Status of the CAS/HKUST Joint Project BLOSSOMS*

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Abstract

In March 2004, recognizing the importance of sensor networks, the Chinese Academy of Sciences and the Hong Kong University of Science and Technology launched a joint effort to investigate both fundamental and practical research issues in sensor networks. The goal of this research is to build lightweight optimized sensor systems on a massive scale, namely the BLOSSOMS project. The objective of this research project is to identify research issues at all levels from practical applications down to the design of sensor nodes. This paper reports the status of the project as of April 2005. First, other than making MOTE-compatible sensor nodes, this project has studied the hardware and software co-design and the associated “sensor node on a chip” technology with the aim to make sensor nodes small in size, light in weight, cheap in cost, and low in power consumption. Second, additional toolkits for simulation/emulation and evaluation of sensor networks have been developed to support research at different levels. Third, a number of applications have been investigated and implemented since the launch of this project, and this paper will address two of them. One is an embedded remote health care system based on wireless sensor network technologies to introduce a scalable wireless personal medical network around human’s body. The other is a moving object counting system based on an ultrasonic sensor network, which can be used but not limited to crowd estimation and traffic monitoring and coordination.

1. Introduction

Wireless Sensor Network (WSN) has gained great attention these years. Researches are in progress to improve the design and performance of the WSNs in various aspects. Yet we lack a systematic analysis of design issues related to WSNs. In order to construct the next-generation WSNs, CAS and HKUST have established a joint project BLOSSOMS [1] since March 2004. It aims at identifying fundamental research issues and practical constraints at various levels between the high-level application support and the low-level sensor node design. Such investigations help to achieve our ultimate goal, which is to develop a lightweight, inexpensive and power-efficient sensors system at massive scales. The extensive studies of the software and hardware behaviors and their interactions with the environment also favor the implementation of simulation/emulation and evaluation toolkits that provide a reliable means for application development at a lower cost and in a shorter time. Using these toolkits, the developers and researchers can design and test their applications and protocols on workstations without deploying the real sensors.

This paper will give an overview of our BLOSSOMS project and describe our recent progress. We will focus on the advances in the sensor node design using the “sensor node on a chip” technology and the design of our evaluation tool. In addition, two applications on medical use and object counting with our recently developed sensors will be presented.

2. Project Overview

BLOSSOMS is a project for developing state-of-the-art components for WSNs based on their design requirements. It has a four-level architecture including the heterogeneous sensor nodes, communication protocols, ontology-based middleware and application/user interface (Figure 1). An additional module is designed to tightly cooperate with the three lower layers for monitoring and emulation in workstations. The...
two lower layers contain components that reside in the individual sensor nodes while the two upper layers are located in more powerful gateway or application nodes. Specific research issues are identified at various levels and solutions are under development. The collections of these solutions also serve as a complete and systematic model for our WSNs. The research scopes at different aspects are summarized as follows.

- **Heterogeneous sensor node**
  WSN applications are believed to be highly application-specific. The requirements for different applications could vary. In particular, sensors in potential applications are one of our major concerns. Two important issues are being considered – design of new type of sensors and investigation of innovative use of existing sensors. In addition to traditional sensor nodes, a variety of special-purpose sensor nodes such as monitoring sensors should be invented to collect performance data and simulate the real environment. Moreover, the power consumption of sensor nodes could be reduced by better software and hardware co-design. Last but not least, important features such as security management may be integrated into the hardware design to further improve the practility of sensor nodes.

- **Communication protocols**
  With its mobile, ad-hoc and power-limited nature of sensor nodes in WSNs, it is widely accepted that multi-hop transmission is the dominant model for data dissemination. However, it lacks of a further study of communication patterns for such transmissions. Analysis of various communication types could improve the design of the routing and other communication protocols in terms of power-efficiency. Effect of multiple gateways for routing protocols will also be studied. RF signal strength will be our major focus for localization and its refinement.

- **Ontology-based middleware**
  Context is believed to be an important component in WSNs. A middleware for capturing and managing context collected from sensor nodes are crucial for context-aware applications. We aim at developing a reusable and reliable context system over the error-prone communication wireless channels and possibly inconsistent data collected by sensor nodes. The system is capable to repair corrupted data and handle exception properly.

- **Emulation and evaluation toolkits**
  The toolkits aid the application and protocol development by performing massive scale testing and tuning on workstations without real deployment on sensor nodes. The challenges include the development of a highly consistent emulation model for the real sensor nodes and speed of emulated network. Recent analysis suggested building the virtual sensor network based on the response time and power consumption models of sensor nodes. The toolkits are able to emulate various network environments for a variety type of sensor nodes with appropriate parameters. Benchmarks for various performance parameters are designed for comparison and evaluation.

![Figure 1: Architecture of BLOSSOMS](image)

3. **Sensor Nodes Design with Hardware and Software Co-design and SOC**

With the goal to make the sensor nodes small in size, light in weight, cheap in cost, as well as low in power consumption, projects have been carried out to study the hardware and software co-design and to develop sensor node SOC technology. We have proposed a general “sensor node on a chip” approach with two typical SOC architectures for different application areas[2]. The first architecture of sensor node supports basic functionalities which perform relatively simple tasks with fixed protocols. Figure 2 shows the schematic diagram of the first architecture. The second architecture of sensor node favors complex functionalities and advanced jobs. Figure 3 shows the schematic diagram of the second architecture. With advanced SOC FPGA/ASIC technology, it is possible to design and manufacture the next generation sensor node on a single chip which meets the requirements on size, weight and cost at the same time.

So far, we have developed the Sensor Interface module, MCU module and the Transceiver Interface module for the simple node design. Figure 4 shows experimental result indicating real time data collection (from temperature, humidity and light sensors) and wireless data transmission by a completed FPGA node of basic functions.
The proposed SOC structures is built on top of optimized interface modules, algorithm and network protocols. Once the software protocols and algorithms are optimized and fixed, it is possible to transform the complete or part of the software design into a Network Protocol hardware module to improve the computation and power efficiency of the embedded system. In order to achieve the conversion, it is important to study the software and hardware co-design. To illustrate the idea, we have studied the SOC implementation of a novel difference compression arithmetic [3] module as part of the network protocols hardware module.

In order to evaluate the performance of sensor network applications in general and in-network sensor query processing systems in specific, we have developed a set of tools including a network emulator VMNet [9], a sensor query processing benchmark Bisque, and generators for network topology and sensory data.

4.1 The network emulator

Currently there are both real hardware platforms, e.g., the Motelab [7] at Harvard University, and simulation tools, e.g., TOSSIM [5], PowerTOSSIM [8], and EmStar [4], for WSNs. Hardware platforms are the most realistic test bed, but they are hard to deploy for controlled experiments of various settings. In contrast, simulation tools facilitate a wide range of studies but some performance factors may be omitted due to their high level of abstraction. Leveraging the benefits from these two extremes, our WSN emulator, VMNet, serves the purpose of realistic application performance evaluation.

In VMNet, a target WSN is emulated as a Virtual Mote Network (VMN). Each sensor node is emulated as a Virtual Mote (VM). The processor of a virtual mote is emulated at the clock cycle level while the sensing units and other hardware components are also emulated in sufficient details. The radio signal transmission is modeled by the communication channels with path loss and noise. Last but not least, the binary code of the target WSN application can be run directly on the VMN for debugging, testing and, most importantly, performance evaluation.

We select three performance metrics for evaluation: response time, power consumption, and sensory result accuracy. Response time is vital for time-critical WSN applications, such as chemicals detection, whereas power consumption is a common concern in WSN. Finally, sensory result accuracy is a desirable metric for data-centric applications. Communications in WSNs are unreliable but the applications care about the accuracy of returned sensory results with respect to the raw measurement results at the sensor nodes. Such metric is hard to measure in a real WSN, as it involves collection of raw sensory values at sensor nodes and comparison with the results obtained from the WSN application.

In order to evaluate these performance metrics, VMNet logs detailed running status of emulated nodes. The running status is categorized by the operations of the CPU, the flash memory, the sensing units, and the communication units. The virtual running time (i.e., the time in the emulated world) of each operation...
is also logged so that the response time can be reported. Power consumption can be estimated in VMNet by using the logged emulation statistics and the sensor node parameters (e.g., electric current) from real world measurements. In addition, VMNet can report the sensory result accuracy with comparison between the input sensory data and the returned sensory results.

We have evaluated the performance of VMNet with real WSNs, TOSSIM and PowerTOSSIM. The results demonstrate that, the estimated running time and power consumption in VMNet are close to those in the real environment. In addition, VMNet facilitates detailed study on running status and data delivery schemes. Despite of its high fidelity, VMNet still has an emulation speed of 1/7 of that of TOSSIM.

4.2 The benchmark for in-network sensor query processors

In-network query processing systems such as TinyDB [6] and Cougar [10] are useful for acquiring sensory data in WSNs. As these sensor query processing systems involve both new hardware (e.g., the Crossbow MICA2 motes [11]) and new networked embedded system software (e.g., the Berkeley TinyOS [12]), it is difficult to conduct end-to-end comparative performance studies. Therefore, we have developed a benchmark, Bisque (Benchmark for In-network Sensor Queries) for this purpose. In Bisque, we define the System Under Test (SUT), the network topology, the sensory data schema, the sensory data population, and the query workload.

An SUT in Bisque is an in-network sensor query processing system. It consists of three layers: (1) the MAC (Medium Access Control) layer, which manages the wireless, multi-hop radio communication channel; (2) the routing layer, which is responsible for transmitting queries and data over the network topology; and (3) the query layer, which executes selection, projection, aggregation, and other query operations in each sensor node. This layered description is for general purpose. SUTs with cross-layer design are also allowed in Bisque.

For simplicity and controllability, we define the network topology in Bisque to be an m*m grid, where m is the length of each side of the square. Sensor nodes can be placed inside each grid. We have developed a network topology generator to produce a target topology based on the user input.

The Bisque data schema is similar to those used in the current sensor query processing systems, which consists of a single virtual relational table named sensors. A virtual table composes of sensory attributes as well as non-sensory attributes. The sensory attributes include light, temperature, humidity, pressure, acceleration and magnet values. The non-sensory attributes include the sensor node ID, the x- and y-coordinates of the node location, the timestamp of the sensory data tuple, the voltage at the sensor node, the current size of free memory in the node, the ID of the parent node, and the hop count from the gateway node. We have developed a data generator to produce realistic data sets that follow this data schema and satisfy user requirements.

Finally, we have designed the query workload as a set of data acquisition queries and aggregation queries. The data acquisitions queries perform simple selection and projection with single, conjunctive or disjunctive predicates on sensory attributes or with spatial selection predicates on the location attributes. The data aggregation queries involve duplicate-insensitive aggregates such as MAX, duplicate-sensitive ones such as AVG, and aggregation with group by and having clauses. The purpose of this query workload is to represent common functions of data acquisition workloads and to exercise the SUT to a full extent.

We have implemented several representative SUTs and used the VMNet emulator as the sensor network platform to evaluate the performance of these SUTs running Bisque.

4.3 The generators for network topology and sensory data

As accompanying tools of the Bisque benchmark, the network topology and sensor data generators are provided to produce a target network topology and sensory data for users to run their systems using Bisque.

The topology generator TOPOGEN takes the number of nodes, the node transmission range, and the width of the square area as the input. It sets the width of each grid to be the transmission range or half of the transmission range, and distributes the nodes to each grid. It then generates communication links between nodes based on the distance between nodes. If the distance is within the transmission range, there is a communication link between them. Finally, it outputs the generated topology in two tables: a node position table and a link table.

The data generator SDGEN aims at generating data sets that are realistic and satisfy the testing requirements. It takes a sample data set, the description of the sample data set (schema, sampling period, and network topology), and the description of the target data set (schema, sampling period, duration, and network topology) as inputs. It then maps the target net-
work topology to the original network topology so that the target data set can be generated from the sample data set. Finally, it utilizes spatial interpolation and temporal interpolation to generate the target data set that satisfy the user requirements and preserve the spatial and temporal trends in the sample data set.

5. Applications

We have implemented and investigated two prototypes using our recently developed sensor nodes. They illustrate some possible applications in medical use and object count estimation.

5.1 Wireless sensor network for remote medical care

An embedded remote health care system [13] based on wireless sensor network technology was developed in CAS. In this work, we firstly proposed a new system architecture which introduced a scalable wireless personal medical network around human’s body as shown in Figure 5. Then we designed several special purpose sensor nodes and a home base-station. In this system, the sensor module is controlled by a MSP430 series processor from TI Corporation. The RF module is CC2420 from Chipcon Corporation. The wireless communication between the sensor nodes and the home base-station used IEEE 802.15.4 / Zigbee standard whilst the home base-station and the remote service center can be connected in either of the following ways, including computing network, GSM short message service and telephone modem. The sensors we have adopted so far include a blood oxygen module (Shanghai Berry Electronic CO LTD), a blood glucose unit and a blood pressure unit (both from TaiDoc Technology Corporation, Taiwan). Figure 6 (a) and (b) show the photos of the hardware for a home base station and a blood glucose sensor node. The blood oxygen concentration was measured by the sensor node. The measurements were transmitted wirelessly to the base-station and they were displayed against time on the LCD screen of the base-station which is shown in Figure 6(c). Furthermore, by connecting the base-station with a networked home PC via the RS232 serial communication interface, the measurements can be transferred to the remote server. Doctors may check the data shown on the networked computer, as shown in Figure 6(d), to see if the result is normal or not. The measurements can also be transmitted to doctor’s mobile device through the GSM short messages from the home base-station. This system can be used for remote health care at home or in the hospitals.

5.2 Moving Object Counting

Applications like crowd estimation and traffic monitoring and coordination involve decision making processes based on estimation of the number of the object in an area. Intensive researches have been conducted in object counting for tens of years in order to developing solutions for those applications. There are a few requirements for a good estimation system. They include but are not limited to the ease and cost of deployment, estimation accuracy and secrecy.

Existing approaches make use of different technologies to realize the count estimation. However, we are still lacking of solutions for moving object counting. There are many challenges inside. In particular, the estimation accuracy could easily be deteriorated when environmental effects are taken into account. For examples, thermal detection could be significantly affected by sunlight in outdoor. Furthermore, sensor and material behaviors also limits the use of several techniques such as vehicle counting using electromagnetic technologies.

Ultrasonic sensor network would be a promising solution to the problem. Ultrasonic wave works well in the indoor and outdoor environment. Environmental effect could be minimized by adjusting the orientation in deployment. With the integration into a network, the detection information from individual sensors
could be shared with neighbors to improve the accuracy of count estimation.

Our application focuses on counting the number of people who has entered the entrance. Arrays of sensors are installed at the ceiling of the entrances. Figure 7 shows an array of three sensors. The middle one will emit ultrasonic wave while the other two will detect the bounced signal. While a person is moving from left to right, the sensor array will detect two bounced signals. This paired signal ensures the person has walked from left to right. This improves the accuracy of the detected signal over the one with a single transmitter and receiver. A single pair of transmitter and receiver may provide false detection when the person is approaching the transmitting sensor but returning without reaching the other end (Figure 8). With the cooperation between neighboring sensor arrays, the detection range could cover the whole entrance. The count estimation could be made by the detection information collected by the sensors.

With little adjustment to the deployment, the ultrasonic sensor network could be adopted to the traffic monitoring. Decision on traffic coordination could be made to ease the traffic congestions.

6. Conclusions and Future Work

The BLOSSOMS project targets at identifying and solving both fundamental research and practical issues in WSNs. Achievements on hardware and evaluation tools have been made since the launch of the project. It has designed new architectures for sensor nodes which adopted the concept of “sensor node on a chip”. The new generation of sensor nodes is manufactured with smaller size, lower power consumption and at cheaper price. Evaluation tools are also provided to aid developers and researchers to speed up the application development and conduct performance evaluation. The project will carry on to investigating solutions at different layers of WSNs.

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