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Innovative Applications of O.R.

A column generation heuristic for optimal wireless sensor network design with mobile sinks

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ABSTRACT

Wireless Sensor Networks (WSNs) consist of a high number of tiny, multi-functional, electronic devices called sensors. They collectively provide a distributed environment that is capable of monitoring remote areas. Collected information is transmitted in a direct or multi-hop fashion to the gateway nodes called sinks. An even distribution of energy loads among the sensors is critical for elongating network lifetime. There are four main WSN design issues that substantially affect the distribution of the energy: locations of the sensors, schedule of the active and standby periods of the sensors, trajectory of the mobile sink(s) and routes for data flows. As a result, many studies try to make energy usage more efficient by optimal determination of these design issues. However, only a few of them provide a unified frame in which all four design issues are integrated. In this work, we follow this line of research and propose a column generation heuristic for a Mixed Integer Linear Programing (MILP) model that integrates all design issues. Based on the extensive numerical experiments, we can say that the heuristic outperforms its competitors in the literature.

1. Introduction

Wireless Sensor Networks (WSNs) consist of high number of tiny, multi-functional, electronic devices called *sensors* which are deployed over a region of interest called the *sensor field*. A sensor can collect data from the neighboring area lying within its sensing range and the collected information is transmitted in a direct or multi-hop fashion to the gateway nodes called *sinks*. Communication between sensors or between a sensor and a sink is possible only if the receiver sensor or the sink lays within the communication range of the transmitter sensor. The collaborative effort of the sensors provides a distributed environment that is capable of monitoring remote areas. This is why WSNs have a wide range of application (Yick, Mukherjee, & Ghosal, 2008). Sensors can be in active or standby modes. An active sensor performs sensing, data transmission and data receiving duties and consumes energy. On the other hand, a standby sensor consumes negligible energy.

Low energy capacities of the sensors is a prominent limitation of WSNs. As there are huge number of sensors in a typical WSN application, replacing depleted batteries is generally considered out of option. Moreover, an even distribution of energy loads among the sensors is critical for elongating network lifetime. Therefore, a precise management of energy affecting factors is critical in order to obtain network lifetimes which are long enough.

There are four main WSN design issues that substantially affect the distribution of the energy among the sensors: locations of the sensors, schedule of the active and standby periods of the sensors, locations or trajectory of the sinks and routes for data flows. Locations and numbers of the sensors should be determined so that the coverage requirements of the sensor field are satisfied. This problem is called as the Coverage Problem (CP). It is generally assumed in WSN design studies that coverage requirements of the field are characterized by a discrete set of points called coverage points. As some parts of the sensor field can be more critical than the others, requirements of the coverage points can be differentiated implying a heterogeneous CP. Another concern is that some of the deployed sensors can be taken into standby mode in some periods. Hence, there should be enough number of sensors in order to provide some sort of flexibility for the activity schedules of the sensors. In addition, total sensor deployment cost cannot exceed the allocated budget. Next important WSN design issue is to schedule the activities of the deployed sensors which is called Activity Scheduling Problem (ASP). Sensors having relatively lower residual energies can be put into standby mode while some standby sensors are made active at the same time. Scheduling the set of active sensors results in a balanced distribution of the sensors' residual energies. However, it should be noted that the coverage requirements of the field should be satisfied throughout

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the network lifetime. Hence, the set of active sensors at any period should be able to meet the coverage requirements. Third energy affecting WSN design issue is the deployment of the sinks which is called Sink Location Problem (SLP). Locations of the sinks play an important role on the energy load distribution. Another form of this problem is named Sink Routing Problem (SRP) if sinks are mobile. It is a known phenomenon that sensors near to the sinks, which are called relay sensors, spend more energy than others. This is due to the fact that the collected data of the whole network are transmitted to the sinks through the relay sensors. This may cause the depletion of the relay sensor batteries at relatively early phases of the network lifetime. After the death of the relay sensors, sinks become disconnected from the network implying that data collection duty is over. This problem is called differently in several sources such as “crowded center effect” (Popa, Rostamizadeh, Karp, Papadimitriou, & Stoica, 2007), “energy hole problem” (Li & Mohapatra, 2007; Wu, Chen, & Das, 2008), and “sink neighborhood problem” (Basagni, Carosi, Melachrinoudis, Petrioli, & Wang, 2008). Changing the set of relay sensors by controlled sink mobility is offered as a remedy of this phenomenon. Hence, controlled mobility of the sinks plays a regulatory role on the energy distribution. Most of the mobile sink studies from the literature assume that the sink(s) has limitless energy and it instantaneously jumps from one point to another. Hence, sink travel times are usually taken as zero in the literature and the data collected during the sink travel times are also neglected. One of the rare studies that puts some limitations on the mobility of the sink is due to Liang, Luo, and Xu (2010) which considers the sink as an energy limited device that is powered by petrol or electricity. This implies that the sink has to go to the petrol stations or to the electric charge stations periodically to renew its energy. Keskin, Altınel, Aras, and Ersoy (2011) extends the idea of the limited sink mobility by assuming nonzero sink travel time for a single mobile sink. Sink travel time is considered as a part of the network lifetime and the data accumulated during the sink travel time is also taken into account. Authors manage to show that considering nonzero sink travel time produces networks with significantly longer lifetimes if the sink is to repeat its tour many times and the network field is relatively large. The case with multiple mobile sinks is analyzed by Keskin (2014) and it is shown in the study that considering nonzero sink travel times is important for the situations where the sink speeds are slower than 1 kilometer per hour, i.e., for the networks under extreme conditions. Hence, there is no harm in assuming zero sink travel times for WSN applications with multiple mobile sinks if they travel faster than 1 kilometer per hour. We also assume in this study that sink movements take negligible amount of time. In addition, the relocation costs of the sinks are also taken as zero. It should be noted that sinks travel from one point to another only between the periods and they stand on their locations within the periods implying that each sink travels a limited distance. Therefore, the relocation cost that occurs during sink travels is negligible compared to the revenue gained by having a network with longer lifetime. Final important WSN design issue affecting energy loads of the sensors is due to the routes for the data flows. The determination of the most energy efficient route is called Data Routing Problem (DRP). Although DRP is easy for given locations of the sinks and active sensors, problem complexity increases substantially when it is integrated with other problems.

It should be noted that an energy affecting WSN design issue affects the quality of the other design issues. For instance, it is not possible to obtain a good activity schedule of the sensors if sensor deployment issue is handled miserably. Similarly, controlled sink mobility may not be able to provide balanced energy loads if the activity schedule of the sensors is poor. Finally, one cannot create good data flow strategies for a bad set of active sensors and bad sink mobility structures. Therefore, these WSN design issues should be handled together within a unified frame implying integration of CP, ASP, SLP or SRP with DRP. However, most of the studies concentrate only on a subset of these problems and assume that the results of the other problems are ready at hand a priori. This approach produces suboptimal solutions since the optimality of the assumed results is not guaranteed. For instance, Altınel, Aras, Güney, and Ersoy (2008) concentrate only on the CP. Similarly, Wang, Basagni, Melachrinoudis, and Petrioli (2005), Basagni et al. (2008), Basagni, Carosi, Petrioli, and Phillips (2011), and Keskin et al. (2011) try to solve SRP for given sensor location, activity schedules and data flow protocol. In all these studies, activity schedules are taken exogenously and deployed sensors are kept active throughout the network lifetime. Only the studies that deliberately focus on ASP provide varying schedules. There are quite a number of studies which integrate SRP and DRP for given sensor locations and activity schedules. Some of the earliest studies of this kind are due to Gandham, Dawande, Prakash, and Venkatesan (2003), Azad and Chockalingam (2006) and Alsalih, Akl, and Hassanein (2007) in which energy efficient sink and data routes are sought. They all divide the time into equal-length periods but handle each period independently. This deficiency is resolved by Luo and Hubaux (2005) in which a Mixed Integer Linear Programing (MILP) model for optimum sink and data routes is found for multiple periods simultaneously. Xia and Shihada (2015) try to jointly minimize the energy consumption of the energy-critical sensors and the data transmission delay throughout the network. These five papers provide mathematical programing models but they concentrate on energy usage characteristics of the sensors rather than direct maximization of the WSN lifetime. On the contrary, Linear Programing (LP) model of Papadimitriou and Georgiadis (2005) combines DRP with SRP and maximizes the lifetime in the objective function. Gatzianas and Georgiadis (2008) revisit the model of Papadimitriou and Georgiadis (2005) to provide a distributed solution strategy which makes use of Lagrangian decomposition that is first offered by Madan and Lall (2006) for a model with static sinks. Yun and Xia (2010) extend the model of Papadimitriou and Georgiadis (2005) into two new models so that delay tolerant applications are also handled within. Yun, Xia, Behdani, and Smith (2010) and Behdani, Yun, Cole Smith, and Xia (2012) come up with decomposition strategies for one of the models of Yun and Xia (2010) which provide data and sink routes depending only on the local sensor characteristics. Finally, Güney, Aras, Altınel, and Ersoy (2010) extend the model of Papadimitriou and Georgiadis (2005) for multiple but static sinks while Luo and Hubaux (2010) provide a model including multiple mobile sinks. An interesting underwater application of WSNs combining SRP with DRP is due to Basagni et al. (2014) in which an autonomous underwater vehicle visits the sensors to collect their data. The data produced by each sensor is associated with a value indicating the importance of the knowledge captured within the data and this value is assumed to be decreasing by time. Therefore, the analysis is more suited for the event driven applications in which immediate intervention is required during event occurrences. The authors try to find a route for the autonomous underwater vehicle that maximizes the value of the collected information. They also offer a heuristic that delivers more than 80% of the theoretical maximum value of the information. Our analysis is different since we assume that each sensor is able to send its data to the sink either directly (if the sink is nearby) or through other sensors (if the sink is far away) immediately after producing it. Moreover, we also assume that each sensor periodically generates a scalar data. Maximization of the lifetime implies the maximization of the collected data in such a framework.