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Optimal placement of relay nodes in wireless sensor network using artificial bee colony algorithm

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A B S T R A C T

Deploying sensor nodes randomly most of the time generates initial communication hole even in highly dense networks. These communication holes cannot be totally eliminated even when the deployment is done in a structured manner. In either case, the resulting inter-node distances may degrade the performance of the network. This paper proposes an enhanced deployment algorithm based on Artificial Bee Colony (ABC). The ABC-based deployment is guaranteed to extend the lifetime by optimizing the network parameters and constraining the total number of deployed relays. Simulations validate the effectiveness of the proposed strategy under different cases of problem complexity. Results show that the proposed approach improves the network lifetime considerably when compared to solutions reported in the literature such as Shortest Path 3-D grid Deployment (SP3D) algorithm.

1. Introduction

Wireless sensor networks (WSNs) have tiny, low-powered and multi-functional nodes. Through collaborative efforts, these nodes have the capabilities of performing complex tasks. Simultaneously maximizing both the connectivity and the lifetime of WSN from the design standpoint is considered a challenging task (Al-Turjman et al., 2013; Chang, 2012). Relay nodes (RNs) are generally employed to reduce the energy utilization of the sensor nodes. Owing to the fact that relay nodes are fabricated using powerful transceivers, they have better transmission and reception capabilities (Song et al., 2010; Cheng et al., 2008). It is worthy of note that the cost of powerful transceivers and complex embedded circuitry makes RNs much more expensive than normal sensor nodes.

In some applications, relay nodes are not only forwarding and collecting data in the horizontal plane but also in the y–z plane (Al-Turjman et al., 2013, 2009). So, maximizing the lifetime of a WSN with constraints on both cost and connectivity has been shown to be a challenging task especially in 3-D deployment – where nodes are arranged in three-dimensional pattern (Son et al., 2006; Song et al., 2010). The overall deployment cost is minimized if less number of RNs is deployed. In a large 3-D space, previous work shows that the deployment of nodes is not a trivial task because the search space is wide. Each position yields different connectivity levels and hence, the optimization technique has to be selected carefully to ensure convergence (Bari et al., 2007; Yang et al., 2013). Most of the time, heuristic algorithms are introduced to improve the solution and the computational efficiency (Al-Turjman et al., 2013).

Artificial intelligent(AI) approaches, especially those that are biologically inspired, are commonly used nowadays to solve many complex engineering problems. In the last few decades, different engineering problems have been solved successfully using evolutionary techniques. More recently, a new metaheuristic optimization approach which was first inspired in 2005 and was later modified into what is known today as Artificial Bee Colony (ABC) (Karaboga, 2005; Karaboga and Basturk, 2007).

The major contribution of this work is to enhance the network lifetime by proposing an ABC-based two-phase relay node deployment strategy in 3-D space called Improved Lifetime Deployment subject to Cost Constraint (ILDCC). The placement problem addressed in this work has been shown in Bari et al. (2007) to be NP-hard, and locating approximate solution is NP-hard as well (Efrat et al., 2008). This complexity can be circumvented using a two-phase, two-layered approach. In the first phase, the backbone of the network is connected using minimum number of relay nodes for cost efficiency (Al-Turjman et al., 2013). In the second phase, a novel approach using heuristic method for searching the global optima is introduced. The parameters of the

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network are optimized in such a way that the minimum objective function is guaranteed and the desired network connectivity is maintained. The proposed technique shows its effectiveness in solving the placement problems associated with WSNs, and the solution can be adopted in wide range applications such as WSN for Volcanic Monitoring; relay node deployment in forests to detect fires and report wild life activities; CO_2 flux monitoring and imagery; many other outdoor monitoring applications where sensor networks may work under harsh environmental conditions.

The rest of this paper is organized as follows: Section 2 discusses the state-of-the-art literature review. Section 3 presents the problem formulation. Section 4 gives a detailed presentation of the proposed deployment strategy and how it is mapped with ABC. Section 5 discusses the implementation of the proposed strategy and the simulation results. Section 6 concludes the paper and highlights some future works.

2. Related work

Recently, the effectiveness of deploying relay nodes in wireless sensor networks has been widely investigated. In Younis and Akkaya (2008), classification of deployments into random and grid-based are highlighted by the authors. The grid-based deployment yields more accurate positioning and data measurements because nodes are arranged on the grid vertices. Whereas, in random deployment, nodes are randomly scattered and are organized in an ad hoc manner. In 3-D settings, grid deployment is used because it simplifies the placement problem. In Cerpa and Estrin (2004), connectivity problems were addressed using node redundancy. Redundant nodes are switched off and isolated from the network when idle. However, some of the redundant nodes are turned on to repair connectivity whenever there is network partition. The use of nodes mobility was proposed in Marta (2009) to repair the disconnected network.

Likewise in Lee and Younis (2010) and Lee et al. (2010), an optimized approach for connecting disjointed WSN segments was proposed and achieved by modeling the deployment area as a grid with equal-sized cells and carefully populating few relay nodes. The network is then optimized such that fewest count of cells are selected to be populated by relay nodes till all segments are connected. This is considered a non-deterministic polynomial-time hard (NP-hard) problem. The two layer procedure was basically used to reduce the complexity of the deployment strategy from an NP-hard to a more realistic one (Al-Turjman et al., 2013; Abbasi et al., 2009). It must be remarked that, the major task of the sensor nodes is to collect and transmit data to the closest Cluster Head (CH) or RN. Hence, the sensor nodes occupy the first layer of the architecture. In this way, the energy consumption of sensor nodes will be considerably minimized as the nodes go back to sleep immediately after transmitting data.

In the first phase of deployment, the Minimum Spanning Tree (MST) is first used to construct the network backbone by placing minimum number of first phase relay nodes (FPRNs) on 3-D grid vertices. These FPRNs set up a connection among the pre-allocated cluster heads and the base station. In the second phase, extra relay nodes are randomly and densely deployed very close to the backbone devices until the desired connectivity is achieved.

The Optimized 3-D deployment with Lifetime Constraints (O3DwLC), an improved version of SP3D, was later proposed in Al-Turjman et al. (2013) to enhance the lifetime of the network. O3DwLC also implements MST to initialize the connection of the backbone. However, a Semi-Positive Definite optimization (SPD) algorithm was proposed in the second phase of the deployment. Even though constraints were put on cost and lifetime, the algorithm efficiently enhances the overall connectivity of the network. While the SP3D and O3DwLC approaches aim at improving the connectivity of the network, the proposed approach in this work focuses on maximizing the useful lifetime of the wireless sensor network.

Artificial intelligent approaches have also been used to optimize the lifetime of the network. Multi-objective territorial predator scent marking algorithm was presented to maximize both the coverage and the connectivity of the network using the least energy consumption (Abidin et al., 2014). ABC and Particle Swarm Optimization algorithms are used to solve placement problem and maximize the lifetime (Mini et al., 2014). In addition, ABC based algorithm was proposed to determine the optimal 3-D position that satisfies k-coverage and Q-coverage criteria and subsequently, to extend the lifetime and the coverage of the WSN (Udgata et al., 2011; Ajayan and Balaji, 2013). To recover partitioned WSNs, a distributed relay node positioning approach was proposed in Senturka et al. (2014) using virtual force-based movements of relays and Game Theory. Also in Liu and He (2014), an ant colony optimization with greedy migration mechanism was proposed to deploy sensor nodes in order to maximize coverage and minimize the deployment cost.

Unlike Udgata et al. (2011), Mini et al. (2014), Abidin et al. (2014), and Liu and He (2014) which focus on finding the optimal placement of sensor nodes, the proposed solution in this study focuses on extending the network lifetime with optimal deployment of relay nodes. The proposed approach makes the deployment algorithm less complicated when compared with existing solutions with similar objectives.

3. Problem formulation

3.1. Assumptions

A two-layer hierarchical structure is considered in this paper to address the heterogeneous nature of wireless sensor network. The network mainly comprises of devices such as sensor nodes, cluster heads, relay nodes and the base station. The sensor nodes are localized in the lower layer where their primary role is to sense the targeted phenomena in the form of data. The measured data is then sent to RN or CH in the upper layer of the architecture. In this work, the design approach is adopted such that sensor nodes minimize their energy usage by transmitting sensed data over short distance and go to sleep mode when not sensing or transmitting. The upper layer of the architecture consists of cluster heads, relay nodes and base station. The upper layer devices are equipped with better capabilities and can transmit and receive data over longer distances (Al-Turjman et al., 2013). They also convey the data from lower layer devices periodically to the base station.

In order to drift the attention away from the lower layer, it is assumed in this work that sensor nodes have enough resources to perform their tasks. This allows us to pay more attention to the upper layer devices. It was established in Santamaria et al. (2010) and Olariu (2006) that the cost of sensing the environment and encapsulating it into a packet is much smaller than that used in transmitting and receiving such packets. Thus, the energy dissipated during the communication phase is only taken into consideration. Besides, the two-layer architecture facilitates the decoupling of the energy consumptions in the upper and the lower layer. Other assumptions made in this paper are:

- All nodes are static.
- A periodic data gathering application where data is sensed and is sensed and transmitted by each sensor to its cluster head (CH) and from the CH to another CH or relay node.
- Multi-hop communication.
- All CHs have the same transmission range.
- All relay nodes have the same transmission range of “r” units.
- Ideal Media Access Control (MAC) layer with no collisions and retransmissions.