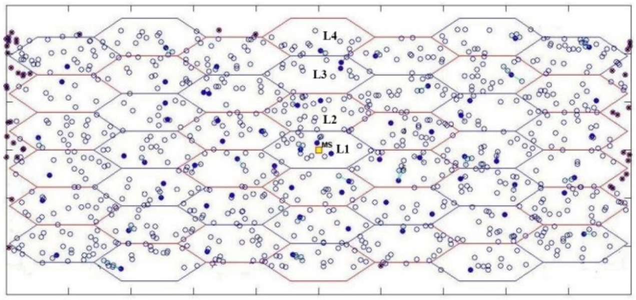

Fig. 1. FUCP network model

location) with signal strength enough to reach all nodes in its hexagon using a nonpersistent CSMA MAC protocol [14].

C. Steady-state:

Steady-state phase consists of rounds as discussed next.

- **Cluster Head Selection:** Nodes make independent decisions for becoming cluster heads using Fuzzy Inference System (FIS) without any centralized control. Mamdani Model is used for developing FIS for cluster head selection as discussed next [15].

i) Fuzzification of inputs and outputs:

Input variables:

Residual Energy (*represented by* ENERGY): It is energy remaining in the node. To become a cluster head, node should have more ENERGY compared to its neighbors.

Centerness of node (*represented by* HEX_CENTER): It is distance of node from center of hexagon. To become a cluster head, node should have low HEX_CENTER to decrease intra-cluster communication cost.

Link Quality Indicator (*represented by LQI*): It is the average of link quality indicator of links between a node and all its neighbors. *LQI* of a node *i* is defined as,

$$LQI(i) = \frac{1}{N}\left(\sum_{j=1}^{j=N-1} LQI_{ij}\right) \qquad (7)$$

where *N* is total number of nodes in the hexagon, LQI_{ij} is *LQI* of node *i* and *j*. To become a cluster head, node should have a higher value of *LQI*. Nodes calculate their *LQI* during their neighbor finding phase.

Output variable:

Chance (*represented by* PROSPECT): It is likelihood of node to become a cluster head. A large value of PROSPECT indicates a more likelihood of node to become a cluster head.

The linguistic variables used to characterize ENERGY, HEX_CENTER, LQI of node are separated into three levels: low, medium and high. The linguistic variable to characterize PROSPECT of node is separated into seven levels: very small, small, rather small, medium, rather large, large, and very large.

ii) Defining membership functions: Triangle membership functions are used to characterize the fuzzy input sets medium and trapezoid membership functions to characterize low and high fuzzy sets. Similarly, triangle membership functions are used to characterize output sets small, rather small, medium, rather large, large, and trapezoid membership functions to characterize very small and very large fuzzy sets.

L=Low, M=Medium, H=High, S=Small, RS=Rather Small, VS=Very Small, L=Large, RL= Rather Large, VL=Very Large				
Rules	**Antecedents**			**Consequents**
	ENERGY	**HEX_CENTER**	**LQI**	**PROSPECT**
1	L	L	L	S
2	L	L	M	RS
3	L	L	H	M
4	L	M	L	S
5	L	M	M	RS
6	L	M	H	M
7	L	H	L	VS
8	L	H	M	S
9	L	H	H	RS
10	M	L	L	RL
11	M	L	M	RL
12	M	L	H	L
13	M	M	L	L
14	M	M	M	RL
15	M	M	H	L
16	M	H	L	RS
17	M	H	M	M
18	M	H	H	RL
19	H	L	L	RL
20	H	L	M	L
21	H	L	H	VL
22	H	M	L	L
23	H	M	M	RL
24	H	M	H	L
25	H	H	L	M
26	H	H	M	RL
27	H	H	H	L

Table 1 Fuzzy rule base for cluster head selection

iii) Application of fuzzy operators and fuzzy rule evaluation: With three input variables and three levels for each, there are 3^3 =27 possible combinations for Rule base. Table 1 shows fuzzy rule base for cluster head selection.

iv) Aggregation and Defuzzification: Finally maximum region covered for output value is taken for aggregation of outputs and centroid of area method is procedure for defuzzification.

- **Deciding number of cluster heads in a layered-hexagon:** If nodes in a hexagon are far from each other (scattered), cluster heads should be more to decrease the intra-cluster communication cost. Further, with multihop architecture nodes close to the MS are loaded with large amount of traffic consisting of relay packets from distant cluster heads, data packets generated by its cluster members, and its own data packets. Thus, there should be more cluster heads near the MS to dispense load midst the cluster heads evenly and avoid *hot spots*. To address these issues, FUCP decides number of cluster heads in a hexagon based on the scatter factor and distance of hexagon from MS. FIS for deciding number of cluster heads in a hexagon is discussed next.

i) Fuzzification of inputs and outputs:

Input variable:

Node scattering factor (*represented as* SCATTER_FACTOR): It is average of distance of each node to other node in the same hexagon. SCATTER_FACTOR for a hexagon will be high if nodes are scattered and far from each other compared to hexagon which has nodes very near to each other. Thus, if SCATTER_FACTOR is high more number of cluster heads are required in that hexagon to reduce intra-cluster communication cost. Sum of distance *Dis(i)* from a node *i* to each node in the same hexagon is,

$$Dis(i) = \left(\sum_{j=1}^{j=N-1} d(i,j) \right) \qquad (8)$$

where *Num* represents total nodes in the hexagon, d_{ij} is distance between node *i* and *j*. The SCATTER_FACTOR *Scatter(h)* of a hexagon *h* is then given as,

$$Scatter(h) = \frac{Dis(1) + Dis(2) + ... + Dis(N)}{Num} \qquad (9)$$

Distance of hexagon from MS (*represented as* HEX_DISTANCE): It is distance from center of hexagon to the MS. To share forwarding traffic amongst cluster heads near the MS in a multihop inter-cluster routing scenario, there should be more number of cluster heads near MS.

Output variable:

Number of cluster heads in the hexagon (*represented by* CLUSTER_HEAD_NUMBER): It characterizes number of cluster heads that should be elected in the hexagon.

Cluster head advertisement radius (*represented by* RADIUS): It is the maximum radius within which the node does cluster head advertisement. To avoid *hot spots* problem cluster heads near MS will have smaller value of RADIUS and those which are far will have a larger value of RADIUS. With less RADIUS, less number of members will join its cluster heads near MS. This preserves their energy for forwarding data packets of distance cluster heads. Cluster heads far from MS will have large RADIUS and hence will have more cluster members increasing their intra cluster traffic. However, since these cluster heads have less relay packets their inter cluster traffic is less. Thus, the overall network energy consumption is well-adjusted.

The linguistic variables to characterize SCATTER_FACTOR and HEX_DISTANCE are separated into three levels: low, medium and high. The linguistic variable to characterize CLUSTER_HEAD_ NUMBER and RADIUS is separated into three levels: low, medium and high.

L=Low M=Medium H=High				
Rules	**Antecedents**		**Consequents**	
	SCATTER_ FACTOR	**HEX_ DISTANCE**	**CLUSTER_HE AD_NUMBER**	**RADIUS**
1	L	L	M	L
2	L	M	L	M
3	L	H	L	M
4	M	L	H	L
5	M	M	M	M
6	M	H	L	H
7	H	L	H	M
8	H	M	H	H
9	H	H	M	H

Table 2 Fuzzy rule base for number of cluster heads in a hexagon

ii) Defining membership functions: Triangle membership functions is used to characterize fuzzy input/output sets medium and trapezoid membership functions to characterize low and high fuzzy sets.

iii) Application of fuzzy operators and rule evaluation: With two input variables and three levels for each, there will be 3^2 i.e. 9 possible combinations to define rule base. Table 2 shows fuzzy rule base for number of cluster heads in a hexagon.

iv) Aggregation and Defuzzification: Finally maximum region covered is used for deciding the output value and centroid method is used for defuzzification.

Each node calculates PROSPECT value and then use a non-persistent CSMA MAC protocol [14] to advertise a PROSPECT_MESG (containing PROSPECT, ID and hexagon ID) to reach nodes within its hexagon. The node with the highest PROSPECT value within the hexagon becomes a leader cluster head. The leader cluster head then runs FIS to find number, actual cluster heads and cluster head advertisement in its hexagon. It broadcasts a PROSPECT_INFO_ MESG (containing list of chosen cluster heads with their PROSPECT and RADIUS value) in its hexagon. A node on receiving this message from a neighbor in its hexagon, adds neighbor's PROSPECT details in its NIT.

- **Cluster set up:** The cluster head then uses a non-persistent CSMA MAC protocol [14] to broadcast CLUSTER_HEAD_ADV_MESG (containing node's ID) within its RADIUS by setting it's transmit power. Each non-cluster head node then chooses its cluster head as one for with highest received signal strength of CLUSTER_HEAD_ADV_MESG assuming it to be the nearest cluster head. If there are ties, cluster head with least ID is chosen. Each node then sends JOIN_CLUSTER_MESG (with node's ID and cluster head's ID) to its chosen cluster head using a non-persistent CSMA MAC protocol. The cluster head decides TDMA schedule for data transmissions for cluster members. It then transmits schedule to its cluster members. On completion of first round all nodes in network know their cluster, their cluster members, and their PROSPECT value. Thereafter, the data gathering phase starts.
- **Data gathering at cluster head:** This operation is broken into frames. Non-cluster heads send their data to cluster head once per frame. This is done during designated transmission slot to decrease collisions. To save energy and avoid interference, cluster members send data with minimum transmit power required to reach their cluster head and turn off their radio for rest of time. On getting data cluster head does data aggregation and forwards it to MS through neighbor cluster heads.
- **Data transfer to MS:** For data transfer to MS, a simple forwarding mechanism is used, in which source node in *layered-hexagon* selects node in layer towards MS as its forwarding node to send the data packet.

IV. SIMULATION AND ANALYSIS OF FUCP

In the straightforward versions of LEACH and CHEF, each cluster head communicates directly with MS and hence any reasonable scheme using multi-hop routing will do better than both of them. Therefore, performance of FUCP is compared with LEAH+MTE, CHEF+MTE and clustering protocols like HEED and DWEHC. In LEACH+MTE protocol configuration, cluster head selection and cluster formation algorithms are used as defined in LEACH and MTE [18] is used for inter-cluster routing to route data to MS. Similarly for CHEF+MTE, cluster head selection is done by CHEF algorithm and inter-cluster routing by MTE. The simulations are performed using Matlab [22] with 1000 nodes randomly deployed in 100×100 m area and MS at (0,0) m as in Fig. 2. Initial energy of all the nodes is 0.5 J, size of data packet is 6400 bits, size of control packet is of 100 bits, radio parameters are: E_{DA}=5 nJ; E_{elec}=50nJ/bit; ε_{f_s}=10 pJ/bit/m^2; ε_{mp}=0.0013 pJ/bit/m^4 and $d_{crossover}$= 87.7 m.

To check energy efficiency of all protocols amount of residual energy of nodes is traced every 20 rounds. As in Fig. 3, FUCP is about 40% more energy efficient compared to DWEHC. As the network runs, nodes consume their energy. At some point of time they can no longer transmit or receive data and are said to be dead. As seen in Fig. 4, total number of nodes that die over simulation rounds is much slower in FUCP compared to other protocols.

Fig. 5 shows that FUCP sends maximum number of data packets to MS compared to other protocols. More specifically, FUCP sends 57% more packets to MS compared to DWEHC. Fig. 6 shows network lifetime performance in expressions of first node dies (FND), half of the nodes alive (HNA), and last node dies (LND) for all the protocols. As seen in the figure FUCP has 31% more network lifetime compared to DWEHC. Finally, Fig. 7 shows average energy consumed by cluster heads is minimum in FUCP and variation in energy consumption is also less compared to other protocols.

The explainations of all above results are discussed next. The number of cluster heads generated in DWEHC is almost double than that generated in FUCP. This increases contention and hence energy consumption during data transmissions to MS. The performance of LEACH protocol is poorest because it uses probabilistic method for cluster head selection which does not take into account node parameters like energy or location. HEED and CHEF+MTE show moderate performance. The restrictions in cluster head selection in HEED results in many forced cluster heads and single node clusters which increases interference among cluster heads and hence overall energy consumption of nodes. Energy consumption in HEED further increases due to several iterations required for cluster head selection. Further tentative cluster heads in HEED are randomly selected residual energy and hence residual energy is not deterministic factor for the final cluster head election. Use of MTE for inter-cluster routing in CHEF does not equally distribute energy consumption among the nodes and creates several *hot spots* near MS. FUCP uses fuzzy logic with residual energy and centerness of node with respect to its neighbor for cluster head selection. This distributes energy consumption of nodes and also decreases intra-cluster communication cost.

Further, use of fuzzy logic with unequal clustering node distribution and distance from master station to decide number of cluster heads and cluster head advertisement radius in a given area forms unequal clusters. This lessens energy consumption of nodes adjacent to MS and in turn avoids *hot spots* and decreases number of dead nodes for all the rounds. Use of LQI for cluster head selection and parameters for selection of relay node increases number of packets received at MS in case of FUCR compared to other protocols.

V. CONCLUSION

This paper proposes FUCP protocol for WSN that minimizes energy consumption of cluster head by choosing cluster heads with: high residual energy; at center with respect to neighboring nodes (to decrease intra-cluster communication cost). Use of LQI for cluster head election increases reliability in intra-cluster communication. To avoid *hot spots* problem FUCR uses fuzzy logic with node distribution and distance from MS to decide number of cluster heads and their cluster head advertisement.

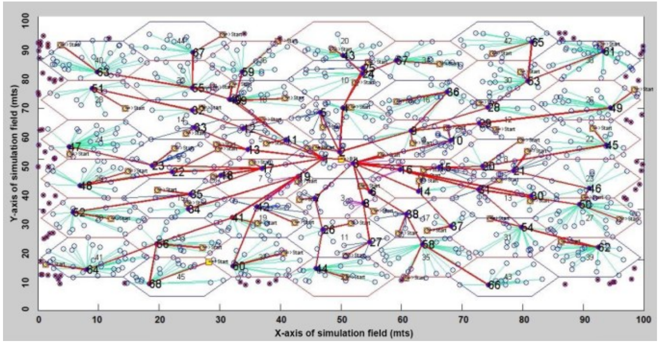

Fig. 2. Cluster formation and routing in FUCP

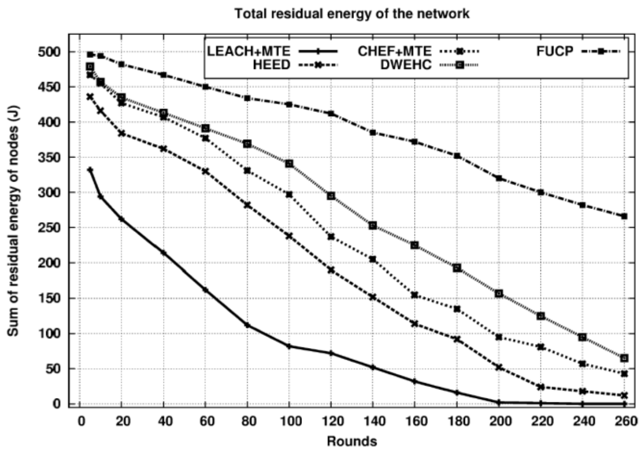

Fig. 3. Cluster formation and routing in FUCP

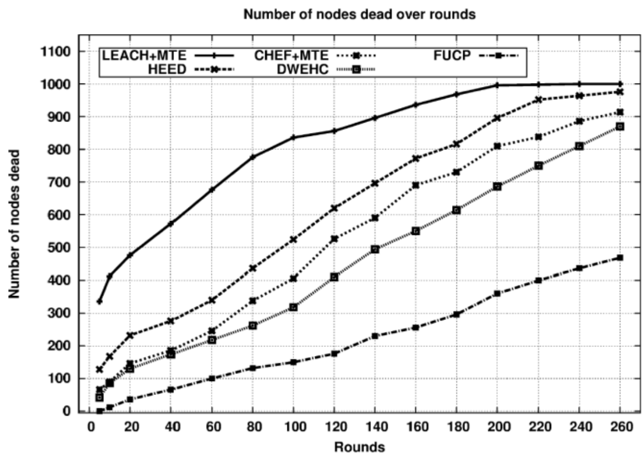

Fig. 4. Number of nodes dead over rounds

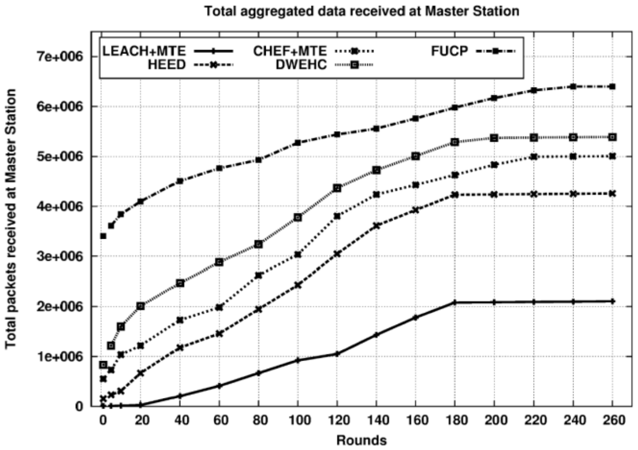

Fig. 5. Total data received at MS over rounds

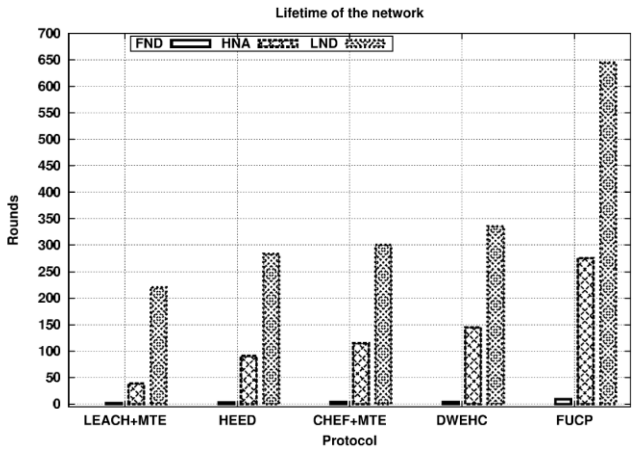

Fig. 6. Time when FND, HNA, LND

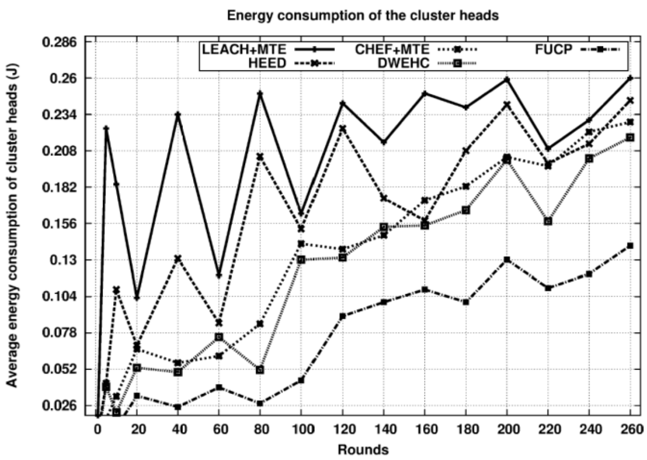

Fig. 7. Energy consumption of cluster heads over rounds

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