Constrained Resource Optimization in Wireless Sensor Networks with Mobile Sinks

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***Abstract*—In this position paper we address key challenges in the deployment of wireless sensor networks (WSNs) with mobile sinks for large-scale, continuous monitoring. We propose a heterogeneous and hierarchical WSN architecture for such purpose. We also introduce several novel, constrained optimization problems related to this new paradigm of data gathering, which serve as the potential research topics in this area.**

I. Introduction

Driven by steady miniaturization of computer chipsets and by continuing proliferation of wireless devices and communication technology, Wireless Sensor Networks (WSNs) have emerged as a major, inter-disciplinary area of research and industrial application [1]. WSNs have been seen as a promising solution to large-scale tracking and monitoring applications, because their low-data rate, low-energy consumption and short-range communication presents the great opportunity to instrument and monitor the physical world at unprecedented scale and resolution. Deploying large number of sensors that can sample, process and deliver information to external systems such as fixed or mobile sinks and even Internet applications opens many novel application domains. These include industrial control and monitoring, home automation, security and military sensing, asset tracking and supply chain management, intelligent agriculture and health monitoring, environmental and habitat monitoring, and so on. However, the deployment of WSNs for large-scale, continuous monitoring still necessitates solutions to a number of theoretical and technical challenges that stem primarily from the constraints imposed on the tiny sensor components: limited power, limited communication bandwidth, limited processing capacity, and small storage capacity. The central challenge among these is the provision of quality-guaranteed monitoring while minimizing critical WSN resource consumption. Thus, most resource optimization problems in WSNs can be formulated as *constrained optimization problems* with one or multiple constraints, and much of the research on these optimization problems has focused on developing *exact* and *heuristic* solutions [2], [8], [13], [16], [17], [22], [23], [25], as these problems are usually NP-hard. Exact procedures are limited to solving smaller instances and are not applicable to large-scale networks, due to exponential running time. Although heuristic techniques can yield solutions for some WSN optimization problems, they do not guarantee the *quality* of the solutions obtained. This results in a lack of precision in the management of critical WSN resources. To utilize the critical WSN resources precisely, the development of *approximation algorithms* with performance-guaranteed solutions for WSNs is desperately needed, and the search for these approximation algorithms is a key research issue.

In this paper we will address key challenges in the deployment of WSNs with mobile sinks for large-scale, continuous monitoring by proposing a heterogeneous and hierarchical WSN architecture. We also pose several novel, resource-constrained optimization problems associated with the adoption of this new paradigm of data gathering. To the best of our knowledge, these optimization problems have not yet been explored, developing approximation algorithms with guaranteed performance for them is quite challenging. They are the potential research topics of this field in the near future.

The rest of this paper is organized as follows. Section II addresses our motivations and introduces related works. Section III proposes a heterogeneous and hierarchical WSN architecture for large-scale, continuous monitoring. Section IV introduces several open constrained optimization problems, and the conclusion is given in Section V.

II. Related work

Although several approximation algorithms for various optimization problems in *stationary* WSNs have been proposed in the past few years [9], [10], [11], [19], [27], [28], developing approximate solutions to optimization problems in *dynamic* WSNs with *mobile sinks* poses great challenges and is largely unexplored except very few results available [15], [21]. The theoretical difficulties lie in the *network dynamics* and the *constraints on mobile sinks*: On one hand, the physical network topology dynamically changes with the mobile sink moving to different locations and the data routing pattern changes as well. On the other hand, the mobile sink usually is restricted not only by its maximum travel distance but also by its travel region, as the mobile sink is mechanically driven by petrol or electricity and should avoid travelling towards obstacle locations or regions in the monitoring area. As a result, the development of any efficient algorithm for such dynamic networks must take into account both network dynamics and constraints on mobile sinks.

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To develop novel solutions for quality-guaranteed monitoring in dynamic WSNs with mobile sinks, the key challenges associated with this investigation lie in (i) how to collect enormous amount of sensing data generated by sensors efficiently and effectively while minimizing the consumption of critical network resources; and (ii) how to ensure the quality of the collected data by mobile sinks while meeting specified stringent constraints on mobile sinks. In the following we elaborate on these issues.

Traditionally, a WSN consists of a fixed sink (a base station) and many sensors. The data generated by the sensors is transmitted to the fixed sink through multi-hop relays for further processing [3], [12], [18]. Since the sensors near to the sink have to relay data for others, they usually bear disproportionate amounts of traffic and thus deplete their energy much faster. Such an unbalanced energy consumption among the sensors will shorten the network operational time and affect data delivery reliability and other network performance. To mitigate this uneven energy consumption among sensors, the concept of mobile sinks has been exploited by many researchers, and such studies often assume that a mobile sink (or multiple mobile sinks) can either traverse *anywhere* across the entire network or, alternatively, be constrained to stop only at some *pre-defined strategic locations* in the monitoring area for data collection [7], [14], [25], [32]. Recent studies have shown that the use of mobile sinks can significantly improve various network performance, including network lifetime, connectivity, data delivery reliability, throughput, etc [2], [8], [14], [16], [21], [25], [26], [29].

Extensive studies on optimizing critical WSN resources with mobile sinks, such as maximizing the network lifetime and/or minimizing the number of mobile sinks used, have been conducted in the past few years, by finding an optimal trajectory and/or sojourn time scheduling for each mobile sink [2], [8], [13], [14], [15], [16], [17], [21], [25], [28], [32]. Although the benefits brought by the use of mobile sinks have been well recognized, their deployment poses great challenges in terms of managing critical WSN resources, due to the network dynamics and the constraints on mobile sinks. Most existing studies in literature focused on either minimizing the number of mobile sinks with the travel distance constraint on mobile sinks [17], [28], or maximizing the network lifetime with and without constraints on mobile sinks by developing exact and heuristic solutions [2], [8], [14], [16], [17], [25], [32]. Although several approximation algorithms have already been developed [15], [21], [28], [32], they are based on simplified assumptions. To be explicit, existing works suffer the following four major drawbacks.

The first drawback is over simplified assumptions that mobile sinks can traverse anywhere or stop at some specified locations in the monitoring region. In reality, these assumptions are questionable.

- How do we know "which locations" should be the strategic locations beforehand?
- Is that possible that it takes a mobile sink no time to travel from one location to another location?
- Can a mobile sink travel forever without being recharged or refuelled?

In many realistic application scenarios, a mobile sink in fact cannot travel everywhere without restriction, it may only be allowed to travel in some restricted regions and must be prevented to travel towards obstacles such as rivers, water ponds, big rocks, buildings, bushes, etc. In addition, not only its travel distance but also its travel speed must be bounded, as the mobile sink is mechanically driven by petrol or electricity with finite fuel resources. In some circumstances, the mobile sink (e.g., a moving vehicle) is not allowed to "stop" on a high-speed highway or a busy traffic street for data collection.

The second drawback is that almost all existing studies on network resource optimization have focused on either mobile sinks [17], [24] or the network lifetime [2], [14], [32]. Very few works that took both of them into account are based on unrealistic assumptions. For example, the result in [28] was based on the assumption that every relay node relays the same amount of (data) load and is irrespective of the number of descendants of the node if a tree routing structure is employed. As another example, the approximate result in [32] was obtained by assuming that each sensor can transmit its data to a mobile sink through multihop relays when the mobile sink is within a given distance of the sensor. It incorporated neither the travel distance nor the travel speed of the mobile sink into their problem formulation.

The third drawback is that existing studies assume that it takes a mobile sink no time to collect data from *gateway nodes*, where a gateway node can be either a common sensor or a more powerful sensor (than the common sensor) that can communicate with the mobile sink directly [17], [24], [28]. Recent studies however showed that this time is significant and cannot be neglected [23], [33].

Finally, the fourth drawback is that most studies are based on a "flat" WSN architecture, consisting of homogeneous sensors and mobile sinks. Although this flat architecture may work very well for small to medium-size sensor networks, it definitely is not suitable for large-scale, continuous monitoring because of (i) the poor scalability. With the growth of network size, the average routing path from each remote sensor to the mobile sink(s) becomes longer, and it is more likely that more and more links in the path will be broken, as wireless communication is unreliable. This will incur much longer delays on sensing data delivery to the mobile sinks. And (ii) the availability of mobile sinks. It is infeasible to keep all mobile sinks in working status, they need be refuelled or recharged over time. During their absence, the component sensors will not be able to hold all the generated sensing data. Some important sensing data will be lost due to the buffer overflow of sensors. Consequently, the quality of monitoring of the network cannot be guaranteed and will be compromised.

III. A NEW WSN ARCHITECTURE

To overcome the mentioned drawbacks in the deployment of a WSN for large-scale, continuous monitoring, in the following we propose a new heterogeneous and hierarchical WSN architecture for such purpose.

A. The architecture

The proposed architecture consists of a large number of low-cost sensor nodes for sensing and a few powerful, large-storage *gateway (sensor) nodes* (sometimes referred to as aggregate nodes or base stations [20], [31]). The main roles of each gateway node are to store the sensing data generated by its nearby sensors temporarily, perform data aggregation if needed, and transmit the stored data to mobile sinks or other gateway nodes. Note that here "a few" gateway nodes is relative to "the large number" of low-cost sensors in the network. To incorporate the constraints on the travel distances and the travel regions of mobile sinks, we assume that there is a *road map* available in the monitoring area and the mobile sinks are only allowed to travel along the roads in the road map, assuming that gateway nodes are deployed along road shoulders. We assume that the gateway nodes can be recharged by mobile sinks through the infrared ray, or by reusable energy like solar energy. Thus, mobile sinks can travel along pre-defined or to-be-determined trajectories to collect data from gateway nodes where they pass by. The collected data by mobile sinks finally will be uploaded to the mainframe computers for further processing.

The proposed WSN architecture can be treated as a three-tier architecture. The top tier consists of mobile sinks to collect data from gateway nodes directly. The bottom tier consists of sensors sensing and transmitting data to the gateway nodes in the middle tier. The middle tier consists of gateway nodes storing sensing data temporarily. Two extreme cases of this hierarchical paradigm of data gathering are as follows. One is that all sensors serve as "gateway nodes" uploading their data to mobile sinks when the mobile sinks are within their transmission ranges, i.e., they can communicate with the mobile sinks directly. Doing so is most energy-efficient by eliminating the energy consumption on multi-hop relays. However, this approach may result in much longer delays on data delivery. Another is that there is only one gateway node (a static sink or a base station) in the entire network and all sensors have to relay their data to it. This will lead to much less delay on data delivery but much more severe energy imbalance among the sensors. It can be seen that the proposed WSN architecture can achieve a desirable trade-off between the energy consumption of sensors and the data delivery latency. It thus is appropriate for large-scale, continuous monitoring.

B. Application backgrounds

It must be mentioned that the proposed heterogeneous and hierarchical WSN architecture falls into several realistic application scenarios. In particular, a large-scale *smart city* network could be realized through the deployment of such a heterogeneous and hierarchical WSN consisting of different types of sensors (e.g., scalar sensors and multimedia video sensors), gateway nodes, and mobile sinks. The deployed sensors are used to monitor various *attributes* of a city such as the structural health of key infrastructures (e.g., landmark buildings and bridges), security surveillance of public places, road traffic, electricity and water-meter readings, and so on. There are also a number of gateway nodes installed along both sides of streets, which are used to store the sensing data generated by nearby sensors temporarily. The gateway nodes can communicate with each other by transmitting the received data to the mainframe server(s) for further processing through *long range transmission*, at the cost of the consumption of significant amount of energy. Alternatively, mobile sinks can be employed to collect data from gateway nodes through *short range transmission*, and the cost by doing so is quite cheap, because public transports like buses equipped with transceivers can serve as the mobile sinks to collect data stored at the gateway nodes on bus routes.

C. Challenging problems

To deploy the introduced heterogeneous and hierarchical WSN architecture for large-scale, continuous monitoring, we have the following observations.

Assuming that the tour of each mobile sink is pre-determined, then the travel distance of the mobile sink in the tour is fixed. If the mobile sink travels at constant speed along the tour, then the *duration* spent by the mobile sink per tour, which is the distance of the tour divided by its speed, is fixed. Note that this duration is also the longest delay of a sensing (reading) value from its generation to its collection by the sink. We refer to this duration as the *tolerant latency* on data delivery, reflecting the "freshness" or "obsoleteness" of the collected data. Meanwhile, the amount of data collected by a mobile sink from a gateway node is determined by both its duration within the transmission range of the gateway node and the transmission rate of the gateway node. This implies the faster the mobile sink travels, the less data it collects per tour. Now, if the volume of data stored at a gateway node is larger than the amount of data the sink can collect per tour, then it is unavoidable that some of the stored data will not be collected in the current or future tours and will ultimately be discarded. Consequently, *the quality of monitoring* of the network may be seriously compromised, since not all sensing data has been collected.

To maximize the quality of monitoring in the proposed heterogeneous and hierarchical WSN with mobile sinks, while meeting the given tolerant latency and the constraints on the travel distance and on the travel region of each mobile sink, the following questions need to be answered.

1) If not all sensing data generated by the sensors can be collected by the mobile sinks per tour, then which sensors should be identified and have their data collected in order to maximize the quality of monitoring?
2) What is the optimal routing strategy to route the sensing data from the chosen sensors to which gateway nodes such that the network cost is minimized? And how should the chosen sensors be partitioned?
3) If not all gateway nodes can be visited by a single mobile sink per tour, then multiple mobile sinks should

be deployed. What is the minimum number needed?

4) Given the number of mobile sinks K, what is the optimal trajectory for each of them so that the quality of data collected by them is maximized?

All above mentioned questions can be cast in a unified framework, namely, *the constrained optimization problem* in a dynamic WSN, with an optimization objective under the constraints on the travel distance and the travel region of each mobile sink and on sensors. To the best of our knowledge, none of them has been explored, and the existence of approximate solutions to them therefore is still open. In the following we describe these problems in detail.

IV. Potential research problems

In this section we introduce several potential research problems related to the deployment of the proposed heterogeneous and hierarchical WSN with mobile sinks for large-scale, continuous monitoring.

A. Capacity-constrained data quality maximization problem

Since sensors in WSN networks usually are densely and randomly deployed, the data generated by the sensors are *spatio-temporally correlated*. Instead of transmitting all sensing data to gateway nodes, we can identify a subset of sensors whose sensing data are not highly correlated with each other and transmit only these data to the gateway nodes. We will use these data to "represent" all sensing data of the entire network approximately. Thus, all data stored at the gateway nodes can be collected by mobile sinks per tour. We refer to these identified sensors as the *chosen sensors*. Thus, the problem becomes to identify a subset of sensors whose data can be used to provide an approximate representation of the data of the entire network so that the quality of monitoring is maximized.

To measure the data quality of the collected data by mobile sinks per tour at constant speed v with the given tolerant latency τ, we will use *the mean of the squared prediction error* $\text{MSE}(v, \tau)$ to measure the data quality,

$$\text{MSE}(v, \tau) = \frac{\sum_{i=1}^{n} \sum_{t=1}^{\tau} (\hat{x}_{i,t} - x_{i,t})^2}{n\tau}, \tag{1}$$

where and n is the number of sensors, τ is the duration taken by each mobile sink per tour, and $\hat{x}_{i,t}$ is an approximate estimation of the actual sensing value $x_{i,t}$ of sensor i at time t assuming that a sensing value is generated at constant rate, $1 \le i \le n$ and $1 \le t \le \tau$. Maximizing the data quality is thus equivalent to minimizing $\text{MSE}(v, \tau)$.

The *capacity* $c(g)$ of a gateway node g is defined as the number of chosen sensors sending their data to gateway node g during τ time units (the duration of each mobile sink per tour) such that all the data stored at g will be collected by the sink at its next tour. Note that $c(g)$ is determined by the data transmission rate of g, the generation rate of sensing data, the duration of the sink passing by the transmission vicinity of g, and the duration τ of the sink per tour. Thus, the number of chosen sensors is the sum of the capacities of all gateway nodes in the network. We thus have the following constrained optimization problem.

The *capacity-constrained data quality maximization problem* is to identify a subset of sensors from the entire set of sensors such that the quality of monitoring is maximized, under the capacity constraint of each gateway node.

A generalization of this problem is to maximize the quality of monitoring under the assumption that either different mobile sinks have different travel speeds or each mobile sink has multiple travel speeds, while the maximum duration of all mobile sinks per tour τ is fixed. Also, it is also worthwhile to investigate at which time instance the data correlation analysis and sensor selection procedures are to be re-run to reflect changes of sensing data over time.

B. Capacitated minimum forest problem

Suppose that the number of sensors has been chosen, what comes the next is to find an optimal routing protocol to route the data from the chosen sensors to the gateway nodes such that *the cost* of network resource consumption is minimized, where the cost measure of network resources can be the number of relay sensors needed, the amount of energy consumed, or the other network resources. To simplify our discussion, in the following we adopt the cost measure as the number of relay nodes needed.

To relay data from the chosen sensors to gateway nodes, a routing forest, consisting of routing trees rooted at gateway nodes and spanning chosen sensors, needs to be established. However, such a forest may not exist since the chosen sensors and the gateway nodes may not be within the transmission range of each other. Therefore, some unchosen sensors will be requisitioned as relay nodes, and the number of these requisitioned sensors will also need to be kept to a minimum to minimize the network cost. We thus have the following constrained optimization problem.

The *capacitated minimum forest* problem (CMF) is to find a forest consisting of routing trees rooted at gateway nodes and spanning chosen sensors such that the network cost (e.g., the number of relay sensors) is minimized, subject to the number of chosen sensors in each tree rooted at a gateway node being equal to the capacity of the gateway node.

C. Quality-guaranteed monitoring by mobile sinks

Recall that a road map in the monitoring area is used to describe the restriction on the travel distance and the travel region of each mobile sink in Section III. If all roads in the road map can be visited by a single mobile sink per tour, then all sensing data stored at gateway nodes can be collected by the mobile sink, following the sensor selection and the construction of the forest of routing trees in the previous subsection. However, for a large-scale WSN with a stringent constraint τ on tolerant data latency, it may not be sufficient to employ just a *single* mobile sink for data collection, instead, *multiple* mobile sinks should be deployed, and the new challenges associated with the employment of multiple mobile sinks need to be addressed. For example, how many mobile sinks are needed so that all data stored at the gateway nodes can be collected by them per tour, while the specified constraints on the travel distance and the travel region of each mobile sink are still met? If the number of mobile sinks K is given and it is impossible for the mobile sinks to visit all roads without violating the specified constraints, then what is the optimal trajectory for each of the K mobile sinks such that the quality of the data collected by them is maximized? We refer to these two optimization problems as the *distance-constrained mobile sink minimization* problem and the *distance-constrained data quality maximization* problem, respectively.

V. Conclusion

In this position paper we have addressed several key challenges in the deployment of WSNs with mobile sinks for large-scale, continuous monitoring. We detailed a new heterogeneous and hierarchical WSN architecture for such purpose. We also posed several novel, constrained optimization problems related to the adoption of this new paradigm of data gathering, which will serve as the potential research topics in this area in the near future.

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