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Survey on wakeup scheduling for environmentally-powered wireless sensor networks

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ABSTRACT

Advances in energy harvesting technologies and ultra low-power computing and communication devices are enabling the realization of environmentally-powered wireless sensor networks (EPWSNs). Because of limited and dynamic energy supply, EPWSNs are duty-cycled to achieve *energy-neutrality*, a condition where the energy demand does not exceed the energy supply. Duty cycling entails nodes to sleep and wakeup according to a *wakeup scheduling* scheme. In this paper, we survey the various wakeup scheduling schemes, with focus on their suitability for EPWSNs. A classification scheme is proposed to characterize existing wakeup scheduling schemes, with three main categories, namely, *asynchronous*, *synchronous*, and *hybrid*. Each wakeup scheduling scheme is presented and discussed under the appropriate category. The paper concludes with open research issues.

1. Introduction

An environmentally-powered wireless sensor network (EPWSN) is an ad hoc network consisting of sensor nodes powered by energy harvested from the environment. EPWSNs recently gained traction due to breakthroughs in energy harvesting technologies and ultra low-power computing and communication devices [1–4]. One of the major appeals of EPWSNs is its potential to address the problem of limited lifetime which is a major drawback of battery-powered wireless sensor networks. By powering nodes with renewable energy, EPWSNs can operate perpetually without the need for battery replacement which is not only laborious or expensive but also infeasible in certain scenarios.

While energy harvesting can theoretically enable perpetual network operation, it poses a major constraint on energy availability: the amount of energy available for consumption at any given instant can be unpredictable and changes significantly over time [5–7]. Thus, unlike battery-powered WSN where the aim is to minimize energy consumption [8], the key objective in EPWSN is to efficiently and adaptively utilize available energy to optimize the network throughput or end-to-end delay. The new guiding principle in EPWSN is *energy neutral operation*, which means operating nodes in a sustainable manner wherein energy supply and energy demand are balanced [5,6,9,7,10].

To achieve energy neutral operation in the face of unpredictable and dynamic energy availability, adaptive duty cycling algorithms have been proposed [5,6,9,10]. These algorithms aim to dynamically adjust a node's duty cycle given its energy supply, energy buffer capacity as well as current and predicted future harvesting rates. Duty-cycled operation necessitates the use of *wakeup schedules* which indicate the time intervals at which a node activates its radio transceivers to perform either packet transmission or reception. In this paper, we present a survey of the state-of-the-art in wakeup scheduling. Our ultimate aim is to characterize and differentiate the various schemes and determine their suitability for EPWSNs.

The rest of the paper is organized as follows: Section 2 motivates the survey with a presentation of the unique characteristics and challenges of EPWSNs. This section will also introduce the important factors that must be considered in designing wakeup scheduling schemes for EPWSNs. Section 3 presents the fundamental characteristics and properties of wakeup scheduling schemes and most importantly, the classification system that will be used to describe the various schemes. Sections 4–6 contain detailed descriptions and discussions of asynchronous, synchronous, and hybrid scheduling schemes, respectively. Section 7 concludes the paper with a qualitative assessment of their suitability for EPWSNs and open research issues.

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2. Energy harvesting in sensor networks

To set the scene for this survey paper, we present an overview of energy harvesting in wireless sensor networks. We describe the various components needed to assemble an environmentally-powered wireless sensor node (or EPWSN node for short), followed by a discussion of the challenges faced by EPWSNs and the notion of energy-neutrality. We end the section with an enumeration of the important factors that must be considered in the design of wakeup scheduling schemes for EPWSNs.

2.1. Energy harvesting

Energy harvesting, also referred to as "*energy scavenging*" in the literature, is the process of converting ambient energy from the environment into electrical energy to power devices such as sensor nodes and mobile electronics [2]. Fig. 1 shows the various components of an EPWSN node: (i) *energy harvester* for converting ambient energy to electrical energy; (ii) *energy storage* for storing harvested energy; and (iii) *sensor load* which essentially consists of the sensor node electronics (mainboard, microcontroller, radio, sensors and other peripherals). Because ambient energy is readily available, energy harvesting could enable perpetual operation without the need for battery replacement [3,4].

There are numerous sources of ambient energy and they can be grouped into several classes according to their underlying physical process [2]:

- **Mechanical:** from sources such as wind, vibration, mechanical stress and strain and human body movement.
- **Light:** from sunlight or room (artificial) light.
- **Thermal:** waste energy from engines, furnaces, heaters and friction sources.
- **Electromagnetic:** from inductors, coils, transformers and radio frequency sources.
- **Others:** from chemical and biological sources.

The conversion of ambient energy to electrical energy requires the use of an energy harvester or transducer. Table 1 provides a summary of achievable energy harvesting rates of several state-of-the-art energy harvesting technologies [2,4,11,12]. Solar energy, which is one of the most abundant and readily available energy, can be harvested using photo-voltaic (PV) cells which can have 25% efficiency [11]. When such a PV cell is directly exposed to sunlight which has an irradiance of 1000 W/m^2 (this is a typical value of direct solar irradiance [13]), it can potentially generate 250 W/m^2 or 25 mW/cm^2.

2.2. Energy storage technologies

Energy storage or buffer is an important component of an EPWSN node. It serves two important functions [6]: (i) to act as storage for unused or excess harvested energy; and (ii) to act as additional energy supply when load consumption is not met by harvested energy. It is possible to power a sensor node directly from an energy harvester without any energy buffer but its operation will be severely constrained. In particular, such a node can only operate when the amount of harvested power is greater than or equal the required node consumption. When the amount of harvested power is not sufficient, the node will not operate and the harvested power will be wasted. In cases where the amount of harvested power exceeds the node consumption, the excess will likewise be wasted.

Currently, there are two dominant energy storage technologies that can be utilized in EPWSN [1,6,14,10,4,11]: (i) secondary or rechargeable batteries; and (ii) supercapacitors, also known as ultracapacitors or electrochemical double layer capacitors. Although there are many types of rechargeable batteries available in the market, nickel metal hydride (NiMH) and lithium ion (Li-ion) are considered to be more suitable for sensor nodes [14,4].

As far as EPWSN is concerned, the most important characteristics of an energy storage technology are energy storage capacity, number of full recharge cycles, and self-discharge rate or leakage. Table 2 provides a comparison of several energy storage devices in terms of the three characteristics [14]. In general, rechargeable batteries provide high energy capacity while supercapacitors can provide low to moderate energy capacity. In terms of self-discharge rate, Li-ion batteries are slightly better than supercapacitors. One major advantage of supercapacitors is the number of full recharge cycles which is three orders of magnitude higher than that of rechargeable batteries. This has significant impact on the lifetime of the storage device, enabling supercapacitors to last for 10–20 years compared to a maximum of 5 and 3 years for Li-ion and NiMH, respectively [14].

2.3. Challenges

As enumerated by Akyildiz et al. [15], WSNs pose numerous challenges including highly dynamic network topology due to failure-prone nodes and wireless links, limited memory and processing power and most importantly, limited network lifetime due to battery capacity limitations. Energy harvesting has the potential to eliminate the problem of limited network lifetime but it poses a major constraint on the amount and consistency of energy that can be supplied to the sensor node. Unlike a battery-powered WSN node where the energy supply is guaranteed (while its battery is not exhausted), the **energy supply of an EPWSN node can be unpredictable and varies over time** [5–7].

Unsuitability of energy conservation as a design objective. In battery-powered WSN, network protocols are designed to conserve as much energy as possible, knowing that the energy supply is finite and will eventually be depleted. Network lifetime can be maximized by minimizing the energy consumption of individual nodes while at the same time balancing the energy consumption across nodes [8]. In EPWSNs where the energy supply can be replenished, the notion of network lifetime is inappropriate and this renders energy conservation as an unsuitable design objective.

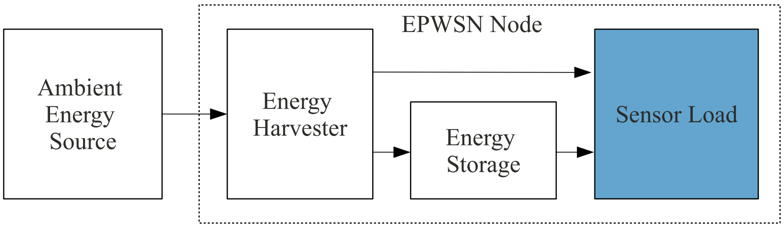

Fig. 1. Components of an EPWSN node.