Cross-Layer Optimization for Sensor Networks

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***Abstract*—In this paper, we study the application oriented cross-layer protocol design and optimization. The goal of the study is to provide a feasible and flexible approach to solve the conflicts between the requirements of large scale, long life-time, and multi-purpose wireless sensor networks and the constraints of small bandwidth, low battery capacity, and limited node resources. We justify that the cross-layer optimization is a promising solution and sometime is critical to enable wireless sensor network applications.**

I. Introduction

A. Issues in Wireless Sensor Networks

With the development of large scale integrated circuits and wireless communication technologies, the application prospective of wireless sensor networks (WSN) by interconnected tiny sensor nodes becomes more and more attractive. However, killer applications that take advantages of these technologies are yet to appear due to unsolved issues.

(*i*) Scalability. Potential application systems of WSN might contain thousands, if not millions, of sensor nodes. The cost of such systems will be unaffordable if the unit price per sensor node is not low enough. The affordability requirement imposes budget constraints on hardware components at each sensor node that directly affect its communication bandwidth, computing/storing capabilities, and availability of specific devices such as GPS receivers. This also brings challenges to protocols' design for WSN so that their implementations can be scalable and simple.

(*ii*) Network lifetime. The long lifetime requirement of applications and the limited capacity of batteries create a wide gap between the node power consumption and the node power supply. Current solutions include: power-aware protocols [3-6], low power hardware design [7], power-saving sleep mode, and transmission range optimization [2][8].

(*iii*) Functionality. In WSN some nodes are expected to take multiple responsibilities of collecting various types of data, processing and fusing data to improve communication efficiency, and relaying data via multi-hop transmission. This multi-responsibility requirement is challenging to the resource-constrained sensor node, let alone that there are above-mentioned issues of scalability and network lifetime.

Summarizing the existing issues and considering currently available technologies, there are challenges to make tradeoffs and optimizations between several pairs of parameters such as the network scale and the system throughput [1], the power consumption and the system lifetime, as well as the implementation simplicity and the system functionality. In this paper, we argue that a new dimension for the optimization, in addition to the existing tuning of individual protocols, which is *cross-layer optimization*, is necessary to be introduced into the research to overcome the challenge.

B. Related Work

In recent years, there are researches using cross-layer design for high efficiency and low cost multi-hop wireless communication systems. These efforts can be roughly classified into four categories according to their optimization goals. First, relaxing power constrains [3][4]. Recently, Min studied the necessity and possibility of taking advantages of cross-layer design to improve the power efficiency in wireless networks. Second, improving system throughput. For example, theoretical analysis and possible approaches have been pointed out in [2] in order to solve the scalability problem. Third, fulfilling QoS requirements [5][8]. Fourth, achieving better resource efficiency [6].

The major methodology of the studies include (*i*) designing application-driven, adaptive and resource-aware layers that can benefit from sharing information across the protocol stacks, e.g., rate-adaptive MAC [5][6], power-aware routing [1][3], resource-aware compression [4] and so on; and (*ii*) coupling adjacent layers such that performance penalties due to layering overhead can be reduced[8].

All these results target only at one or two performance aspects. While the goal of our study is to solve multiple conflicts in order to build feasible and flexible systems.

The paper is organized as follows. In Section II, we clarify and justify the optimization goals at which we will target in this research, and the motivation to take the cross-layer optimization approach to achieve these goals as well. Then we present preliminary results that have been achieved and a brief list of future work in Section III. Finally Section IV concludes the paper.

II. Goals and Motivations

A. Goals

The overall goal of this study is to provide a feasible and flexible means to solve the conflicts between the requirements and the constraints of current wireless sensor networks. It will be a key step to make actual WSN applications into reality. Our research will target three major optimization problems that have been proposed to solve the conflicts for years but still exist as major obstacles.

The first problem or optimization goal is how to support a large scale network [11] while keep feasible per-node throughput from each node to designate data sinks. Gupta and Kumar [1] have shown that in a general wireless network, the available per-node throughput can be estimated by $O(W/N)$, where W stands for the bandwidth between direct neighbors and N

represents the total number of nodes in the network. How to address individual nodes and how to provide QoS services are also related with the problem. Thus our first optimization goal is to find a systematic way to study the relationship among those factors.

The second problem or optimization goal is to fill the gap between the power consumption and the limited power supply. Requirements to solve this problem include: (*i*) improving the power efficiency in the system; and (*ii*) preventing the system deconstruction due to unfair power usage. General approaches to deal with the power problem include: (*i*) using power-aware protocols and working mode decisions to improve the power efficiency; (*ii*) optimizing the transmission range according to the system topologies; and (*iii*) taking the low power hardware design or using more powerful batteries.

The third problem or optimization goal is to improve the versatility with the strictly limited node resources, such as computing power, storage capacity, and interruption availability. By versatility there are two aspects. One is that each node may take the responsibilities of collecting, processing, storing, and sending the real-time sensing data as well as fusing, buffering, analyzing and relaying the passing-by data simultaneously. The other is that a practical application may need to support multiple functional modules that may require various working protocols in a single node during the same time period.

B. Motivations

Multiple reasons have motivated the cross-layer research for the wireless sensor networks.

1) Optimization can be achieved in multiple layers.

As shown in Table I, all three optimization goals we are targeting at can be achieved in all five layers of the system. This fact provides a rationale for the cross-layer optimizations to achieve our research goal.

2) Optimization in one layer may need cooperations of other layers to show its effects.

Cross-layer optimization is necessary because it is possible that different approaches for the same optimization target may counteract each other. For example, if we want to optimize the power usage in a WSN system and we design a power-saving routing protocol. Let's assume the routing protocol will always select among the shortest routes so that they will pass the most densely deployed area. This kind of routes may take advantage of the fact that for the same transmission distance taking more number of smaller-distance hops will save transmission powers compared with a single larger-distance hop. However, data transmission with more hops may have larger contention possibilities. If the MAC layer is not optimized accordingly, the advantages of the routing design may be counteracted by the increasing power consumption due to the increase of contention possibility.

3) There exist conflicts between optimization goals.

Table I shows that some solutions for those three optimization goals are either conflict with each other or orthogonal to each other. This makes all-in-one consolidate design the most promising solution for actual applications. The core idea of such design is to fit every optimization into a complete application context and achieve all possible optimization goals in an integrated way.

4) Some situations do not need supports by all layers.

In those situations, the most efficient way of optimizing the system is to remove those unnecessary layers. A good example for such applications is a multi-hop Local Positioning System (LPS), which is based on hop-by-hop distance measurements and redundant information to estimate the relative distance between any nodes and anchor nodes. The network layer and transport layer that handle the end to end data transmissions will be of no use in this application. It suggests that the composition of the protocol stack to support certain applications can also be optimized by the cross-layer approach.

TABLE I. OPTIMIZING APPROACHES AT EACH LAYER

Layer	Network Scale	System Life-time	Node Versatility
Application	Data fusion, Compression	Power-aware mode control	Load detection, Automatic mode decision
Transport	Bounded Delay	QoS-power tradeoff	Load-aware transport control
Network	Node naming, Efficient routing, Efficient node discovery	Power-aware routing, Reduced overhead	Load-aware routing, Simplified node discovery, Distributed storage
MAC	Contention control, Channel reuse	Synchronized sleep, Transmission range control	Load-aware channel allocation
Physical	Ultra-wide Band	Low-power design, Powerful battery	Attach specific accessories (GPS)

III. PRELIMINARY RESULTS

A. Preliminary Results

1) Protocol design for the optimization framework

a) Routing protocols

Two routing protocols have been proposed for the data collection from sensor nodes to sinks (*self-nominating* [10]) and the task assignment from the sinks to the sensor nodes (*floossiping*).

Self-nominating is a robust and flexible routing framework. It differs from its peers in that the routing decision is made by the receiver rather than the sender. This mechanism improves the system robustness under harsh working conditions. Using the mechanism and various routing decision algorithms, different routing implementations can be composed. Although it out-performs peer routing approaches, the actual gain is found to depend on MAC layer details.

Consider the simplest routing protocol for task distribution such as *flooding*[14], *gossipping* [14], and their limitations, we have proposed a lightweight alternative approach, *floossiping*. In floossiping, several controllable random selected branches as well as a gossiping branch are combined to achieve the optimal power-delay tradeoff. To find the optimal parameter set, information from both upper layers and the lower layers is needed. This suggests the necessity of a cross-layer design.

b) Efficient broadcasting MAC

We have also proposed a broadcasting MAC based on a stand-alone contention reporting channel. In this protocol, each node will report its non-idle status by keep sending ticks in the contention reporting channel. While a node tries to broadcast something, it first listens to both the contention reporting channel and data channel for certain period of time. If either channel is not clear, the node will delay its broadcasting for a well designed period of time; otherwise the node begin to broadcast. After finish the broadcasting, the sender will listen to both channels again to make sure there is no contention happens. The mechanism for the contention detection is each node that gets corrupted data will keep sending tick in the contention reporting channel for a longer enough time after the data channel has been cleared. So after finishing the data broadcasting, if the data channel or the contention reporting channel is not clear, the sender will know that there has been some contention during the just finished broadcasting. It is intuitive that this MAC layer can improve the broadcasting efficiency, however, which is the optimal design parameters depends on the upper layers' implementations.

c) Time synchronization [12]

In order to achieve better performance, time synchronization between nodes is essential to the system. In order to achieve high enough synchronization accuracy with bounded resource consumption, we proposed a light weighted time synchronization protocol called LESSAR. It takes a hieratical approach to reduce the multi-hop complexity. In each level, some specific chosen nodes called adjusters are used instead of all downstream nodes in estimating an average round trip time in the level. Simulation result shows that although the resource consumptions decreased significantly compared with existing approaches, the accuracy achieved by LESSAR is comparable with more complex protocols.

2) Key applications

Several key applications have also been proposed to study the effectiveness of the cross-layer design. (*i*) Local data exchanging system: an example is the multi-hop local positioning system that depends only on data transmissions within direct neighborhood. (*ii*) Global data collecting system: in the global data collecting system, a large amount of data will be collected and relayed to several designate data sinks to achieve certain objective. (*iii*) Sensor network and robots collaborative system: it combines the information collecting and location detecting capability of sensor networks so that the sensor network provides event reporting and navigating functionality for the automatic robots in order to achieve some complex goals such as the automatic examination and defect repairing for large constructions. (*iv*) Sensor network and human collaborative system: the sensor networks can also be interfaced with human. Practical applications may include firefighting assistance in large building, smart battle field, and remote experiment conducting.

B. Future Works

The study will focus on the problem of system throughput, network scalability, time synchronization, smart channel allocation and node mode decisions. In the process of implementing and optimizing applications, we will try to tune the protocols in a cross-layer way to approach the theoretical limitations for each application.

IV. Conclusions

In this paper, we study the application oriented cross-layer protocol design and optimization. The goal is to provide a feasible and flexible approach to solve the conflicts between the requirements of large scale, long life-time, and multiple purpose wireless sensor networks and the constraints of tight bandwidth, low battery capacity, and limited node resources. We justify that the cross-layer optimization is a promising solution and sometime is a must to enable some killer applications of WSN, such as Local Positioning System.

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