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Research paper

Clustering Techniques and Need of Computational Intelligence for Topology Control in Wireless Sensor Networks: an Investigation

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Abstract

Wireless sensor networks is an accrue of sensing devices usually called nodes that communicate wirelessly. These networks are characterized by limited resources such as power, memory, processing or computation and communicating ability. This gives rise to several challenges in node deployment, scalability and changes in the topological structure. Energy being one of the critical resources in wireless sensor networks, may require the sensor nodes to organise or reorganise which may lead to reduction in the energy consumption of individual and therefore of the entire network as well. A topology control mechanism by means of clustering may help in enhancement of the network performance by being energy efficient and scalable. In this paper a few standard clustering techniques are discussed and possible design objectives are focussed upon. Also a need to employ the techniques to develop "adaptive" capabilities along with clustering techniques are highlighted which may help to improve their functionality and survival aspects along with wise utilization of resources. An inspection of various computationally intelligent models that may be considered for adaptation in topology control is presented in the paper.

Keywords:*Wireless sensor networks; Clustering techniques; Computational intelligence; Adaptability.*

1. Introduction

Wireless sensor network can be viewed as a distributed network where the devices are deployed in an unattended environment to monitor or sense the ambient conditions by co-operating among themselves for remote operations. The devices are autonomous sensor nodes that are limited in terms of power, storage, computation and communication capabilities. These limitations along with the characteristics of wireless sensor networks such as ultra large number of nodes, denser deployment and change in the topological structures pose certain challenges[1]. While communicating with each other, the sensor nodes make use of various topologies like mesh, tree, chain etc. These topologies keep on changing due to the node movements or due to unexpected node deaths. Hence there is a critical need of forming an efficient topology which can take care of minimization of messages being lost among the sensor nodes along with the reduction of interference and ensuring neighbouring nodes are at minimum distance to reduce waiting time for data transfer [2]. Minimization of energy consumption of the nodes in the network due to their limited battery levels is of major concern. The applications usually being remote cannot be handled manually. One approach that can yield to the enhancement of the network lifetime by monitoring the energy usage of individual node is the topology control technique. Topology control characterises the grouping of nodes or formation of sub-networks and helps in adding or deleting the nodes in the group. The topology of the network may be altered by the change in the transmission range or node scheduling. Thus controlling the topology may lead to more reduction in energy consumption [3]. As can be seen in the Figure 1., the topology control can have homogenous and non-homogenous approaches or centralized and distributed approaches.

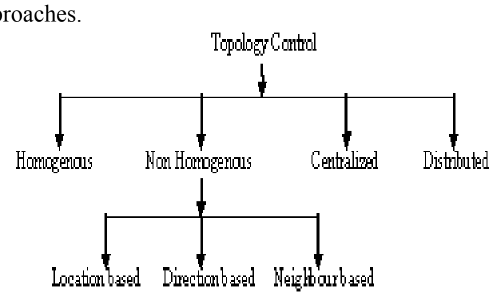

Fig.1. Categorization of topology control

In homogenous approach, the sensor nodes are said to use the same transmitting power taking care of the critical transmitting range into account. In non-homogenous approach the nodes can be configured with different transmitting ranges. Also there are subcategories of this approach based on the location, direction and neighbour organizations. In the centralized approach one or more nodes in the network act as a centralized administrator to gather the information based on location and transmission ranges of the nodes [4]. But this technique produces considerable message overhead. In distributed approach the sensor nodes preserve energy efficient links and generate necessary links needed to enhance the reliability of the network. There are several distributed topology control approaches such as Power adjustment approaches, Power mode approaches, Transitive approaches, State-scheduling approaches, Clustering approaches, Hybrid approaches etc., In this paper we focus on the clustering aspects of distributed topology control and highlight on the need of some intelligence.

2. Clustering Techniques

In this method the sensor nodes are grouped into clusters where each cluster would be having a node which usually acts as a leader and such a node is called cluster-head (CH). A node that is usually richer in resources compared to the other nodes in the cluster will be taken as cluster-head. The nodes participating in the cluster are called as member nodes (MN) and their number may vary. The data can directly be sent to a base station by the cluster-head of one cluster or it can connect to the destined node by forming a tier-network if needed [7].

2.1. Need of Clustering

Clustering technique is found to manage the energy efficiency and helps to acquire scalability of the network [8]. One critical issue in WSN applications is to ensure that the network is available during the presence of an interruption or fault. The robustness of WSN can be enhanced by a reasonable topology. There are various ways of cluster formation and one can adopt the suitable method [9].

3. Conventional Clustering Approaches

Repetitive changes in the node locations disturb the network topologies and cause several modifications in the clusters because of which the task of CHs become difficult to be handled by the conventional clustering techniques. Research is being carried on in this direction and several probabilistic approaches are identified. But these modifications are usually based on or in accordance with the conventional techniques in order to overcome their ineffectiveness. In this study three famous clustering approaches are focused upon

3.1. LEACH

The LEACH (Low Energy Adaptive Clustering Hierarchy) protocol works with setup phase followed by steady state phase. The network is usually divided into groups called as cluster and consists of a head which is hence called as Cluster Head (CH). This technique seems to be expensive as the CH is assumed to consume the same energy as that of the member nodes and also there is lack of proper node distribution in the algorithm [10].

3.2. HEED

The HEED (Hybrid Energy Efficient Distributed Clustering) protocol helps in mitigating the communication overhead by using the algorithms that are not too complex to implement. The clusters are compact and the CH is elected on the basis of residual energy. This helps to extend the network lifetime but with higher energy consumption in case of local communication between CH and base station [11].

3.3. EEUC

The EECU (Energy Efficient Unequal Clustering) algorithm is designed to create smaller clusters to be near to the base station. This is done based on the understanding that more routing communication is handled by the cluster heads placed near the base station than compared to the CHs that are far from the base station. The cluster size is usually a variable and the CHs are randomly selected. The distribution of the nodes is assumed to be circular and this algorithm is not practical for real time deployment [12].
These algorithms are not sufficient as they cannot calculate the residual energy properly and increase the computational complexity due to non-uniform node distribution [13].

4. Design Objectives for Topology Control by the Method of Clustering

As discussed in the previous sections the topology of a WSN can be controlled in terms of hierarchical spanning trees and scheduling methods aiming to reduce the number of nodes. Overhead minimization, resource enhancement techniques, network scalability and network lifetime can be taken as some of the important parameters to have an efficient clustering scheme. Load balancing, fault tolerance, delay minimization, throughput enhancement and minimum cluster maintenance, improvement in connectivity are considered to be some of the popular objectives for such algorithms.

4.1. Need of an Entity

In this paper we focus on clustering technique as one of the approaches for topology control as it can manage energy consumption of the nodes. According to the survey carried out, the clustering can be considered to be hard when compared with the existing algorithms which has to be solved in an effective way [5]. The normal approaches face several technical challenges in network discovery, network control and routing, tasking, querying and information processing. Therefore there is a need of some entity which can calculate the things as per the requirement and generate proper results which can be used to process further to make them best suited to adapt to the dynamic nature of WSNs. In general such an entity can be called as intelligence. Intelligence can be defined as a combination of elements like learning, evolution and adaptation. Some of the intelligent mechanisms are discussed in the following section. Researchers have tried to use the intelligent techniques to address several problems in robotics, biometrics, intelligent control and sensor networks [6]. These intelligent approaches though not used much in WSN, may provide the researchers in the field of WSN with new ideas and incentives.

5. An Overview of CI Paradigms

As we are by now aware that many low cost Micro-Electro-Mechanical-Systems with low energy are grouped together to form the WSN. Low power consumption and cluster formation techniques used in any aspects for lowering the power consumption have become important in order to get connectivity between these kind of networks. However, routing methods and control approaches with clustering followed by conventional methods are not suitable for WSNs due to the dynamic behaviour of the nodes. Therefore some paradigms are identified and are found to be computationally intelligent to be used to cluster the WSN.

5.1. Genetic Algorithm (GA)

Authors in the work have proposed the use of Genetic Algorithms (GA) in order to optimize the network by selecting the best possible number of CHs. The identification of a node in the network and CH is coded by 0 and 1 respectively and is shown in chromosome representation of 9 bits [14]. Here the outcome of this algorithm was optimal number of CHs. The transmission schedule is identified by the cluster numbers where an assumption is that the sink receives directly from the CH. This algorithm proves to be better than LEACH but without much significant improvements. This may be due to consideration of many parameters each of which is assigned a weight. This enhances the complexity the fitness function, for the calculation of which distance between nodes, CHs and sinks is taken into account. Genetic Algorithm is the class of evolutionary algorithms which carry out the tasks of reproduction, mutation, computation and symbiosis. The algorithm works on the basis of survival of fittest concept by using a fitness function eliminating the chromosomes that are found to be unfit and using the fit ones for next movements.

5.2. Particle Swarm Optimization

Intelligence of swarms and their movements are taken to develop a robust and stochastic nonlinear optimization technique. Various local or global search methods are combined to locate the best achieved position by interaction with the particles [15]. The PSO particles update themselves with an internal velocity and usually do not die. It follows either star topology or ring topology where the convergence of star topology is faster but misleading in some cases[16].

Evaluation and update of the population is done by the use of some fitness function. For example, Velocity V_{id} at every position X_{id} are related by (1) and (2) to steer the particles.

$$V_{id}(k+1) = w.V_{id}(k) + C_1.r_1.(p^{best_{id}} - X_{id}) + C_2.r_2.(g^{best_{id}} - X_{id}) \quad (1)$$

$$X_{id}(k+1) = X_{id}(k) + V_{id}(k+1) \quad (2)$$

Where r_1 and r_2 are random numbers distributed uniformly between 0 and 1 [17]. w denotes co-efficient of inertia, k indicates the number of iterations. C_1 and C_2 are acceleration constants where C_1 takes the particle towards the highest fitness position and C_2 accelerates the particles towards the one with highest fitness.

5.3. Ant Colony Optimization

Yet another algorithm whose idea is based upon how ants explore their surroundings to gather food is ACO. Once an ant finds any food, the quantity and quality is evaluated and deposits a chemical pheromone along the path while taking a part of the food to nest which helps other ants to find the food location [18]. The probability of suitable path selection between food source and nest is shown by the relation (3).

$${}^{P}_{A}(t+1) = \frac{(C+{}^{n}_{A}(t))^{\propto}}{(C+{}^{n}_{A}(t))^{\propto}+(C+{}^{n}_{B}(t))^{\propto}} = 1 - {}^{P}_{B}(t+1) \quad (3)$$

This relation expresses the path selection probability for path A among the two existing paths A and B at time step $t+1$, where ${}^{n}_{A}(t)$ and ${}^{n}_{B}(t)$ shows the number of ants or nodes.

5.4. Artificial Immune Systems (AIS)

The AIS algorithm is developed based on the functioning of the biological immune system that protects the body from foreign pathogens [20]. The network can be modelled using this concept by the incorporation of the methods like Negative selection, Clonal selection and Immune network model. These AIS algorithms and methods can be successfully applied in the areas of fault detection, computer security, abnormality detection, data mining and optimization.

5.5. Reinforcement Learning (RL)

Reinforcement learning would be a best suited decision maker in order to enhance the lifetime of the network. RL is a sub-area of machine learning in which the learning tasks are described as a Markov decision process. It is a biologically inspired process where in the data is collected by exploring the environment continuously [21]. The steps taken to decide an optimal policy π without having any prior knowledge are as follows

i. An agent,
ii. Possible States 'S',
iii. Possible actions $A(S_t)$, for all possible states S_t
iv. Reward function $R(S_t, a_t)$,
v. Policy π_t which defines behaviour of learning agent at some time-step 't',
vi. Value function $V(S_t, a_t)$ which gives the total reward, where a_t is action for every state S_t or next state S_{t+1} .

RL is suitable for problems like distributed routing where individual node computations are carried to decide possible actions. RL is highly flexible for the changes in topologies and gives optimal results, easy to implement though needs time to converge. Q-learning, Dual RL, TPOT RL and Collaborative RL are some of these methods[22,23,24].

5.6. Artificial Neural Network Approach (ANN)

Artificial Neural Network (ANN) is one of the generalized techniques which takes care of processing information in terms of mathematical models by the elements called neurons. The signal transmitted between the neurons gets multiplied with the weight of the connected links and the resultant signal stimulates the neuron at the other end of the connection link. The activation function determines the output signal based on a threshold value for further actions [25]. Suppose X_i is the n^{th} input of j^{th} neuron where i=1,2,.... n. Then W_{ji} is the weight of the link as shown in the Figure 2.

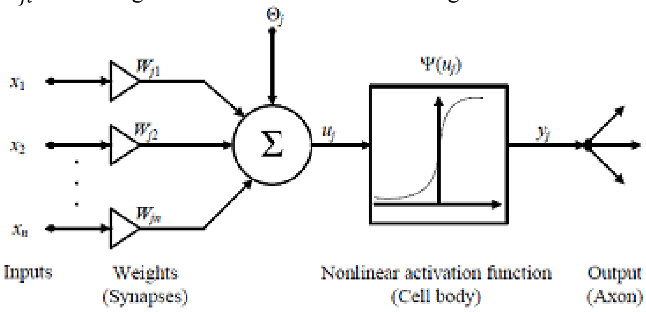

Fig.2. Structure of a neuron

These weighted inputs are summed up by an aggregation function defined by (5) so as to compute the activation function.

$$U_j = \theta_j + \sum_{i=1}^{n} X_i W_{ji} \quad (5)$$

Where θ_j is the bias. Usually bias is taken as the weight for an input $X_0$and the value equals to one always. Hence the relation is redefined as in (6).

$$U_j = \sum_{i=1}^{n} X_i W_{ji} \quad (6)$$

This U_j value is mapped to V_j by an activation function Ψ with the relation shown in (7).

$$V_j = \Psi(U_j) \quad (7)$$

The learning algorithms helps in determination of weights and further actions [26].

One of the suitable unsupervised technique which can study the pattern and architecture of wireless sensor network is the Kohenen's Self Organizing Maps (SOM). Sensor Intelligent Routing (SIR) is one such work based on SOM where an artificial neural network is designed for QoS enhancement [19]. This technique may be incorporated for topology control to manage the clusters[27].

5.7. Fuzzy Logic

Fuzzy logic helps in drawing appropriate and reasonable conclusion based on the concept of set theory. The characterization of the dynamic behaviour of a system is possible which includes a set of linguistic fuzzy rules [28]. The linguistic variables are determined by the rule which works on the concept of antecedent and consequents which forms input and output [29].

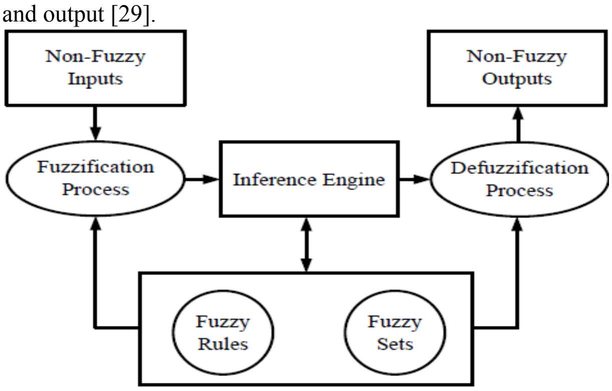

Fig. 3. Fuzzy inference system

The inference methods used are based on the fuzzy sets and fuzzy rules together which carries out a process called fuzzification in which the non-fuzzy inputs are mapped to their fuzzy representation as shown in the figure 3.

6. Optimization – Need of CI

The categorization of the CI techniques discussed in the paper based on their applications, their approaches, flexibility, computational complexity, memory requirements are as shown in the Table 1.

Table 1. CI properties, deployment strategies and applications in WSN

CI-Paradigm	**Computational requirements**	**Memory requirements**	**Deployment**	**Flexibility**	**Optimality**	**Centralized or Distributed**
Evolutionary Algorithm	Medium	High	Real Deployment	Low	Optimal	Centralized
Reinforcement Learning	Low	Medium	Simulation	High	Optimal	Distributed/ Semi-distributed
Swarm Intelligence	Low	Medium	Simulation, Real Deployment	High	Optimal	Centralized
Artificial Immune Systems	Medium	Low/Medium/High based on the problem	Simulation	Medium	Near Optimal	Centralized, Semi-distributed
Fuzzy Logic	Medium	Medium	Simulation	High	Optimal	Centralized
Neural Networks	Medium	Medium	Simulation	Low	Optimal	Distributed

The applications of these solutions depend on the amount of computational complexity and memory requirement. For centralized computational approaches carried out by the base stations, there is a need of heavy computations and memory. The distributed approaches yield lesser computational complexity and lesser memory requirement as the process is carried out at each node. Some of these CI approaches provide optimal solutions and few of them may provide sub-optimal results. Optimality is not an approximation, but can be treated as the measure of the CI's ability to come out with the best possible solution. The adaptability of the algorithms for the changes in topological structures or node failures can be referred to as flexibility.

7. Conclusion

A wireless sensor network (WSN) is a network of devices which can sense events, process and communicate the data. The applications being critical require an efficient maintenance of the network. Energy is the main criteria to be concentrated upon in the WSNs. Hence managing the energy levels of individual nodes and therefore of the entire WSN is to be focused upon. One of the popular method to enhance the energy efficiency as well as the scalability of the WSNs is the clustering technique which involves grouping of the nodes into clusters. A few standard clustering techniques, need of clustering, parameters that can be considered during the design are highlighted.

This paper also reveals that clustering technique alone is not sufficient to generate practical optimal / sub-optimal solutions. Hence there is a need of an adaptability in the formation of clusters and for communicating between the nodes and inter-clusters. One approach that may help in promising proper node deployment and energy minimization in a much better way would be the incorporation of an intelligent mechanism along with the clustering techniques. Many such intelligent techniques have been discussed in the paper and are usually referred to as computational intelligence (CI). There are various possibilities and ongoing research efforts to develop methods that can enhance the network performance. Incorporation of machine learning and deep learning concepts along with the existing solutions may further help in improving the network functionality.

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