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Impact of redundant sensor deployment over data gathering performance: A model based approach

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ABSTRACT

This paper proposes an efficient sensor deployment model, called 'MOdel Driven GRAdient Deployment for Irregular Terrain' (MoDGraDIT), for increasing network lifetime and data gathering accuracy. MoDGraDIT uses two steps for computing the sensor deployment density. First, the number of children for any intermediate node has been estimated based on the connected-coverage criteria. Second, sensors are deployed in high redundancy to sustain node failures. The density of deployment has been estimated that depends on the computed 'Energy Dissipation Factor' (EDF), considering the gradient effect of energy depletion. The performance of MoDGraDIT has been analyzed using theoretical and simulation results.

1. Introduction

Data gathering and processing in a distributed environment is one of the most widely used applications for wireless sensor networks (WSN). A number of efficient data gathering approaches have been proposed in the literature, such as collection tree protocol (Gnawali et al., 2009) and its variants, minimum cost tree (Zhang et al., 2005), differentiated tree protocol (Naderi and Mazinani, 2012), TREEPSI (Satapathy and Sarma, 2006), fast data collection (Durmaz Incel et al., 2012), and source routing tree (Sergiou and Vassiliou, 2012). It has been well studied that tree based data collection, particularly breadth first search (BFS) tree, is most efficient for sensor networks, as it provides fast collection with minimum duplicate delivery and data loss (Chen et al., 2012; Li et al., 2011). As shown in Chen et al. (2012), a simple BFS tree based data collection method can lead to order-optimal performance for any arbitrary sensor networks. Further, most of the tree based data collection methods, as mentioned earlier, converge to a BFS tree like structure at the steady state, and therefore, BFS tree based data collection can be considered as the mostly used and most effective data gathering protocol for a general purpose sensor network.

A sensor lifetime directly depends on the traffic load that it forwards (Chen et al., 2012). For a tree based data aggregation, the energy dissipation for a sensor node gradually increases from the leaf of the tree towards the sink. To save critical sensor resources, a number of schemes has been proposed in the literature, like data gathering medium access control (DMAC) (Lu et al., 2007) and its variants, where sensors follow a periodic sleep wakeup schedule to save battery power. In this mode of operation, the nodes that does not have data to transmit or receive go to the sleep state. However, sleep–wakeup based data gathering schedule is not applicable for all sensor applications, as it increases data delivery delay, as well as the sensory activities depend on the scheduling strategy (Kim et al., 2011; Suriyachai et al., 2012; Chao and Hsiao, 2014; Chakraborty et al., 2014). Based on this, sensor operation mode can be classified into two types – *periodic sensing* that supports sleep–wakeup based scheduling, and *steady sensing* where nodes remain active throughout the lifetime, and participate in data gathering activities all the time, until they die-out of energy or crash. Both of these sensing modes have their direct implication over the network lifetime:

(a) For periodic sensing, sensor nodes that neither transmit nor receive, go to sleep state to save energy. The amount of sleep duration increases gradually from the sink to the leaf nodes of a data gathering tree where in-network data aggregation is not possible (Zheng et al., 2011). Thus, energy dissipation of the leaf nodes is significantly less compared to the nodes near the sink. This results in an early die-out of sensors near the sink.

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(b) For steady sensing, the sensors that neither transmits nor receive, remains in the idle state. However, the energy dissipation for idle state is less than that of transmit or receive state. For tree based data gathering, the nodes near the leaf spends more idle time compared to the nodes near the sink. As a consequence, the nodes near the sinks dies out early compared to the nodes near the leaf.

Both periodic sensing and steady sensing result in an early die-out of sensors near the sink, and affects both the connectivity and the sensing coverage in the network. On failure of a sensor node, the maintenance of the data gathering tree by reconstructing the tree from the scratch is not at all cost-effective (Zhang et al., 2005; Diallo et al., 2012; Ammari and Das, 2009; Turau and Weyer, 2009). Additionally, an involvement of all nodes in the maintenance activities introduces a global freeze, which in effect, degrades QoS for the application. Tree maintenance in reactive approach charges a significant cost in terms of control message communication as well as repairing delay. Proactive repairing with a low cost serves better in this scenario. However, considering an irregular topology, the proactive repairing also fails to perform well. Moreover, multiple simultaneous node failures in a close vicinity would be difficult to incorporate as this type of maintenance scheme increases per node load after repairing the tree on every node failure.

Redundancy in sensor deployment is an efficient method to ensure uninterrupted data delivery and improved network lifetime (Shen and Wu, 2011). However, a proper estimation of redundancy is required based on the traffic load at different level of data gathering tree to ensure balanced energy dissipation throughout the network. Further, in real life, the area of interest or the terrain may be irregular as well as inaccessible in nature. Homogeneous deployment density would not be suitable for an irregular terrain as the deployed redundant nodes might not be able to serve the faulty node in this case (Zou and Chakrabarty, 2004). Therefore, the initial deployment of sensor nodes plays a crucial role in prolonging the network lifetime while maintaining the connectivity and the coverage.

In this paper, a gradient based node deployment framework, termed as *MoDGraDIT*, has been introduced considering both the cases of sensor energy dissipation model – the periodic sensing and the steady sensing. Considering irregular terrain, MoDGraDIT deploys a sufficient number of redundant nodes that can replace a faulty node on failure, while maintaining the sensing coverage and network connectivity. Based on the energy dissipation model for tree based data gathering, MoDGraDIT calculates sensor density as a function of the distance from the sink. The proposed scheme designs a model to estimate the number of nodes in the rooted subtree of an intermediate node in the data gathering tree, assuring the network connectivity and the sensing coverage during a node failure. Based on the estimation, the number of redundant nodes required to be placed is calculated. Applicability of the proposed mathematical model and the trade-off among the connectivity, coverage, fault-tolerance and the redundancy are justified through analysis using sensor network calculus (Schmitt and Roedig, 2005). Finally, the performance of the proposed gradient based sensor deployment framework is compared with the deployment frameworks proposed in Liao and Lin (2011) and Yun et al. (2010) through the simulation results. An initial version of this concept has been presented in Chakraborty et al. (2013), where the gradient deployment effect has been computed and analyzed for periodic sensing only. This paper extends the previous version through rigorous analysis of the deployment strategy for both steady sensing and periodic sensing, with performance results from a more realistic scenario.

The rest of the paper is organized as follows: Section 2 gives a brief description of state of the art works on sensor deployment strategies. Section 3 provides the system model and assumptions for the proposed framework. Few concepts and definitions required to establish the proposed theory are provided in Section 4. Section 5 describes the mathematical analysis for the estimation of the proposed gradient based deployment density. The theoretical analysis through sensor network calculus is provided in Section 6. Finally, Section 8 presents the simulation results followed by a conclusion of the contribution in Section 9.

2. Sensor deployments strategies in the literature: a brief survey

Initial deployment of sensor nodes plays a crucial role in prolonging the network lifetime while maintaining the connectivity and the coverage. A set of works has been proposed to deploy the sensor nodes in the network such that some predefined QoS requirements are satisfied (Bojkovic and Bakmaz, 2008; Ma et al., 2011; Gajbhiye and Mahajan, 2008; Oldewurtel and Mä, 2012; Liu et al., 2013; Tarng et al., 2009). Most of the applications require the area of interest to be sensing covered by enough number of sensors. However, finding the minimum number of sensors to cover an area is known to be NP-hard (Ghosh and Das, 2008). A two-level deployment strategy is proposed in Iranli et al. (2005), where the low power sensor nodes forward data to the high power micro-servers, that in turn, forward data to the sink. This type of heterogeneous sensor deployment is difficult for rough and irregular terrain. Xu and Sahni (2007) have designed an integer linear programming formulation to find the minimum cost deployment of sensors that provides a desired coverage. They have proposed a greedy algorithm to solve the integer linear programming. Their proposed algorithm can also provide a fault tolerance for k-coverage. That means the proposed deployment strategy is able to monitor all the points as long as $k-1$ sensors fail. However, the scheme supports the grid coverage only. They have not considered the gradient effect of energy dissipation for tree based data forwarding. The sensors are deployed uniformly in the terrain. Seetharam et al. (2008) have proposed a method to estimate the number of nodes to be deployed in a given area for a predetermined lifetime. In this method, the area is divided into equal size strips. The density of the deployed sensors increases as the distance between a strip and the sink decreases. The method neither considers the coverage issues nor handles the node failure situations. A predetermined sensor deployment strategy is proposed in Halder et al. (2011) to prolong the network lifetime. Their proposed scheme assumes the location information of the sensors which is hard to find out in an irregular and rough terrain. Though the scheme supports the coverage and the load based deployment of sensors, it is only suitable for a small terrain, where manual node placements are possible. Yun et al. (2010) have studied different deployment patterns to achieve the full sensing coverage and k-connectivity under different ratios of sensor communication range to sensing range for homogeneous WSN. They proposed that there exists a universally elemental pattern that is hexagon based, which is able to generate all known optimal patterns with different connectivity. They designed a new deployment-polygon-based approach for proving the pattern optimality. Their scheme does not consider the traffic load pattern in the sensor network that is important for delay sensitive tree based data forwarding. The given theoretical analysis is abstract in nature that does not deal with implementation specific feasibility issues like network lifetime, fault-tolerance and QoS requirements. In Yoon and Kim (2013), the authors have proposed a maximum coverage sensor deployment pattern based on Monte-Carlo method. They used a genetic algorithmic approach over Monte-Carlo method to