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Energy Aware Multi-Hop Routing Protocol for WSNs

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ABSTRACT In this paper, we propose an energy-efficient multi-hop routing protocol for wireless sensor networks (WSNs). The nature of sensor nodes with limited batteries and inefficient protocols are the key limiting factors of the sensor network lifetime. We aim to provide for a green routing protocol that can be implemented in a wireless sensor network. Our proposed protocol's most significant achievement is the reduction of the excessive overhead typically seen in most of the routing protocols by employing fixed clustering and reducing the number of cluster head changes. The performance analysis indicates that overhead reduction significantly improves the lifetime as energy consumption in the sensor nodes can be reduced through an energy-efficient protocol. In addition, the implementation of the relay nodes allows the transmission of collected cluster data through inter cluster transmissions. As a result, the scalability of a wireless sensor network can be increased. The usage of relay nodes also has a positive impact on the energy dissipation in the network.

INDEX TERMS Clustering methods, energy efficiency, wireless sensor networks.

I. INTRODUCTION

In order to detect environmental or physical conditions such as heat, light, sound, pressure, vibration, electromagnetic field over an area of interest, wireless sensor networks (WSNs) with a large number of sensor nodes are used. Sensor nodes are typically equipped with one or many sensors, a wireless communication device such as a radio transceiver, a processing unit and a battery as a power source [1].

Since its introduction, WSNs are considered as an active research area as they can provide a large number of WSN applications in different areas. The starting idea of a WSN was to build military applications such as battlefield surveillance but it quickly spread into a vast number of applications including healthcare, habitat monitoring, environmental monitoring, traffic control, home automation, disaster relief and smart cities [2].

Especially for monitoring applications, a large number of sensor nodes are deployed over an area so that a certain event (heat, light, sound, etc.) can be detected. The event detected by the sensor node is reported to the base station afterwards. The base stations are the gateways between the end users and the sensor nodes and they are considered as distinguished components of WSNs. Compared to sensor nodes, they have more communication resources, computational power, energy supplies [3].

The power consumption constraint of the sensor nodes has a major impact on the lifetime of a sensor network. Typically, the power source of each sensor node is limited and the nodes consume energy during data sensing, processing and communication. The sensing and processing parts consume relatively low energy compared to the communication part. In the literature, various communication and routing protocols have been developed for WSNs. A key characteristic to evaluate the performance of the WSNs or WSN protocols is the network lifetime.

If the sensor nodes transmit their sensed data directly to the base stations, the distance between a sensor node and the base station will be the most significant factor on energy consumption. With direct communication, a sensor node which is away from a base station will quickly drain their batteries and they will fail. With this type of data collection, the lifetime of the sensor network will be short.

To overcome this problem, cluster based transmission protocols have been widely studied and proposed. In a cluster based protocol, the WSN is divided into regions called as clusters. When clustering is implemented, some of the sensor nodes denoted as cluster heads become responsible for collecting sensed data in the cluster. The cluster heads later transmit the sensed data to the base stations. A sensor node belonging to a cluster transmits its sensed data to its cluster head instead of the base station, thus by reducing the effective communication distance the energy consumption in these nodes are decreased. A cluster head generally aggregates the whole data sensed in its cluster before transmission to the base station. Although these protocols can offer different ways for the formation of the clusters and cluster head selection process, providing an energy-efficient [4]–[6] protocol will directly increase the network lifetime. In fact, energy-efficient communication known also as green communication [7], [8] is vitally important for the human beings.

With this study, we propose an energy-aware multi-hop routing (EAMR) protocol for a WSN. The distinguishing property of EAMR is its employment of fixed clustering, multi-hop routing and threshold based cluster head selection mechanisms together. The initial cluster head election process is performed in a similar way as in the traditional LEACH [9]–[11] protocol, but afterwards new cluster heads selections are based on the threshold mechanism described in section III. In addition, the clusters formed at the start of the algorithm stay fixed and inter cluster data transmission through relay nodes are used. These mechanisms reduce the overhead seen in LEACH and its variants significantly and contribute to energy consumption reduction in WSNs. Consequently, the network lifetime increase is achieved.

The remainder of this paper is organized as follows: In section II, brief information about some of the novel cluster based routing protocols used for WSNs is given. In section III, the proposed EAMR protocol and its phases are described in detail. In section IV, the implemented system and channel model is explained. In section V, the performance studies of EAMR through some performance metrics such as network lifetime and energy consumption are presented. Finally, our paper concludes with conclusions presented in Section VI.

II. CLUSTER BASED WSN ROUTING PROTOCOLS

The direct transmission of the data sensed by a sensor node to a base station is a significant energy consumption factor. Direct transmission can reduce the WSN lifetime significantly. As a solution, cluster based WSN protocols have been developed for lifetime maximization, energy minimization and scalability. With cluster based WSN protocols, the deployed sensor nodes are divided into clusters. A representative of each cluster called as a cluster head collects the sensed data from its clusters for transmission to the base station. In this section, some of the well-known cluster based protocols in the literature are briefly explained.

LEACH can be considered as the classical WSN protocol. It is a simple, efficient and based on a round based adaptive routing protocol. Under LEACH, sensor nodes are able to form clusters without any assistance from an external agent or another node in the WSN. The set-up phase is responsible for electing the cluster heads and forming the clusters. The election of the cluster heads is performed through a probability function. Each sensor node may select itself to become a cluster head depending on this function. When the election of the cluster heads is completed, each cluster head makes an announcement to denote itself as a cluster heads to the remaining nodes. Upon receipt of the announcement messages, the sensor nodes not elected as cluster heads attach to the nearest cluster head to form the clusters. Then, each cluster head schedules its intra-cluster communication through the TDMA schedules that it prepares. With the conclusion of the set-up phase, the steady state phase starts. The steady-state phase is responsible for transmitting the sensed data from each sensor node to the cluster head and transmitting the collected data by the cluster head to the base station. The combination of a set-up and a steady-state phase constitutes a round. The above described process is repeated for every round. Thus, at every round new clusters are formed by new elected cluster heads. The interference of the transmissions among different clusters can be prevented by using different CDMA. From a list of spreading codes, each cluster head randomly chooses one and filter the incoming signals using this spreading code. By this way, the radio signals received from neighboring clusters can be filtered out. As a result, the interferences from the transmission of the sensor nodes are minimized.

Following the success of LEACH, numerous LEACH variants have also been proposed to improve its performance. Most of the LEACH variants propose a different cluster head selection process for increasing the network lifetime. Leader Election with Load Balancing Energy (LELE) [12] proposes a different cluster head selection process by including the remaining energy and distance of a sensor node to its neighbors. However, LELE requires the location information of the sensor nodes. In [13], an optimal cluster head selection process without the requirement of sensor node location information is developed. Stable Cluster Head Election (SCHE) [14] studies on the probability function that LEACH uses for the sensor nodes to elect themselves as cluster heads. In advanced LEACH (ALEACH) [15] cluster heads are chosen among the most energy efficient nodes. Time-based cluster head selection for LEACH (TB-LEACH) [16] modifies the cluster head election process to form uniform cluster pieces. In [17], an adaptive management for the cluster head election process is proposed depending on the energy reserves of each sensor node.

Due to the probability function used under LEACH, the number of cluster heads thus the number of clusters can vary at each round. References [10], [18], and [19] propose usage of a constant number of clusters. LEACH Fixed Clustering (LEACH-F) [10] creates fixed clusters by using a centralized cluster formation algorithm. The location information and energy levels of the sensor nodes are used to select the cluster heads with the involvement of the base station. In LEACH-IMP [18], the optimal cluster heads are determined based on its position in the cluster and the cluster heads stay constant. Reference [19] introduces dynamic round time based LEACH-F where the round times are decided depending on the energy levels of the sensor nodes. Two Step Cluster Head Selection (TSCHS) [20] uses two stages for cluster head election: temporary cluster head election stage and optimal cluster head election stage. For optimal cluster head election stage, the distances between the base station and the temporary cluster heads are considered as well as the current energy levels.

In Modified LEACH (ModLEACH) [21], an efficient cluster head replacement scheme is proposed with dual transmission power levels. Dual power levels are implemented for reducing collisions and interference coming from other signals. As a result, packet drop ratio is decreased. When a sensor node becomes a cluster head, it uses high power amplification and when it becomes a regular cluster member, it uses low power amplification mode. In addition, ModLEACH implements a threshold based cluster head changing mechanism. When the energy of the existing cluster head is higher than the threshold value it continues to stay as a cluster head. On the other case, a new cluster head for the corresponding cluster is elected and new cluster members are determined.

Heterogeneous cluster based protocols include some sensor nodes more powerful than the remaining ones. Stable Election Protocol (SEP) [22] implements advanced nodes with extra energy. If t is the ratio of the advanced nodes with a times more energy than the remaining sensor nodes, the total initial energy of the WSN will be increased with a ratio of $1 + at$ when compared to a homogeneous WSN. The cluster heads are determined by a weighted election probability based approach. The additional energy of an advanced node forces it to be selected as a cluster head. DEEC [23] is another heterogeneous and distributed clustering protocol where the cluster heads are selected through a probability function based on the ratio between the residual energy of each node and the average energy in the network. The sensor nodes which have high residual energy are more likely to be selected as cluster heads.

III. ENERGY AWARE MULTI-HOP ROUTING PROTOCOL

Our proposed energy aware multi-hop routing protocol (EAMR) uses fixed clusters to provide communication between a sensor node and the base station. In EAMR, when a sensor node is attached to a cluster, it will be a member for that cluster for whole lifetime of the network. The purpose of using fixed clustering is to reduce the energy consumption overhead needed to form new clusters at every transmission round which is a common procedure for most WSN routing protocols.

Under the EAMR, the clusters which are in the vicinity of the base station transmit their collected data to the base station directly through their cluster heads. On the other hand, the remaining cluster heads forward their collected data to the relay nodes for a multi-hop transmission towards the base station. The employment of the multi-hop approach not only increases the scalability of the protocols such as LEACH and its variants but also decreases the overall communication energy from a sensor node to the base station as the intermediate data transmission distances are reduced.

The operation of the EAMR protocol is composed of two major phases: set-up phase and steady-state phase. During the set-up phase, fixed clusters are formed by electing the initial cluster heads, determining all remaining sensor nodes' cluster memberships and choosing the initial relay nodes. With the steady-state phase each cluster head starts to collect data from its own cluster for transmission to the base station either directly or indirectly using the relay nodes. In addition to data collection and transmission, cluster head and relay node change decisions are also implemented during the steady-state phase if needed. In the remainder of this section, the details of the EAMR is explained through description of the two EAMR phases.

A. SET-UP PHASE

The EAMR initiates itself with the set-up phase, after the sensor nodes are deployed in the sensor field. All the deployed sensor nodes are identical with same energy levels but they are assigned unique ID numbers. During this phase, the clusters, cluster members, the initial cluster heads are determined. Since the clusters and cluster memberships will not change under the operation of EAMR, this phase is realized only once as opposed to LEACH and its variants. In addition, the cluster head changes are implemented not every round but only if needed. This process is implemented during the steady-state phase if the necessary conditions exist. The set-up phase is initialized with the selection of the cluster heads using a probabilistic approach. Then the formation of the clusters is completed. Thus, the set-up phase consists of two parts: cluster head selection and cluster formation.

EAMR uses a similar approach to LEACH for the initial cluster head selection. Each sensor node can elect itself as a cluster head randomly with a probabilistic function. The suggested percentage of cluster heads for the WSN are determined a priori. If there are K sensor nodes in the WSN and the number of the clusters as well as the number of cluster heads are determined to be m, then every sensor node has an equal chance of m/K probability to be elected as a cluster head. Thus, a sensor node i randomly chooses a number p_i uniformly distributed between 0 and 1 where $1 \leq i \leq K$.

Under EAMR, all the sensor nodes are identical and have the same energy levels when they are initially deployed. Thus, any one of them can successfully elect itself as a cluster head depending on the chosen random number p_i. A sensor node i can elect itself as a cluster head if $p_i \leq m/K$. If the chosen probability $p_i > m/K$ for sensor node i, then that sensor node is not elected as a cluster head and thus it needs to determine the cluster that it will attach to. Note that, a sensor node which is not chosen as a cluster head has a chance to be chosen as a cluster head in the following rounds, if a cluster head change becomes necessary. The cluster head selection after the initial set-up phase is one of the major differences between LEACH and EAMR. In LEACH, the cluster head election process is repeated at every round, but EAMR will allow a sensor node to act as a cluster head until its energy level falls below a threshold value. Thus, an elected cluster head will stay as a cluster head for multiple rounds as opposed to LEACH. In addition, the probabilistic cluster head election is realized only at the start of the algorithm with sensor node deployment. For the upcoming rounds, when a cluster head change is required, the current cluster head is authorized for choosing the new cluster head from the members of its cluster.

An example depicting the initial cluster head election process is illustrated in Fig. 1. Suppose that 20 sensor nodes with unique ID numbers from 1 to 20 are deployed in the sensor deployment area and after the probabilistic cluster head election process, the randomly deployed sensor nodes with identification numbers 5, 11, 15 and 20 have elected themselves as cluster heads, while the remaining sensor nodes stayed as non-cluster head nodes.

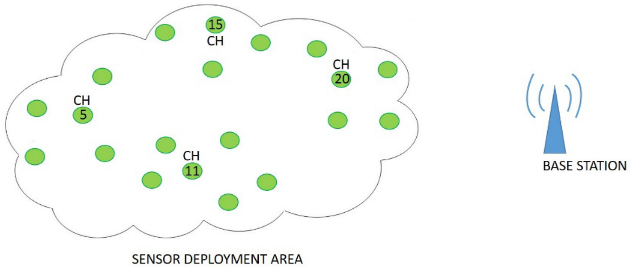


FIGURE 1. **Cluster head election.**

When the election of the cluster heads is complete, the clusters will be formed and each sensor nodes' cluster memberships will be decided. Once the cluster memberships are finalized, a sensor node will stay in the same cluster throughout the whole WSN lifetime.

In order to determine the cluster membership for the sensor nodes deployed in the network, all the sensor nodes that has elected themselves as a cluster heads broadcast information to the network about their identities through advertisement messages to notify the remaining nodes. With the carrier sense multiple access (CSMA) MAC [9] protocol, all cluster heads transmit their advertisement (ADV) messages. During this phase, all non-cluster head nodes listen the communication channel by keeping their receivers so that they can hear the advertisement messages.

The advertisement messages are generated by all the cluster heads and include the following fields about the cluster head as shown in Fig. 2.

Member ID	CH ID	CH Location	ToM

FIGURE 2. **ADV message structure of EAMR.**

- The member ID corresponds to the ID number of the cluster head. Before the initiation of the EAMR, each node is assigned a specific ID number and the sensor nodes elected as cluster heads use this number in the member ID field.

- The cluster head ID (CH ID) is the ID number of the cluster. The initially elected cluster heads can assign their member IDs to the CH ID value.

- CH location field includes the coordinate information for the location of the cluster head. This information will be used to identify the relay nodes for multi-hop inter cluster communication.

- Type of Message (ToM) field specifies that the type of the message is cluster head advertisement.

The non-cluster head nodes that are listening the communication channel receive the broadcasted ADV messages. A node decides to attach to a cluster depending on the received signal strength (RSS) of the incoming ADV messages. In order to consume the minimum communication energy for the collected data transmission from a sensor node to a cluster head, a sensor node attaches to the cluster head whose ADV message has the maximum RSS. In case of a tie for the RSSs, the sensor node chooses the cluster head that it will attach randomly.

When the non-cluster head nodes make a decision on the cluster heads that they will join to, they need to inform the cluster heads. For this purpose, each non-cluster head node transmits a join request (join-REQ) message to its cluster head. The structure of the join-REQ message is illustrated in Fig. 3.

Member ID	CH ID	ToM

FIGURE 3. **Join-REQ message structure of EAMR.**

- The member ID is the ID number of a sensor node.

- The CH ID field corresponds to the cluster number that the sensor node wants to attach to. The sensor node copies this value from the CH ID field of the ADV message with maximum RSS.

- ToM field indicates that this message is a join-REQ message.

After broadcasting ADV messages, cluster heads start listening to the communication channel in order to collect the join-REQ messages. The reception of join-REQ messages will indicate the identity of the members of a cluster to the corresponding cluster head.

The join-REQ messages are then collected by the cluster heads. The ToM field helps the cluster heads to distinguish the join-REQ messages. When a cluster head starts receiving the join-REQ messages, it compares the CH ID field of the join-REQ message with its member ID. If the CH ID field of a join-REQ message matches with the member ID of the cluster head, then the cluster head records the member ID field of the join-REQ message. Thus, that sensor is accepted to join the cluster. If the CH ID field of the join-REQ message does not match with the member ID of the cluster head, no action is taken. Note that, the CH ID is the same as the member ID of the cluster head at the start of EAMR.

When the receptions of the join-REQ messages are completed, each cluster head is aware of the number of members in its cluster and the member IDs. Now, the data collection schedule among the members of a cluster can be decided. For this reason, each cluster head decides on a TDMA schedule telling each node in its cluster when to transmit. The structure of the TDMA schedule message is shown in Fig. 4.

TS (Member ID_1)	TS (Member ID_2)	......	TS (Member ID_{n-1})	TS (CH ID)	ToM

FIGURE 4. Time slot assignment for cluster members in a EAMR cluster.

- TS (Member IDi) shows the time slot for a cluster member i allocated for data transmission, where $1 \leq i \leq N_{CHID} - 1$ and $N_{CH\ ID}$ denotes the number of cluster members (including the cluster head) for the cluster whose cluster head is CH ID.

- TS (CH ID) is the time slot allocated for data transmission reserved for a cluster head.

- ToM shows that this message is a TDMA schedule message.

Afterwards each cluster head broadcasts the TDMA schedule message to all the sensor nodes of its cluster. The reception of the TDMA schedule message will let each sensor node when it can transmit and when it cannot. After the non-cluster head nodes receive the TDMA schedule message, they can turn off their radio components if they are not transmitting. By this way, the power dissipation in individual sensors can be minimized.

Fig. 5 shows an illustration of the cluster formation with the ADV, join-REQ and TDMA schedule messages. Each non-cluster head node chooses a cluster to attach to under EAMR. For example, nodes 1, 2, 3 and 4 join cluster 5.

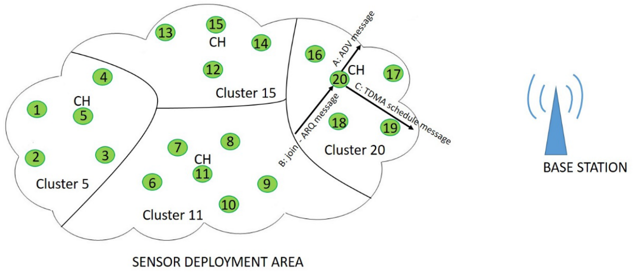


FIGURE 5. Cluster formation after joining of cluster members.

After the determination of the cluster heads, cluster memberships and the TDMA schedules, the relay nodes are needed to be chosen to conclude the set–up phase of EAMR. EAMR allows any cluster head to become a relay node for helping inter cluster communication. Instead of identifying an arbitrary node as a relay node, already elected cluster head nodes assume the responsibility of the relay nodes. When a cluster head node changes, the relay node duties are also passed on to the new cluster head node. In this way, the complexity and management of the algorithm does not get complicated.

During the ADV message exchanges, the cluster head nodes learn CH ID of the other cluster head nodes that are in range. In addition to CH ID, the location information of a cluster head is embedded into CH location field of the ADV messages. Thus, each cluster head is able to learn the location information of the remaining cluster heads. For forwarding the collected cluster data to the base station, each cluster head chooses the nearest forward neighbor cluster head towards the direction of the base station as a relay node.

When a cluster head selects the nearest neighbor cluster head to act as a relay node, it should inform the other cluster head about this selection. For this reason, it sends a relay selection message as shown in Fig. 6. The relay selection message includes the following fields.

- CH ID is the ID of the cluster

- Relay Node ID (RN ID) is the ID of the cluster head to be used as a relay. The RN ID is the Member ID field of the ADV message for the cluster to be used as a relay.

- ToM field indicates that this message is a relay selection message.

When a cluster head receives a relay selection message and if its member ID matches with the RN ID of the received message, it will be responsible for relaying the data coming from the cluster indicated with the CH ID of the relay selection message. Depending on its location in the network, the relay node can either choose its own relay node to transmit the data or directly transfer to the base station.

CH ID	RN ID	ToM

FIGURE 6. Relay node selection notification message structure in EAMR.

Fig. 7 illustrates an example on the relay node determination of EAMR. For example, for cluster 5 node 11 is chosen as a relay node, while for cluster 11 node 20 is chosen as a relay node. Note that for cluster heads which are in direct communication range with the base station, no relay nodes are selected. Thus, the data collected from cluster 20 will be directly transmitted to the base station.

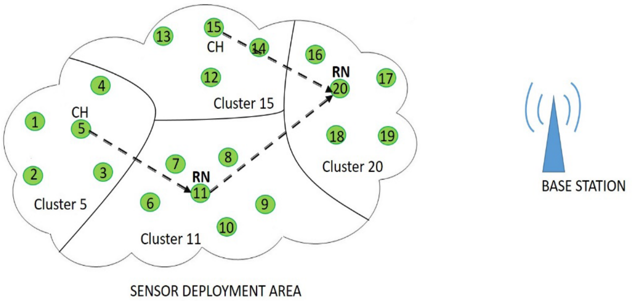


FIGURE 7. Multi-hop relay node determination in EAMR.

The relay node selection completes the set-up phase for the EAMR. Following the set-up phase, data collection and transmission from the sensor network will be accomplished by the steady state phase.

The set-up phase is executed only once under EAMR and during this phase clusters, cluster memberships and TDMA schedules for data transmissions are decided. As a consequence, it is not possible to add new nodes to the network after initial clusters and CHs are chosen.

B. STEADY STATE PHASE

Once the clusters, cluster memberships, TDMA schedules and relay nodes are known, the EAMR can start data collection from the sensor nodes for transmission towards the base station. The steady-state phase of the EAMR is responsible for this part. In addition to data transmission, occasional cluster head changes are executed during the steady-state phase. Since EAMR employs cluster heads as relay nodes, relay node changes are carried out together with cluster head changes.

Under the EAMR, the steady-state phase consists of periodic time frames. We call each of these time frames as a round. Two parts at each round of EAMR make up the steady-state phase: data transmission and cluster head change.

At each round, cluster heads collect the data sensed by the sensor nodes and transmit them towards the base station with the assistance of relay nodes. With the distribution of the TDMA schedules during the set-up phase, all the sensor nodes in the WSN are aware of their time slots for data transmission. Consequently, a cluster head gets the data belonging to its cluster based on the TDMA schedule decided in the set-up phase. Then, the data is aggregated and passed towards a relay node for distribution towards the base station. If a cluster head is in close proximity to the base station and does not have a relay node to transfer to, then the collected data is directly transmitted to the base station.

Data aggregation under EAMR is performed on all the unprocessed data at the base station and also locally at the CHs. If the energy for communication is greater than the energy for computation, then performing data aggregation locally at the CHs can reduce the overall system energy consumption since much less data needs to be transmitted to the BS. Data aggregation cost is *5 nj/bit/signal*.

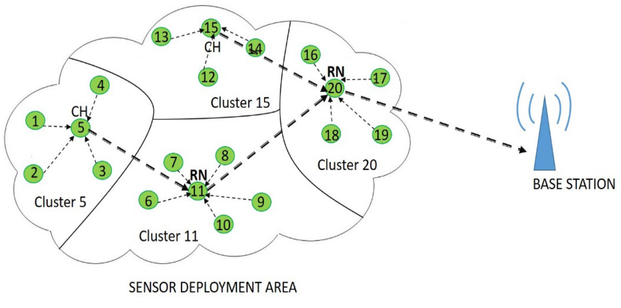


FIGURE 8. Data transmission in EAMR.

Fig. 8 shows a typical data transmission pattern under the EAMR. For example, the data collected in Cluster 15 is collected by the cluster head whose Member ID is 15. Then, this data is passed onto relay node whose Member ID is 20. Finally, the data is delivered to the base station by the relay node.

In a steady-state phase round, cluster head change is only carried out if the necessary conditions for a change exists. Without the existence of such conditions, the current cluster heads will stay as a cluster head in the following round.

The rest of this section describes the data transmission and cluster head change parts happening in the steady-state phase during a single round.

For every round of the steady-state phase, each cluster collects data based on the TDMA schedules of the cluster. During the time slot allocated to a cluster member, the member node transmits its collected data to its cluster head. In order to collect data from its cluster, each cluster head listens to the communication channel. When the data collection is over, the collected data is aggregated by the cluster heads and transferred to either its relay node or the base station.

Transmissions occurring in a cluster can affect communication at the clusters in a close proximity. To eliminate inter-cluster interference, all the clusters in EAMR communicate with the help of unique spreading codes. Within a cluster, each sensor node uses a common transmitting code so that there is no inter-cluster collision in transmitter-based code assignment mechanism. The usage of TDMA schedules eliminates intra-cluster collisions as each node is assigned distinct time intervals for data transmission. Thus, combining DSSS with TDMA scheduling under the EAMR inter and intra cluster interferences are reduced.

In order to transfer the collected data through relay nodes, each cluster head transmits the collected data belonging to its cluster using a fixed spreading code and a CSMA structure. By this way, data transmission among relay nodes can be possible.

Under the EAMR, a cluster head change is realized only when needed. This approach is quite different from LEACH and its variants, as those algorithms tend the change cluster heads and clusters at every round. Thus, EAMR reduces the overhead of new cluster head selections by reducing the frequency of cluster head changes. In addition to the reduction in the cluster head change numbers, the clusters stay fixed under the EAMR. The cluster memberships decided during the set-up phase do not change. This also helps to reduce the significant cluster formation overhead. However, any member in a cluster can later become a cluster head if the current cluster head energy level falls below the threshold.

After the data transmission part in a round is complete, each cluster head decides whether it will continue to act as a cluster head in the next round or a new cluster head needs to be selected. This choice is based upon the cluster head's remaining energy level. If a cluster head's remaining energy level is more than the threshold value (ThV), it keeps on its duty as a cluster head for the following round. If a cluster head's remaining energy level falls below the ThV, a new cluster head needs to be chosen for the following round. When a new cluster head will be elected, the acting cluster head chooses a new cluster head from the members belonging to its cluster. This selection is made in a random fashion among all the alive members of the cluster. In order not to increase the complexity of EAMR, the new cluster head election is done randomly. Any node in the cluster can be chosen as the new cluster head. If no alive sensor nodes are left belonging to a cluster except the current cluster head, the current cluster head continues as a cluster head in the next round as well.

The current cluster head notifies the members belonging to its cluster about the cluster head change through broadcasted cluster head change messages. The structure showing a cluster head change message is given in Fig. 9. In order to prevent a CH from running out of its energy before it can transmit the cluster head change message, the ThV is determined by adding some safety margin. Under EAMR, the lower bound of ThV is calculated which would guarantee network connectivity in the upcoming round and as a safety margin 10 times more of this value is used so that the current CH can live at least for 10 more rounds.

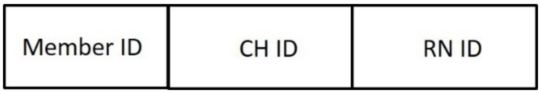


FIGURE 9. **Cluster head change message of EAMR.**

The cluster head change message includes the following fields.

- Member ID shows the Member ID of the cluster head for the following round. If no change is going to occur, then the current cluster head copies its Member ID into this field. If a change is going to occur, then the cluster head writes the randomly selected Member ID of a sensor node among the alive members of the cluster.

- CH ID is a number which identifies the cluster. CH ID is set during the set-up phase and it is the same member ID of the first cluster head of the cluster. The value does not change for the whole sensor network lifetime.

- RN ID is the member ID of sensor node used as a relay node for the cluster. With this information the new cluster head learns about the relay node and transfers the collected cluster data towards the relay node. A value of 0 indicates that the cluster does not use a relay node and in this case the data is transmitted to the base station directly.

- ToM indicates that this message is a cluster head change message

The value of ThV has a considerable effect for the performance of EAMR. A high value of ThV can result in frequent cluster head changes. In fact, if the ThV is set to be equal to the initial sensor node energy levels, cluster heads will change at every round and the EAMR will show a similar performance to LEACH except the fixed clusters. On the other hand, a low value of ThV can result in the failure of a cluster head by death in the next round and the network connectivity might fail. Thus, the ThV needs to be chosen in such a way that the network connectivity will not be sacrificed.

The energy consumed by a cluster head during a single round can be expressed with (1), where l denotes the length in bits of the transmitted data by each cluster member, E_{elec} is the transceiver energy, E_{DA} is the aggregation energy per bit, $\frac{K}{m}$ is the average number of sensor nodes belonging to a cluster, $\in_{mp}$ is multipath amplifier energy with d^4 power loss and d_{toBS} denotes the distance of the cluster head to the base station

$$E_{CH} = lE_{elec}\left(\frac{K}{m} - 1\right) + lE_{DA}\left(\frac{K}{m}\right) + lE_{elec} + l \in_{mp} d^4_{toBS} \tag{1}$$

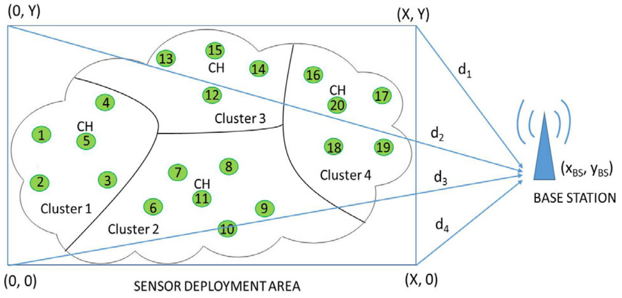


FIGURE 10. **Outside base station situation.**

In order to find a lower bound for the *ThV* that would guarantee the network connectivity for the next round, the farthest point from the base station in the sensor deployment area is considered. Suppose that the sensor deployment area is an X by Y area as shown in Fig. 10. If a sensor node is placed in the farthest point of the deployment area and elected as a cluster head, that node's energy dissipation E_{CH} should be larger than *ThV* so that it will not die for at least one round.

If the base station is located at coordinates (x_{BS}, y_{BS}), the farthest possible points to the base station can be either $(0, 0)$, $(X, 0)$, $(0, Y)$ or (X, Y). The distances from these points to the base station can be described by the set of equations in (2-5).

$$d_1 = \left(\sqrt{(x_{BS} - X)^2 + (y_{BS} - Y)^2}\right) \tag{2}$$

$$d_2 = \left(\sqrt{(x_{BS})^2 + (y_{BS} - Y)^2}\right) \tag{3}$$

$$d_3 = \left(\sqrt{(x_{BS})^2 + (y_{BS})^2}\right) \tag{4}$$

$$d_4 = \left(\sqrt{(x_{BS} - X)^2 + (y_{BS})^2}\right) \tag{5}$$

Thus, assuming that a sensor node is chosen as a cluster head at the farthest point of the sensor deployment area from the base station, the distance between that node and the base station will be given by (6).

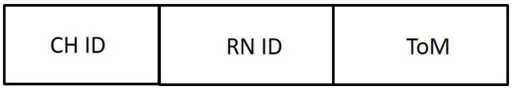
$$d_{toBS} = \max(d_1, d_2, d_3, d_4) \tag{6}$$

TABLE 1. Determination of THV

Number of Sensor Nodes	Sensor Deployment Area	Base Station Coordinates	E_{CH}	ThV
100	$100\,m\,x\,100\,m$	(150,50)	0.0052	$ThV > 10E_{CH}$
200	$100\,m\,x\,100\,m$	(150,50)	0.0053	$ThV > 10E_{CH}$
100	$200\,m\,x\,100\,m$	(250,50)	0.0352	$ThV > 2E_{CH}$
200	$200\,m\,x\,100\,m$	(250,50)	0.0353	$ThV > 2E_{CH}$

Using (6) in (1) will give a lower bound for the *ThV* that would guarantee the network connectivity for at least one more round. For the EAMR, we have used a *ThV* which is *10* times more than obtained by the above procedure. Table 1 illustrates some examples on the *ThVs* by considering the location of the base station, the number of nodes in sensor deployment area and the propagation model.

If a cluster head node is also acting as a relay node, it also notifies the cluster heads that are using itself as a relay node through a relay change message as shown in Fig. 11.



CH ID	RN ID	ToM

FIGURE 11. Relay node change message of EAMR.

The other cluster heads shall forward their data towards the new cluster head (i.e new relay node) after the receipt of this message. The relay node change message includes the following fields.

- CH ID is the ID of the cluster.

- Relay Node ID (RN ID) is the member ID of the new cluster head.

- ToM field indicates that this message is a relay change message.

Under EAMR, the cluster head changes will not occur frequently because EAMR aims to utilize cluster heads as long as possible until their energy level fall below the ThV. Although the cluster heads consume more energy compared to the remaining non-cluster head nodes, the energy levels of non-cluster head nodes are kept as high as possible. Consequently, the entire network lifetime is increased. The proposed cluster head change mechanism also provides significant energy consumption savings for the entire network. With fixed clusters and reduced cluster head changes, the overhead of ADV and join-REQ messages are minimized.

The relay nodes positively impact the energy dissipation in the sensor network. The introduction of relay nodes makes the algorithm scalable and help increase the lifetime of the remote clusters. For most of the algorithms in literature, the remote sensor nodes have the shortest lifetimes due to the large sensor to base station transmission distance as shown in equation (1). By using relay nodes, the energy dissipated at remote nodes are decreased as $d_{toRN}^4 + d_{RNtoBS}^4 < d_{toBS}^4$ where $d_{toBS} \sim d_{toRN} + d_{RNtoBS}$. As a result, remote clusters can live longer under EAMR. Thus, a more uniform distribution of the alive sensor nodes is possible which will allow data collection from every part of the network even when the remaining alive nodes are only a few.

The steady-state phase of the EAMR repeats itself for the whole sensor network lifetime. Figure 12 illustrates a high level representation of the proposed EAMR flowchart and the performance analysis of EAMR is described in the following sections.

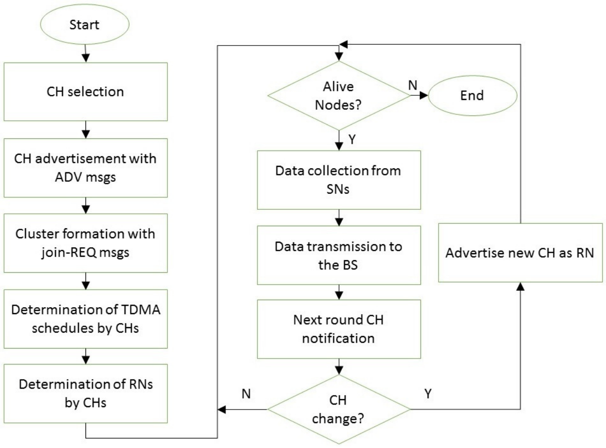


FIGURE 12. EAMR flowchart.

IV. SYSTEM AND CHANNEL MODEL

In this section, the system and the channel model used under the simulation for EAMR is discussed. The same model also applies to other protocols simulated so that we can make fair comparisons and understand the performance gains under EAMR.

A total of *100* or *200* sensors are deployed over a sensor deployment area of *100 x 100* meters. All the deployed sensor nodes are assumed to be identical except for DEEC and SEP protocols. The base station is located outside the sensor deployment area at coordinates *(150, 50)*.

The following model is used for the energy consumption of the radio hardware: while the transmitting sensor nodes consume energy for the radio electronics as well as the power amplifier, the receiving sensor nodes dissipate energy for the radio electronics. Based on the distance between a receiving node and a transmitting node, cross-over distance d_{co}, *fs* (free space with d^2 power loss) or *mp* (multipath fading with d^4 power loss) channel models are used [10].

As a result, in order to transmit an l-bit message to a distance of d, the radio consumes energy depending on d_{co} as shown in equation (7).

$$E_{TX}(l,d) = \begin{cases} lE_{elec} + l\,\epsilon_{fs}\,d^2, & d < d_{co} \\ lE_{elec} + l\,\epsilon_{mp}\,d^4, & d \geq d_{co} \end{cases} \qquad (7)$$

In order to receive a message, the dissipated radio energy can be described by equation (8).

$$E_{RX}(l) = lE_{elec} \tag{8}$$

The transceiver energy (E_{elec}) depends on modulation, digital coding, filtering and spreading of the signal. The multipath amplifier energy ($\in_{mp}$) and the free space amplifier energy ($\in_{fs}$) depend on the distance to the receiver as well as the acceptable bit-error rate.

Table 2 shows the environment parameters used for our simulations.

TABLE 2. Simulation environment parameters.

Parameters	Values
Sensor deployment area	100 m x 100 m
Number of nodes	100
Coordinates for base station	(150,50)
Initial energy of each node	2 J
Packet size for data	6400 bits
Packet size for control info	200 bits
Transceiver energy	50 nJ/bit
Aggregation energy for each bit	5 nJ/bit/signal
Free space amplifier energy	10 pJ/bit/m^2
multipath amplifier energy	0.0013 pJ/bit/m^4
Threshold Value (ThV)	0.05 J

V. EVALUATION FOR THE PERFORMANCE OF EAMR

For the evaluation of the performance of the proposed EAMR, network lifetime, network energy dissipation and the amount of data transmitted to the base station is measured. In addition, to observe the energy dissipation inside the network, the energy map of the network is obtained. In order to understand the efficiency, EAMR is compared with cluster based algorithms, such as the traditional LEACH algorithm, and its novel variant ModLEACH as well as SEP and DEEC.

All the simulations are repeated *100* times with Matlab for different network topologies by distributing the sensor nodes randomly at the start of each simulation. Then, the averages of these simulations are computed and the obtained results are shown in the figures and tables. Consequently, each data point on a figure (except for part *E*) represents the average of *100* different network topologies.

A. NETWORK LIFETIME

The network lifetime is a good indication of how long data can be collected in a WSN. One of the key issues of the EAMR is the reduction of the overhead when compared with other WSN protocols. The clusters set during the set-up phase of EAMR do not change during the rounds of the steady-state phase. In addition, the cluster head changes are reduced by utilizing a cluster head as long as possible. As a result, the energy dissipation for cluster and cluster head changes are minimized and the network lifetime is increased.

Table 3 presents the average and maximum lifetime of EAMR and the compared protocols with respect to the total initial network energy. For all protocols, the simulations are repeated *100* times with different network topologies (random sensor deployments in the sensor area) and the average and maximum lifetimes are shown. While EAMR, LEACH and ModLEACH are homogeneous protocols, thus all the sensors have equal initial energy levels, DEEC and SEP are heterogeneous protocols. Some of the nodes under those protocols start with higher initial energy levels.

TABLE 3. Network lifetime comparison.

Algorithm	Average Lifetime	Maximum Lifetime	Initial Network Energy
EAMR	5774	6015	200 J
EAMR	7157	7280	250 J
DEEC	5221	5941	250 J
SEP	5059	6177	250 J
ModLEACH	3742	4123	200 J
LEACH	3478	4216	200 J

The maximum average lifetime is obtained under the EAMR. Even though DEEC and SEP start with %25 more total initial network energy, the lifetime under EAMR is increased %10.5 when compared to DEEC and %14.1 when compared to SEP. The lifetime increase is significantly better when compared with ModLEACH and LEACH.

Fig. 13 gives another illustration of the network lifetime comparison when the number of remaining alive nodes are considered. Under the EAMR, the node deaths occur evenly. For the remaining protocols, following the initial node deaths, the remaining node deaths occur very quickly.

By varying the value of the ThV, EAMR can be adjusted to different sensor networks' specific needs. If for a sensor network, the extension of the first node death time is crucial, larger ThV values can be used. But if the last node death time needs to be extended, the ThV values can approach to 0, provided that a current CH still has some energy to transmit the next CH ID to its cluster members, so the next CH can start collecting data in the next round. Fig. 14 shows the number of dead nodes as a function of the round number for three different ThV of *0.05 J*, *0.25 J* and *1 J* and compares the results with LEACH and ModLEACH. As the ThV increases, the first node death time also increases.

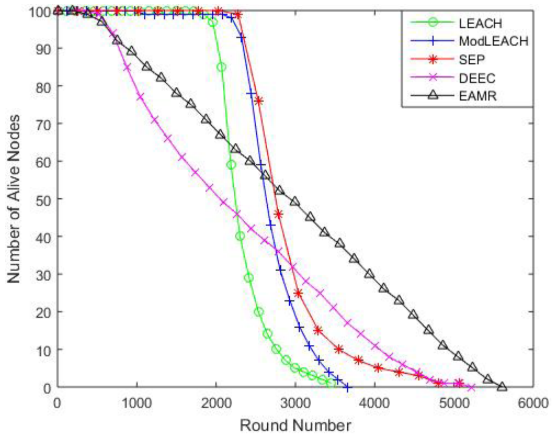


FIGURE 13. **Round number vs. number of alive nodes for different algorithms.**

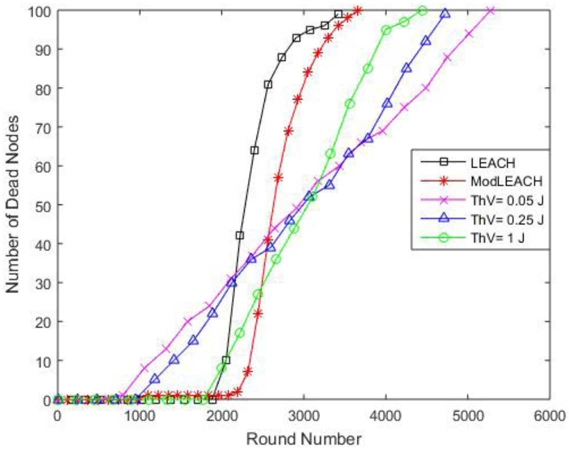


FIGURE 14. **Round number vs. number of dead nodes for different ThV.**

B. RESIDUAL ENERGY

The energy dissipation rate is an important factor representing how green a network protocol is. Energy dissipation in a WSN is directly proportional to the efficiency of the employed protocol and has a considerable effect on the network lifetime.

Fig. 15 shows the total residual energy under EAMR for each round and compares EAMR with LEACH, ModLEACH, DEEC and SEP. As stated earlier, DEEC and SEP employ heterogeneous networks where some of the nodes have higher initial energy levels. Thus, DEEC and SEP start with a total network energy of *250 J*, while the remaining protocols start with *200 J* (*2 J* per sensor node).

EAMR energy dissipation ratio is lower than all the compared protocols. As a matter of fact, around *2000*th round EAMR residual energy surpasses SEP and DEEC residual energies, even though they have started with 25% more total network energy. EAMR tries to preserve the network energy in a better way, not only by using fixed clustering but also by increasing the utilization of the cluster heads.

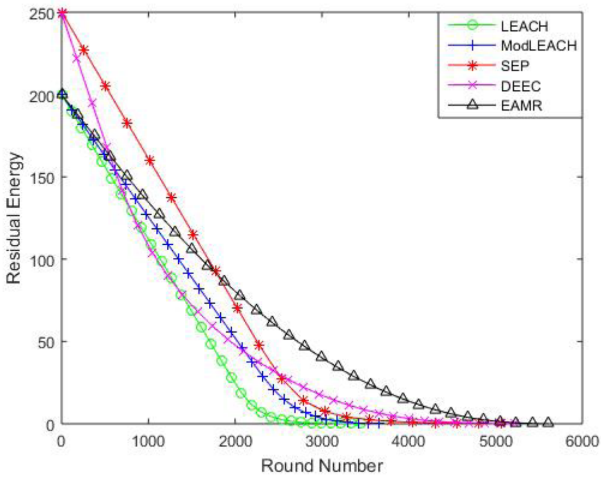


FIGURE 15. **Round number vs. residual energy.**

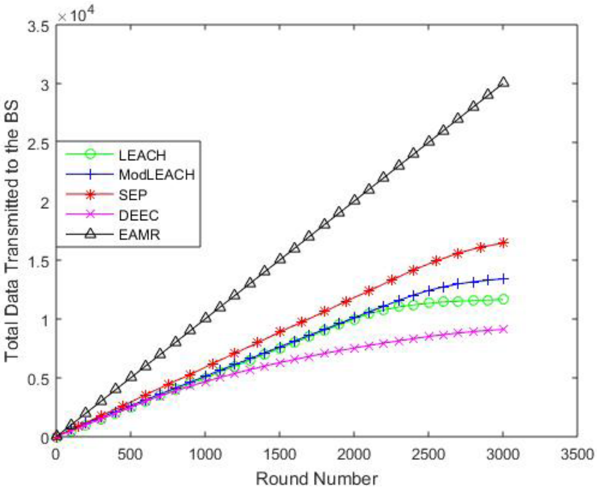


FIGURE 16. **Round number vs total data transmitted to the base station.**

C. TOTAL DATA TRANSMITTED TO THE BS

The cumulative amount of data delivered to the base station under EAMR and the compared protocols is plotted in Fig. 16. For data transmission, EAMR also has a better performance. Due to the relatively constant nature of the node death ratios, EAMR keeps collecting data throughout the entire network in a steady manner. However, for other protocols, the instantaneous data transmission drops significantly after the node deaths start. Because, the node deaths occur very frequently when compared with EAMR.

D. SENSOR NODE DENSITY

Fig. 17 illustrates the simulation results for *200* nodes. When the number of nodes increase in the network for the same area, it is expected that, the distances between the nodes decrease. This decrease causes to consume lower energies for transmissions hence it extends the network lifetime of all protocols. Also, the increase in the node number causes to increase the number of messages in the network, however the decrease in distance is more effective on the lifetime performance of the network when compared with *100* node network as shown in Fig. 13.

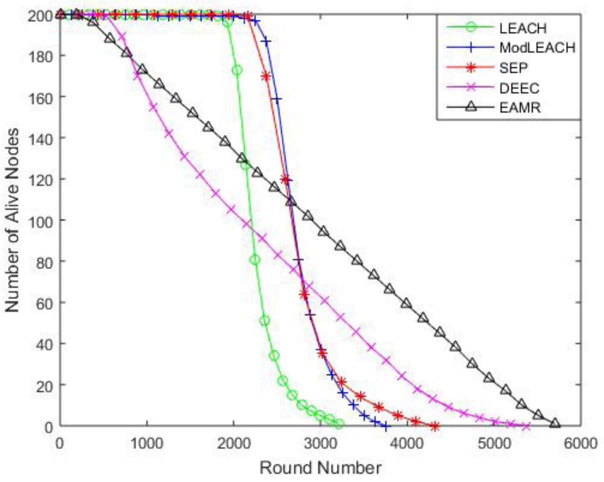


FIGURE 17. Number of alive nodes for 200-nodes network.

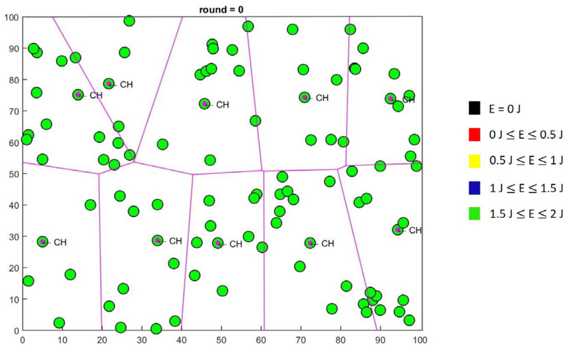


FIGURE 18. Energy map of the sensor network at the deployment.

E. ENERGY MAP OF THE SENSOR NETWORK

Under EAMR, the energy distribution of the sensor nodes in the network are plotted for the initial round and at *1000th* round in Fig. 18 and 19 respectively. In these figures, the sensors are marked with green, blue, yellow, red and black for different energy levels.

The base station is located outside the sensor deployment area at coordinates *(150, 50)* and all the sensor nodes start with an energy level of *2 J*. Since CH changes occur only when the CH energy levels fall below the ThV, except for the CHs, all of the remaining sensor nodes energy levels are maintained at high levels. As EAMR utilizes CH nodes more, the nodes which are selected as CHs die earlier, but the rest of the nodes live longer, leading to an increase in the network lifetime.

VI. CONCLUSION

With this paper, we have proposed an energy-aware multi-hop routing (EAMR) protocol for WSNs. The rapid deployment of WSNs in the past few decades is expected to grow larger in the future with new application types. Consequently, energy-efficient solutions for WSNs have been very essential. Since energy-efficiency increases the lifetime of the WSNs and reduces the overall data collection cost from a sensor field, it has become a key and active research area.

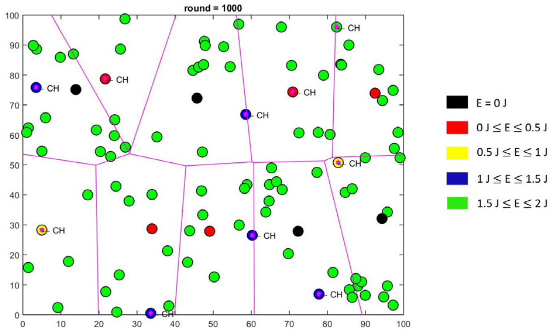


FIGURE 19. Energy map of the sensor network after 1000 rounds.

With EAMR we aim to achieve this objective by reducing the excessive overhead observed in LEACH and its variants by implementing fixed clusters and minimizing the quantity of cluster head changes. Since the formation of clusters and in addition selection of cluster heads can be costly, the reduction of the overhead results in energy-efficiency, improvement in the network lifetime and a better utilization. The clusters formed during the set-up phase stay fixed, however new cluster heads can be chosen following the initial cluster heads of the set-up phase not very frequently but only when needed. The implementation of the threshold based cluster head change mechanism utilizes cluster heads as long as possible before the need for choosing new cluster heads emerges. Instead of direct transmission of data between the cluster heads and the base station, EAMR uses inter-cluster transmission using relay nodes. Decreasing the effective transmission distances with relay nodes can be considered as another major component for lifetime improvements. In order not to increase the complexity of the EAMR protocol, the cluster heads also assume the responsibility of a relay node.

When compared with other protocols, significant improvements have been observed under EAMR in terms of lifetime, energy dissipation and the amount of data transmitted to the base station. Thus, EAMR might be a good candidate for a green WSN protocol.

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