Ad Hoc Networks 46 (2016) 37–47

Contents lists available at ScienceDirect

Ad Hoc Networks

journal homepage: www.elsevier.com/locate/adhoc

A distributed algorithm for *Ad-hoc* network partitioning based on Voronoi Tessellation

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ARTICLE INFO

Article history:
Received 2 July 2015
Revised 7 March 2016
Accepted 18 March 2016
Available online 31 March 2016

Keywords:
Voronoi partitioning
Wireless sensor networks
Energy-saving algorithms

ABSTRACT

This paper presents a data sink node election algorithm for multi-hop Wireless Sensor Networks (WSNs) with multiple data sink nodes. For energy-saving considerations, these nodes should be evenly (spatially) distributed on the network area. To achieve this objective, it proposed a distributed and iterative algorithm, which periodically re-assigns the data sink roles to selected WSN nodes. The main innovation of the algorithm is that, even if it does not need to explicitly compute the Voronoi partition of the WSN at each iteration, it eventually partitions the network according to a Centroidal Voronoid Tessellation, which leads to a spatially well-balanced distribution of the data sink nodes. Analytical proofs as well as simulation results validate the approach.

1. Introduction

Management of Wireless Sensor Networks (WSNs) is a widely researched topic in the literature, since an efficient operation of WSNs is relevant to many applications, e.g., just to mention a few, process control monitoring [31], critical infrastructure monitoring [26], health care monitoring [21], environmental sensing [19], air quality monitoring [30]. WSNs are basically composed by sensor nodes and data sink (DS) nodes; the sensor nodes, spread over the monitored area, collect the measures of interest and send them to one or more DS nodes, which elaborate the received measures and convey the elaborated data to a remote data center. Usually, the sensor nodes are directly connected to the DS nodes (one-hop communication), but the application of WSNs with multiple DS nodes and supporting multi-hop communications is becoming more and more frequent: when the area to monitor is wide, multi-hop communications are used to extend the network coverage and each DS node collects data from the sensor nodes nearby, i.e., from the sensor nodes in its cluster (see [22] and references therein).

Two of the main problems that a WSN has to face are the energy autonomy of the nodes and, especially in the case that the WSN is deployed in a harsh environment, its tolerance to node failures. The DS nodes are likely to suffer from faster energy depletion with respect to the other nodes, since they have to collect all the data from the surrounding sensor nodes and to perform scheduling and data fusion tasks [27]. Therefore, in many applications it is crucial that the role of DS can be played by any nodes, so that, if a DS node is becoming depleted or it is experiencing a failure, another node can be selected as the new DS node; this procedure is referred to as *data sink election*, and the fact that the role of DS is exchanged between two nodes is referred to as *data sink migration*. Energy and fault tolerance considerations also favor the deployment of multi-sink multi-hop WSNs. In fact, the presence of multiple DS nodes shortens the paths between each sensor node and the closer DS node, whereas the impact of the additional communications due to the fact that multiple DS nodes have to upload their data to the data center is alleviated by data fusion algorithms, which reduce the size of the exchanged data. Moreover, if multiple DS nodes are deployed, the fault of a single DS node does not imply that data of all the sensors are lost.

The problem dealt with in this paper is the data sink node election problem in WSNs and includes the general case of multi-hop and multi-sink networks[1]. In multi-sink WSNs, the DS migration problem has also to consider that the spatial distribution of the DS nodes over the mission area impacts on the WSN performances.

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[1] Even if this paper focuses on the DS election, it is necessary to underline that DS migration requires the 'old' DS nodes to send the collected data to the 'new' DS nodes: the effectiveness of the DS migration strategy is then dependent on the implemented data fusion algorithms, which reduce the size of the exchanged data, and on the frequency with which the DS nodes upload their data to the remote centre, which reduces the amount of data that each DS node has to store.

http://dx.doi.org/10.1016/j.adhoc.2016.03.008
1570-8705/

Then, the problem of selecting the best new DS node to migrate to can be formulated as a network partitioning problem. The proposed algorithm, based on Voronoi partitioning concepts, is performed on-line and converges to a balanced mission area partitioning known in the literature as Centroidal Voronoi Tessellation (CVT).

The research presented in this paper has been performed within the European project SWIPE, aimed at developing a WSN suitable for planetary exploration [23], which has to face (to the highest degree) the problems outlined above, and which, therefore, highly benefits from energy saving and fault tolerant approaches.

The paper is organized as follows: Section 2 presents the state of the art the innovations of the proposed algorithm, Section 3 provides the basic Voronoi partitioning concepts; Section 4 presents the algorithm, the convergence proof and some implementation details; Section 5 shows some simulation results; Section 6 draws the conclusions.

2. State of the art and paper contributions

2.1. Data sinks election and mission space partitioning

Explicit data sinks election algorithms have not been studied intensively in the literature. This is mainly due to the fact that researchers have focused their attention to networks composed by only one DS. In [4], multiple DS nodes are used to optimize the energy consumption of a single-hop sensor network, where the DS nodes are deployed along the periphery of the sensing area. An optimization problem is built and solved off-line to decide the best placement for the DS nodes, in order to minimize the overall transmission power of the sensor nodes. A genetic algorithm optimization is performed in the case of two DS nodes, whereas a heuristic algorithm is used in the case of three DS nodes. Differently, the algorithm proposed in this paper is applicable to multi-hop WSNs as well, and finds on-line a balanced placement of the DS nodes by means of an iterative approach which migrates the DS role among the WSN nodes.

A problem similar to the data sink election and extensively studied in the literature is the Cluster Head (CH) election problem. CH election problems refer to WSNs in which nodes are grouped in clusters, each managed by a CH node. In clustered WSNs, the objective is typically that of efficiently conveying the information (e.g., sensed data) from each node to one or more gateway nodes (GWs) serving as collection points in communication with a remote control center or unit. That is achieved through a combination of intra-cluster (i.e., from a node to the corresponding CH) and inter-cluster communication (i.e., multi-hop CH-CH communication). In this context, the problem of intelligent CH election has been addressed by several works in literature, with the main objective of achieving a balanced configuration of the clusters (in terms of energy consumption, workload distribution, etc.). Moreover, similarly to what done in this paper, it has been widely recognized in literature that the CH role could be periodically rotated among the network nodes, in order to balance and to share in time the additional communication and processing efforts required by the CH role. The key difference between the CH and the DS election problems is that the DS node election problem does not require the DS nodes to form a connected subset of nodes, whereas CHs have to form a connected subnet in order to fully support inter-cluster communication. A brief review of relevant papers dealing with CH election is reported in the following. In LEACH [12], few nodes are randomly selected as CHs. The CH role is rotated periodically to distribute the effort among the nodes in the network. Each CH compresses the data coming from the nodes of the cluster and sends an aggregated packet to the GW. Dealing with the CH election process, at each turn a fraction p of nodes elect themselves as CHs, in the following way. Each node i chooses a random number r between 0 and 1: if $r < T(i)$, then the node becomes a CH for the current round, where $T(i)$ is computed based on (i) the desired fraction p of nodes to become a CH, (ii) the current round and, (iii) the set G of nodes that have not been selected as a CH in the last $1/p$ rounds. The election rule is the following one:

$$T(i) = \begin{cases} \frac{p}{1-p \cdot mod(r, 1/p)} & \text{if } i \in G \\ 0, & \text{otherwise} \end{cases}, \tag{1}$$

where $mod(\cdot,\cdot)$ denotes the modulo operator. An extension of LEACH is HEED [29]. It introduces limits on the communication range and cost terms in the intra-cluster communication. Moreover, the probability to become a CH in HEED also depends on the residual battery of the nodes. The main problem of LEACH-based approaches is that, since the election is random, without position or distance considerations, the elected CHs are not necessarily well-distributed over the network. In this sense, EECS [28] is a LEACH-like algorithm for single-hop WSN, which introduces a novel distance-based method to balance load among CHs. EECS is divided in two main phases: the CH election phase and the cluster formation phase. In the CH election phase, WSN nodes become CH candidate nodes according to a certain probability. Then, each CH candidate broadcasts its candidacy to nodes falling within a certain radius R; each candidate actually assumes the CH role only if no other CH candidate he is aware of (i.e. falling within R) has higher battery level (thus ensuring an energy-fair election). In the cluster formation phase, the remaining nodes are assigned to the CHs to form the clusters. In EECS, both the distances of the nodes from their CH and from the GW are considered; in this way, clusters which are far from the GW have less nodes compared to clusters closer to the GW (*unequal clustering*). As a result, in [28] it is shown that network lifetime, defined as the time until one of the nodes runs out of energy, is significantly prolonged compared to LEACH and HEED. In [10], a *centralized* extension of the LEACH algorithm is proposed, called partition-based LEACH (pLEACH), in which each node sends to the sink node information on its location and battery level, and the sink node then partitions the network into a given number of clusters and, for each cluster, selects as CH the node with the highest energy level. The drawback of this algorithm lies in the communication burden implied by its centralized nature, which may be unsustainable in case of large WSNs. Advancements of HEED have been proposed as well, as for instance UHEED (G. [5]), which is a clustering modification of HEED aimed at optimizing HEED in multi-hop WSNs. To this end, UHEED modifies HEED formula so that clusters close to the GW are smaller than the ones far from it (the opposite behavior of EECS, which is designed for single-hop communication). Advanced CH election strategies are continuously being developed based on the basic concepts explained above. The interested reader may find additional surveys on WSN clustering in [1,24].

The algorithm proposed in this paper takes some ideas from the CH election strategies described above, namely the round-based approach and the strategy of network partitioning, and relies on graph-theory concepts, namely, on Voronoi partitioning [7]. Some works recently appeared in the literature propose the Voronoi partition as the fundamental structure for WSN clustering, mainly because: (i) if the number of Voronoi regions is appropriately selected, data inside the same region tend to be homogeneous and thus can be fused, (ii) in single-hop networks, Voronoi partitioning is functional to transmission power control (i.e., the nodes adjust their transmission power in function of the diameter of the Voronoi cell).

A fundamental problem in this chapter of literature regards the computation of the Voronoi partition of a WSN. The paper [2] presents a distributed approach for computing the Voronoi par-