Cluster formation techniques in hierarchical routing protocols for Wireless Sensor Networks

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Critical review

DOI: **10.7251/JIT16005P** UDC: **004.771:004.65**

Abstract: Wireless sensors are an irreplaceable link in the chain of global networking today. There is almost no area of human activity where they are still not used, and they will be used in the near future almost everywhere. Wireless sensor networks consist of a large number of sensor nodes that are arranged (usually randomly) in an area. The main problem is the limited power supply. Sensors are usually powered by the battery which is not possible to replace. The lifetime of the network depends on the duration of battery power of sensor nodes. The largest part of the consumed energy goes for communication with the rest of the network. Therefore, the selection of good routing protocol is essential for the long life-span of the network. There are a large number of proposed protocols and they can be divided into several groups, depending on the approach to the problem. In this paper we present a family of hierarchical protocols, their common features and specific implementation, we will present advantages and disadvantages as well as possible directions of further development.

Keywords: LEACH, CH, Clustering, Wireless Sensor Network.

Introduction

Sensors listen and gather information from the environment and send them to the base station (BS). Energy consumption is a major problem given that spent batteries are very difficult, expensive and usually impossible, to replace. Therefore, it is necessary to save energy wherever it is possible [8], [20]. That is the reason why the routing protocols, which take into account energy efficiency, are a constant object of researching. There are different approaches to this problem. One large group of protocols is hierarchical protocols. In these protocols, there is no direct communication of BS with each sensor node. There are selected nodes that play a special role in communication in hierarchical networks. These protocols start from the clustering concept. The whole network is divided into a certain number of smaller groups, called clusters, and each cluster has one node with special assignments – Cluster Head (CH). Only CH has the ability to directly communicate with the BS. This method reduces the number of nodes which send data to BS. BS is usually located at a relatively large distance and thus performs a significant energy saving. Additional energy saving is achieved by aggregating data in CH. In fact, one CH receives data from the belonging nodes which are usually located at a short distance from each other. For this reason, the data which represent sensed physical phenomenon are quite similar. The redundant data are discarded. This reduces the amount of data that will be sent to the BS, without losing important information. This structure represents a network of multi-hop connections from the nodes to the BS. For this reason, we define such protocols as hierarchical. Topology of hierarchical network is shown in Figure 1. The oldest protocol in this family is the famous Low Energy Adaptive Clustering Hierarchy (LEACH), presented in [14]. Thereafter, a large number of other protocols have been proposed, most of which are modifications of the basic concept LEACH [19]. Some of them are designed as multi-tier, consisting of two or more levels of hierarchy, as presented in [7]. In this work, we briefly introduce the idea of LEACH and then describe the proposed modifications in other similar protocols.

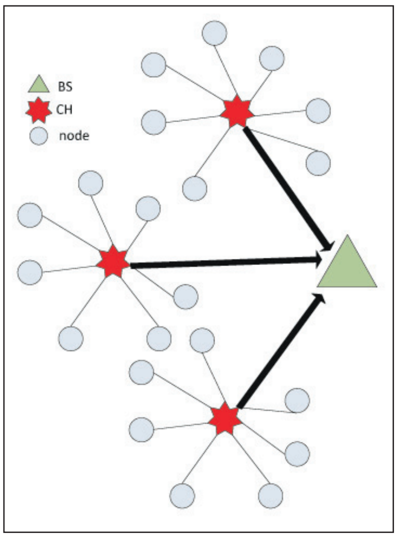

Figure 1. Model of hierarchical network topology

LEACH PROTOCOL

LEACH was proposed in 2000. It is still the basis for the development of other models of hierarchical routing. Since power consumption depends on the distance from the sensor node to the BS, the goal is to reduce the number of connections that are realized over long distances and the number of transfer operations. The LEACH is divided into rounds, where the role of CH rotates in a random manner. In each round there are two phases: setup and steady state. In the setup phase, each node first chooses a random number between 0 and 1. The number is compared to a threshold value T(n) calculated by the expression (1), where P is the desired percentage of CH in the network, r is the number of the current round, G is a set of nodes which were elected as CH in the last 1 / P rounds.

$$T(n) = \begin{cases} \dfrac{P}{1 - P \times (r \bmod \frac{1}{P})} & if \ \ n \in G \\ 0 & otherwise \end{cases} \quad (1)$$

If the randomly selected number is less than the threshold, this node becomes CH. Each of the CHs creates the corresponding clusters and the TDMA schedule for communication with each of its nodes. In the steady state, nodes sense environment and send data to the CH in time slots allocated to them. CH performs aggregation of all data and forwards them to the BS. In LEACH protocol and in all its successors, a simple radio model is used, as shown in Figure 2. This model describes the power consumption in the network. It is assumed d^2 energy loss due to channel transmission. If the BS is far away from the CH, communication will require a large amount of transmit power.

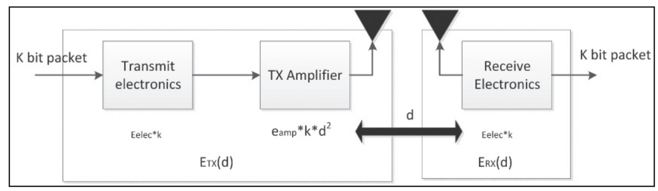

Figure 2. Radio model of energy dissipation

Advantages of LEACH are numerous. It is fully distributed approach without central management of network. It reduces the number of energy-demanding links, since only CH communicates with BS, which is usually at a large distance. At any time, most of the sensors are in passive mode. Through the data aggregation in CH, it reduces the amount of data to be transmitted. Rotation of CH roles evenly distributes energy to all nodes. Furthermore, the localized coordination scheme used in LEACH provides better scalability for cluster formation. LEACH, on the other hand, has a whole range of unresolved issues. Problems arise if the sensors do not have the same initial energy and that is often the case in practice. Then, sensors with less energy have the same chance to become CH as the others with more energy. This allows sensors with a few of residual power to get the role of CH, quickly spend the remaining energy and die while they are in the CH status. This leads to losing of all the data collected by sensors in the corresponding cluster for that round. CHs may also be sensors that are very far away from BS. These CHs will consume very large energy to communicate. Implementation of LEACH is limited to static sensors. If the sensors are mobile LEACH cannot be used. At the same time, there may be very large and very small clusters in the same network. These are the reasons why many authors have tried to improve LEACH with new ideas. These tendencies have created more than a thousand modifications. We outline below some of typical.

Modifications of LEACH protocol

LEACH -B (Balanced) [6] does not take into account the aggregation of data into CH, since it is not usable in all applications of wireless sensors. Protocol calculates energy dissipation for sending broadcast packets to other nodes. With these packets CHs inform all nodes about their new role. The number of clusters per round is not constant. Belonging of node to the CH is not calculated on the basis of the minimum energy path, from node to a potential CH, as in the original LEACH, but on the basis of minimum energy consumed in the entire path from the node to the BS, when the link is established through potential CH.

LEACH-C (Centralized) [13]. In the basic LEACH, clusters are unequal. This results in a difference of energy consumption of individual nodes. This is detrimental to the efficiency and lifetime of the network. LEACH-C uses the centralized clustering algorithm for achieving a better distribution of nodes and similar sizes of clusters. During the set- up phase, each sensor sends data about its current position and the available energy to the BS. BS calculates the average energy of the entire network. The sensors with energy below this value cannot be CH in the next round. In the steady state phase it uses the same algorithm as in LEACH. LEACH-C is in all features beyond the original LEACH, but it is difficult to implement it in practice because of the need for a central management system. In addition, this protocol is not suitable for large- scale networks because nodes on very large distance do not have the ability to send information to the BS about its status.

LEACH-E (Enhanced) [10]. This protocol uses algorithm for the selection of CHs that have global information about all nodes in the network. The main factor affecting the performance of the network is the number of the CH. If the number of CHs is relatively small, then each CH covers a large area, and nodes that are located at a large distance consume a lot of energy to communicate with CH. If the number of CHs is relatively large, the network has a larger number of nodes that consume a lot of energy to communicate with the BS. These are contradictory requirements and both of them affect the lifetime of the network. Communication between CH and BS requires a higher power than communication of CHs with other nodes. Therefore LEACH-E, in the selection of CH, in the first round acts as LEACH. After that, the residual energies of all nodes are different. Because of that, each cluster after each round chooses the node with the highest residual energy for CH and the other nodes are cluster members.

LEACH-F (Fixed number of cluster) In this protocol, clusters are formed in the initial stage. They have that role until the end of the life of the network. In this way, protocol avoids the formation of clusters at the beginning of each round. In this formation of the clusters centralized approach is used, in the same way as it works in LEACH-C. BS uses annealing algorithm to form clusters. BS broadcasts messages which includes cluster ID for each node. Position of nodes in the list indicates the order to become CH in the upcoming rounds. The role of CHs in the next rounds rotate within the nodes of the cluster. The first node listed in the cluster becomes the CH in the first round, the second node listed in the cluster becomes the CH for the second round, and so forth. The advantage of this approach is that there is no setup overhead at the start of each round. The disadvantage of this protocol is that there is no possibility to join the new cluster nodes. In addition, the fixed nature of the cluster creates a situation where the nodes are often closer to other CH than to CH of its own cluster.

I-LEACH (Improved) The sensor field is divided into equal sub-regions [5]. In each of them CHs are elected in the same way as it works in LEACH. This produces a large number of smaller subclusters. The goal is to uniformly distribute CHs on the basis of x-coordinate of the nodes. There is no possibility here that all CHs will be concentrated in one part of the network. This reduces the length of the connections of the ordinary nodes to the CHs , data frame is shorter but the number of frames to reach the BS is increased. Instead of probability, as a criterium for the selection of CH, the residual energy is used.

K-LEACH (K-medoids) [3]. This protocol also tries to make more uniform distribution of the clusters and nodes in them. In the basic LEACH, it is possible that some clusters contain a large number of nodes and some very small number of them. The proposed K- LEACH protocol uses the K-medoids clustering algorithm. For the first round, clusters are formed using K-medoids cluster formation algorithm and CHs are selected as a node which lies at the center or nearer to the center of the cluster using Euclidian distance. For the rest of the rounds, nodes nearest to the CH of the first round selection are chosen as CH. There are variants with re-using existing clusters and with a choice of new clusters in the upcoming rounds.

L-LEACH (Energy balanced). CH is selected based on a threshold which is a function of residual energy and distance [21]. This algorithm measures normal distance between the node and the BS and compares this distance to the distances from the node to the CH. If the node is closer to the BS, no optimal CH will be selected. This node will send directly controlling packages to the BS and then transmit data packages. Otherwise, CH whose distance to the node is smaller than the distance from the node to the BS are regarded as candidate CH. Then, the node chooses the optimal one among the candidate CH, according to the cost function. If the cost function value is the least, it will be chosen as the optimal CH. The energy of the nodes may be heterogeneous.

LEACH-M (Mobile). In this protocol authors take into account the mobility of nodes during the transfer phase [17]. Node with minimum mobility and lowest attenuation power is selected as CH. Mobile nodes can leave the cluster before they send their data to the CH in a given round. It is necessary to check if a node is able to communicate with associated CH in accordance with the TDMA schedule. At the beginning of each TDMA slot, CH sends a test message to the appropriate node. CH waits for a response during the two consecutive slots. If there is no reply then CH concludes that the node is outside the range and removes it from the list. It is possible that CH leaves its own cluster. In this case, the nodes are joined to the other CH.

LEACH-ME (Mobile enhanced) [18]. This protocol is the enhanced version of LEACH-M. The CH rotation process considers the nodes mobility. Mobility factor is calculated based on the number of times a node changes from one cluster to another or on the basis of remoteness. Every node sends a number of the transitions to the CH during its CH TDMA slots. CH counts the average number of transitions for its members over the last few cycles. For the role of CHs, nodes that are less mobile in relation to its neighbors are selected.

LEACH-S (Solar) [14]. In this protocol, some nodes have solar power supply. During set-up phase only those nodes are selected for the CHs. They send their status and amount of the residual solar energy to the BS. Nodes with the highest residual energy are chosen for the CHs. Increasing the number of sunny days directly affects the lifetime of the nodes and the whole network. The principle is applicable as an upgrade for centralized and distributed LEACH. On the basis of this proposal, many new protocols have been proposed.

T-LEACH (Treshold based) [15]. This method minimizes the number of CH choices using threshold for residual energy. As long as a CH has a residual energy greater than a given threshold, it retains its role from round to round. The thresholds are set especially for each node in the network. They are different since each CH has a different number of nodes. After the residual energy of CH becomes less than the threshold, new CH is elected. Reducing the amount of CH selection and replacement cost, the lifetime of the entire networks can be extended.

TB-LEACH (Time based) [16]. In the basic LEACH, number of the CH may vary from round to round, due to the random selection of number for comparison with the threshold. In this protocol in each round constant number of CH is elected, exactly 4 % of all nodes. They are chosen on the basis of randomly given timer. At the beginning of each round, all nodes generate random timers. The value of the timer is not affected by the residual energy of the node . When the timer expires, the node checks the number of received CH advertisement messages. If this number is less than four, it declares itself for the CH. The rest of the process after the election of the CH is the same as LEACH.

V-LEACH (Vice) [4]. In each round, in addition to CHs, vice CHs are elected. Their role is to replace the CH in case that it dies during the round. In this way, all collected data is delivered to the BS even if CH died, and there is no need to elect a new CH (See Figure 3).

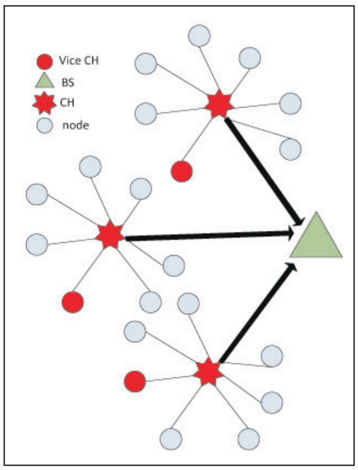

Figure 3. V-LEACH topology

W-LEACH (Weighted) [12]. In the setup phase, the algorithm first calculates value of weight Wi for each sensor. P is a percentage of the maximum number and not the actual number of CHs as defined in the original LEACH. CH is selected on the basis of weight values, regardless of whether the node was CH previously. The decentralized version of the same algorithm [1] introduces the idea that if the sensors are close together there is no need to send all data to the CH. Sensors in each round are divided into sleeping and alive sensors.

PEGASIS (Power-Efficient Gathering in Sensor Information Systems) [19]. There is no clustering in this protocol. The basic idea is forming a chain so that each node communicates only with nodes that are closest to him. Chain can be formed by the nodes themselves using the greedy algorithm or can be established by the BS. To locate the closest neighbor node, each node uses the signal strength to measure the distance to all neighboring nodes, and then adjusts the signal strength so that only one node can be heard. Construction of chain begins with choice node that is furthest from the BS. It selects a node that is the second farthest from the BS for the next member, etc. When some node died, chain is reconstructed in the same way by avoiding dead node. During steady state phase, each next node in the chain combines the received data with its own data. The last node in the chain is called the leader. Only the leader can communicate directly with the BS and send all data from the chain to the BS. In each subsequent round, a new leader is chosen and a new chain is formed. The nodes that are located at a large distance from the BS cannot be selected for leaders.

TL-LEACH (Two-level) [23]. This protocol uses PEGASIS to improve basic LEACH protocol. It consists of three phases. The first phase of CH selection is composed of two secondary phases: Selection of the CHs on the first and selection of the CHs on the second level. CHs on the first level are selected using a modified expression for the threshold value (2):

$$T(n) = \begin{cases} (r+1)\bmod(\frac{1}{P})*\mathrm{P} & if \;\; n \in G \\ 0 & otherwise \end{cases} \tag{2}$$

Clusters are formed in the same way as it is done in basic LEACH. The algorithm chooses N*P CHs of the first level. After that, it selects the CHs at the second level. It chooses N'*P second level CHs of the previously selected first level CHs. Only the second level CHs can communicate with the BS. They receive data from the first level CHs and, together with their own data, forwarded them to the BS. Data fusion is performed on the secondary and the primary level. TL-LEACH significantly reduces the number of nodes for data communication over long distances and decreases energy consumption of entire network. Topology of TL-LEACH is shown in Figure 4.

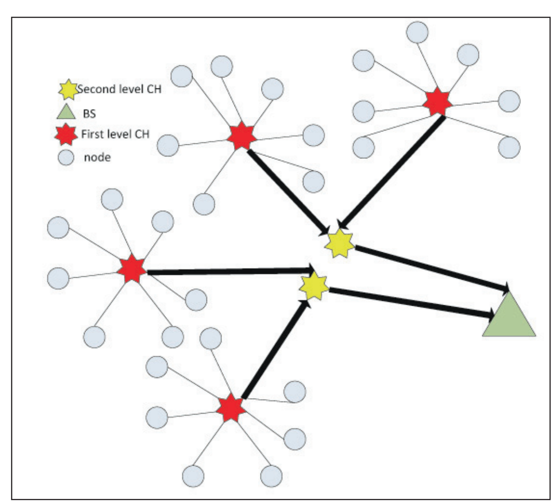

Figure 4. TL-LEACH topology

SEP (Stable Election Protocol) [22] takes into account the heterogenity of the network. The probability of the selection of node as CH depends upon its residual energy. The nodes are heterogeneous and divided into normal and advanced. Differences in energy can be initially set or can be result of the work of sensors in previous rounds. Both types of nodes are randomly distributed throughout the field. Advanced nodes are elected for CH more often. Algorithm avoids a situation in which all normal nodes will die and only advanced nodes will remain, regardless of the spatial distribution.

A-LEACH (Advanced) [2]. This protocol was created from the idea to extend the time before the death of the first node in the network (stable period). The nodes are divided into group with higher residual energy (called CAG) and group whose energy is lower. In the setup phase, basic LEACH is performed for all nodes, regardless of the available energy. If CH belongs to the group of CAG nodes it sends data directly to BS and everything takes place as in basic LEACH. If CH is among the nodes that have less energy it identifies the closest CAG and selects it for its gateway node. It establishes a connection with the BS through this gateway. (See Figure 5)

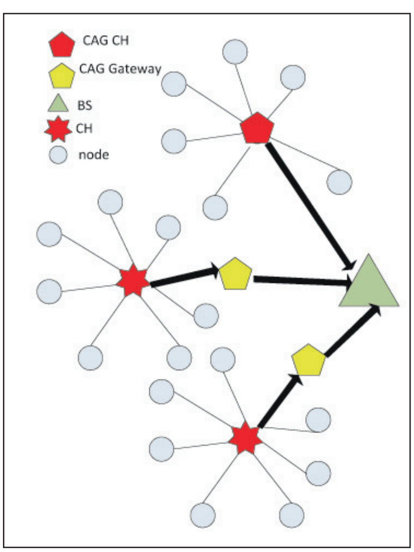

Figure 5. A-LEACH topology

Conclusion

A hierarchical model of organization of wireless sensor networks has many advantages compared to other models, especially in the case of large-scale networks, mobility nodes, node failures, insertion of new nodes and removal of existing nodes. However, the hierarchical organization of the network also brings many problems. Basic LEACH, which remained a role model to all subsequent protocols inherently, has significant shortcomings and unresolved issues. Removing these defects is the aim of a large number of researchers for decades. From this tendency, they created a large number of modifications to the original LEACH. Each of these versions overcame results of LEACH to some extent, but did not cancel the basics of protocol. This paper provides a brief description of the techniques used for clustering and selection of CHs in some typical protocols. The aim was not to present the improvements that have been already introduced in these protocols, but to present ideas on which they are based. These ideas should serve as a basis for further researching. Hierarchical networks are definitely the best concept for organizing wireless sensor networks, but researchers have to do more to reduce power consumption of the network to the minimum.

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Goran Popović earned his PhD at the Faculty of Computer Sciences, John Naisbitt University Belgrade. He is Head of Department for Acces Network Operations and Maintenance at Mtel, a.d. Banja Luka. Goran is Assistant Professor at the Faculty of Polytechnical Sciences of International University of Travnik and at Technical Faculty of European University Kallos Tuzla, where he teaches graduate and undergraduate level courses on telecommunications. His primary fields of interest are: Dynamic spectrum management and Wireless sensor networks.

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Submitted: June 2, 2016.

Accepted: June 10, 2016.