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Topology control with coverage and lifetime optimization of wireless sensor networks with unequal energy distribution☆

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ABSTRACT

In this work, we use an unequal energy distribution algorithm, with which we succeed to extend network lifetime. In the sequel, we, we provide the best effort coverage by arranging the nodes using topology control principles. We formulate an optimization problem and define an objective function that incorporates both network coverage and lifetime that should be both maximized. Such a complex problem can be solved in polynomial time through Simulated Annealing (SA). An updated topology is evaluated in each convergence point and a near optimal node placement together with near optimal unequal energy allocation charge scheme is achieved. Results reveal that the proposed near optimal topology leads to greater coverage and lifetime as compared to several random deployments. We complete this work by providing a reliability study of the results, which is carried out by analysing the survival function of the derived statistical propertied of the proposed objective function.

1. Introduction

A wireless sensor network (WSN) consists of tiny nodes with sensing, information processing and transmission capabilities. WSNs can be used to collect information from a coverage area especially where the physical environment is harsh. They are comprised of several nodes and a base station (BS) for data collection. This WSN model is used in a wide range of applications, which range from military to civil, such as environmental monitoring, smart house management, industrial automation, structural health monitoring (SHM), precision agriculture [1,2]. The sensor nodes are devices with limited battery power and thereby, their main constraint is energy consumption, which as a consequence lead to limited operational network lifetime. However, even though scarce resources compel researchers from deploying tiny nodes, a solution to overcome energy scarcity problems for real deployments is given in [3]. To this end, one of the fundamental problems in WSN is expressed as follows: *How To Maximize the Network Lifetime*. Network lifetime is defined as the time when all nodes are operational and able to sense, receive and transmit data [4].

Significant research has been carried out towards network lifetime extension in WSNs. In [5] authors propose an energy efficient routing protocol and apply linear programming optimization for maximizing lifetime for a given stationary network. In principle, protocols for WSNs try to use the resources of each node efficiently in order to extend individual

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node lifetime. Authors in [7] present extensive research results towards energy efficient routing protocols for WSNs, which are classified into four main schemes: Network Structure, Communication Model, Topology Based and Reliable Routing. In [6] authors present a novel family of mixed integer programming models to analyse the impact of hop counts on lifetime maximization. Additionally, they try to minimize total communication messages exchanged among nodes, which are essential for synchronization and broadcasting information about their energy levels. In other works, clustering-based approaches are considered, in which network topology is organized into groups of cluster-heads to control packet traffic and aggregate packets [8–10]. Clustering algorithms usually utilize two techniques, namely by selecting cluster heads with more residual energy and by rotating cluster head role periodically, in order to evenly distribute node's energy consumption per cluster and extend network lifetime [11].

Towards the same research direction, authors in [12], propose an Energy Efficient Unequal Clustering (EEUC) mechanism for periodical data gathering in WSNs. The proposed algorithm balances energy consumption fairly among all nodes and achieves an obvious improvement on the network lifetime. Other ways to extend lifetime is by adding redundant sensors close around BS and to apply appropriate topology control algorithms, which govern sensor placements. Authors in [13] propose a non-uniform sensor distribution strategy by adding more nodes to the heavier energy load area. In [14] authors introduce a new distributed topology control algorithm based on a game-theoretic approach that maps the problem of maximizing the network's lifetime to an ordinal potential game. They prove the existence of *Nash equilibrium* in their game and extend lifetime by more than 50%.

In [15], authors propose a wake - up scheduling protocol through which some nodes stay active whereas others enter a sleep state to conserve energy. Their proposed self-scheduling algorithm decides which nodes have to switch to sleep state and which to remain active based on a low residual energy level metric. Simulations reveal that wake-up scheduling extends lifetime considerably in cases of stationary networks. It is obvious from the above literature that lifetime maximization can be achieved by applying several techniques depending on the application scenario. In all aforementioned works an equal energy charge for every node is implied. Despite the various energy efficient routing protocols in WSNs [16], no significant consideration is given to the large overhead created by the nodes communication and synchronization messages needed for the protocols to work. These messages could be a serious factor responsible for depleting the node battery fast [17].

Therefore, the first contribution of the paper is the design of an energy allocation algorithm, which applies unequal energy charge scheme and static routing among nodes. Instead of treating all nodes as candidates for equal energy charge, our heuristic finds a non-uniform energy allocation scheme that leads to lifetime extension. Direct signal transmission seems a simple and logical approach to minimizing inter-node communications and avoid energy consumption due to overhearing [4], especially if the network is dense. However, if the BS is far away, the cost of sending data is larger than to use relays. By applying static routing, the choice of relay node is hard-coded, so protocol synchronization messages are useless. The nodes that do not take a great part in routing process should be loaded with less initial energy levels compared to those that are focal points of data dissemination. Under these premises, we devise an algorithm that shares an initial energy load among all nodes in the network non-uniformly in a manner that will extend the total node and network lifetime. Henceforth, the network goes through a *training* phase throughout our simulation scenarios and converges to near - optimal values of network lifetime.

1.1. Related works

Appropriate protocols for WSNs should be designed for both network lifetime and coverage extension. The problem objective is to both optimize energy consumption while maintaining sensing and communication coverage. This joint - optimization lifetime and coverage is critical for WSNs [27]. Sensor deployment problem to both satisfy lifetime and coverage is not trivial. According to application scenario, coverage could be traded for network lifetime and vice versa. In [18], authors provide an analytical framework for the coverage and lifetime of a WSN that follows a 2D Gaussian distribution of sensor nodes. They identify intrinsic properties of coverage and lifetime in terms of Gaussian distribution parameters, which is a fundamental issue in designing a WSN. They quantify the impact of Gaussian distribution and network parameters on the lifetime and coverage. In [19], a generic multi-objective optimization technique is used for optimizing the contradictory problems of energy load balancing and network coverage. The strategy used provides a compromise to network coverage, network energy load balancing and network connectivity. This strategy can adjust metric weights to energy consumption and energy load balance to achieve the optimum performance of the WSN.

Coverage, efficient energy consumption and optimal node placement are fundamental goals for the design of a WSN. In [21] authors categorize the placement strategies into static and dynamic depending on whether the optimization is performed at the time of deployment or while the network is operational. In static approaches, optimized node placement is pursued in order to achieve some desired properties for network topology and coverage. On the other hand, dynamic repositioning after initial deployment can be viable for boosting network performance. The topology control of nodes' position for an optimal network deployment in terms of coverage and energy consumption is complex especially for a large number of nodes. For complex and NP-Complete problems probabilistic random search using meta-heuristic method with selective acceptance of the solutions is preferred. Such a method is the Simulated Annealing (SA) [26]. The channel assignment problem (CAP), i.e. the task to assign the channels to the radio base stations in a spectrum efficient way, is an NP-complete optimization problem occurring during design of cellular radio systems. Authors in [22] provide a near optimal solution to