

# System Design Issues in Sensor Databases

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## ABSTRACT

In-network sensor query processing systems (ISQPs), or sensor databases, have been developed to acquire, process and aggregate data from wireless sensor networks (WSNs). Because WSNs are resource-limited and involve multiple layers of embedded software, the system design issues have a significant impact on the performance of sensor databases. Therefore, we propose this tutorial to study the state of the art on these issues with a focus on their interaction with query processing techniques. Our goal is to present the challenges and efforts in developing holistic, efficient ISQPs. Specifically, we will cover architectural design, scheduling, data-centric routing, and wireless medium access control. This tutorial is intended for database researchers who are interested in sensor networks.

## Categories and Subject Descriptors

H.2.4 [Database Management]: Systems – concurrency, distributed databases, query processing.

## General Terms

Algorithms, Measurement, Performance, Design, Experimentation.

## Keywords

Sensor networks, in-network query processing, scheduling, data-centric routing, wireless medium access control.

## 1. INTRODUCTION

Wireless sensor networks (WSNs) as a research area has a rather short history [2]. So far, the database community has produced several in-network sensor query processing systems (ISQPs), or sensor databases, including the earlier ones Cougar [43] and TinyDB [22], and most recent ones SwissQM [25] and DSN [6]. There have also been a fair number of query processing techniques proposed for sensor networks [5] [8] [16] [21] [23] [30] [31] [32] [42] [44]. As the performance of ISQPs is greatly affected by the system design issues, we discuss the state of the art on these issues for sensor databases in this tutorial.

The goal of this tutorial is to present the challenges and efforts in developing holistic, efficient sensor databases, with a focus on the interactions between system design issues and query processing techniques. Specifically, query processing techniques often assume a fixed tree-network topology and ignore scheduling, time synchronization, and other low-level mechanisms. Meanwhile, a fair amount of work has been done on these systems mechanisms

from the networking and systems communities with little consideration about query processing workloads [3] [7] [10] [13] [15] [26] [27] [28] [45] [46]. Therefore, we attempt to bridge the gap and to raise the awareness with this tutorial.

Our tutorial will be organized as follows. The first half will be spent introducing existing and emerging architectural designs for sensor databases and briefly surveying a few query processing techniques for sensor networks. The second half will focus on the system support mechanisms, including routing, scheduling, and medium access control. Our intended audience is database researchers who are interested in working on data management for sensor networks. We assume that the audience has general knowledge about computer networks.

## 2. ARCHITECTURAL DESIGN

Figure 1 illustrates a generic ISQP in three layers. The MAC (Medium Access Control) layer manages the wireless, multi-hop radio communication channel of a WSN. Its tasks include energy conservation, bandwidth allocation, and time synchronization for the channel. The routing layer maintains the network topology to disseminate queries from a sink node into the network and to transmit sensor readings in the network. Finally, the query layer executes declarative, SQL-style database queries. In this layer, relational query operators are applied to the sensor readings before the data are transmitted by the routing layer. Additionally, scheduling can be done in each layer or across layers.

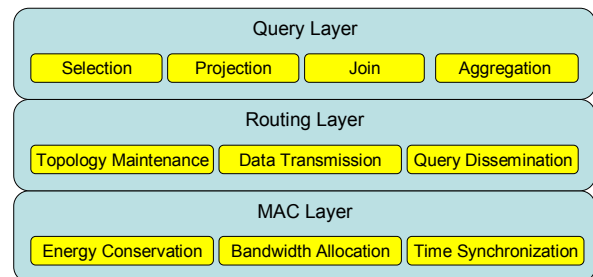


Figure 1: A Three-Layer ISQP

Both Cougar [43] and TinyDB [22] fall into this architectural design. Because TinyDB is based on the commonly used TinyOS [37] system environment and is publicly available, we will use it as examples to discuss system design issues.

Most recently, SwissQM [24][25] is proposed as a next-generation data processing system for sensor networks. It implements query processors for sensor nodes as virtual machines. These virtual machines are similar to those in Mate [17], but they are specialized for data processing.

Finally, DSN [6], a declarative sensor network system is proposed to address the difficulties in sensor network programming. It provides a declarative language as well as a compiler and a runtime environment for the language to support a wide range of applications, including query processing.

Additionally, there has been recent development on programming environments and operating system support for WSN application. The most recent OS for sensor networks, t-kernel [11], is able to support three key OS features, including OS protection, virtual memory, and preemptive scheduling and execution. Both MANTIS [4] and Contiki [9] support multi-threading features on a sensor node. Additionally, with MANTIS, users can test a target sensor code either on a PC or on a sensor node using remote login. Contiki features lightweight loading or unloading of programs. Similarly, SOS [12] enables dynamic module loading, which can reduce the program loading time, especially in wireless networks. These OSs can all run in a tiny sensor mote, which has about 4-10 KB RAM and a CPU of a few MIPS. Most recently, researchers at Sun Microsystems Laboratories have been building a SunSPOT system [34] to enable WSN application developers to use a compact Java language to program on sensor nodes for the portability and flexibility of sensor node programs. Moreover, SunSPOT will be able to provide better security support on sensor devices. The SunSPOT system runs on a 32-bit ARM-7 CPU and 11 channel 2.4 GHz radio.

### 3. MAC

We introduce four MAC protocols that are designed specifically for sensor networks as opposed to general MANETs (Mobile Ad-hoc Networks) and discuss their implications on ISQPs.

The MAC protocol [39] in TinyOS [37] is a contention-based protocol. Its major contribution is its adaptive rate control mechanism to improve power efficiency and to balance the bandwidth allocation among all nodes in a multi-hop WSN for fairness. In addition, in performing the carrier sense multiple access (CSMA), the protocol optionally adds a random delay before listening to the wireless channel to avoid repeated collision. This repeated collision is severe especially when the sensor nodes are time synchronized [33] and the sensor nodes are all trying to send data towards the sink node(s), which is usually the case for current ISQPs.

Sensor-MAC (S-MAC) seeks to schedule nodes to periodically enter the sleep mode for power efficiency [45]. In S-MAC, a node constructs a sleep schedule that specifies the active and sleep periods. T-MAC is another contention-based MAC protocol for wireless sensor networks [7]. It extends the sleep and active scheduling in S-MAC via dynamically ending the active period of a schedule, i.e., the active period in T-MAC is not fixed whereas that in S-MAC is constant. These sleep scheduling mechanisms are crucial for the WSN power efficiency, especially because ISQPs often produce periodic data flows.

Finally, the Sparse Topology and Energy Management (STEM) protocol [27] is designed for WSNs used in applications that do not have heavy communication traffic. As a result, it is suitable for an event-monitoring ISQP as opposed to a data acquisitional one. In STEM, the radio modules of nodes are put in sleep modes in the monitoring state until there are packets ready for transmission. For

the nodes to be informed when events occur, each node should periodically turn on its radio to listen if someone wants to communicate with it.

### 4. ROUTING

Recently, researchers have proposed a number of routing protocols specifically for WSNs [1][3][14][15][35][36][40][46]. Among these protocols, the location-based ones require sensor nodes to have location-aware hardware or to be deployed at specific locations [15][46]. In contrast, several existing protocols, including MintRoute [40], the routing protocol in TinyDB [35] (TinyDBRoute) and TinyAODV [36], require no location information, which are suitable for general ISQPs.

MintRoute is a widely used protocol on top of TinyOS [37]. It focuses on improving link and route reliability through neighborhood table management. The routing protocol used in the TinyDB system, TinyDBRoute, is a shortest path one. It is similar to MintRoute in that it also uses a distance-vector approach. Both MintRoute and TinyDBRoute send out control packets to maintain routes periodically and the cycle of their route maintenance is fixed. Finally, TinyAODV is a WSN version of the Ad hoc On-Demand Distance Vector (AODV) protocol [26]. It sets up a route only when there is a demand and invalidates the route upon receiving an error message.

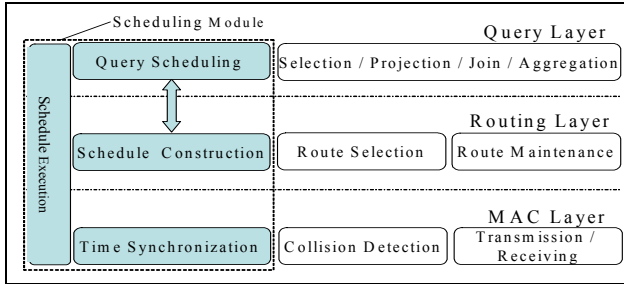
### 5. SCHEDULING

Scheduling has been proposed for WSNs to reduce idle listening, overhearing, collision, and control packet overhead [10][13][28][38][44] and to guarantee real-time delivery [18][19]. Scheduling is an effective means to power efficiency, the major concern for data-intensive WSN systems, such as an ISQP. Specifically, the power consumption of data transmission is much higher than CPU computation. As a result, idle listening is similar to, or even more than, transmission uses, because idle listening requires both the CPU and the transceiver of a node to be active. Given that the electric current in a node is at the micro-Ampere level in sleeping and at the milli-Ampere level when active, the most effective way to save power is to make nodes sleep whenever possible.

Two representatives of WSN sleep scheduling protocols are Flexible Power Scheduling (FPS) [13] and the scheduling scheme proposed by Sichitiu (SS) [28]. Both schemes allocate specific time slots for communication. In FPS, a parent allocates the transmission slots for its children so that the children do not compete. In comparison, SS is a cross-layer scheduling scheme that constructs both schedules and routes.

Existing scheduling schemes fall into two categories: topology-dependent and topology-independent. The topology-dependent schemes, such as FPS [13] and SS [28], construct a schedule based on the network topology and usually take a long time in subsequent schedule updates. In contrast, topology-independent schemes, such as the scheduler in TinyDB [36], are immune to topology changes but they usually keep nodes idle-listening, which is inefficient. As the topology of a WSN often changes due to various factors and queries in an ISQP come and go, it is desirable to make scheduling schemes adaptive.

Our previous work [41] on DCS, a distributed, cross-layer scheduling protocol is an example of making scheduling work for in-network sensor query processing. Its architecture in an ISQP is shown in Figure 2.



**Figure 2: DCS in an ISQP**

In DCS, each node employs its MAC, routing, and query layers to negotiate with its parent its timing for transmission, and constructs a schedule for its query processing. It then follows the schedule to compute, communicate, and sleep in each query processing cycle. This scheduling reduces wasted listening and receiving, as well as the switching between active and sleeping modes. Consequently, it resulted in a 50-60% power saving with real sensor nodes in our experiments. Additionally, it outperforms FPS [13] and SS [28] both on schedule construction efficiency and on schedule quality. However, DCS has a few shortcomings, with the major one being the lack of support for incremental schedule updates in response to the changes in an ISQP.

## 6. FUTURE DIRECTIONS

There are a number of open problems and future directions for system design issues in sensor databases. In the following, we outline three of them.

The first direction is multi-query processing. Current ISQPs support no more than two concurrent queries. With the advances in the sensor node hardware, we see great opportunity for supporting multi-query processing. This capability will improve resource sharing significantly and requires considerations on scheduling at multiple layers.

The second direction is join and user-defined function processing. So far, joins in sensor networks have been restricted to a sensor stream joining with a static table. It is desirable to support window joins over multiple sensor data streams. Additionally, user-defined functions, especially signal processing ones, are common in ISQP applications. Supporting these advanced query processing capabilities efficiently demands considerations on routing, scheduling as well as architectural design.

The third direction is to design an ISQP for a multi-sink network will require completely rethinking of issues in scheduling, routing, and MAC support, since existing ISQPs all assume a single-sink tree structure network. Nevertheless, to enable users to inject queries and to obtain results anywhere in a network, a multi-sink design is mandatory.

Finally, for all of these directions, we advocate the cross-layer design methodology because it optimizes multiple layers of a sensor

network system and will make an ISQP more efficient, as exemplified in recent work [20][21][22][24][29][38][44].

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