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Predictive power consumption adaptation for future generation embedded devices powered by energy harvesting sources

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ABSTRACT

The number of small embedded devices is constantly growing and it is expected that there will be 50 billion of Internet connected devices in the 2020. One of the open challenges is the way of powering these devices. At the beginning they were battery powered, but now the energy is usually harvested from the environment and then accumulated. At the same time various adaptation methods have been introduced to manage the power consumption and adaptation appropriately to the energy remaining in the batteries in order to extend battery lifetime. We think that in the future, the next generation of embedded devices will take advantage of the Internet connectivity and accessibility to the weather forecasting models in order to enhance adaptability methods by analyzing the forthcoming harvested power levels. Unfortunately, these devices will use low power and lossy network protocols which may influence the quality of adaptation. In the paper, we propose the concept of the two-stage predictive power adaptation method for embedded devices that uses the weather forecast services and is designed to handle unavailability of network connection.

1. Introduction

Embedded systems play currently an important role in many applications, such as, industrial automation, automotive, domotics and eHealth. It is expected that in 2020 there will be 50 billion of smart embedded devices connected to the Internet allowing them to communicate and share information creating Internet of Things (IOT). Providing power supply for these energy-constrained embedded devices has always been a challenge. They are equipped with various peripheral devices which are responsible for significant amount of the energy consumption [1]. At the beginning, the devices were powered by non-rechargeable electrochemical batteries but more recently, the batteries are being substituted with rechargeable ones or super-capacitors [2]. In that approach, the batteries are recharged from most likely renewable energy sources, for instance by means of energy harvesting, i.e. scavenging energy from any locally available source. Engineers, having in mind that power is limited, introduced various internal adaptation methods to manage the state of connected peripherals that adapt appropriately to the energy remaining in the batteries. All the knowledge necessary for adaptation purposes, i.e. predictions of power consumptions, battery behavior and others, are entirely located in the device.

We think that the new generation of such devices will take advantage of the omnipresent Internet connectivity and will use globally available services i.e. they might utilize the weather forecast services to envisage the amount of energy harvested from renewable sources. We recognize two different realizations of such an adaptation. One method assumes that adaptation of several embedded devices is performed centrally by the service deployed in the cloud. That service would have the state of embedded devices and would only transmit simply control actions to the devices, e.g., switching lights off. The second approach assumes that the device downloads weather forecast and independently calculates the adaptation actions. The advantage of the first approach is that having the appropriate representation of each device in one place, it would enable the possibility to control them as a group. For example, for the citizens it is not important how power is distributed between the lamps if only street is lighted enough to walk safely. Moreover, it can be applied for tiny devices with very scarce computational resources. Unfortunately, the embedded devices usually use low power and lossy networks [3,4] that might result in the connectivity problems which further may lead to the unforeseen situations when the control actions will not be received by the device. On the other hand, in the second approach, when adaptation methods rely entirely on the weather

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forecast and there is no Internet connectivity, the device would not be adapted correctly due to the lack of most updated information.

In this paper we address the second approach and propose the concept of predictive power adaptation that uses the Internet connectivity and handles interruptions in the network availability. Thus the proposed method combines the advantages of internal and cloud-based adaptation approaches. The main idea of the method is to perform a two-stage adaptation. At the first stage, the proposed method uses one of the well-known internal adaptation logic and at the second stage, the behavior of the device is simulated for several time steps ahead using the weather forecast. Analysis of the envisaged device states results in the modification of the adaptation decision. For example, it might be noticed that in the couple of hours there will be no wind and the system will drain the battery off. In such situation the system should preserve some energy by powering off some of its components. Our method uses the high level model of the device power to simulate its future states and the weather forecast data to predict future behavior. The concept has linear computational complexity and thus can be implemented in the applications ranging from tiny sensor devices to the complex Linux based embedded systems.

The paper is organized as follows. The following section introduces the motivating scenario, then the state of the art is presented. The next section presents the concept of the method. The concept is verified by several use cases. The last section contains the conclusions and future work.

2. Motivating scenario

Well-functioning public lighting improves a city's quality of life, but contributes also significantly to its energy consumption and greenhouse gas emissions. The use of renewable energy in public street lighting presents opportunities to reduce energy demand, to harvest financial savings from reduced electricity use and finally to reduce related gas emissions. In the future, street lamps will be equipped with various sensors and detectors such as accident detection systems, video surveillance cameras, and others. This will increase the demand for additional energy, larger solar panels, wind turbines and more capacious batteries to satisfy power demands. Over time, the capacity of the installed batteries will deteriorate; thus, they will not accumulate energy for the weather breaks, so it will be necessary to replace them. To extend the period between maintenance actions, street lamps will be connected to the Internet. As a result, they could download weather forecast and predict the amount of energy that might be harvested and accumulated. On that basis it will decide to reconfigure some of the peripherals and limit their functionalities in order to accumulate the energy during the break in the weather and to adjust to the capacity loss in the batteries over time. The order and priorities of switching off the subsystem will be maintained by the system administrator and it will be possible to change it at runtime, e.g., due to the summer/winter period or public events.

3. Related work

There are a few approaches to providing power supply for energy-constrained embedded devices. In the classical approach, that class of embedded devices is powered with non-rechargeable electrochemical batteries. The devices are typically designed in a way that their power consumption is optimized in static manner, i.e., it does not depend on battery charge level [5]. In particular, the optimization strategies may concern utilization of specialized data transmission protocols [6,7] and controlling radio transmission power [8].

More recently, the non-rechargeable batteries are being substituted with rechargeable ones or super-capacitors [2]. In that approach, the batteries can be charged from renewable energy sources, i.e., scavenging energy from any locally available source. For example, outdoors above ground, sunlight is a good source of energy with high energy density, and good predictability. Wind can be suitable for applications where there is a need for electricity during a night and are high up enough to provide clear air paths. Reviews on many different renewable energy sources for harvesting applications can be found in the literature. Particular papers describe harvesting energy from heat, vibrations [9], raindrops [10], human walk, or even pushing a button [11]. Many renewable energy sources can be described as stochastic, however – in general – they are non-deterministic. This leads to further challenges in providing power to the energy-constrained device that should be able to adapt to ever-changing power conditions [12].

The project DiVA (Dynamic Variability in Complex Adaptive Systems, [13]) focuses on dynamic variability in complex, adaptive systems. Runtime variability [14] offers dynamic reconfiguration capabilities for systems requiring continuous or periodic adaptations. In this way, dynamic built-in system features can trigger runtime reconfigurations to activate and deactivate system features when needed, and these features can adapt system behavior to different scenarios. Examples using runtime reconfiguration and autonomic behavior can be found in smart systems or sensor networks. In most papers, researchers consider reactive-adaptation in which the device changes its feature set or parameters (such as radio transmitting power) in response to a level of accumulated energy and availability of renewable energy [15,16].

Improvements in power efficiency can be made by utilizing proactive adaptation in which the device can predict power supply conditions. This research area was investigated by many researches, e.g. [17,18,2]. However, it should be noted that in the available literature researchers concentrate their attention on *current* and *past* states of environmental conditions which constitute a knowledge for proactive adaptation or reconfiguration steps which should be taken. In that approach each device or a whole system (e.g. a sensor network) tries independently to predict future conditions and then make a decision on how to adapt to them.

In our article we go further by employing numerical weather forecasts, which are freely available as global Internet services, to determine future power supply conditions. This approach has a few advantages over the previously mentioned ones. First, due to the usage of weather forecast service, it offloads the complex computations from the device. Second, the accuracy of modern weather forecast services is far better than much simpler predictions made by an autonomous local systems. This is because (i) such predictive systems work on locally gathered data while commercially available weather forecasts rely on data gathered across a significantly larger area (e.g. a whole continent) and (ii) the weather forecast services use reliable and well-established models (e.g. UM and COAMPS [19]) which require far more computational power than can be achieved in an embedded device. Third, our concept is designed in such a way that handles the Internet connection unavailability. In the next section we present a concept how the weather forecast data might be used for adaptation purposes.

4. Predictive power adaptation for embedded devices

It is envisaged that future generation of embedded devices and sensors will be powered from renewable energy sources. As most of the energy is consumed by the device peripherals, the overall energy consumption of the device might be changed by switching the operation mode of them. Power consumption adaptation for embedded devices is the problem of optimal control which goal