A QoI-Aware Middleware for Task-Oriented Applications in Wireless Sensor Networks

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***Abstract*—We propose a management procedure and a middleware architecture for wireless sensor networks (WSNs) tending to multiple, simultaneously executing sensing tasks with varying quality of information (QoI) requirements. The management procedures are founded on: (a) a *QoI satisfaction index*; (b) a QoI-centric *sensor network capacity*; and (c) an admission negotiation process that uses the above to iteratively reconfigure and optimize usage of the network's resources to accommodate new tasks while respecting the QoI-related constraints of the current ones. The paper highlights the above items, their organization in a middleware layer, and performance results for the admission of sensing tasks.**

I. Introduction

Quality of information (QoI) relates to the ability *to judge* information fit-for-use by applications [1]; for modeling and computational aspects of QoI and VoI (which stands for *value of information*) see [2]. For the purposes of this paper, we assume that QoI is characterized by a number of quality attributes such as accuracy, latency, and spatiotemporal relevancy of the sensor information related to an application's goals. In this research, we are interested in bridging between the operation characteristics of WSN with the quality-related information requirements of tasks. Addressing this problem gives rise to the novel research direction of *QoI-aware* operation and management (O&M) of WSNs.

We approach this problem via a sensor network management middleware layer which is founded upon the following novelties: (a) the *QoI satisfaction index*, which quantifies the degree to which a WSN satisfies the QoI requirements of a task it supports; (b) the QoI-centric *sensor network capacity*, which expresses the ability of a WSN to host a new task (with specific QoI requirements) without sacrificing the QoI of other currently hosted tasks; (c) a negotiation-based task admission process which, when new tasks are to be admitted to the network, uses the aforementioned items to iteratively adjust the network's resources and tasks' QoI levels to maintain desirable and predictable QoI satisfaction for all hosted tasks.

Next, we highlight the key design elements that help achieve optimal O&M for underlying QoI-aware applications

II. Key Design Elements

A. QoI Satisfaction Index

We introduce a QoI satisfaction index as means to describe how the QoI attained during task execution by the WSN compares against QoI desired requested by the task. For each task j, in a set of tasks $\mathcal{J}$ under execution by the WSN, and QoI attribute x (e.g., accuracy, latency, etc.), we define the QoI satisfaction (x-)index by

$$\mathbf{I}_j^x \triangleq \tanh\Big\{k \ln \frac{x_j^a}{x_j^r}\Big\}, \forall j \in \mathcal{J}, \tag{1}$$

where the subscripts a and r denote *attained* and *required* value, respectively, and k is a scaling factor. We also define the per task satisfaction index $\mathbf{I}_j \triangleq \min_x\big(\mathbf{I}_j^x\big)$. Note that $\mathbf{I}_j \in (-1, 1)$, with nonnegative values representing the desirable region of operation; the minimum desirable $\mathbf{I}_j$ is 0, i.e., $x_j^a = x_j^r$ for at least one QoI attribute x, and $x_j^a > x_j^r$ otherwise.

B. Sensor Network Capacity

To support the QoI requirements of tasks, we must be able to assess the QoI capacity of the WSN and relate the utilization of its resources to QoI. Specifically, the *sensor network capacity* corresponds to the maximum number of tasks supported (i.e., with $\mathbf{I}_j \geq 0$) for any combination of sensing tasks with different QoI requirements. It can be interpreted as a time-varying capability beyond which the QoI required by at least one of the sensing tasks can no longer be provided. This capacity can be a scalar or a vector, and analyzed in terms of, say, maximum information accuracy and/or smallest information gathering delay the network can support at any given time.

The sensor network capacity relates to the maximum task-level benefit (or utility) derived by the sensor network. Utility-based management of WSN is a growing area [3], however the need for having prior knowledge of an analytically tractable, closed form utility relationship between QoI vs. network capacity may be too strict as such relationship is too hard to derive and express. Thus, we adopt a black box view of

This research was sponsored by US Army Research laboratory and the UK Ministry of Defence and was accomplished under Agreement Number W911NF-06-3-0001. The views and conclusions contained in this document are those of the authors and should not be interpreted as representing the official policies, either expressed or implied, of the US Army Research Laboratory, the U.S. Government, the UK Ministry of Defense, or the UK Government. The US and UK Governments are authorized to reproduce and distribute reprints for Government purposes notwithstanding any copyright notation hereon.

this relationship and represent it by a mapping $y = f(\mathbf{w})$, for appropriate system and QoI attributes $\mathbf{w}$. This mapping is estimated at runtime by comparing the QoI attained vs. required by the tasks, i.e., using the $\mathbf{I}_j$'s. For example, considering detection tasks with QoI requirement the detection probability α^r, the sensor network capacity relates to the scalar $\overrightarrow{\mathbb{C}}(t) \triangleq \alpha^{\max}(t)$. Then the black box representation at *current time* becomes: $y = f\big(n(0), \alpha(0)\big)$, where $n(0)$ denotes the number of currently executing tasks, and $\alpha(0)$ denotes the worst-case guaranteed detection probability. By smoothly interpolating across the QoI satisfaction indexes experienced by the currently running tasks, we use Taylor expansion to approximate the current excess sensor network capacity as:

$$\overrightarrow{\mathbb{C}}(t) \triangleq \alpha^{\max}(t) = \alpha(0) - \frac{f\big(n(0), \alpha(0)\big) + f'_{n(t)}}{f'_{\alpha(t)}}. \tag{2}$$

For discussion on this approach see [4].

C. Negotiation-based Admission Control for Sensing Tasks

We use the (estimated) knowledge of the current sensor network capacity to manage the admission of newly arriving tasks according to the following rules:

$$\begin{array}{l} \text{Admission, if } \overrightarrow{\mathbb{C}}(t) \succeq \text{QoI requirements,} \\ \text{Negotiation, otherwise,} \end{array} \tag{3}$$

where the notation $\succeq$ denotes the element-by-element comparison. Contrary to typical admission schemes, we opt, whenever possible, first to negotiate with the sensing tasks, new and old, in search of an acceptable (to the sensing tasks) and attainable (by the network) compromise regarding the QoI satisfaction index delivered by the network and consequently manage WSN resources to achieve this. Resource management in this case includes scheduling, rate and power control allocation, sensor selection, integration of data compression, etc.

D. Middleware Architecture

The management of the sensor system is aided by a middleware layer that supports the above operations, see figure 1. Specifically, it deals with: (a) the identification of WSN status in terms of the amount of available resources and achievable QoI level; (b) the negotiation between sensing tasks' QoI requirements and a WSN's resource configurations; and (c) the optimization of a WSN's resource utilization for ongoing sensing tasks to accommodate radio conditions and other resource availabilities.

III. Numerical Results

We have evaluated the performance of our QoI-aware task admission scheme for an intruder detection application [5]. Sensors are deployed for detecting possible intrusions at various regions, with various tasks declaring the region they need to monitor and their required probability of detection (the QoI metric). Through simulations, we have evaluated three cases: (a) simply accept new tasks; (b) perform access control (AC); and (c) perform AC with QoI negotiation. Figure 2 shows the average QoI outage probability, i.e., the probability that tasks attain QoI less than requested, i.e., $\mathbf{I}_j < 0$, at some points during their execution time.

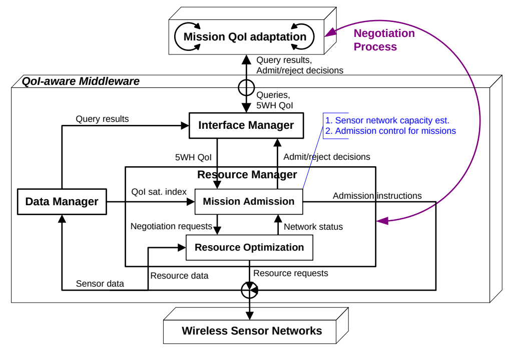

Fig. 1. The QoI-aware middleware architecture for proposed O&M framework.

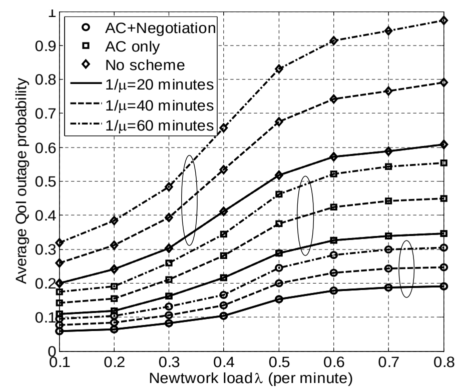

Fig. 2. The average QoI outage probability as a function of the arrival rate λ of new tasks and parameterized on their average duration $1/\mu$.

IV. Conclusions

In this paper, a new approach to QoI-aware O&M design for task-oriented applications in WSNs was proposed. The proposal is built around the novel concepts of QoI satisfaction index, a QoI-centric sensor network capacity, a negotiation-based admission control process, and the optimal resource allocation. A design perspective is employed where the WSN learns at runtime the relationship task QoI satisfaction and network capacity and uses it subsequently to administer admission control of new tasks and QoI-oriented resource allocation. A middleware design and numerical evaluation have also been highlighted. We currently investigate resource allocation techniques to complement the negotiation process.

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