Computer Networks 74 (2014) 89–108

Contents lists available at ScienceDirect

Computer Networks

journal homepage: www.elsevier.com/locate/comnet

CONFab: Ontology and component based optimization of WSN protocol stacks with deployment feedback

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ARTICLE INFO

Article history:
Received 8 November 2013
Received in revised form 12 July 2014
Accepted 27 August 2014
Available online 16 September 2014

Keywords:
Ontology
Knowledge base
Component based design
Protocol stack composition
Optimization
Deployment feedback

ABSTRACT

Extreme diversity of application requirements and a large number of different available protocols are key characteristics of Wireless Sensor Networks (WSNs). There is a need for a systematic approach to rapidly compose and optimize application specific protocol stacks in an automated fashion. In this article we present the design, implementation and performance evaluation of CONFab, a framework for automatic protocol stack composition founded on the component based optimization approach. We treat a protocol stack as a collection of interdependent configurable components and have a goal to find the most suitable composition of components, as well as optimal parameters selection of individual components in an optimal fashion. CONFab captures a deployment scenario description, relates it to the desired performance metrics, and suggests suitable protocol stacks and parameter settings. It utilizes an ontology centric knowledge base to select components from a pool of alternatives and reason on their compatibility, thus creating appropriate protocol stacks. The framework is equipped with a number of additional plugins that allow, for instance, incorporating feedback from deployed systems and user inputs to anticipate network performance. The plugin mechanism also enables incorporating further advanced optimization routines, such as genetic algorithms, which can be used for optimization of component parameters and efficient exploration of the corresponding state space. We use a set of well-known medium access control and routing protocols to validate the framework on the Indriya testbed in different user specified application and deployment conditions. Our experimental results show that CONFab framework with its component based design is a powerful enabler in obtaining protocol stacks that suit application requirements and thereby achieving high performance characteristics for the network.

1. Introduction

Wireless Sensor Networks (WSNs) and embedded networked systems are deployed for a wide range of applications [1]. Each of these applications has distinct performance objectives and requirements, which must be considered in conjunction with the platform constraints when choosing protocols to be deployed in a network. Due to this diversity of applications, numerous protocols have been proposed for WSNs and embedded networks in general. However, the performance characteristics and interactions of these protocols are often poorly understood, making it difficult for the network operator or field engineer to pick the "best" set of protocols for a given application and deployment scenario. Thus scenario specific

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http://dx.doi.org/10.1016/j.comnet.2014.08.018
1389-1286/

protocol stack composition by exploiting the insights from earlier deployments emerges as the *core design problem* for sensor networks. Moreover, the economic cost and the required human effort should be kept at a minimum by *partial automation* of this task.

In this article we describe the design and implementation of a framework, called CONFab (Ontology and Component based Optimization of WSN Protocol Stacks with Deployment Feedback),[2] that assists and partially automates the task of selecting an appropriate protocol stack for a given WSN application. We follow an optimization driven approach [3,4] to address this problem and take the component based (CB) view on realizing a protocol stack [5,6]. In line with the TinyOS [7] component oriented design philosophy, we view a protocol stack as a collection of interconnected components of various granularities, ranging from simple modules, such as timers and packet sending functionalities to complete protocols or even whole stacks. The key question in our work regarding the component-based design is the granularity of the modules and their abstraction to users. We chose the granularity that we believe is beneficial to users, which are familiar with programming and networking, but are not experts in sensor networking per se. Their goal is to automatically find a viable solution for their application based on the development already done by nesC networking engineers as well as the deployment and testing experience of the respective software of the community as a whole. Each component is associated with both general and deployment specific metrics, which in turn lead to valid interconnections or "wirings[3]" of these components. Additionally, each component might offer reconfiguration options (such as various protocol parameter settings), which influence these metrics. Using suitable level of abstraction we can formalize the task of selecting the best collection of components, their interconnections and parameter settings as an optimization problem, which can be solved using information from the scenario description, past deployment experiences, and expert inputs.[4] The solution of this optimization task yields an abstract stack description, which can then be mapped to a real implementation and deployment. Our approach of dynamic composition of protocol stacks and selection of appropriate parameter settings based on the user specified application criteria is generic. This concept can be applied to a wide variety of networks including Software Defined Networks (SDNs), as well as Internet of Things (IoT). In this article, we validate our approach on WSN for machine assisted generation of optimized protocol stacks for a given application and deployment scenario.

[2] An earlier version of CONFab and preliminary evaluation results were described in [2]. This article presents significant design enhancements for CONFab and new experimental results.

[3] We use the term "wiring" for dynamic composition and connection of components.

[4] CONFab has the capability to learn from earlier deployment results. These results are either collected by CONFab after carrying out a deployment and validation study, or directly fed-in as qualitative summaries which we refer to as "expert inputs". "User inputs" on the other hand refers to the application and deployment criteria based on which CONFab suggests an appropriate protocol stack.

The core of CONFab is a Knowledge Base (KB) that employs ontology and description logic [8] for suggesting an appropriate combination of components. The KB stores information on protocol stack organization, available components, and scenarios in a structured manner, and further reasons on it. The natural advantage of the KB is its ability to capture and operate on descriptions at various levels of granularity, provide mapping and define relationships among different categories and sets of components. For example, this allows users to define high level scenario goals that are subsequently mapped by CONFab to protocol performance metrics, as well as store and represent knowledge gained from prior deployments. CONFab is easily extendible and can be enhanced with further functionalities realized either as plugins to the framework or through additions to the structure of the KB as an extension of its ontology. For example, we introduce a plugin to find commonalities among different protocol stacks to derive a new stack. Furthermore, we demonstrate the optimization of component parameters and efficient exploration of optimization state space using a genetic algorithm based plugin.

We have validated CONFab using well-known Medium Access Control (MAC) and routing protocols on the Indriya testbed [9] with different application and deployment settings. We show that CONFab with its component based approach can assist and partially automate a protocol stack design that leads to improved performance and higher network lifetimes. For instance, we observe up to 37% increase in energy efficiency at a comparable packet delivery ratio for medium sized networks (30–70 nodes) compared to the corresponding contemporary approach of monolithic protocol stack design (cf. Fig. 12(b) and (c)).

The rest of the article is structured as follows. Section 2 reviews the related work. Section 3 describes the design methodology and realization of CONFab, with evaluation results for the framework presented in Section 4. Finally, Section 5 concludes the article.

2. Related work

To the best of our knowledge, there is no other framework for the development of WSN protocol stacks completely analogous to CONFab. However, there is, of course, considerable amount of relevant work on the concepts employed by our framework.

A large number of independent MAC [10] and routing [11] protocols have been proposed during the past years. While performance evaluation of individual protocols have been carried out by designers, one of the dilemmas that practitioners and researchers face is that there is a limited understanding on the behavior of a particular WSN stack given the application requirements and the deployment conditions. Furthermore, since many applications have varying QoS demands over time, a protocol stack is expected to adapt its behavior to the changing application requirements and the environmental conditions. One of the major problems with existing WSN stacks is that they consist of protocols that are often implemented in monolithic style and have arbitrary or even incoherent interfaces, which restricts possibilities for runtime