α-coverage Scheme for Wireless Sensor Networks

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Abstract

The problem of prolonging system lifetime in Wireless Sensor Networks (WSNs) while guaranteeing the entire coverage of the interest zone is very challenging mainly due to constraint-energy of sensors that composed these networks. In most applications, system lifetime is defined as the time elapsed until the last sensor dies. However, this evaluation should not be used in some critical applications such as intrusion detection and surveillance applications, where coverage ratio must be raised enough. Thus, to fulfill successfully the objective of deploying WSNs for these types of applications, it is often required that ratio of alive sensors should be higher than a certain value α-coverage. In this paper, we propose an efficient α-coverage scheme to maximize the ratio of alive sensors that is necessary to guarantee the entire coverage of the interest region. This scheme is based on substantial performance gains of scheduling and broadcasting solutions proposed to prolong system lifetime in WSNs. Simulation results show that our scheme prolongs considerably network lifetime when compared with LEACH [1] and LEACH-C [2].

1. Introduction

Recent advances in MEMS, Nanotechnology and wireless communications are enabling the emergence of low-cost tiny devices equipped with one or more sensors, a processing unit and radio transceiver. These small devices collaborate with each other to form a wireless sensor network (WSN) for both monitoring and control purposes. Generally, sensor nodes may be deployed with a large number in an interest field for sensing certain phenomena and reporting data through a short transmission range to a data collection point called sink or base station. However, they are often powered with onboard batteries with limited energy. Recharge and replacement of the batteries are usually impractical in most of applications due to remote or hostile environments where sensors are deployed. As a result, WSNs should be dynamically self-organized in order to conserve energy and prolong network lifetime while ensuring proper operations of the network.

The problem of conserving energy and prolonging system lifetime in WSNs while guaranteeing a maximal coverage of the interest zone is very challenging mainly due to constraint-energy of sensors that composed these networks. A number of schedule-based and broadcast-based solutions have been proposed to save node's energy and prolong network lifetime. In schedule-based solutions, authors are mainly interested to optimize the behavior of sensors at the level of MAC layer (Medium Access Control). The problem of designing a MAC layer for wireless networks to achieve proportional fairness of media access that adapts to different traffic requirements have been studied in [3],[4]. There are two main propositions in this direction. In first, the on-duty sensors keep in work stage while other redundant sensors fall asleep and the sleeping sensors wake up and turn to be on-duty when the working sensors die. In second, the sleeping sensors wake up periodically to probe their neighborhood and start working only when there is no working sensor within the probing range. Both propositions are acquiring longer system lifetime with deployment of a number of backup redundant sensors. In broadcast-based methods, authors focus on the routing protocols performance. There are several propositions in this direction such as LEACH [1] and its variants.

On the other hand, the proposed methods are based on networks organization: centralized methods and cluster-based methods. Centralized methods require many control messages and thus cause long latency to route a collected data from a sensor to the base station. Furthermore, cluster-based methods involve reduced control messages. However, in cluster-based methods, if cluster-heads are fixed, then they carry out more energy-intensive processes. To benefit from substantial gains performance of proposed solutions, we propose an efficient cluster-based self-organization scheme, in which we combine jointly schedule-based and broadcast-based paradigms for communications. Schedule-based methods are used for intra-cluster communications whereas broadcast-based methods for inter-cluster communications.

In most works, system lifetime in WSNs is defined as the maximum last sensor dying time. However, this evaluation should not be used in some critical applications such as intrusion detection and surveillance applications, where coverage ratio must be raised enough. Thus, to fulfill successfully the objective of deploying WSNs for these types of applications, it is often required that ratio of alive sensors should be higher than a certain value α-coverage. α-coverage represents the ratio of alive sensors that is necessary to guarantee the entire coverage of the interest region. So once, its value descends than a certain threshold, WSNs are considered as worthless WSNs.

The rest of this paper is organized as follows. In Section 2, we provide notations and hypothesis necessary for describing our scheme. Section 3 reviews several cluster-based algorithms proposed previously. In Section 4, we present our contribution, and Section 5 presents performance analysis of proposed scheme and compares it to other protocols performance. Finally, Section 6 concludes our paper by pointing out some possible future research directions.

2. Notations and hypothesis

Before heading into the technical details of our contribution, we first give some definitions and notations that will be used in our paper later.

A wireless sensor network is represented by an undirected graph $G=(V,E)$, where V represents the set of sensor nodes and $E\subseteq V^2$ is the set of edges that gives the available communications : an edge $e=(u,v)$ belongs to E if and only if the node u is physically able to transmit messages to v and vice versa i.e all links in the graph are bidirectional. Each sensor node $u\in V$ is assigned a unique value to be used as an identifier, so that the identifier of u is denoted by $Node_{Id}(u)$. The neighborhood set of a node u is represented by $N_1(u)$ as in (1) and the size of this set is known as the degree of u, denoted by $\delta(u)$.

$$N_1(u)=\{v\in V \mid v\neq u \wedge (u,v)\in E\} \quad (1)$$

The 2-hop neighborhood set $N_2(u)$ of a node u contains the nodes which are the neighbors of u's neighbors except those that are the u's neighbors, is represented by as follows:

$$N_2(u)=\left\{ w\in V \;\middle|\; \begin{array}{c}(v,w)\in E \text{ where} \\ v\in N_1(u)\wedge w\in N_1(v)\wedge w\notin N_1(u)\end{array}\right\} \quad (2)$$

The combined set of 1-hop and 2-hop neighborhood sets of u is denoted as $N_{12}(u)$:

$$N_{12}(u)=N_1(u)\cup N_2(u)=\{v\in V \mid v\neq u \wedge d(u,v)\leq 2\} \quad (3)$$

In a general manner, the k-hop neighborhood set of a node u is represented by $N^k(u)$ as in (4), and its closet set of k-hop neighborhood is denoted by $N^k[u]$ as in (5). The size of $N^k(u)$ is known as the k-degree of u and denoted by $\delta^k(u)$. Here, $d(u,v)$ represents the minimal distance in number of hops from u to v.

$$N^k(u)=\{v\in V \mid v\neq u \wedge d(u,v)\leq k\} \quad (4)$$

$$N^k[u]=N^k(u)\cup\{u\} \quad (5)$$

The k-density of a node u represents the ratio between the number of links in its k-hop neighborhood (links between u and its neighbors and links between two k-hop neighbors of u) and the k-degree of u; formally, it is represented by the following formula:

$$k-density(u)=\frac{\left|(v,w)\in E \mid v,w\in N^k[u]\right|}{\delta_k(u)} \quad (6)$$

However, since the calculation of the k-density requires a k-hop positional knowledge and sensors have low capacity storage, we propose interested only in calculation of the 2-density nodes as presented in (7) not to weaken our scheme of its performance.

$$2-density(u)=\frac{\left|(v,w)\in E \mid v,w\in N_{12}[u]\right|}{\delta_{12}(u)} \quad (7)$$

In this paper, we assume that all sensors are given in a two dimensional space. Each sensor has an omni-directional antenna what allows for a single transmission of it can be received by all nodes within its vicinity and we consider that sensors have a 2-hop positional information. We also assume that each sensor node has a generic key and it is able to evaluate it. This key represents the fitness of each node to be a cluster-head and the higher key means the higher priority.

3. Related work

Recently, many cluster-based schemes [1]-[6] have been proposed to deal the main challenges inWSNs. In this section, we reviewed some of the most relevant papers related to cluster-based network architecture, which have been carried out to prolong lifetime in WSNs.

In [1], authors propose LEACH protocol, which is a distributed, single hop cluster-based scheme without any central control. In LEACH, cluster-heads are periodically selected. After each round, each sensor elects itself as cluster-head with a probability which is equal to:

$$p_{CH} = k\frac{E(u)}{E_{Total}} \qquad (8)$$

where $E(u)$ represents remaining energy of node u, E_{Total} is the total energy in the whole network and k is the optimal number of clusters. However, the evaluation of E_{Total} presents a certain difficulty since LEACH operates without other routing schemes and any central control. After electing the cluster-heads, all the non cluster-head sensors decide on the cluster to which they will belong for the current round. This decision is based on the received signal strength of the advertisement messages.

In [5], authors compared homogeneous and heterogeneous networks in term of energy dissipation in the whole network and analyzed both single-hop and multi-hop networks performance. They chose LEACH as a representative of a homogeneous, and compared it with a heterogeneous single-hop network. The authors noticed that using single-hop communication between cluster members and their corresponding cluster-head may not be the best choice when the propagation loss index k (k>2) for intra-cluster communication is large, because LEACH might generate clusters whose size is important in dense networks and clusters whose size limited in small networks. In both cases, cluster-heads might rapidly exhaust their battery power either when they coordinate among their cluster members or when they are placed away from the base station. Therefore, the authors proposed an improved version of LEACH called M-LEACH [5] (Muti-hop LEACH), in which cluster members can be to more one hop from their corresponding cluster-head and communicate with it in multi-hop mode, and they also illustrate the cases in which LEACH-M outperforms LEACH protocol. However, this proposed version requires that each sensor is capable to aggregate data, what increases the overhead for all sensors. To improve the performance of this strategy, in [6] authors focus on heterogeneous sensor networks instead of using homogeneous sensors, in which two types of sensors are deployed: super and basic sensors. Super sensors have more capabilities on processing and communication, and act as cluster-heads, while basic sensors are simple with limited power, affiliate to nearby cluster-head and communicate with it via multi-hop mode.

Furthermore, in [2], another variant of LEACH called LEACH-C was conceived to improve LEACH performance. This variant utilizes a centralized architecture to select cluster-heads while using base station and location knowledge of sensors. However, it enormously deploys energy to achieve this task and it consequently increases network overhead since all sensors send their location information to the base station at the same time during the set-up phase. On the other hand, as it was proven in several works, a centralized architecture is particularly suitable for small networks, whereas it lacks scalability to handle load when number of nodes increases in a network.

In the proposed scheme, we aimed to self-organize WSNs in the purpose to maximize their lifetime. For that, we involved determining factors in node's key computation.

4. Cluster formation

In this section, we present our proposed scheme that enables to generate balanced clusters. For the execution of our scheme, we assume that:

- all sensors are homogeneous with constrained energy and the same transmission range,
- sensors are immobile,
- sensors have 2-hop neighborhood positional knowledge and operate asynchronously without a centralized controller,
- each sensor is able to calculate its key according to its k-density and residual energy.

Cluster formation process consists to generate 2-hop clusters. Each cluster has a cluster-head, which is elected among its 2-hop neighborhood based on sensors' keys. The key of each sensor is a combination of k-density and residual energy as in (9). We involve k-density factor in key computation of each sensor in the purpose to generate homogenous clusters. On the other hand, we also imply remaining energy factor in order to choose the sensor having more energy in its 2-hop neighborhood.

$$Key(u) = \alpha * 2\text{-}density(u) + \beta * Res\text{-}Energy(u) \qquad (9)$$
$$where \quad \alpha + \beta = 1$$

Since cluster-head is responsible to achieve several tasks such as coordination among the cluster members, transmission gathered data to the remote base station, and management of its own cluster; we propose to set up periodically cluster-head election process after each round so that cluster-heads do not rapidly exhaust their battery power. We also propose that each cluster has a size ranging between two thresholds $Thresh_{Lower}$ and $Thresh_{Upper}$ and cluster members are at most 2-hops from their respective cluster-head.

In our scheme, each sensor is identified by a state vector as follow: $(Node_{Id}, Node_{Ch}, Key, Hop, Size, Thresh_{Lower}, Thresh_{Upper})$ where $Node_{Id}$ is the sensor identifier, $Node_{Ch}$ represents the identifier of its cluster-head, *Hop* indicates the number of hops separating it from its respective cluster-head, and *Size* represents cluster size to which it belongs. Each sensor is responsible to maintain a table called '$Table_{Cluster}$' in which the information of the local members cluster is stored. The format of this table is defined as $Table_{Cluster}(Node_{Id}, Node_{Ch}, Key)$. The sensors could coordinate and collaborate between each other to construct and update the above stated table by using Hello messages. We used Hello messages to achieve these operations in order to alleviate the broadcast overhead. Moreover, each cluster-head has another table called '$Table_{CH}$', in which information of cluster-heads is stored. The format of this table is defined as $Table_{CH}(Node_{Ch}, Key)$. The proposed scheme is performed in three consecutive phases: set-up, re-affiliation and steady-state.

4.1 Set-up phase

At the beginning of each round, each sensor calculates its key and generates a 'Hello' message including two extra fields addition to other regular contents: *Key* and $Node_{Ch}$, where $Node_{Ch}$ is set to zero. Then, it broadcasts it to its 2-hop neighborhood via a 'Hello' message as well as it eavesdrops its neighbor's 'Hello' message. The sensor having the greatest key in its 2-hop neighborhood is chosen as cluster-head during the current round. Each cluster-head updates its state vector by assigning to $Node_{Ch}$ the value of its identifier $Node_{Id}$, sets respectively *Hop* and *Size* with 0 and 1. Then, it broadcasts an advertisement message *(ADV_CH)* including its state vector to its 2-hop neighborhood to request them to join it. Each sensor that receives the massage and does not belong to any cluster as well as its key is lower than CH's key, transmits *REQ_JOIN* message to *CH* to join it. Corresponding cluster-head checks if its own cluster size does not reach $Thresh_{Upper}$, it will transmit *ACCEPT_CH* message to this sensor.

4.2 Re-affiliation phase

During the set-up phase, it may not be possible for all clusters to reach $Thresh_{Upper}$ threshold. Moreover, it is possible that there is creation of clusters whose size is lower than $Thresh_{Lower}$ since there is no constraint relating to the generation of these types of clusters. In this phase, we proposed to re-affiliate the sensors belonging to clusters that have not attained cluster size $Thresh_{Lower}$ to those that did not reach $Thresh_{Upper}$ in the purpose to reduce the number of clusters formed and obtain balanced clusters.

The execution of this phase proceeds in the following way. Cluster-heads that belong to clusters whose size is strictly lower than $Thresh_{Upper}$ and higher than $Thresh_{Lower}$ broadcast a new message called *RE-AFF_CH* to re-affiliate nodes belonging to the small clusters to them. Each sensor that receives this message and belongs to a small cluster, should re-affiliate to the nearest cluster-head based on the received signal strength. Thus, after the unfolding of this phase, we obtain a reduced number of balanced clusters. Finally, cluster-heads construct a cluster-to-cluster (CH-to-CH) routing paths to use them for data transmission.

After the end of both phases, each cluster-head creates a time schedule, in which time slots are allocated for intra-cluster communication, data aggregation, inter-cluster communication, and maintenance process. Then the generated clustered sensor network starts the steady-state phase of round to transfer collected data to the remote base station.

4.3 Steady-state phase

During the steady-state phase, sensors can begin sensing and transmitting collected data to their respective cluster- heads. The radio of each non cluster-head sensor can be turned off until the sensor's allocated transmission time. The cluster-heads, after receiving all data, aggregate it before sending it to the remote base station. Each cluster-head communicates using different CDMA codes in order to reduce interference from nodes belonging to other clusters.

5. Simulation results

In our experiments, we have carried out extensive simulations to evaluate our scheme and compare it with LEACH and LEACH-C in terms of system lifetime. To achieve this goal, we have performed simulations with NS-2 [7] using the MIT_uAMPS ns code extensions [8].

We have considered a network topology with 100 sensors, where each one of them with a sensing range of 25 meters. Sensors were randomly placed in a square area 100m×100m by using a uniform distribution function and the remote base station was located at position $x = 50$, $y = 175$ i.e. it was placed outside the area where the sensors were deployed. Initially, all sensors have an equal amount of energy i.e. sensors start with 2 Joules of energy. In our context, we defined system lifetime as the time elapsed until a fraction of sensors die. Hence, simulations were carried out until all a fraction of sensors exhausted their battery power. In addition, we have performed simulations using threshold $Thresh_{Upper}$= 30, threshold $Thresh_{Lower}$=15 and α-coverage=50% i.e. fraction of alive sensors.

To illustrate the substantial gains performance of our scheme, we have used the same model as presented in [2]. Simulated model parameters were set as shown in Table 2. We have assumed that energy consumption was mainly divided into two parts: receiving and transmitting message. The transmission energy consumption needs additional energy to amplify signal depending on the distance to the destination. Thus, to transmit a k-bit message to a distance d, the radio expends energy as described by the formula (10), where ε_{elec} is energy consumed for radio electronics, $\varepsilon_{friss\text{-}amp}$ and $\varepsilon_{two\text{-}ray\text{-}amp}$ for a amplifier. The reception energy consumption is represented by the formula (11). The data size was 500 bytes/message plus a header of 25 bytes.

$$E_{Tx} = \begin{cases} \varepsilon_{elec} \times k + \varepsilon_{friss-amp} \times k \times d^2 & if\ d < d_{Crossover} \\ \varepsilon_{elec} \times k + \varepsilon_{two-ray-amp} \times k \times d^4 & if\ d \geq d_{Crossover} \end{cases} \quad (10)$$

$$E_{Rx} = \varepsilon_{elec} \times k \quad (11)$$

Table 1. Simulation parameters

Parameter	Value
Network Grid	(0,0) × (100,100)
Position of Base Station	(50,125)
ε_{elec}	50 nJ/bit
$\varepsilon_{friss\text{-}amp}$	10 pJ/bit/m^2
$\varepsilon_{two\text{-}ray\text{-}amp}$	0.0013 pJ/bit/m^4
$d_{Crossover}$	87 m
Duration of a round	20 Seconds
Data packet size	500 Bytes
Packet header size	25 Bytes
Initial energy per sensor	2 Joules
Number of sensors	100
-coverage	50%
$Thresh_{Upper}$	30
$Thresh_{Lower}$	15

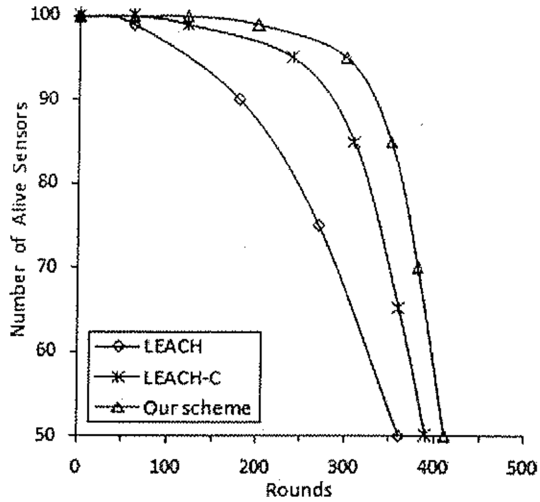

Figure 1. System lifetime

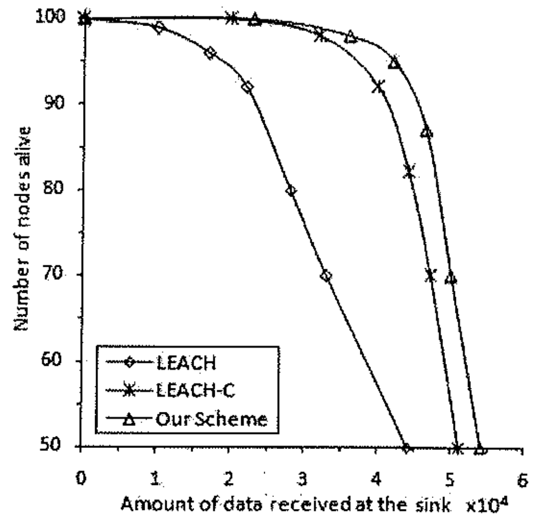

Figure 2. Amount of data received at the sink during system lifetime

Figure 1 shows that the proposed scheme lasts longer than LEACH and LEACH-C. In LEACH, the first sensor dies after 55 rounds, whereas with our scheme the first sensor dies after 210 rounds, because our scheme distributes evenly energy consumption among the sensors. However, LEACH chooses cluster head nodes randomly regardless of the amount of energy of each sensor and in certain cases it chooses the sensor that has weak energy as cluster-head. In addition, the time difference between demise of first and last sensor is too small contrary to LEACH.

Figure 2 illustrates that our scheme sends more data packets to the base station than LEACH and LEACH-C. It exceeds LEACH by 23% and LEACH-C by 13%.

6. Conclusion

In this paper, we proposed a schedule-based and Broadcast-based α-coverage Scheme for Wireless Sensor Networks, which rely on weighted criteria for cluster-heads' election. The proposed scheme carries out periodically cluster-head election process after each round. Moreover, it creates balanced 2-hop clusters.

Simulation results demonstrate that our scheme provides better performance than LEACH and LEACH-C in terms of system lifetime and the amount of data packets sent to the base station during system lifetime.

With these results obtained, our scheme can be regarded as a promising scheme to deal the main challenges in WSNs. Therefore, its evaluation could be the subject of future work.

7. References

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