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Biased sink mobility with adaptive stop times for low latency data collection in sensor networks

Athanasios Kinalis [a], Sotiris Nikoletseas [a,*], Dimitra Patroumpa [a], Jose Rolim [b]

[a] University of Patras and Computer Technology Institute, Patras, Greece
[b] Centre Universitaire d' Informatique, Geneva, Switzerland

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ABSTRACT

Collecting sensory data using a mobile data sink has been shown to drastically reduce energy consumption at the cost of increasing delivery delay. Towards improved energy-latency trade-offs, we propose a biased, adaptive sink mobility scheme, that adjusts to local network conditions, such as the surrounding density, remaining energy and the number of past visits in each network region. The sink moves probabilistically, favoring less visited areas in order to cover the network area faster, while adaptively stopping more time in network regions that tend to produce more data. We implement and evaluate our mobility scheme via simulation in diverse network settings. Compared to known blind random, non-adaptive schemes, our method achieves significantly reduced latency, especially in networks with non-uniform sensor distribution, without compromising the energy efficiency and delivery success.

1. Introduction

Wireless sensor networks are visioned as large collections of very small autonomous devices, that can sense environmental conditions in their immediate surroundings and have limited processing and communication capabilities. These smart nodes form ad hoc *distributed, sensing and data propagation networks* that collect quite detailed information about the ambient environment. In a usual scenario, such networks are largely deployed in regions of interest for fine grained monitoring in different classes of applications. The sensor devices are battery powered thus energy is the most precious resource of a wireless sensor network, since periodically replacing the battery of the nodes in large scale ad hoc deployments is infeasible. The collected data in wireless sensor networks is usually disseminated to a *static* control center (called data sink) in the network, using node to node – *multi-hop* data propagation [1–3]. Such settings have increased implementation complexity and sensor devices consume significant amounts of energy, since a distributed routing protocol for disseminating data towards the sink is executed in each sensor node. Also, in the area around the control center, nodes need to heavily relay the data from the entire network, thus a hotspot of increased energy consumption emerges and failure, due to strained energy resources, of these nodes leads to a disconnected and dysfunctional network [4–6]. Towards a more balanced and energy efficient data collection sink mobility can be used.

1.1. Sink mobility: opportunities and challenges

In recent years, a new category of important sensor networks applications emerges, where motion is a fundamental characteristic. In such applications sensors may be attached to vehicles, animals or people that move around large geographic areas, while robotic elements may be present as well. Data exchange between individual sensors and infrastructure nodes will drive applications such as traffic and wild life monitoring, smart homes and pollution control.

Motivated by these developments, a new approach has been introduced that shifts the burden of acquiring the data, from the sensor nodes to the sink. The main idea is that the sink has significant and easily replenishable energy reserves and can move inside the region the sensor network is deployed, in close proximity to a (usually small) subset of the sensor devices, collecting the recorded data from the sensor nodes at very low energy cost.

This data collection paradigm has many attractive properties. The major advantage of having a mobile sink (or more) is an increase in system lifetime. In sensor networks, the sustainable lifetime is severely limited by the battery capacity of the sensor nodes, since replacing or recharging of batteries can be extremely costly and impractical. A mobile agent that moves closer to the nodes can help conserve energy since data is transmitted over fewer hops, thus reducing the number of transmitted packets. The extra energy spent for the operation and movement of the sink does

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* Corresponding author.

E-mail addresses: kinalis@cti.gr (A. Kinalis), nikole@cti.gr (S. Nikoletseas), patroumpa@cti.gr (D. Patroumpa), rolim@com.gr (J. Rolim).

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not affect overall sensor network lifetime since the mobile sink is considered an external to the network factor, e.g. could be a man navigated vehicle or an unmanned robot that periodically returns to a fixed point in order to recharge itself. Another important advantage is that connectivity of the network is not required, thus sparse networks can be better handled, and additionally, fewer sensor devices may be deployed, to reduce the operational cost of the network. Also, the sensor devices can reduce their transmission range to the lowest value required to reach the mobile infrastructure, thus saving energy. Moreover, the mobile sink can navigate through or bypass problematic regions where sensor devices cannot operate, such as small lakes, large boulders that block the propagation path.

Moreover, increased throughput and data fidelity can be achieved, In networks with a mobile sink, since the number of transmissions decreases, thus the probability of transmission errors and collisions is also reduced. This further reduces the energy spent at the resource constrained static nodes by reducing the required retransmissions. Also, for applications where security is concerned, with the use of a mobile sink it is more difficult to overhear information. Only the information regarding a small area can be collected by an adversary, since few low power transmissions are used and data does not traverse many hops. Furthermore, attempts to compromise or destroy hub sensor nodes to hinder the operation of the network become irrelevant since there are no hot spot areas where messages are routed.

However, many apparent difficulties arise as well since traversing the network in a timely and efficient way is critical. Failure to visit some areas will result in data loss, while infrequently visiting some regions will result in high delivery delays. Also, routing and localization problems in the case of mobile sinks become more difficult to cope with.

Additionally, critical issues arise in node to sink communications. For single hop communication, the sink should eventually come within range of every sensor. Furthermore, to successfully complete the communication, it must remain within the range of the transmitter for the entire period that the message is transmitted. This problem can be severe when there is high density of sensors in an area or when some sensors have recorded a significant amount of data. In such cases, the communication time between the nodes and the sink is not enough to upload their data, thus they need to wait for the sink to return. This results in high delivery delays or even data loss when the nodes have limited buffers. This problem can be mitigated or even completely eliminated if the sink pauses the network traversal in order to collect the data. In our work we investigate sink mobility strategies that follow this approach, since we introduce adaptive stop times which are proportional to the local data traffic.

1.2. Our contribution

We propose biased sink mobility with adaptive stop times, as a method for efficient (with respect to both energy and latency) data collection in wireless sensor networks. We assume a weak model of a single mobile sink and propose a strategy for network traversal, which serves nodes in a balanced manner. The traversal is performed on a per region basis: the sink visits regions one after another, stopping at each region for an appropriate interval to collect data.

When moving in a random manner, we propose an efficient biased random choice method that favors less visited and more dense areas. Also, our method locally determines the stop time needed to serve each region with respect to some global network resources. More specifically, we estimate an upper bound for the available total pause time, based on the initial energy reserves of the nodes and hence the expected lifetime of the network. We disperse the total pause time, based on local, at each region, criteria, stopping for a greater time interval at regions with higher density, and hence more traffic load. In this way, we achieve accelerated coverage of the network as well as fairness in the service time of each region.

Besides randomized mobility, we also propose an optimized deterministic trajectory without visit overlaps, including direct (one-hop) sensor-to-sink data transmissions only.

We evaluate our methods via simulation, in diverse network settings and comparatively to related state of the art solutions. Our findings demonstrate: (a) for both network traversal methods (e.g. the randomized and deterministic) the introduction of stop times (both constant and adaptive) reduces latency a lot, while keeping high (or even increasing) the delivery success rate, and also reducing the energy consumption and (b) especially in the case of adaptive stop times, the latency improvements are very significant; in fact, our adaptive random walk outperforms the optimized deterministic traversal.

1.2.1. Information fusion perspective

The adaptive procedure for service time calculation can be considered a fusion process (see e.g. [7]) in three ways: (a) the design of our method is based on local network densities; this information is obtained throughout the network via gathering and combining topology related data from multiple sensors in different regions. This fusion based approach leads to a more accurate and complete inference of topology features; also, it is dynamic and can capture network topology changes; (b) at the potential application level, again our approach is based on fusion, in the sense that the sink adaptively stops at each network region for time depending on the local density; thus, the sink stays more in areas with plenty of data generation so the data collected is more complete and can be combined and fused to become more accurate and dependable; (c) our method can also be smoothly combined with fusion at the sensors level, e.g. when nearby sensors aggregate and/or compress data.

1.2.2. Information fusion versus latency

As previously mentioned, the adaptive service time calculation procedure can be considered as a fusion process, since multiple information gathered by the sink is combined to decide the stop time. However, simple fusion techniques, such as aggregation and compression [7], could be utilized by the sensor nodes too, in order to summarize data produced, thus reducing energy consumption and bandwidth needed for communication with the sink. In such a case, higher latency should be expected, since those techniques need extra time and data may not be ready to be sent at the time when the sink arrives at their region.

2. Related work and comparison

In mobile settings, the protocols and findings of previous research on static wireless sensors networks cannot be (at least directly) applied. Efficient solutions in the state of the art become inefficient or even inoperable. Even well studied algorithms need to be redesigned; as an example [8] proposes a leader election algorithm suitable for mobile networks. Also, new problems arise due to the high dynamics, e.g. maintaining system integrity [9] and security [10] becomes more difficult.

Recently, applications that motivate mobility in wireless sensor networks appeared. In [11] the authors address sensory mobility by investigating the computational power of networks of small resource-limited mobile agents. Two relevant new models of computation based on pairwise interactions of finite-state agents in populations of finite but unbounded size are defined. With a