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On optimal resource allocation in virtual sensor networks

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ABSTRACT

Sensor network virtualization is a promising paradigm to move away from highly-customized, application-specific wireless sensor network deployment by opening up to the possibility of dynamically assigning general purpose physical resources to multiple stakeholder applications. In this field, this paper introduces an optimization framework to perform the allocation of physical shared resources of wireless sensor networks to multiple requesting applications. The proposed optimization framework aims to maximize the total number of applications which can share a common physical network, while accounting for the distinguishing characteristics and limitations of the wireless sensor environment (limited storage, limited processing power, limited bandwidth, tight energy consumption requirements). Due to the complexity of the optimization problem, a heuristic algorithm is also proposed. The proposed framework is finally evaluated by simulation considering realistic parameters from actual sensor nodes and deployed applications to provide a detailed performance evaluation and to assess the gain involved in letting multiple applications share a common physical network with respect to one-application, one-network vertical design approaches.

1. Introduction

In the Internet of Things (IoT) vision, the Internet is "pushed down" to everyday objects which are equipped with sensing capabilities to gather information on the environment they are immersed in, processing/storage capabilities to locally filter and store data, and communication peripherals to deliver the collected/processed data remotely either directly, or through multi-hop paths leveraging the cooperation of other smart objects for traffic relaying. In this last case, network of smart objects, often referred to as Wireless Sensor Networks, are set up to collect and deliver data in specific areas. WSNs can be deployed in diverse scenarios and environments to support diverse application/services ranging from smart home or environmental monitoring based on scalar sensed data to more demanding applications based on multimedia sensors.

Usually, WSNs are designed and deployed in a "vertical", application-specific way, in which the hardware and network resources are customized to the specific application requirements. On one hand, such design paradigm allows to have "optimal" performance on the specific application, but, on the other hand, it precludes resources (hardware and software) reuse when other applications and services must be contemplated. In the end, this has led in the past to the proliferation of redundant WSNs deployments [1].

In this context, novel approaches are recently being investigated targeting the smart reuse of general purpose wireless sensor networks to dynamically support multiple applications and services. The key idea behind these approaches, which often go under the names of Virtual Sensor Networks (VSN) [2] or Software Defined Sensor Networks (SDSN) [3], is to decouple the physical infrastructure and resources from application ownerships which leads to more efficient resource utilization, lower cost and increased flexibility and manageability in WSN deployments [4]. Network virtualization technologies are used to abstract away "physical resources" including node processing/storage capabilities, available communication bandwidth and routing protocols, which can then be "composed" at a logical level to support usage by multiple independent users and even by multiple concurrent applications [5]. While network virtualization and software defined networks are already a reality in many communication networks [6,7], research on sensor network virtualization is still in its infancy and comprehensive

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solutions still need to be found to cope with the specific characteristics of WSNs in terms of limited node capabilities and communication bandwidth.

In this work, we focus on the design of a virtualization engine for WSNs. Namely, we consider a general purpose WSN which can be used to support multiple applications and we propose a mathematical programming framework to optimally allocate shared physical resources to the requesting applications. In more details, the proposed framework allocates the physical resources of the general purpose WSN to multiple concurrent applications while accounting for the network- and hardware-specific constraints (processing, storage, available bandwidth, limited communication range) and the specific application requirements. Due to the high computational complexity of the resulting optimization model, a heuristic algorithm is also proposed. Numerical results are then obtained by applying the proposed framework to realistic WSN instances to assess the efficiency of the virtualization process.

The paper is organized as follows: Section 2 overviews the related work in the field of sensor network virtualization. Section 3 describes the proposed system model and the optimization problem for resource allocation in virtual sensor networks, including a complexity analysis of this problem. Section 4 explains the proposed heuristic algorithm. In Section 5, the proposed optimization model and heuristic algorithm are evaluated by simulation for a set of scalar and multimedia applications also with different types of sensor nodes. Finally, some conclusions are provided in Section 6.

2. Related work

The emergence of shared sensor networks has stimulated research efforts in the field of novel programming abstractions at the node level and management framework at the network level to support multiple applications over a shared physical infrastructure [8–11].

At the node level, architectures based on virtual machines are proposed to enable virtualization and re-programmability. As an example, Matè [12], ASVM [13], Melete [14] and VMStar [15] are frameworks for building application-specific virtual machines over constrained sensor platforms.

At the network level, several virtualization management platforms have been introduced. SenSHare [16] creates multiple overlay sensor networks which are “owned” by different applications on top of a shared physical infrastructure. UMADE [17] is an integrated system for allocating and deploying applications in shared sensor networks based on the concept of Quality of Monitoring (QoM). Fok *et al.* [18] introduce middleware abstractions to represent multiple QoM requirements from multiple applications, whereas a service-oriented middleware is presented in [19] to address the challenges faced by running multiple applications onto heterogeneous WSNs. A prototype of Software Defined Wireless Sensor Network is proposed in [20] where a centralized control plane dynamically manages communication routes in the network with the goal of augmenting the energy efficiency.

Generally speaking, the aforementioned work provides “practical” building blocks to build up virtual sensor networks. Differently, we focus in this paper on the “intelligence” to properly allocate physical resources to virtual applications, which can be cast as a general resource allocation problem. Even if radio/network resource allocation is a widely debated topic in the literature, still very few works have appeared on the optimal resource allocation in the field of Virtual or Shared Sensor Networks.

In [21] the authors propose an optimization framework to maximize the Quality of Monitoring (QoM) in shared sensor networks. The proposed framework focuses on environmental monitoring applications whose reference “quality” can be modeled as dependent on the variance in the sensed data, and derives the application-to-sensors assignment which minimizes such variance. The same authors address in a later work the case where the application assignment problem is no longer centralized but rather distributed by resorting to game-theoretic tools [22]. Ajmal *et al.* leverage the concept of QoM and propose an admission control scheme to dynamically “admit” applications to be deployed on physical sensor networks. The authors of [23] focus on the problem of scheduling applications to shared sensor nodes with the ultimate goal of maximizing the sensor network lifetime. Along the same lines, Zeng *et al.* propose in [24] an optimization framework to prolong network lifetime by properly scheduling the tasks in a shared/virtual sensor network.

The problem of allocating physical resources to multiple applications is also often cast as an auction. In [25], the authors propose a reverse combinatorial auction, in which the sensor nodes act as bidders and bid cost values (according to their available resources) for accomplishing the subset of the applications’ tasks. Optimal bidding strategies are then studied to make the auction effective and truthful.

To the authors’ knowledge, this is the first approach to model and analyze the physical resource allocation problem (processing, storage, available bandwidth, limited communication range) for different applications in virtual sensor networks from an optimization point of view. This work extends and completes our previous work [26] with three main additional contributions: (i) we provide a complexity analysis of the proposed optimization problem, which is proven to be NP-complete; (ii) consequently, we introduce a heuristic iterative algorithm to obtain sub-optimal solutions of the resource allocation problem by reducing its complexity. We show in the performance evaluation section that, as the problem size grows, the heuristic algorithm provides results close to the optimum with a much lower computation time; (iii) a more comprehensive performance evaluation analysis of the proposed approach is carried out: in [26] we mainly focus on showing the benefits of virtualization. In this work we analyze thoroughly the impact of varying the main model parameters (number of scalar and multimedia nodes; number of sinks; lifetime; type of routing) in the system performance and we also evaluate the performance of the proposed heuristic algorithm.

3. System model and optimization framework

Table 1 summarizes the notation used through this section. Let $S = \{s_1, s_2, \ldots, s_l\}$ be a set of sensor nodes, $A = \{a_1, a_2, \ldots, a_m\}$ a set of applications which are to be deployed in the reference area, and $T = \{t_1, \ldots, t_n\}$ a set of test points in the reference network scenario. These test points are physical locations where the application's sensing parameter must be measured (e.g., a test point can be a physical location where a temperature monitoring application need to collect a temperature sample). To simplify notation, in the following we will use the subscript index i (or h) to refer to a sensor node s_i (or s_h), the subscript index j to refer to an application a_j and the subscript index k to refer to a test point t_k.

Each application j requires to sense a given set of test points $T_j \subseteq T$. Formally, the application j has to be deployed in a subset of sensor node set S such that all the test points in T_j are sensed. We consider that a test point is covered by a sensor node i if it is within its sensing range, R_i^s. Thus, given a test point, a set of sensor nodes can *cover* it (the test point can be in the sensing range of several nodes), but only one sensor node will *sense* it.

Therefore, it is convenient to introduce as well the set S_{jk} defined as the set of sensor nodes which cover the test point k, with $k \in T_j$. In other words, if the application j is deployed on any of the sensors in set S_{jk}, then the target test point k is sensed for