Energy Efficient Scheme for Large Scale Wireless Sensor Networks with Multiple Sinks

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Abstract- In this paper, we consider the multiple sinks placement problem in large-scale Wireless Sensor Networks (WSN). The objective is to determine optimal sinks’ positions that maximize the network lifetime by reducing energy consumption related to data transmissions from sensor nodes to different sinks. Balanced graph partitioning techniques are used to split the entire WSN into connected sub-networks. Smaller sub-networks are created, having similar characteristics and where energy consumption can be optimized independently but in the same way. Therefore, different approaches and mechanisms that enhance the network lifetime in small-size WSN can be deployed inside each sub-network. In this paper, we propose a simple and efficient approach for the placement of multiple sinks within large-scale WSNs. Performance results show that the proposed technique significantly enhances the network lifetime.

I. INTRODUCTION

A stationary sensor network is a static ad hoc network composed of hundreds or thousands of sensor nodes. Each sensor node is equipped with a sensing device, a low computational capacity processor, a short-range wireless transmitter-receiver and a limited battery-supplied energy. Sensors monitor some surrounding environmental phenomenon, process the sensed data and forward it towards a “close” base station (i.e. a sink). This latter collects the data from the different sensor nodes and transmits this data to some remote control station where the data will be exploited at the application level.

Achieving maximum lifetime in stationary WSNs by optimally using the energy within sensor nodes has been the subject of significant researches in the last recent years. In this field, radio transmission and reception operations are being identified as the most energy consuming features.

On the other hand, the development of large-scale sensor networks has drawn a lot of attention. One of the main challenges is to set up new architectures and mechanisms that can efficiently scale up with the growing number of nodes that may be required to ensure adequate coverage of large areas of interest. At the same time, these new architectures and mechanisms should maintain low energy consumption per node so as to get by with energy guaranty acceptable network lifetime.

Most of known existing protocols and mechanisms are not scalable. They are mostly conceived and adapted to relatively small networks (i.e. reduced number of nodes) and/or when the amount of data being gathered and transmitted is small. In particular, centralised approaches, where data from each sensor is sent to a central base station, are not efficient and can not scale for large wireless sensor networks.

The use of multiple base stations is one possible solution for large-scale WSNs. The idea is to shorten the path (distance) between each sensor node and the nearest base station, leading to save energy consumption for transmission operations. To achieve this efficiency, the multiple base stations should be optimally placed within the sensed area.

In this paper we propose to use graph theory techniques and in particular graph partitioning in order to determine a balanced partition of large-scale WSNs and then to optimize the placement of the different sinks over the obtained smaller sub-networks to minimize the energy consumed for data transmissions.

The remaining of this paper is organized as follows:

After discussing the related work in section II, the proposed scheme is described and explained in section III. Simulations, performance results and analysis are presented and discussed in section IV. Finally, concluding remarks are given in section V.

II. RELATED WORK

Numerous applications of WSNs call for a large number of nodes, typically hundreds or thousands. In certain cases, dense node distributions in small areas are required, for instance to achieve redundancy. In such networks, important scalability issues have to be tackled to avoid high rates of collisions and retransmissions, larger routing tables, higher control overhead, etc. If no adequate solutions are adopted, these issues will
inexorably cause high energy consumption that certainly will shorten the network lifetime.

In the following, we present different approaches and techniques that can help increasing the scalability of large scale WSNs. We will discuss in particular the influence of the network topology, multiple sink usages and graph partitioning techniques (from graph theory).

A. Network topologies for Large-Scale WSNs

Scalability of methods, algorithms and protocols used in WSNs mostly depends on the interconnection topologies of sensor nodes. Two main architectures are proposed and studied in the literature: Hierarchical and Flat topologies.

Hierarchical topologies allow easier scalable mechanisms. Within these topologies, nodes are connected in a tree like configurations according to a given hierarchy. An example of hierarchical topologies is the clustered two tier architecture where a single cluster head handles several member nodes in its neighbourhood (i.e. its cluster). The cluster heads form a separate top layer communication structure. Network protocols designed for these architectures are highly scalable. However, they require the definition of specific roles and mechanisms for cluster heads as well as specific signalling mechanisms.

As opposed to these hierarchical topologies, flat distributed topologies are easier to deploy but more difficult to scale. Here, nodes are connected in a complete ad-hoc fashion. All sensing nodes have equivalent roles with no specific hierarchy between them. The main advantages of flat topologies are their easy deployment and reduced cost. However, such a topology are difficult to scale up since communications between thousands or perhaps millions of nodes in a ad hoc fashion lead to degraded performances and hence higher energy consumption. For instance, routing protocols are a prominent factor of the scalability of sensor networks. In recent researches, the proposed routing protocols require that some of the sensors have knowledge of the topology of the entire network at every point in time. This requires a lot of signalling and do not scale well with a high number of nodes. Different solutions are proposed in the literature to overcome these weaknesses. For instance, a distributed protocol for large-scale WSNs is proposed in [1]. It is based on localized interactions and does not require global knowledge such as the current network topology. In [2], authors proposed to use specific mobility patterns in order to achieve higher capacity in large scale WSNs.

In these studies, the evaluation of the scalability of the proposed protocols is mainly based on a well known metric for WSNs which is the network lifetime. The objective is to avoid significant degradations of the network lifetime when the number of nodes composing the WSN increases.

Through the analysis of the above sited studies, it appears that no single architecture can be adopted to face the scalability issues. Different solutions should be envisaged since the performances of the WSN may also depend on the type of applications for which they have been conceived.

B. Using multiple sinks in WSNs

In recent researches, energy efficient usages of multiple and/or mobile sinks to increase the network lifetime were proposed [3][4][5][6]. The idea behind this is to decrease the distance between each sensor node and the nearest sink. In fact, when a higher number of sinks are distributed within the WSN, the path lengths from any sensor node to its nearest sink is decreased leading to lower energy consumption and therefore to higher network lifetime. In [3], authors propose to divide time into rounds and to dynamically relocate multiple sinks, at different positions along the periphery of the sensed field, at the beginning of each of these rounds. An integer linear program is used to determine the new locations of the different base stations. Results have shown that the energy consumption of individual sensors is better balanced and the overall energy consumption of all sensors is minimized. In [4], authors propose another approach to find the optimal locations of multiple stationary sink nodes. The proposed scheme allows sensor nodes to communicate with one or multiple sinks through multiple paths in order to improve the network lifetime. In [5], authors claim that finding the optimal placement for a given number of sinks is equivalent to the clustering problem and should be solved using a clustering algorithm. Another approach to solve the problem of multiple mobile base station placements is proposed in [6]. An electrostatic model is applied to determine sinks’ locations and to coordinates the movements of these sinks considering the network state.

Fig.1. Multiple sink placement.
Unfortunately, most of the above strategies are proposed and evaluated over small to medium size wireless sensor networks (typically less than 100 nodes). For large scale wireless sensor networks, where hundreds or thousands of nodes can be deployed, the placement of multiple sinks still requires advanced studies. For instance, and as illustrated on Fig. 1, if we consider the case where the sinks are located along the periphery as stated in [3], the paths between each node and its nearest sink is relatively short when the number of nodes is limited. However, the more the area size increases and/or the number of nodes within it increases, the longer this path is and the shorter the sensor nodes lifetime will be.

C. Graph partitioning approach

Graph partitioning is a promising approach to split a large sensor network into balanced sub-networks. In graph theory related literature, different approaches and techniques are proposed for balanced graph partitioning. In [7], a fast approximate graph partitioning algorithm is proposed. The authors unified the problems of b-balanced cuts and k-multiway separators using a new approach called minimum capacity ρ-separators. They studied the graph partitioning problems on graphs with edge capacities and vertex weights and described a simple approximation algorithm for minimum capacity ρ-separators leading to a fast approximation algorithm both for b-balanced cuts and k-multiway separators. They define a ρ-separator as a sub-set of edges whose removal partitions the vertex set into connected components such that the sum of the vertex weights in each component is at most ρ times the weight of the graph. In [8], authors considered three problems to find an (l, u)-partition of a given graph. They proposed to partition a graph G into connected components by deleting some edges from G making the total weight of each component equal at least to l and at most to u. The minimum partition problem is to find an (l, u)-partition with the minimum number of components, the maximum partition problem is defined in the same way and the p-partition problem is to find an (l, u)-partition with a fixed number p of components. Authors proved that the three problems are NP-complete or NP-hard. In [9], authors studied the approximation of the Maximally Balanced Connected Partition problem (MBCP). They first presented the optimization problem that finds the maximally balanced connected partition for a graph G. It results in a partition (V₁, V₂) of V composed of disjoint sets V₁ and V₂ such that both sub-graphs of G induced by V₁ and V₂ are connected, and maximize an objective function “balance”, B² (V₁, V₂) = min(w(V₁), w(V₂)). Authors proved that the problem is NP-hard.

In this paper this last approach will be adapted and applied to large scale Wireless Sensor Networks. Our choice is mainly motivated by the practical approach provided in [9] and based on the use of a polynomial-time algorithm that gives an approximate solution.

III. PROPOSED APPROACH

Through the analysis of existing techniques, it seems appropriate to enhance sink placement in large scale WSNs by optimally partitioning the underlying sensor network and then by optimizing energy usage in each of the sub-networks independently. The objective is to take advantage of the powerful and efficient sink placement techniques proposed for small scale WSNs. In order to apply these techniques over large scale WSNs, we propose to first divide the network into sub-networks according to specific criteria. An adequate sink placement technique can then be applied independently within each of the defined sub-networks. Over the partitioned WSN, we suppose that a higher layer mechanism is in charge of managing data collection from the different sinks (i.e. sub-networks).

In practice, different criteria can be considered in order to partition a large scale wireless sensor network. One simple objective is to create balanced sub-networks (in terms of number of sensors) that group the sensors according to their neighbourhood. This allows creating smaller sub-networks with similar characteristics that can be easily optimized, independently but in the same way. In addition to the use of multiple sinks, existing protocols and mechanisms for routing and multiple access optimizations, already tested for small size WSNs, may be adapted and employed within each sub-network independently.

In the following the Maximally Balanced Connected Partition (MBCP) technique [9] is adapted and formulated for partitioning a large WSN. A corresponding approximate resolution algorithm is then presented.

A. Model formulation

Assume that G = (V, E) is a connected graph where V is a set of nodes and E is the set of all links connecting two nodes of V.

In our case, V represents the set of sensors and E represents the set of all links connecting two sensors belonging to V. The objective is to partition G into connected balanced sub-graphs (in terms of number of nodes). We assume that all sensors have the same initial energy.

To achieve this objective, let w be a non-negative vertex-weight function representing the balancing criteria. In this case, w will reflect the number of nodes. Hence w(V) = |V|.

This MBCP problem can then be formulated as follow:

Maximize $B^2(V_1, V_2) = \min(w(V_1), w(V_2))$

Subject to

1. (V₁, V₂) is a partition of V into nonempty disjoint sets V₁ and V₂ such that sub-graphs of G induced by V₁ and V₂ are connected.
The resolution of this model will result into two balanced sub-networks. Each of them can be partitioned again using the same process. This partitioning technique should be applied as much as required according to the targeted size for the sub-networks and taking into account the number of available sinks to be placed. The final result should be $2^n$ equivalent smaller sub-networks where $n$ is the number of partitioning iterations.

B. Problem resolution

To solve this model, we used the polynomial approximation algorithm presented in [9] that finds an approximate solution for the MBICP problem.

In order to select neighbouring sensors within the same sub-networks, we adapted the algorithm by sorting the list of candidates for each partition according to their distance (vicinity).

The algorithm can be written as follow:

**Input:** $G = (V, E)$. $V = \{v_1, v_2, v_3... v_N\}$ where $N = |V|$.

0. Initialize $V_1 = \{v_1\}$, $V_2 = V \setminus V_1$ such $v_1$ a node near the periphery.

1. If $|V_1| \geq 1/2 |V|$ then Step 3 else Step 2.
2. Let $V_0 = \{u \in V / (V_1 \cup \{u\}, V_2 \setminus \{u\}) is a connected partition of $G\}$. Choose $u$ of $V_0$ such that $u$ the closest element to $V_1$.
   If $|u| < |V| - 2|V_1|$
      then $V_1 := V_1 \cup \{u\}$, $V_2 := V_2 \setminus \{u\}$, Step 1
   else Step 3
3. Return $(V_1, V_2)$.

IV. SIMULATION RESULTS AND ANALYSIS

The effect of the proposed partitioning technique on the WSN lifetime is investigated using numerical simulations over Matlab environment. A circular large scale wireless sensor network, with a radius $R = 500m$ is considered. 1000 nodes are randomly (uniformly) deployed over the network area. Sensors are similar with a communication range $r= 80m$ and an initial energy of 1000J unit. The cost of sending and receiving operations is 1mJ per packet. Sinks are assumed to have no energy constraints because they have larger batteries or their batteries are rechargeable. Sensors communicate with the sinks in a multi-hop manner. We assumed that the shortest path routing algorithm is used to find the shortest route to the sink. The network lifetime is defined as the moment at which the first sensor runs out of energy. Time is divided into rounds. Each round is composed of $T=100$ timeframes. Each sensor node generates one data packet every timeframe.

To evaluate the efficiency of the proposed graph partitioning technique in elongating the network lifetime, three comparative scenarios are considered:

1. **Scenario 1:**
   Case 1: An entire large network (not partitioned) is considered. All the sensors have the same capacity. $N$ sinks are randomly fixed inside the coverage area of interest. Each sensor has to send the data it senses to the nearest sink in terms of number of hops.
   Case 2: The graph partitioning algorithm (detailed in section III) is used to define $N$ smaller sub-networks. One single sink is then randomly fixed in each sub network. Each sensor sends its data to the sink deployed in the sub-network the sensor is belonging to.

2. **Scenario 2:**
   Case 1: The entire network is considered. $N$ sinks are deployed randomly. Then, the sinks start to move inside the area of interest following the random waypoint model [10]. In one round each sink moves 60 m.
   Case 2: $N$ sub-networks are defined using the graph partitioning algorithm and one single sink is randomly deployed in each sub network. Then each sink moves 60m each round. The sink can not go outside the area of the sub-network it belongs to. This area is represented by a disc with the geographic centre of the sub-network as centre and the distance between this centre and the farthest sensor (belonging to this sub-network) from it as radius. The sink and all the sensors of the sub-network should be inside this disc.

3. **Scenario 3:**
   Case 1: The entire network is considered. $N$ sinks are deployed randomly on the periphery of the network. Then, the sinks start to move along the periphery. In one round each sink moved 60 m.
   Case 2: The graph partitioning algorithm is used to define $N$ smaller sub-networks. One single sink is randomly deployed on the periphery of each sub network. Then each sink moves 60m each round on the periphery.

![Sinks distribution in a large scale WSN.](image)
Sequences of simulations are then run to compare the network lifetime in the two different cases of each scenario.

Simulation results are presented in figures 3, 4 and 5. They respectively compare the performance of the different sinks deployment strategies in the case of partitioned and non partitioned network (scenario 1, 2 and 3).

First, let’s notice that the simple use of multiple sinks enhances the network lifetime (with and without partitioning). Indeed, the network lifetime increases proportionally to the number of sinks because the distance between the sensors and their correspondent sinks decreases. Second, it can be seen that moving the sinks clearly prolong the operation of the network. In fact, figures show that the network lifetime is much longer when the sinks are moving (scenario 2 and 3 with or without partitioning) than when they are fix (scenario 1).

Third, enhancements of the network lifetime can be observed in the case of partitioned large-scale WSNs compared to non partitioned ones in all the scenarios. But the enhancement is the most significant in the third scenario. This was expected as when one sink is moving along the periphery of each sub-network, the energy consumption is obviously much more distributed over the sensors than when all the sinks are moving along the periphery of the whole network. The nodes that are the closest to the sinks are logically the ones who die first because they not only send their own data but also relay the data of all the nodes in the network. In the scenario 3, the nodes who die first in the case of non partitioned network are the nodes situated all along the periphery whereas in the case of partitioned network, they are the ones situated along the peripheries of the different sub-networks. Then, in this scenario, using the graph partitioning technique to deploy the sinks distributes the load relay and decreases the average distance between the sensors and the sinks. Indeed, the improvement of the network lifetime of the partitioned network is much more important when the number of sinks (or sub-networks) increases.

V. CONCLUSION AND FUTURE WORK

The use of multiple sinks in large scale wireless sensor networks is necessary in order to cover large areas and to minimize energy consumption for data transmission operations. In this paper, we proposed the use of graph partitioning techniques to obtain smaller and balanced sub-
networks over which existing sink placement techniques that are optimized for small to medium scale WSNs can be used.

Performance results show that the proposed technique considerably enhances the network lifetime particularly when the sinks are moving along the periphery.

This first step using graph partitioning approach to improve energy consumption in large-scale WSNs is promising. We will focus in complementary and future work on more elaborated approaches for optimal multiple sinks placement and WSN partitioning. In addition, efficient tools should be proposed to determine the optimal number of partitions and sinks to be used according to the WSN characteristics, applications’ requirements and financial costs.

REFERENCES