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Procedia Computer Science 46 (2015) 1014 – 1021

Procedia Computer Science

International Conference on Information and Communication Technologies (ICICT 2014)

FAMACRO: Fuzzy and Ant Colony Optimization based MAC/Routing Cross-layer Protocol for Wireless Sensor Networks

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Abstract

This paper presents Fuzzy and Ant Colony Optimization (ACO) based MAC/Routing cross-layer protocol (FAMACRO) for Wireless Sensor Networks that encompases cluster head selection, clustering and inter-cluster routing protocols. FAMACRO uses fuzzy logic with residual energy, number of neighboring nodes and quality of communication link as input variables for cluster head selection. To avoid “hot spots”, FAMACRO uses an unequal clustering mechanism with clusters closer to master station having smaller sizes than those far from it. Finally, ACO techinque is used for reliable and energy-efficient inter-cluster routing from cluster heads to master station. The inter-cluster routing protocol decides relay node considering its residual energy, distance from current cluster head, distance from master station and packet reception rate. A comparative analysis of FAMACRO with Distributed Energy Efficient Hierarchical Clustering, Unequal Hybrid Energy Efficient Distributed Clustering, Energy Efficient Unequal Clustering and Improved Fuzzy Unequal Clustering protocol shows that FAMACRO is 82 % more energy-efficient, has 5 % to 30 % more network lifetime and sends 91 % more packets compared to Improved Fuzzy Unequal Clustering protocol.

Peer-review under responsibility of organizing committee of the International Conference on Information and Communication Technologies (ICICT 2014)

Keywords: wireless sensor networks; cluster head selection; clustering; inter-cluster routing; cross-layering; fuzzy logic; ant colony optimization

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Peer-review under responsibility of organizing committee of the International Conference on Information and Communication Technologies (ICICT 2014)
doi:10.1016/j.procs.2015.01.012

1. Introduction

Wireless Sensor Network (WSN) applications range from as simple as precision agriculture, civil infrastructure monitoring, tracking animals to hard to imagine like Internet of things and planetary explorations[1]. The nodes in a typical WSN setup have limited computational, storage and power capabilities and are deployed in hostile environments[2]. This demands energy-efficient, reliable, scalable yet simple WSN protocol stack. This can be achieved by: (i) using cross-layer protocol design that exploit richer interaction among communication layers for decision making (ii) using computational intelligence in protocol design to adapt to complex and changing communication environment (iii) using a hierarchical clustered network in which cluster members transmit their data to cluster heads which relays it to master station (MS) through intermediate cluster heads. Due to limited resources of node, breaking the layered approach helps in protocol design. For example, use of information of signal strength received from a neighboring node (physical layer information) can assist routing protocols (at network layer) to decide next hop in the route (signal is weak if node is far and should not be used as next hop). The protocol design by creating new interfaces between layers (for information sharing), redefining layer boundaries, co-operative tuning of parameters among layers is cross-layer design[3]. Computational Intelligence techniques like fuzzy computing, Ant Colony Optimization (ACO), neuro-computing, reinforcement learning, artificial immune systems have been successfully used to address WSN issues like cluster head selection, routing, data aggregation, security and localization[4]. Clustering offers advantages like: it reduces collision among cluster members by coordinating their media access; balances load by rotating cluster head; reduces information updates as node deaths and joins in a cluster need to be updated only by cluster members; offers scalability and spatial reuse as non-neighbor clusters may use same frequency or code for transmission.

This paper proposes FAMACRO, a cross-layer protocol that combines ideas of energy-efficient hierarchical cluster routing and media access. It uses a fuzzy based cluster head selection technique for selecting nodes with high residualy energy, having more number of neighboring nodes and high quality of communication link. One of the issues of hierarchical clustering is “hot spots” problem which arises due to heavy relay traffic for cluster heads close to MS making them die earlier. This leads to serious connectivity and coverage problems in area close to the MS. To overcome this problem, FAMACRO organizes the network into clusters of unequal sizes with clusters closer to MS having smaller sizes than those far from it. Thus, cluster heads near MS will have less amount of intra-cluster traffic preserving their energy for inter-cluster relay traffic. Finally, for reliable and energy-efficent data transfer to MS, FAMACRO uses ACO techinque for inter-cluster routing from cluster heads to MS. It selects relay cluster head which is: having high residual energy and packet reception rate; is near to current cluster head (to decrease inter-cluster transmission energy); is near to MS (to reduce energy to transmit data to MS).

The remainder of the paper is organized as follows: Section 2 discusses related work. FAMACRO operation is introduced in Section 3. Section 4 provides comparative analysis of FAMACRO with four well referred protocols of similar complexity. Finally, the paper is concluded in Section 5.

2. Related work

Several hierarchical clustering protocols have been proposed for energy efficient data gaterhing in WSN[5]. Hybrid Energy Efficient and Distributed (HEED)[6] periodically selects cluster heads based on a hybrid of two node parameters: residual energy to select an initial set of cluster heads and intra-cluster communication cost for final set. This improves energy efficiency of HEED but its clustering process requires several iterations and a lot of control packets are broadcast in each iteration. Distributed Energy Efficient Hierarchical Clustering (DWEHC) [7] clustering protocol builds multi-level clusters with a cluster head with its first level child, second level child, and so on. For intra-cluster communiction it uses TDMA and for transmissions from cluster head to MS it uses 802.11 based MAC[8]. A limit on number of child nodes makes DWEHC scalable. However, 802.11 based MAC mechanisms are not energy-efficient solutions for multihop wireless networks[9]. Both the above protocols use multihop routing for inter-cluster communicaiton from cluster heads to MS. In this model cluster heads near MS are loaded with heavy traffic consisting of: relay packets (from distant cluster heads); data packets from its cluster members and its own data packets. Unequal HEED (UHEED)[10] overcomes this problem by unequal clustering algorithm based on HEED. In HEED, each cluster head has similar cluster head competition radius leading to uniform clusters throughout the network. UHEED uses competition radius proposed in Energy-Efficient Unequal Clustering (EEUC)[11]. The competition radius in UHEED and EEUC is a function of distance from MS and creates smaller clusters near MS. EEUC also proposes multihop routing protocol for inter-cluster communication which chooses relay cluster head based on energy and distance to MS. UHEED being an extension of HEED suffers from all the disadvantages of HEED. The cluster head selection in EEUC is done only on the basis of residual energy without considering their distance from MS, which might lead to improper cluster head selection. Improved fuzzy unequal clustering (IFUC) protocol uses node's energy, distance to MS and local density as fuzzy descriptors to select cluster heads and also to estimate the cluster head competition radius[12]. ACO is then used to route data packets from cluster heads to MS to balance energy consumption and lengthen the network lifetime. The tentaitve cluster heads in IFUC are selected randomly, which then run fuzzy logic for final cluster head selection. Thus, there are chances that nodes with less residual energy, ones which are far from MS or having less neighboring nodes might become final cluster heads. Energy-Efficient Clustering Scheme (EECS) [13] uses a distance based unequal cluster formation method in single hop networks. It introduces a weight function which lets clusters far from MS have larger sizes. Energy driven unequal clustering protocol (EDUC) [14] is another protocol in which clusters are formed with unequal cluster head competition radius. EDUC also makes sure that each node becomes a cluster head only once during the network lifetime. Both EECS and EDUC being a single hop architecture, consume more energy compared to a multihop architecture[15]. Unequal Clustering Size (UCS)[16] is an energy-efficient protocol for both homogenous and heterogeneous networks with heavy traffic applications. For heterogeneous network, UCS requires certain nodes with more energy (super nodes) to be positioned at some predetermined locations to control cluster sizes. However, in real life WSN applications this requirement would be difficult to meet with. Some of the other unequal clustering protocols are: Unequal layered clustering approach[15], Multihop routing protocol with unequal clustering[17], Energy aware fuzzy unequal clustering algorithm[18].

Most of the protocols cited above do not take the advantage of cross layering techniques that enable a closer coordination between layers to achieve performance gains in terms of network lifetime and reliability[19,20]. To this end, this paper presents FAMACRO, a cross-layer protocol that gives a complete solution for: energy-efficient cluster head selection using fuzzy logic; clustering with technique to avoid "hot spots"; reliable and energy-efficient inter-cluster routing using ACO.

3. FAMACRO operation

The operation of FAMACRO consists of network setup and steady-state phase.

3.1. Network setup

During this phase nodes in the network are organized into "layers" as described in the steps below.

Step 1. MS sends SETUP_MSG message (containing its ID, (x, y) location co ordinates, timing information to synchronize nodes' clocks, transmitting power information P_{MSt}) with signal strength large enough to reach R_{max} m (maximum transmission range of node).

Step 2. Each node estimates its distance from MS using two-ray ground radio propagation model as given below,

$$dis(i) = \sqrt[4]{\frac{P_{MSt} G_{MSt} G_{ir} h_{MSt}^2 h_{ir}^2}{P_{ir} L}} \tag{1}$$

where P_{MSt} and P_{ir} is power, G_{MSt} and G_{ir} is gain, h_{MSt} and h_{ir} is height above ground for MS transmitting antenna and node i receiving antenna respectively[21]. L is path loss. Each node uses the calculated distance to find its layer as discussed next. The first layer is a circular ring with centre at MS and radius as R_{max} m. The second layer is a circular ring with centre at MS, outer radius of R_{max} x 2 m and inner radius of R_{max} x (2-1) m. In general, each N^{th} layer is a co-centric circle with centre as MS, outer radius of R_{max} x N m and inner radius of R_{max} x $(N-1)$ m.

Steps 1 and 2 are then repeated and in each iteration, MS increases signal strength of SETUP_MSG to reach consecutive layers. This is continued until entire sensing field is covered and thus each node knows its layer. Each node then uses a non-persistent CSMA MAC protocol[22] to brodcast a HELLO_MSG message (containing its ID, layer number, location) with signal strength large enough to reach all neighborhing nodes in its layer. On receiving the message each node stores information of neighboring node in its neighborhood table.

3.2. Steady-state

It is divided into rounds consisting of cluster head selection, clustering and data delivery to MS.

- Cluster Head Selection: Nodes make independent decisions for becoming cluster heads using Fuzzy Inference System (FIS) with Mamdani model[23]. FIS design for cluster head is discussed next.
- *Input variables for FIS*
- *Residual energy (represented by* ENERGY*):* It is energy remaining in the node. To become a cluster head, a node should have more ENERGY compared to its neighbouring nodes.
- *Node's neighbourhood nearness (represented by* NBR_NR): NBR_NR*(x)* of a node *x* is defined as,

$$NBR\_NR(x) = \frac{1}{N_{TR}}\left(\sum_{y=1}^{y=N_{TR}-1} d(x,y)\right) \tag{2}$$

where N_{TR} is total number of nodes within transmission range and layer of *x*, *d(x,y)* is distance between node *x* and *y*. To become a cluster head, node should have more nodes in its transmission range to decrease intra-cluster communication cost and consequently should have a lesser value of NBR_NR.

- *Link Quality Indicator (represented by NBR_LQI*): Link Quality indicator (LQI) describes packet reception quality at the node and can be estimated by radio chips like CC2500[2]. NBR_LQI is average of link quality indicator of links between a node and neighbours in its transmission range. Deterioration in reception quality of packet is manifested with decrease in LQI[24]. Thus, for a node to become a cluster head it should have a high NBR_LQI.
- *Output variable for FIS*
- *Capability of becoming a cluster head* (*represented by* CAPABILITY): A large value of CAPABILITY indicates a high possibility of a node to become a cluster head.

Linguistic variables representing node's ENERGY, NBR_NR and NBR_LQI are: low, medium and high. For node's CAPABILITY they are: very small, small, rather small, medium, rather large, large, and very large.

- *Defining membership functions*: Triangle membership functions are used to represent fuzzy input sets medium and trapezoid to represent low and high. Similarly, triangle membership functions are used to represent output sets small, rather small, medium, rather large, large and trapezoid membership functions to represent very small and very large.
- *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. "if then" rules with "and" operators among input variables falling between following two extreme cases are defined:

Case (1): If (ENERGY is low) and (NBR_NR is high) and (NBR_LQI is low) then (CAPABILITY is very small)
Case (2): If (ENERGY is high) and (NBR_NR is low) and (NBR_LQI is high) then (CAPABILITY very large)

- *Aggregation of all Outputs*: Maximum region covered for the output value is used for aggregation of outputs.
- *Defuzzification*: Centroid method is used for defuzzification.

Each node calculates its CAPABILITY value using fuzzy if-then rule discussed above. It then uses non-persistent CSMA MAC protocol[22] to advertise a CONTEND_MESG message (containing its ID, CAPABILITY and layer number) to reach nodes within its layer. The node with highest CAPABILITY value becomes a cluster head.

- Clustering: Cluster heads advertise their role by sending CHADV_MESG message (containing its ID, header) within its R_{adv} (advertisement radius) using non-persistent CSMA MAC protocol. Cluster head ch_i, calculates R_{adv} as,

$$R_{adv}(ch_i) = \left[\left\{1 - w\frac{d_{\max} - d(ch_i, MS)}{d_{\max} - d_{\min}}\right\} \times \left\{\frac{(E_{current})_{ch_i}}{(E_{initial})_{ch_i}}\right\}\right] R_{adv}^{\max} \tag{3}$$

where, $d_{\max}$ and $d_{\min}$ is maximum and minimum distance between nodes and MS respectively, $d(ch_i, MS)$ is distance between ch_i and MS, $E_{current}$ and $E_{initial}$ are ch_i's current energy and initial energy, $R_{adv}^{\max}$ is maximum advertisement radius. *w* decides degree of inequality in cluster size and is kept between 0 and 0.99. Thus, cluster heads near MS will have lesser and far ones will have a larger value of R_{adv}. As a result, less members will join cluster heads near MS decreasing the intra-cluster traffic. This will preserve their energy to relay packets from distance cluster heads. Cluster heads far from MS will have more cluster members. Each normal node selects its cluster head as one with largest received signal strength of CHADV_MESG assuming it to be closet cluster head. In case of ties, cluster head with least ID is chosen. Nodes then send CMREQ_MESG message (containing its ID, cluster head ID) to their respective cluster heads. The cluster head sets up TDMA schedule for intra-cluster communication with cluster member having highest CAPABILITY given first time slot schedule and rest are in ascending order. Each cluster head then transmits schedule to its cluster members. For certain upcoming rounds, clusters are static and cluster heads are rotated among cluster members as per sorted CAPABILITY values (static clustering). Thus CHADV_MESG and CMREQ_MESG need not be sent for each round saving time and energy of nodes. Rotation of cluster head equally distributes energy load among all nodes in network. The static clustering is discontinued when network condition deteriorates and clustering is done afresh. The data gathering operation starts once TDMA schedule is known to all cluster members. It is broken into frames with each cluster member sending data packets to its cluster head once per frame during their allocated transmission slot, which reduces collisions. Node's radio is shut down for rest of the time to save energy. When cluster head receives data packets, it performs data aggregation and relays aggregated data to MS through several cluster heads during data delivery to MS.

- Data delivery to MS: ACO[25] used for inter-cluster routing and data delivery to MS is discussed next.

Step 1. Each cluster head broadcasts a RTINFO_MESG message (containing its ID, residual energy, location, Packet Reception Rate (PRR) (i.e. number of packets successfully received within a time period)) to reach to nodes within two layers. Each cluster head s_i then defines a probable relay set PR_{CH} for choosing relay cluster head as,

$$\mathrm{PR_{CH}}(\mathrm{s_i}) = \left\{\mathrm{s_j} \middle| \mathrm{d}(\mathrm{s_i},\mathrm{s_j}) \le \mathrm{m} \times \mathrm{R_{adv}}(\mathrm{s_i});\, \mathrm{d}(\mathrm{s_j},\mathrm{MS}) < \mathrm{d}(\mathrm{s_i},\mathrm{MS})\right\} \tag{4}$$

where m is minimum integer to let $PR_{CH}(s_i)$ contain at least one item and is set to 2 x R_{max} m for simulations done in paper. Probable relay cluster head selection ensures that data is forwarded in right direction towards MS.

Step 2. To determine a path to MS an ant is placed at each cluster head at regular intervals. The ant determines relay cluster head according to the following equation,

$$\mathrm{Pr}_{ij}^{k} = \frac{[\tau_{ij}(t)]^{\alpha}[\eta_{ij}]^{\beta}}{\sum_{s\in PR_{CH}(s_i)}[\tau_{is}(t)]^{\alpha}[\eta_{is}]^{\beta}} \tag{5}$$

where Pr_{ij}^{k} is probability with which ant k decides to move from node s_i to node s_j. $PR_{CH}(s_i)$ is set from which relay cluster head is to be chosen by k^{th} ant, $\tau_{ij}(t)$ is the pheromone trail value of edge (S_i, S_j) and η_{ij} is the heuristic information value defined as,

$$\eta_{ij} = \frac{RE_j}{\sum_{s\in PR_{CH}(s_i)} RE_s} \times \frac{1}{d^2(s_i,s_j) + d^2(s_j,MS)} \times \frac{PRR_j}{\sum_{s\in PR_{CH}(s_i)} PRR_s} \tag{6}$$

η_{ij} confirms that cluster head with following characteristics is selected as relay (i) having high PRR (to choose reliable communication link) (ii) having high residual energy (iii) near the current cluster head (to decrease inter-cluster communication energy) (ii) nearer to MS (to decrease communication energy to MS). $\tau_{ij}(t)$ ensures that if there are a lot of ants passing between link (S_i,S_j) then it is highly appropriate to use that link. α and β regulate relative effect of pheromone trail and heuristic information.

Step 3. The ants passing through nodes collect path information and reach MS. The MS begins to analyse data after arrival of k^{th} ant. The information collected by k^{th} ant is $\{(S_0,d_{(s0,s1)}), (S_1,d_{(s1,s2)}), (S_2,d_{(s2,s3)}),.., (S_{m-1},d_{(sm-1,sm)})\}$ where S_0 is source cluster head and S_m is destination, the MS. The set of discrete nodes $S\{S_0, S_1, S_2 \ldots S_m\}$ constitutes the path. A function W is defined to estimate the worthiness of path S as below,

$$W_s = \frac{T}{Rate_s \times Vari} \tag{7}$$

where T is constant, $Rate_s$ is communication cost of path S, $Vari$ is variance representing extent of energy balanced among edges in the path. For a lesser distance between transmitter and receiver, energy consumption is proportional to square of transmission distance[21]. Thus,

$$Rate_s = \sum_{x=1}^{m} R_x = \sum_{x=1}^{m} x d^2(S_{x-1},S_x) \tag{8}$$

where R_x is energy consumption in the edge (S_{x-1}, S_x).

The *Vari* is given as,

$$Vari = \frac{1}{m} \times \sum_{x=1}^{m} \left(R_x - \frac{1}{m} \times \sum_{x=1}^{m} R_x \right)^2 \tag{9}$$

Thus, with W_s function MS will get the best path in one iteration. MS then broadcasts UPDT_MESG message (containing path details, its merit) to nodes along the best path to update the pheromone trail value as,

$$\tau_{ij}(t+n) = (1-\rho)\tau_{ij}(t) + \Delta\tau_{ij}$$
$$\Delta\tau_{ij} = W_{s(best)} \tag{10}$$

where ρ is pheromone decay value and thus $(1-\rho)$ is reservation of pheromone since the last time updated. $W_{s(best)}$ is the merit of best path found in an iteration. After several iterations of Step 2 and Step 3, each cluster head node finds best relay and transmits it the data. This is repeated till data reaches MS.

4. Comparative analysis of FAMACRO

Performance of FAMACRO is compared with DWEHC, UHEED, EEUC and IFUC protocols. The simulations are performed using Matlab[26] (for running fuzzy logic) and Network Simulator NS2[27]. The network scenario consist of 1000 nodes randomly deployed in 1000×1000 m area and MS at centre (0,0). Initial energy of all nodes is 0.5 J, data packet is of 6400 bits, control packet is of 100 bits. For node's energy dissipation, model[28] is used with radio parameters E_{DA}=5 nJ/bit/signal; E_{elec}=50 nJ/bit; ε_{fs}=10 pJ/bit/m^2 ; ε_{mp}=0.0013 pJ/bit/m^4, $d_{crossover}$= 87.7 m, R_{max} =80 m, $R_{adv}^{\max}$ =64 m and w=0.5. Initial parameters for ACO algorithm are: α and β=0.5, ρ=0.2, T = 6 x 10^9, initial pheromone value is between 0.000005 to 0.00001, number of iterations = 500 and number of ants = 20. Twenty simulations with different seeds were run for each scenario and average values were accepted as results. Fig. 1 shows cluster formation, unequal clustering and inter-cluster routing to MS in one of the rounds of FAMACRO.

To investigate energy efficiency of protocols sum of residual energy of nodes is traced every 20 rounds. As seen in Fig. 2, FAMACRO is about 82 % more energy-efficient compared to IFUC. At end of each simulation round nodes consume their energy and are finally said to be dead when they can no longer transmit or receive data. Fig. 3 shows total number of nodes that die over simulation rounds is much slower in FAMACRO. Fig. 4 shows number of data packets received at MS in FAMACRO is highest among all protocols and is 91 % more than IFUC. As seen in the Fig. 5, network lifetime in terms of first node dies (FND), half of the nodes alive (HNA) and last node dies (LND) is best for FAMACRO. It is 5 % to 30 % more than IFUC. Finally, Fig. 6 shows energy consumption in cluster heads during each round is least in FAMACRO.

The explainations of all the above results are discussed next. The energy consumption in DWEHC is maximum and lifetime is minimum because it generates maximum cluster heads compared to all other protocols. This increases contention during data transfer to MS. Further, it does not use unequal clustering which generates "hot spots" and decreases number of data packets received at MS. The node requirements for cluster head selection in UHEED results in several forced cluster heads and single node clusters. This in turn increases energy required to transfer data from cluster heads to MS especially when forced cluster heads are far from MS. It also increases interference among cluster heads and hence overall energy consumption of nodes.

EEUC and IFUC show improved network lifetime and reduction in energy consumption of nodes due to unequal clustering and energy-efficient inter-cluster data forwarding. Performance of IFUC is better than DWEHC, UHEED and EEUC because it uses fuzzy logic for cluster head selection and calculation of cluster head competition radius. Cluster head selection ensures that node's with high residual energy and those near MS are selected as heads decreasing overall energy consumption of network. Competition radius in IFUC is calculated such that large size clusters are formed at distances far from MS and smaller ones near MS to evenly distribute traffic amongst cluster heads. This decreases number of nodes dying and increases data packets received at MS.

Performance of FAMACRO is best because selection of cluster heads with maximum number of neighbouring nodes decreases overall intra-cluster communication cost and selection of nearby relay cluster head decreases inter-cluster communication cost. This decreases overall energy consumption of the network. Avoiding cluster advertisement and join messages by keeping clusters fixed and rotating cluster heads after first round saves network energy. Unequal clustering does a uniform energy distribution in the network. Finally, use of LQI for cluster head selection and PRR as metric for selection of relay cluster head increases number of packets received at MS.

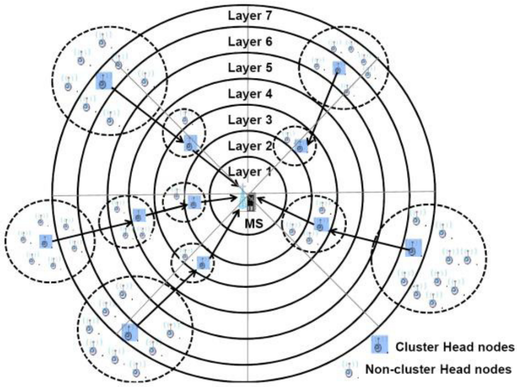

Fig. 1. Cluster formation and routing in FAMACRO

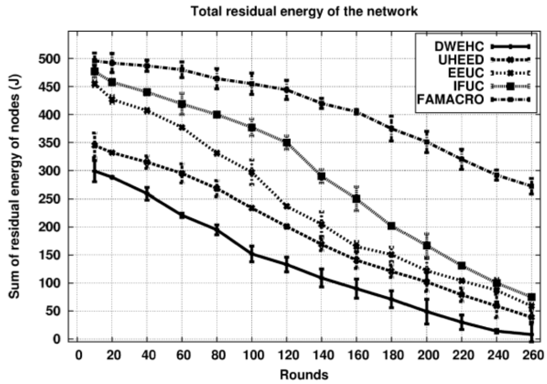

Fig. 2. Total residual energy of the network over rounds

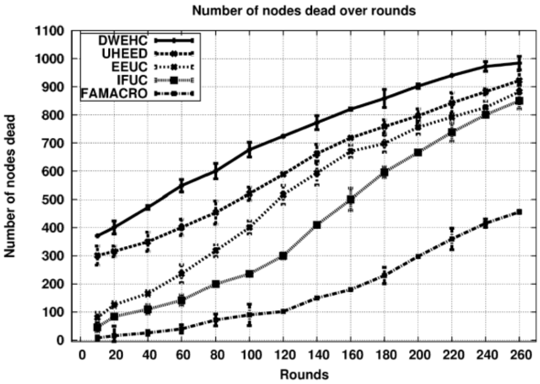

Fig. 3. Number of nodes dead over rounds

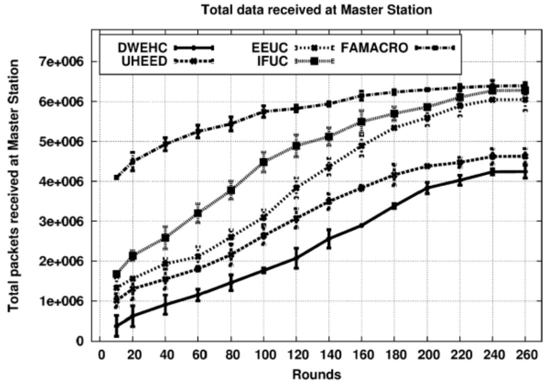

Fig. 4. Total amount of data received at MS over rounds

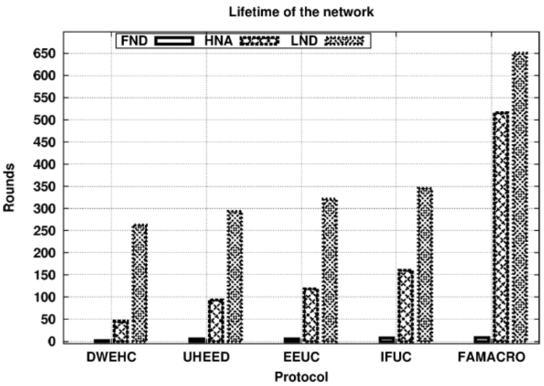

Fig. 5. Time for FND, HNA and LND

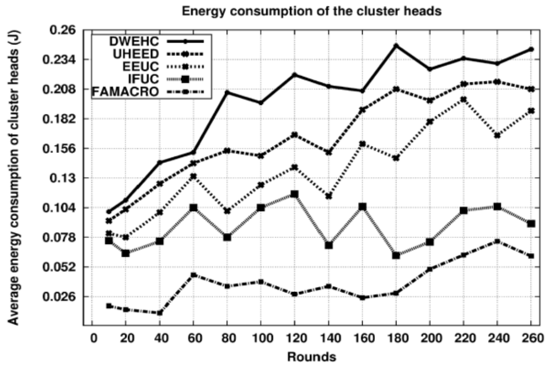

Fig. 6. Energy consumption of cluster heads over rounds

5. Conclusion

The applications and node design of WSN demands an energy-efficient, reliable, scalable yet simple WSN protocol stack. These goals led to design of FAMACRO a cross-layer protocol that combines ideas of energy-efficient hierarchical cluster routing and media access to increase network lifetime. It avoids "hot spots" by unequal clustering and uses fuzzy logic for cluster head selection and ACO for inter-cluster routing. Use of LQI for cluster head selection and PRR for inter-cluster routing increases reliability of protocol. Simulation results show that FAMACRO provides best performance compared to DWEHC, UHEED, EEUC and IFUC protocols.

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