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Adaptive service provisioning for enhanced energy efficiency and flexibility in wireless sensor networks☆

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ABSTRACT

Energy constraints and high connectivity dynamics render Wireless Sensor Networks (WSNs) difficult to program and use. Software applications must be coordinated not only functionally, as is traditionally done, but also in terms of resource utilization and adaptation to a dynamic environment. This paper presents Adaptive Servilla, a middleware that provides adaptive service provisioning capabilities to coordinate the resources used by WSN applications. It demonstrates how adaptive service provisioning enables WSN applications to be more energy efficient while better able to adapt to the changing availability of network resources. This is achieved through novel service binding strategies that automatically adapt application behavior when opportunities for energy savings surface, and switching providers in response to changes in the network topology. The former is accomplished by providing limited information about a provider's energy efficiency, systematically exploiting opportunities for sharing service invocations, and exploiting the broadcast nature of wireless communication in WSNs. The latter is accomplished by monitoring provider availability, seamlessly switching providers when necessary, and judiciously searching for new providers. Adaptive Servilla was implemented on TinyOS and evaluated using two disparate WSN platforms, the TelosB and Imote2. Empirical results show that adaptive service provisioning enables energy-aware service binding decisions that result in increased energy efficiency and service availability, while imposing minimal additional burden on the application, service, and device developers. Two applications, medical patient monitoring and structural health monitoring, demonstrate the efficacy of Adaptive Servilla.

1. Introduction

Software applications for Wireless Sensor Networks (WSNs) [1] must be coordinated both in terms of the resources they consume and how they adapt to changes in the network. This is due to the limited resources available on typical WSN devices and the high levels of network dynamics [2] that characterize WSNs. Service-Oriented Computing (SOC) [3,4] can facilitate this coordination in an elegant, automated, and application-transparent manner. It divides the software into service consumers and providers that are decoupled through a service discovery and matching process, enabling flexible relationships between the two that can be dynamically adjusted to account for energy efficiency concerns and changes in the network. This paper investigates the use of SOC to coordinate resource utilization and adaptation within WSNs. The resulting

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system, *Adaptive Servilla*, provides a framework for addressing fundamental challenges in developing WSN applications due to resource limitations and network dynamics. This work is distinguished from other SOC systems for WSNs that focus primarily on coordinating applications at the functional level [5–13].

Two adaptation mechanisms are investigated that increase WSN energy efficiency and service availability in an autonomous and application-transparent manner. First, an energy-aware service selection strategy is identified and evaluated. This is important and necessary because multiple providers are often available that consume energy at varying rates meaning provider selection affects an application's energy footprint. To ensure energy efficiency, a limited amount of information about a provider's energy-consumption characteristics is sent to the consumer allowing it to select the provider that will result in the highest energy efficiency. In addition, energy efficiency is further increased by exploiting opportunities for sharing service executions. This is particularly useful when combined with the broadcast nature of wireless communication, which enables the results of a single service execution to be simultaneously delivered to multiple consumers.

Second, an adaptive service selection strategy is introduced that automatically adjusts the connections between service consumers and providers in response to changes in the network topology. This is important because WSNs exhibit high levels of dynamics due to the use of low-power radios, node mobility, and exposure to a dynamic environment [14]. The adaptive service connection scheme enables *application-transparent* adaptation to network topology changes, and thus imposes *no additional burden* on application developers. By using Adaptive Servilla, applications automatically become energy-aware and adaptive to dynamic WSNs. A key challenge addressed in this paper is how the adaptive service selection strategies can hide network topology changes from the applications while still remaining energy efficient.

Contributions of this work also lie in the implementation and evaluation of the aforementioned adaptive coordination strategies. They were implemented within an open-source SOC middleware called Servilla [15] that runs on top of TinyOS [16] and is freely available online,[1] hence the name "Adaptive Servilla." In addition, the system was evaluated on two disparate hardware platforms, the Imote2 [17] and TelosB [18], which exemplify the vast differences in energy efficiencies among WSN nodes and demonstrate the need for energy-aware adaptation mechanisms. The evaluation indicates that Adaptive Servilla does *not* impose undue additional burden on the device, service, and application developers. In addition, two real-world application case studies involving structural health monitoring and medical patient monitoring demonstrate Adaptive Servilla's ability to enhance energy efficiency and enable 100% invocation success rate despite frequent topology changes due to user mobility.

The remainder of this paper is organized as follows. The problem definition is given in Section 2. It is followed by an overview of Servilla in Section 3. Section 4 presents the mechanisms for coordinating application resource utilization. The technique for characterizing a service's energy efficiency is given in Section 5. The implementation is presented in Section 6. An evaluation of Adaptive Servilla in the context of two applications is given in Section 7. Section 8 presents related work. A discussion of various trade-offs and alternative designs of Adaptive Servilla are presented in Section 9. The paper ends with conclusions in Section 10.

2. Problem definition

The two problems addressed in this paper are how to (1) coordinate applications to conserve energy and (2) enable applications to automatically adapt to changing network topologies. Before providing the details of these problems, the system model is described. The target network environment is shown in Fig. 1. It consists of a multi-hop WSN in which there are many types of potentially mobile nodes that vary in terms of energy capacity, computational power, and sensing capabilities. Some nodes, like the Imote2, TelosB, IRIS, LOTUS, and MicaZ, operate on batteries resulting in the need to be highly energy efficient. Others, like the Stargate, are line-powered and not energy constrained. The devices also differ in terms of hardware capabilities. For example, the Imote2 and LOTUS have relatively powerful 32-bit processors and megabytes of memory, whereas the rest have significantly weaker 8 and 16-bit processors and kilobytes of memory. Regardless of these differences, they communicate over the same low-power wireless networking technology like IEEE 802.15.4. Such low power radios are highly susceptible to external interference and thus randomly form, break, and vary in throughput over time. The result is a heterogeneous and dynamic network in which devices differ both in terms of hardware capabilities and energy efficiencies.

The WSN runs a service-oriented architecture (SOA) in which each device may host one or more service consumers and/or providers. Consumers are platform-independent and contain application-specific logic. This simplifies application development since the application need not be tailored to every type of WSN device. Platform-specific functionalities are accessed through services that are exposed by providers. Providers are dynamically discovered, connected to, and invoked by, consumers. A consumer and its providers may reside on the same node or on different nodes. While the WSN is multi-hop and providers may implement services that involve WSN devices spread over multiple hops, Adaptive Servilla currently only supports up to one hop between consumers and providers. When a provider and consumer are connected, the provider is considered "*bound*" to the consumer and the actual connection is called a "*binding*". The binding process consists of informing the consumer of the provider's address. Due to variations in network link quality over time, the set of providers

[1] Servilla's website: http://mobilab.cse.wustl.edu/projects/servilla/.