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FAMACROW: Fuzzy and ant colony optimization based combined mac, routing, and unequal clustering cross-layer protocol for wireless sensor networks

Sachin Gajjar[a,*], Mohanchur Sarkar[b,1], Kankar Dasgupta[c,2]

[a] Department of Computer Science and Engineering, Institute of Technology, Nirma University, S.G. Highway, Ahmedabad 382481, India
[b] SATCOM and Navigation Applications Area, Space Application Centre (SAC), Indian Space Research Organization (ISRO), Ambawadi Vistar P.O., Ahmedabad 380015, India
[c] Indian Institute of Space Science and Technology, Valiamala P.O., Thiruvananthapuram 695547, India

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ABSTRACT

This paper presents Fuzzy and Ant Colony Optimization Based Combined MAC, Routing, and Unequal Clustering Cross-Layer Protocol for Wireless Sensor Networks (FAMACROW) consisting of several nodes that send sensed data to a Master Station. FAMACROW incorporates cluster head selection, clustering, and inter-cluster routing protocols. FAMACROW 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* problem, FAMACROW uses an unequal clustering mechanism with clusters closer to MS having smaller sizes than those far from it. FAMACROW uses Ant Colony Optimization based technique for reliable and energy-efficient inter-cluster multi-hop routing from cluster heads to MS. The inter-cluster routing protocol decides relay node considering its: (i) distance from current cluster head and that from MS (for energy-efficient inter-cluster communication), (ii) residual energy (for energy distribution across the network), (iii) queue length (for congestion control), (iv) delivery likelihood (for reliable communication). A comparative analysis of FAMACROW with Unequal Cluster Based Routing [33], Unequal Layered Clustering Approach [43], Energy Aware Unequal Clustering using Fuzzy logic [37] and Improved Fuzzy Unequal Clustering [35] shows that FAMACROW is 41% more energy-efficient, has 75–88% more network lifetime and sends 82% more packets compared to Improved Fuzzy Unequal Clustering protocol.

1. Introduction

Wireless Sensor Networks (WSN) have been focus of research since they expand human capability to observe and interact remotely with the physical world [1–3]. A typical WSN consist of nodes distributed across the sensing area without any fixed infrastructure. These nodes collect sensed data and transmit it to the Master Station (MS). The nodes are constrained in energy, storage, and computational resources [4,5]. Further, the nodes are deployed in hostile environments, where they may die due to deficiency of power, get physically damaged, or may encounter severe environmental interference. This requires the WSN protocols to be simple, energy-efficient, and adapt to varying environmental conditions.

Energy efficiency can be achieved by using cross-layer approaches that exploit interaction among the communication layers for decision making [6]. With protocol design using cross-layer approach, information at a layer can be used to the benefit of protocols at other layer. For example, information of strength of signal received from a neighboring node (physical layer information) can assist routing protocols (at network layer) to decide next hop in the route (if signal is weak, node is far and hence should not be used as next hop candidate in routing). It can also assist data link layer protocols in link adaptive or hybrid Forward Error Correction (FEC)/Automatic Repeat Request (ARQ) schemes [7]. Use of computational intelligence techniques in protocol design facilitates intelligent behavior in complex and varying environments [8]. Computational intelligence paradigms like: neural networks, reinforcement learning, swarm intelligence, evolutionary algorithms, fuzzy logic, and artificial immune systems have been successfully used to address WSN issues like: cluster head selection, routing, data aggregation, security, and localization [9–11].

* Corresponding author. Tel.: +91 9428413275/9978546036; fax: +91 2717 241916/17.
E-mail addresses: sachin.gajjar@nirmauni.ac.in (S. Gajjar), msarkar@sac.isro.gov.in (M. Sarkar), ksd@iist.ac.in (K. Dasgupta).
[1] Tel.: +91 8153000658.
[2] Tel.: +91 9496020001.

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This paper proposes FAMACROW, a cross-layer protocol that combines energy-efficient hierarchical cluster routing and media access. It uses a fuzzy based cluster head selection technique for selecting nodes with high residually energy, having more number of neighboring nodes, and high quality of communication link as cluster heads. One of the issues of hierarchical clustering is *hot spots* problem in which cluster heads near MS are heavily loaded with traffic consisting of their own sensor data packets; relay packets from distant cluster heads (inter-cluster traffic); and sensor data packets from its own cluster members (intra-cluster traffic). This makes cluster heads near MS die earlier than those far from MS leading to severe network connectivity and coverage issues in the region near the MS [12]. To address this problem, FAMACROW organizes the network into clusters of unequal sizes with clusters closer to MS having smaller sizes than those far from it. With a smaller cluster size, cluster heads near MS will have less amount of intra-cluster traffic which in turn preserves their energy for relay traffic. Finally, for reliable and energy-efficient data transfer to MS, FAMACROW uses Ant Colony Optimization (ACO) based technique for inter-cluster multi-hop routing from cluster heads to MS. It selects relay cluster head based on: its distance from current cluster head and that from MS (for energy-efficient inter-cluster communication); residual energy (for energy distribution across the network); queue length (for congestion control) and delivery probability (for reliable communication). The remainder of the paper is organized as follows: Section 2 discusses related work. FAMACROW operation is introduced in Section 3. Section 4 provides comparative analysis of FAMACROW with four well referred protocols of similar complexity. Finally, the paper is concluded in Section 5.

2. Related work

A variety of cluster-based routing protocols have been proposed in the literature [13–16]. Several of these protocols use fuzzy logic to deal with various uncertainties of WSN like unstable channel conditions and varying network topology. Above all, fuzzy logic is flexible; scalable; fault tolerant; requires less system development cost, computation, memory, and design time [17,18]. Hence fuzzy logic has been successfully used for cluster head selection in WSN [19]. Work in [20] proposes intelligent fuzzy based cluster head selection protocol called F3N that uses fuzzy logic with: residual energy; network traffic; number of neighboring nodes; and distance from cluster centroid as fuzzy descriptors for cluster head selection. Fuzzy Relevance Based Cluster Head Selection Algorithm (FRCA) proposed in [21] uses fuzzy logic with: residual energy; signal strength of cluster members; and distance between cluster head and cluster members as fuzzy descriptors for cluster head selection. Work in [22], presents Fuzzy Logic Cluster Formation Protocol (FLCFP), which uses fuzzy logic with: energy of cluster head; distance between MS and cluster head; and distance between cluster head and nodes as fuzzy descriptors for cluster formation. FLCFP differs from the above mentioned protocols in that the non-cluster heads run fuzzy logic and join cluster head with maximum chance value (fuzzy output) to form the cluster. In [23], an Energy Aware Distributed Dynamic Clustering protocol (ECPF) is proposed. Each node in ECPF waits for a time interval inversely proportional to its residual energy before competing for becoming a cluster head or joining a cluster. Thus, nodes with high residual energy will become tentative cluster heads. The final cluster head selection is done using fuzzy logic with node degree (neighboring nodes divided by total number of nodes) and node centrality in a given area. Finally, clustering is performed only when energy of cluster head goes below a threshold value. In [24] a two level fuzzy logic is used to determine a cluster head. In the first level, called local level, cluster heads are selected using fuzzy logic with energy and number of neighboring nodes as fuzzy descriptors. In the second level, called global level, centerness of node with respect to its cluster; distance from MS; and distance from other cluster heads are used as fuzzy descriptors for selecting cluster heads from amongst those selected in local level. Energy Efficient Dynamic Scenario (EEDS) [25] proposes cluster head election using fuzzy logic with: energy and number of neighbors as fuzzy descriptors for cluster head selection at local level. It then uses fuzzy logic with: transmission and residual energy; energy consumption rate; queue size; centrality and proximity to the MS, as fuzzy descriptors for cluster head selection at global level. Work in [26] proposes Differential Evolution (DE) based clustering algorithm to prolong lifetime of the network by preventing early death of the cluster heads. For this, it proposes a local improvement phase in the traditional DE for faster convergence along with an efficient vector encoding scheme for improving the energy efficiency of the network. Advertisement Timeout Driven Bee's Mating Approach (ATDBMA) [27] uses the honeybee mating behavior in electing the standby node for current cluster head. This in turn reduces cluster set-up communication overhead. The standby node is elected in advance and have the capability to withstand for a number of rounds by fair energy distribution. Fuzzy logic for cluster head selection in F3N [20], FRCA [21], FLCFP [22], ECPF [23], two-level fuzzy logic based cluster head selection [24], EEDS [25] and DE in [26] selects the best cluster head in terms of energy and intra-cluster communication cost. However, all the above protocols including ATDBMA [27] do not concentrate on optimizing cluster formation. Further, the selected cluster heads in all the protocols are required to transmit cluster aggregated data directly to MS in each round. Thus, the cluster heads end up using a large fraction of their energy reserves in transmitting data directly to MS. As a solution to this problem, one might think of using inter-cluster multi-hop routing technique instead of direct data delivery to MS by the cluster heads. This will decrease overall network energy consumption and increase scalability of the protocol compared to single-hop approach. One of the initial protocol in this direction called Hybrid, Energy Efficient and Distributed (HEED) [28] is an iterative clustering algorithm. Both election of cluster heads and joining of clusters is performed based on the hybrid combination of two parameters. The primary parameter depends on residual energy of node and the alternative parameter is intra-cluster communication cost. If power level for intra-cluster communication is fixed for all the nodes, communication cost can be proportional to (i) node degree, when application requires load distribution between cluster heads, or (ii) 1/node degree, when it is required to produce dense clusters. If variable power level is permissible, AMRP, the average of minimum power levels required by nodes within cluster range to access the cluster head is used as communication cost. In this approach, every regular node elects the least communication cost cluster head to join it. The cluster heads send aggregated data to MS in a multi-hop fashion. HEED is a fully distributed clustering approach that is benefited by use of two parameters for cluster head election. Further, the probability of two nodes within each other's transmission range becoming cluster heads is negligible. HEED suffers from large transmission overhead, since its clustering process requires several iterations and a lot of control packets are broadcast to update neighbor sets in each iteration. Rotated HEED (RHEED), a modified version of HEED is proposed in [29]. The first round of the setup phase of RHEED is similar to HEED. For the upcoming rounds, the clusters are fixed and only cluster head nodes are rotated among cluster members based on 'cluster head turn schedule' prepared in the first round. This avoids re-election of cluster head in all the rounds and saves network energy compared to HEED. During the cluster head rotation if the residual energy of cluster head goes below a specific threshold the network is re-clustered. However, the rotation of the cluster heads in RHEED is completely random. This might lead to