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Optimal query assignment for wireless sensor networks

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ABSTRACT

Increasing computing capabilities of modern sensors have enabled current wireless sensor networks to process queries within the network. This complements the traditional features of the sensor networks such as sensing the environment and communicating the data. Query processing, however, poses Quality of Service challenges such as query waiting time and validity (age) of the data. We focus on the processing cost of queries as a trade-off between the time queries wait to be processed and the age of the data provided to the queries. To model this trade-off, we propose a Continuous Time Markov Decision Process which assigns queries either to the sensor network, where queries *wait* to be processed, or to a central database, which provides stored and possibly *outdated* data. To compute an optimal query assignment policy, a Discrete Time Markov Decision Process, shown to be stochastically equivalent to the initial continuous time process, is formulated. A comparative numerical analysis of the performance of the optimal assignment policy and of several heuristics, derived from practice, is performed. This provides a theoretical support for the design and implementation of WSN applications, while ensuring a close-to-optimum performance of the system.

1. Introduction

Wireless sensor networks (WSNs) are commonly used to sense environmental attributes such as indoor or outdoor level of CO_2, temperature, noise level [1]. The sensed data is stored in databases, from which queries can be processed at a later stage.

The increasing computing capabilities of modern sensors have enabled the WSNs to become an integrated platform on which local query processing is performed. Consequently, not only storage facilities, such as central databases (DB), are able to process queries, but also the sensors within the WSN. Letting the WSN process queries, however, poses Quality of Service (QoS) challenges. For example, sensors can provide queries with the most recently sensed data. But directing the queries always to the WSN can overload the network and lead to high query waiting times. A trade-off arises between processing the queries within the WSN with the most recently acquired data and the time queries wait to be processed.

In recent years, studies on sensor networks have focused mainly on energy efficient data transmission [2–4] and the traffic was assumed to have unconstrained delivery requirements. However, growing interest in applications with specific QoS requirements has created additional challenges. We refer to [2,5] for an extensive outline of WSN specific QoS requirements. The literature reveals related work on QoS-based routing protocols within the sensor network. Most such protocols satisfy end-to-end packet delay [6] or data reliability requirements [7,8] or a trade-off between the two [9]. However, little work exists on QoS guarantees in the field of sensor query monitoring, as addressed in this paper. In [10] a query optimizer is used to satisfy query delay requirements. In [11] the authors use data validity restrictions to specify how much time is allowed to pass since the last sensor acquisition so that the sensors are not always active and some previously sensed data is used.

This paper analyzes the cost of query processing seen as a trade-off between two QoS requirements commonly encountered in WSNs: the time queries wait to be processed and the age of the data provided to the queries. We consider a system consisting of a central DB and a WSN, both able to solve queries (see Fig. 1).

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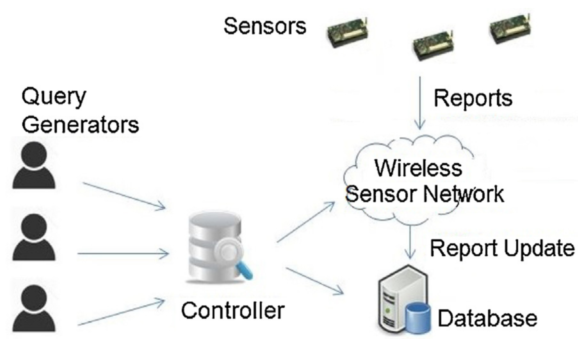

Fig. 1. Wireless sensor network seen as an integrated platform, where queries generated by the end-users are processed either by the WSN or by the DB. Reports are random calls to the WSN and are processed by the WSN. After a report is completed, the DB is updated.

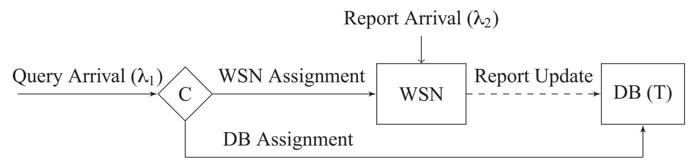

Fig. 2. Proposed model incorporating a controller (C), the database (DB) and the wireless sensor network (WSN). The DB solves queries assigned by the controller. The WSN solves reports and queries assigned by the controller. The data stored in the DB is considered outdated if the age of the data exceeds a validity threshold T. After T is exceeded, the age of the data increases linearly until a report comletion updates again the DB.

We assume that the DB processes queries instantaneously, as the time required to fetch data from the DB is negligible compared to the time a query is processed by the WSN. For the WSN, a processor sharing service type is assumed. This reflects the IEE 802.15.4 MAC design principle of distributing the processing capacity fairly among the jobs simultaneously present in the network. Processor sharing for WLAN was assumed in [11] and validated by simulation in [12].

Queries arriving at a controller are assigned either to the WSN or to the DB. A WSN assignment increases the load of the network and results in large query waiting times. If queries are sent to the DB, the data provided to the queries may be outdated, as the age of the stored data increases over time. The fact that the quality of the stored data deteriorates over time is an essential feature of our system and will pose technical challenges, as seen in the next section. In this paper we provide an approach on how to trade-off between the waiting time of queries and the age of the data, in an optimal and computational manner. In particular, we determine an optimal query assignment strategy that minimizes the processing cost of the queries by trading-off between the waiting time of the queries and the age of the data provided to the queries.

The query assignment problem presented above is formulated as a Continuous Time Markov Decision Process (CTMDP) with a drift. The continuous character of the process, and in particular, the fact that the age component of the process evolves continuously over time, makes the problem non-standard and computationally intractable, i.e. the standard way of deriving an optimal policy recursively using dynamic programming is not directly applicable. Therefore, for computational reasons, we argue a Discrete Time and Discrete State Markov Decision Process. First, we propose a non-standard exponentially uniformized Markov Decision Process, which we show to be *stochastically equivalent* to the original Continuous Time Markov Decision Process with a drift. However, the exponentially uniformized process still contains the age as a continuous state component. Therefore, for further computational tractability, we argue a Discrete Time and Discrete State Markov Decision Process. We then determine an optimal query assignment policy for the discrete time and state process by means of stochastic dynamic programming. Finally, we argue and numerically illustrate that the optimal policy also holds for the original Continuous Time Markov Decision Process with a drift.

In addition, we provide a numerical comparative analysis of the performance of the optimal policy and of several heuristics. The heuristics are simple assignment strategies, commonly used in practice. The results provide a formal support for the design and implementation of query assignment policies in practice so that the system can perform close to the optimum.

The paper is structured as follows. In Section 2, we describe the model of the query assignment problem and define it as a Discrete Time and Space Markov Decision Problem. In Section 4, we assess numerically the performance of our proposed assignment policy and compare it with other feasible heuristics. In Section 5 we discuss the comparative analysis of the proposed assignment policy and the heuristics. Concluding remarks are stated in Section 6.

2. Model formulation

In this section we introduce the query assignment problem formally. In Section 2.2.1, we define the query assignment problem as a Continuous Time Markov Decision Process (CTMDP) with a drift. Next, we construct an exponentially uniformized Markov Decision Process in Section 2.2.2. We show that the exponentially uniformized Markov Decision Process and the initial Continuous Time Markov Decision process (Section 2.2.1) are stochastically equivalent. This leads to the formulation of the query assignment problem as a Discrete Time and Discrete Space Markov Decision Problem in Section 2.2.3.

2.1. Model description

The system consists of a service facility (WSN) with Processor Sharing capabilities and a storage facility (DB). Fig. 2 shows the proposed model.

Two types of jobs: queries and reports, arrive at the system according to a Poisson process. Queries arrive at rate λ_1. Reports arrive at rate λ_2. Reports are requests issued to the WSN to sense the environment and send the data to the DB. Reports update, therefore, the DB. The service requirements of the jobs are exponentially distributed with parameter μ, independently of the job type. To ensure that the system is stable, we assume that $\lambda_2 < \mu$.

Incoming queries are handled by a controller which assigns them either to the DB or to the WSN. When assigned to the DB, queries are immediately answered with stored data. However, the stored data might be outdated, i.e. the age of the data might exceed a validity threshold T. Assigned to the WSN, the queries wait to receive the sensed data, sharing the service with the other jobs present in the network. We assume a Processor Sharing service type of service for the WSN. Therefore, the expected waiting time of the queries is growing linearly with the number of jobs being processed by the WSN (a direct consequence of Little's Law).

The system assumes a query processing cost which is influenced by the type of query assignment (DB or WSN assignment). The cost of a DB assignment is an instantaneous cost, indicating how much the age of the stored data has exceeded a validity threshold T. The cost of a WSN assignment consists of penalties, accumulating over time, related to having queries waiting in the WSN to be processed. These penalties increase upon a WSN assignment, as a consequence of the Processor Sharing service type of the WSN. When a new query arrives at the controller, the model must decide between increasing