A Research Framework Model to Guide Both Broad and Focused Research into Ubiquitous Sensor Networks

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Abstract ***A research framework termed the Four Layer Ubiquitous Sensor Network research (4LUSN) model is proposed in this paper. The 4LUSN model is primarily intended to describe a research framework that organizes the current research conducted by our research team and at the same time provides guiding structure to enable anticipated future research. The model is detailed and subsequently applied in two case studies: a) to describe our current research activities and b) to describe an SCO application. We show that the 4LUSN model is both reasonable and feasible for our purposes; and suggest its desirability for adoption elsewhere.***

Keywords: Sensor networks, Collaborative objects, Research Framework

I. Introduction

Ubiquitous sensor networks (USNs) broadly provide data acquisition anytime, anywhere by anybody. In concept, such sensor networks can be deployed anywhere and everywhere. However, defining a research approach for such a grand vision is made challenging by the particulars of: a) the environment in which the sensors are inserted, b) the many varied technological, design and implementation choices for the sensor network, and c) the demands of the applications for which the sensor networks are targeted to. The complexities of USNs together with potential applications such as Smart Collaborative Objects (SCOs) result in a long-term and wide-scale potential for research developments.

A research framework termed the Four Layer Ubiquitous Sensor Network research (4LUSN) model is proposed in this paper. The 4LUSN model is primarily intended to describe a research framework that organizes the current research conducted by our research team and at the same time provides guiding structure to enable anticipated future research. The model is detailed and subsequently applied in two case studies: a) to describe our current research activities and b) to describe an SCO application. We show that the 4LUSN model is both reasonable and feasible for our purposes; and suggest its desirability for adoption elsewhere.

The rest of this paper is organized as follows. Section II presents the 4LUSN model. Section III describes two case study applications of the proposed model. Conclusions are given in Section IV.

II. Ubiquitous Sensor Network Layered Model

The objectives of the proposed model are to generally support broad research initiatives over a five year time frame relating to sensor network research for SCOs. Specific objectives are:

1) to provide an extensible and flexible research structure that can adapt over time to changing research requirements,
2) to provide a research structure that is directly applicable to autonomic smart collaborative object environments,
3) to support current research efforts of the USN team, and
4) to support future ubiquitous sensor network research directions.

In order to facilitate a general research approach in this area, a four-layered Ubiquitous Sensor Network (4LUSN) model is proposed where each layer captures the required functionality based on lower-layer services to provide higher-layer services. Such

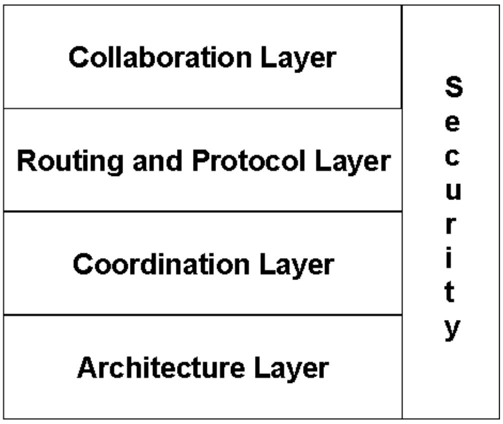

Fig. 1. Four Layer Ubiquitous Sensor Network

a model lends itself to abstraction by parameter definition and functional semantic definitions. In turn, cost and performance models may be subsequently considered to support assessment and evaluation as well as fine tuning the sensor network. The combination of the layered services, abstraction and performance model enable the future research development under the 4LUSN model. We suggest that this approach addresses the needs of ubiquitous sensor networks in general and autonomic smart collaborating objects in particular.

The 4LUSN model is composed of the four layers, lowest to highest: Architecture, Coordination, Routing and Protocol and Collaboration. Security is integrated throughout all of the layers. This model is illustrated in Figure 1. The following sub-sections detail these layers.

A. Architecture Layer

Various types of sensor networks have been described in the literature. Broadly, sensor networks consist of sensor nodes and a communication network. This is a low-level architecture. In order to support general applicability in our research, we consider an approach of abstracting salient features of sensor networks. In particular:

1) Sensor Node Capability Scale: Sensor nodes specifically support data acquisition functions. In addition, sensor nodes may have various processing, memory, power, size, mobility, smartness and communication capabilities. The extent to which sensor nodes in a sensor network support these capabilities defines the Capability Scale. It is a qualitative metric. Low-capable sensor networks provide basic data acquisition and communication; mid-capable sensor networks provide some degree of localized data processing, storage and may be query-enabled, smart-enabled and/or mobility-enabled; high-capable sensor networks provide more sophisticated capabilities.
2) Communication Network Description: Communication networks in sensor networks may be based on wired/wireless, radio/optical or networking/interconnection-networking technologies.
   a) Wired/wireless: Typical sensor networks are wireless based nowadays.
   b) Radio/optical: Typical communication is carried out using radio technologies. However, the use of optical technologies is gaining acceptance as an alternative.
   c) Networking/interconnection-networking: Broadly, networking concerns the communication infrastructure independent of application requirements whereas interconnection-networking concerns a combined communication-application infrastructure. There is much overlap between these two areas.

B. Coordination Layer

Sensor networks consist of multiple sensor nodes, often, organized spatially or by functionality. Dynamic organizations are possible. A typical organization involves clustering where cluster heads are defined as special-function enabled nodes. There are a number of possible collaborations amongst sensor nodes; some of these are:

1) Cluster formation defines the processes associated with selecting, often dynamically, a cluster head and the associate group of sensor nodes within the cluster.
2) Synchronization enables a collection of sensor nodes to function at specific time intervals.
3) Information exchange enables a collection of sensor nodes to acquire non-local data (as for example in a smart object environment).

4) Coordinated deployments and redeployments of sensor nodes enable location placement in an environment.
5) Coordinated distributed computing defines a computational environment where sensor nodes partake in a coordinated distributed application.

The Collaboration Layer is supported by services provided by the Architecture Layer.

C. Routing and Protocol Layer

Once collections of sensor nodes are defined, networking protocols or interconnection network topologies together with switching capabilities can subsequently be defined. And, once such protocols are in-place, various routing algorithms can be designed.

The design of protocols and routing algorithms is dependent both on the coordination achieved in the Coordination Layer as well as on the particular architecture as defined by the Architecture Layer.

D. Collaboration Layer

The highest layer defines collaboration control services. These services provide control over the sensor network in support of specific collaborative higher-level applications. Such control of the sensor network allows the sensor network to be deployed towards specific target applications. This layer forms an upper opened endpoint that middleware and sensor operating systems can hook into. Consequently, some of the components in this layer may overlap with other research initiatives. Specifically, the focus on including a collaboration services layer in the USN model is to emphasize sensor network specific issues that may be too low-level for higher-level functions. This appears to be an emerging research area in the literature. Some collaboration control services are identified here.

1) Query and Filter Services: Data aggregation especially in the context of large amounts of sensor acquired data may be filtered locally or specifically queried by centralized processing nodes.
2) Data Fusion Services: Multiple locally acquired sensor data may need to be combined in some meaningful way.
3) Computation, Communication, Command and Control Services: Some target applications may need to define autonomic responsiveness to environmental or situational change.
4) Orthogonal Organized Finite State Machine representation and associated visualizations: The sensor network and its applications may consist of large numbers of heterogeneous components, each component or groups of components may have different actions and interactions. Understanding of such a systems operational complexity may be facilitated by modeling the system as a special kind of finite state machine together with associated visualizations.
5) Smart Collaborative Objects (SCO): Some target applications may need to define context aware autonomic responsiveness based on the interactions between other smart objects and the environment.

These collaboration control services may be organized into a peer-to-peer organization so that one kind of control service may call upon the functionality of another control service; for example, SCOs could make use of query services to obtain specific information about the environment.

III. APPLICATIONS

Two applications are discussed in this section. In the first, the research of the Ubiquitous Sensor Network research sub-group [1] of the Ubiquitous Computing Laboratory [2] at Kyung Hee University, Korea is re-organized into the 4LUSN model. In the second, we consider the modeling of the Smart-Its platform [3].

A. USN research sub-group of the UCL at Kyung Hee University

1) Current USN Team Structure: The USN Team currently comprises five doctoral students and three faculty as co-advisers [1]. The research is organized into a layered research architecture as shown in Figure 2. Specifically:

- Query Services: Investigate the duplicate and overlapping spatial and attribute information inherent in queries so as to consolidate these queries with the goal of reducing the required overall energy consumption [4], [5].

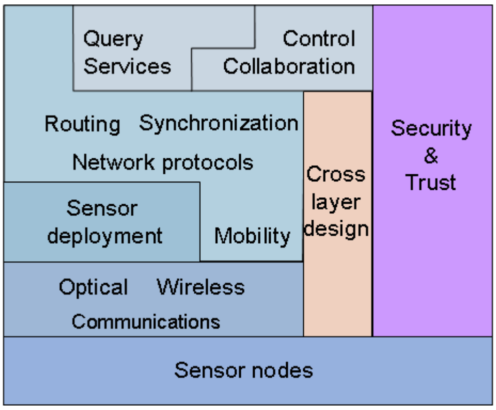

Fig. 2. USN Team Research Architecture

- Control Collaboration: Investigate command and control requirements of as well as mutual coordination between sensors and groups of sensors in the network [6].
- Routing, Synchronization, Network protocols and Mobility: Investigate networking issues in order to support collective communication requirements. Specifically: a. to investigate swarm intelligence routing algorithms [7]–[9], b. to investigate bio-inspired (firefly-inspired) pulse-coupled oscillators for network synchronization [10], c. to investigate mobility management mechanisms that balance network reliability and efficiency [11], and d. to consider other network protocols.
- Sensor Deployment: Investigate algorithms for the deployment and re-deployment of sensors [12]–[16].
- Optical/Wireless Communications: Investigate radio and free space optical communication technologies to exploit advantages derived from the use of these technologies [17].
- Cross-layer Design: Investigate the effect of physical and MAC layer protocols on broadcast and routing [18], [19].
- Security and Trust: Investigate lightweight security trust and privacy protocols for sensor networks [20]–[22].

2) 4LUSN Model and the USN Team Research: There is a direct correspondence between the proposed 4LUSN model and the current USN Team Research. The research descriptions of the previous sub-section are matched to the appropriate layers in the 4LUSN model: this is illustrated in Figure 3.

B. Smart-Its Platform

Smart-Its [3] are small computing devices that are intended to be attached to common objects so as to provide processing, context-awareness and communication capabilities associated with these objects. The objects can be diverse in nature, for example, coffee cups, chest of drawers, notice boards. The potential of Smart-Its lead to its incorporation in embedded sensor systems in ubiquitous computing environments.

The Smart-Its architecture consists of two hardware modules: the communication board for communicating with other Smart-Its or with the backbone services and the sensor board(s) for integrating different sensor functions together. These two modules are interconnected via a data bus and a power bus. Available systems software includes sensor/actuator and communication libraries that include network drivers, context tuple abstractions and low-level operating system functions.

In [23] a dynamic menu application using Smart-Its is described. Briefly, customers order food and drink items (here, wine and cheese). These items together with the associated environment system (here, serving tray and refrigerator) form an order. The application determines when the food and drink items are ready to be served based on checking the quality of the items (here, whether the “wine had not been roughly handled and that the cheese is at its appropriate serving temperature” [23]).

This section identifies the components of Smart-Its and its associated systems individually and together with the dynamic menu application that relate with the proposed 4LUSN model.

1) Architecture: The core units are made up of processing, sensing (i.e. physical environment interaction) and communication capabilities that include short range RF. The network drivers and operating system functions provided by the system libraries also relate to the architecture level of the 4LUSN model. More importantly: “The Smart-Its architecture implies that a hardware/software platform has to integrate physical I/O, a processing environment, and wireless networking. Constraints are imposed by the anticipated unobtrusive embedding of the

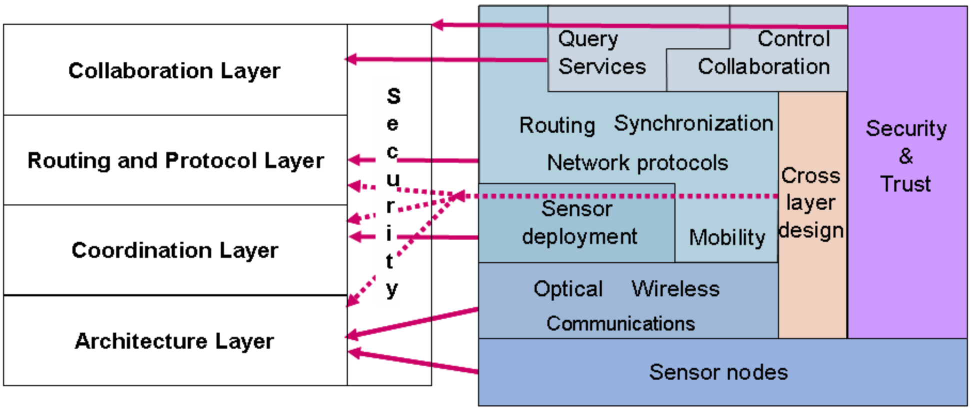

Fig. 3. Current USN Team Research in context of the 4LUSN Model

technology this has implications for physical dimensions and energy management of Smart-Its." [3] This statement relates with the intent of the Sensor Node Capability Scale metric defined in the 4LUSN model; here, Smart-Its appear to be in the mid-capable to high-capable range.

2) Coordination: One of the operations defined in this layer of the 4LUSN model is cluster formation. In the dynamic menu application, a cluster may be formed under two definitions, first, when the customer initially orders the menu items, second, when the menu items are placed on the serving tray. Both involve secondary cluster formation, for example, in the first case, there may be multiple possible menu items that could be 'instanced' for the order whereas in the second case, the refrigerator is added to the cluster. Furthermore, dynamic cluster head formations could be considered, for example, the serving tray could act as the cluster head.

Another of the operations defined in the 4LUSN model is that of information exchange. Clearly, information exchange is necessary in the dynamic menu application. The Smart-Its systems software also provides for this capability.

3) Routing and Protocol: Routing and communication protocols at the low-level are supported by the Smart-Its libraries. However, such protocols emphasize fast network discovery and context exchange. Specifically, a stateless peer-to-peer protocol implementing physical access for the medium coding, data link layer and abstract communication layer is defined.

The dynamic menu application would also need to define higher level routing and protocols necessary to manage and manipulate the services of the coordination layer and to support those of the collaboration layer.

4) Collaboration: This layer is closely tied in with the nature of the applications. Here, the primary service required is that of the Smart Collaborative Objects and the implied requirements of context delivery. The dynamic menu application may also benefit from formalized Query and Filter services as well as Data Fusion services.

IV. Conclusion

A research framework termed the Four Layer Ubiquitous Sensor Network research (4LUSN) model is proposed in this paper. The model is based on a four layer service-oriented design: Architecture, Coordination, Routing and Protocol, and Collaboration layers. Security is integrated throughout the layers. The 4LUSN model is primarily intended to describe a research framework that organizes the current research conducted by our research team and at the same time provides guiding structure to enable anticipated future research. Specifically, these two goals are broken-down into four stated objectives.

We have considered the reasonability and feasibility of the 4LUSN model by applying the model in two case studies. In the first, we show how our research activities over the past several years can be described by the model. In the second, we show that the model can adequately describe a particular SCO project that is described in the literature.

Based on the general way in which the 4LUSN framework model is developed together with the studied case studies: we suggest its desirability for adoption elsewhere.

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