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A task scheduling algorithm based on supercapacitor charge redistribution and energy harvesting for wireless sensor nodes

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ABSTRACT

This paper studies a task scheduling problem for wireless sensor nodes that harvest energy from the ambient environment and use supercapacitors to store the scavenged energy. Power management for supercapacitor-based wireless sensor nodes usually takes into account the supercapacitor self-discharge characteristic. Recently, another supercapacitor characteristic called charge redistribution has also been investigated. This paper considers a task scheduling problem, which is a fundamental power management problem in wireless sensor networks, and develops a modified earliest deadline first (MEDF) algorithm based on supercapacitor charge redistribution and energy harvesting. The MEDF algorithm modifies the earliest deadline first (EDF) algorithm by taking into account the energy constraints of tasks in addition to their timing constraints. The MEDF algorithm is developed and implemented based on a model used to analyze the power flow in wireless sensor nodes. Two metrics are defined to evaluate the MEDF algorithm performance: deadline miss rate for timing performance and energy violation rate for energy performance. The MEDF algorithm is evaluated using both experiments and simulations. Measurement and simulation results show that the MEDF algorithm improves the energy performance of the EDF algorithm while maintaining its timing performance.

1. Introduction

As a critical enabling technology, wireless sensor networks have been developed for many applications. A wireless sensor network consists of a large number of wireless sensor nodes that are spatially distributed over the area of interest. Wireless sensor nodes are usually powered by nonrechargeable batteries with limited capacity and thus energy efficiency is a major concern. To maximize the network lifetime, various energy efficient algorithms [1–6] have been proposed to minimize the energy consumption. In addition to this approach, numerous energy harvesting technologies [7–10] have been developed to further extend the network lifetime. Environmentally powered wireless sensor nodes usually need energy storage systems [11] to buffer the harvested energy. Typical energy storage systems include rechargeable batteries [12,13], supercapacitors [14–16], and hybrid systems [17–19]. In general, rechargeable batteries have a larger capacity and supercapacitors have a much longer cycle life. The major drawback of supercapacitors is their high self-discharge rate.

When considering power management problems for environmentally powered wireless sensor nodes, the available ambient energy must be taken into account in addition to the energy stored in rechargeable batteries or supercapacitors. Instead of minimizing the energy consumption, the power management goal is to achieve energy neutral operation by effectively utilizing the harvested energy [20]. An energy management framework for energy harvesting embedded systems is proposed in [21]. Dynamic voltage and frequency scaling (DVFS) is introduced to improve the system energy efficiency in [22]. Other than these works on wireless sensor nodes employing rechargeable batteries, power management strategies for supercapacitor-based energy storage systems have also been investigated. An energy synchronization framework is developed for a supercapacitor-based system in [14]. A switching policy for a hybrid energy storage system is developed in [17]. Supercapacitor charging and discharging strategy is optimized in [23].

To develop energy efficient power management solutions, supercapacitor characteristics must be taken into account. For instance, supercapacitor self-discharge is considered in [14,17,23]. This is because the supercapacitor terminal voltage is a critical parameter in analyzing the power behavior of supercapacitor-based energy storage systems and self-discharge results in voltage

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drop. Because of the significance of the voltage drop during self-discharge, this characteristic has been extensively examined [24–28].

While supercapacitor self-discharge leads to voltage drop, this characteristic cannot completely characterize the supercapacitor voltage behavior. In fact, the supercapacitor voltage may increase under the open circuit condition [29,30], which is due to the charge redistribution characteristic. Different from the self-discharge process during which the charge carriers undergo side reactions, charge redistribution is the process during which the charge carriers redistribute or relax because of concentration gradients [29,30]. The mechanisms of the supercapacitor voltage change during charge redistribution are studied in [24]. The effects of charge duration and temperature on the supercapacitor voltage decay are examined in [29,30]. A mechanism of the low ionic mobility in supercapacitor micro-pores is identified in [31]. The impact of charge redistribution on power management is investigated in [32]. A detailed analysis of the voltage change during charge redistribution is performed in [33]. The differences between self-discharge and charge redistribution are further examined in [34,35].

To utilize the supercapacitor voltage behavior during charge redistribution, this paper develops a task scheduling algorithm for wireless sensor nodes with energy harvesting capabilities. Task scheduling is a fundamental power management problem in wireless sensor networks. The modified earliest deadline first (MEDF) algorithm is developed for independent and nonpreemptable tasks. This algorithm takes into account the supercapacitor charge redistribution characteristic and the energy harvesting scenario. While the earliest deadline first (EDF) algorithm only considers the timing constraints of tasks, the MEDF algorithm also considers the energy constraints. Therefore, the MEDF algorithm improves the energy performance and maintains the timing performance of the EDF algorithm.

The remaining part of this paper is organized as follows. Section 2 describes a system model for analyzing the power flow in wireless sensor nodes. Section 3 develops the MEDF algorithm. Section 4 illustrates the implementation setup and defines the evaluation metrics. Section 5 demonstrates that the MEDF algorithm improves the EDF algorithm energy performance using an example. Section 6 shows the qualitative and quantitative results to comprehensively evaluate the MEDF algorithm performance. Section 7 concludes this paper.

2. A power model for wireless sensor nodes

2.1. System model

Fig. 1 shows a power model [36–39] for wireless sensor nodes with energy harvesting capabilities. This model is composed of five modules: energy harvester, input power conditioning unit, energy buffer, output power conditioning unit, and energy user. Energy harvesters such as solar cells and piezoelectric films convert energy in other forms to electricity. Typically, an input power conditioning unit is needed to bridge the energy harvester and the energy buffer. For example, a solar powered wireless sensor node usually includes a maximum power point tracker (MPPT). Energy buffers such as rechargeable batteries and supercapacitors are devices that store the harvested energy. An output power conditioning unit is often necessary to generate a suitable power supply for the energy user. DC–DC converters are commonly used modules to bridge the energy buffer and the energy user. Energy users are mainly RF transceivers, microcontrollers, and sensors.

The power model can be further abstracted to facilitate analyzing the power flow in wireless sensor nodes. As shown in Fig. 1, the power model used in this paper has three components: energy source, energy storage, and energy consumer. The energy source includes the energy harvester and the input power conditioning unit. For clarity, the energy buffer is referred to as the energy storage in this three-component model. The energy consumer combines the output power conditioning unit and the energy user. This abstracted model introduces two benefits. First, by separating energy buffers and power conditioning units it is more convenient to study the impact of energy buffer characteristics on power management in wireless sensor nodes. Second, experiments with energy buffers (supercapacitors in this paper) can be readily designed and performed. The effects of input and output power conditioning units are taken into account in the process of designing the experiments.

2.2. Energy source model

The component models are shown in Fig. 2. The energy source is modeled as a current pulse train. As shown in Fig. 2(a), each current pulse is characterized by three parameters: begin time B_S, duration D_S, and weight W_S, which is the current magnitude. It should be noted that the energy source pulse is the conditioned pulse that is actually injected into the energy storage system. For example, in a solar powered sensor node, the current pulse conditioned by the MPPT and fed into the energy storage system is the current pulse described in this energy source model. By tuning these three parameters, energy source profiles with different characteristics such as time span and power level can be generated.

2.3. Energy storage model

The energy storage system is a single supercapacitor in this paper. Fig. 2(b) shows the variable leakage resistance (VLR) model [27,28,32,33] for supercapacitors, which is a simplified equivalent circuit model. In this model, the first branch has three components: resistor R_1, constant capacitor C_0, and voltage-dependent capacitor $K_V * V$. The total capacitance of the first branch is $C_1 = C_0 + K_V * V$. This branch models the voltage dependency of supercapacitor capacitance. The second branch includes resistor R_2 and capacitor C_2. This branch models the charge redistribution behavior. The variable leakage resistor R_3 characterizes the time varying self-discharge.

In addition to the model parameters, the voltages across the capacitors in the VLR model are also critical to determine the supercapacitor state. As discussed in Section 1, the charge stored in a supercapacitor tends to redistribute among RC branches after a charging or discharging process. Charge redistribution is a transient response to the supercapacitor initial state, which is characterized by the initial voltages V_1 and V_2 across the capacitors C_1 and C_2. For example, if $V_1 > V_2$, the supercapacitor terminal voltage decreases with time because part of the charge stored in C_1 is transferred to

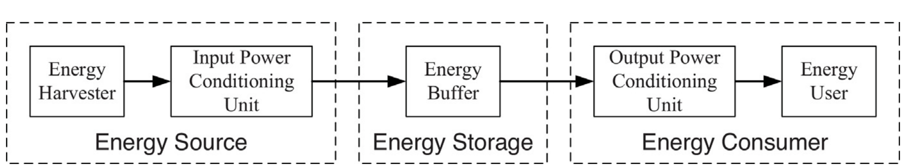

Fig. 1. A power model for wireless sensor nodes.