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Energy-neutral scheduling and forwarding in environmentally-powered wireless sensor networks

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ABSTRACT

In environmentally-powered wireless sensor networks (EPWSNs), low latency wakeup scheduling and packet forwarding is challenging due to dynamic duty cycling, posing time-varying sleep latencies and necessitating the use of dynamic wakeup schedules. We show that the variance of the intervals between receiving wakeup slots affects the expected sleep latency: when the variance of the intervals is low (high), the expected latency is low (high). We therefore propose a novel scheduling scheme that uses the *bit-reversal permutation sequence* (BRPS) – a finite integer sequence that positions receiving wakeup slots as evenly as possible to reduce the expected sleep latency. At the same time, the sequence serves as a compact representation of wakeup schedules thereby reducing storage and communication overhead. But while low latency wakeup schedule can reduce per-hop delay in ideal conditions, it does not necessarily lead to low latency end-to-end paths because wireless link quality also plays a significant role in the performance of packet forwarding. We therefore formulate *expected transmission delay* (ETD), a metric that simultaneously considers sleep latency and wireless link quality. We show that the metric is left-monotonic and left-isotonic, proving that its use in distributed algorithms such as the distributed Bellman–Ford yields consistent, loop-free and optimal paths. We perform extensive simulations using real-world energy harvesting traces to evaluate the performance of the scheduling and forwarding scheme.

1. Introduction

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

But while EPWSN can theoretically enable perpetual network operation, the use of energy harvesting poses a major constraint on energy availability: the amount of energy available for consumption at any given instant is 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 utilize available energy. The new guiding principle in EPWSN is *energy neutral operation*, which consists of two simultaneous goals: (i) optimizing

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the network performance while (ii) ensuring that 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 specify the times at which a node listens for transmissions from its neighbors [11–15].

A major challenge in both static and dynamic duty cycling networks is *sleep latency* which is the delay incurred when a transmitting node must wait for the receiving node to wakeup before it can commence packet transmission [16,14,17]. In battery-powered WSN where duty cycles are static, static wakeup schedules that minimize sleep latency and end-to-end delay can be computed prior to the operation of the network [14,15]. These pre-computed and fixed wakeup schedules cannot provide optimal performance in EPWSN where duty cycles are dynamic and vary from node to node. Essentially, dynamic wakeup scheduling needs to be adopted wherein every node must compute its low latency wakeup schedule according to its instantaneous duty cycle.

In this paper, we introduce an energy neutral scheduling and forwarding scheme for EPWSN that aims to reduce end-to-end delay due to sleep latency while maintaining low computational complexity and low communication and storage overheads. The major contributions of this work are as follows:

- We show analytically that the expected sleep latency of a wakeup schedule is related to the variance of the intervals between receiving wakeup slots. In particular, when the variance of the interval is low (high), the expected latency is low (high). Hence, the ideal scheduling scheme is the one where the receiving wakeup slots are positioned at equal intervals since its variance is 0.
- To reduce the overhead for storing and exchanging schedules, we propose sequence-based scheduling – a compact representation of dynamic wakeup schedules where the receiving wakeup slots can be obtained using an integer sequence. We design a sequence-based scheduling scheme that uses *bit-reversal permutation sequence* (BRPS) and analytically obtain its worst-case sleep latency which is slightly worse than the ideal scheme but better than schemes where the receiving wakeup slots are spaced uniformly or exponentially.
- To enable the selection of low latency and high reliability paths, we formulate a metric called *expected transmission delay* (ETD), which simultaneously considers sleep latency (due to duty cycling), and wireless link quality. We show that the metric is left-monotonic and left-isotonic, proving that its use in distributed algorithms such as the distributed Bellman–Ford will yield consistent, loop-free and optimal paths.
- We evaluate our design in simulations using real energy harvesting traces to verify and compare the performance of the scheduling and forwarding scheme with existing schemes.

The rest of the paper is organized as follows: Section 2 presents a review of related work and challenges in EPWSN while Section 3 discusses the models and assumptions that are used in the development of the proposed scheme. Sections 4 and 5 provide a detailed presentation of the scheduling and forwarding schemes, respectively. The simulation models and parameters are discussed in Section 6 while the simulation results are presented in Section 7. We finally state our conclusions and future work in Section 8.

2. Related work and motivation

Numerous data delivery protocols have been proposed for battery-powered WSN [18]. The key objective of these protocols is to conserve as much energy as possible, knowing that the energy supply is finite and will eventually be depleted [8]. Evidently, this design principle is not suitable for EPWSN where energy supply can be replenished. In this section, we briefly discuss why dynamic duty cycling is needed in EPWSN and the challenges that it poses to wakeup scheduling and packet forwarding.

2.1. Dynamic duty cycling

The new guiding principle in EPWSN is the notion of *energy neutral operation*, which means operating the nodes such that energy supply and energy demand are balanced [5,6,9,7,10]. To achieve energy neutral operation in the face of dynamic energy availability, adaptive duty cycling algorithms have been proposed [5,6,9,10]. Adaptive duty cycling algorithms aim to dynamically adjust a node's duty cycle given its energy supply, energy buffer capacity and current harvesting rate. Some algorithms also consider future harvesting rates, in which case an accurate prediction scheme (e.g. [19,20]) needs to be employed to ensure optimal algorithm performance. Duty cycling itself is not new and has been proposed as an energy conservation method in battery-powered WSN because radio transceivers consume significant amounts of energy even when idle [21,14,22,17,15].

2.2. Wakeup scheduling

In duty cycled operation, a node "sleeps" (powers off its transceiver) and "wakes up" (powers on its transceiver) according to a schedule[1]. A node's wakeup schedule can be generated using either *random* [11–13] or *coordinated* [14,15] scheduling. In the former approach, a node randomly and independently generates its schedule without considering the schedules of other nodes. In the latter approach, a node considers the schedule of the other nodes in the network in the computation of its own schedule such that a performance metric is optimized. Sleep scheduling can either be *locally* or *globally* coordinated. Locally coordinated

[1] Duty cycling can also be applied to other aspects of a sensor node including its sensors. But in this paper, our focus is on duty cycling of radio transceivers which affects network connectivity and consequently packet forwarding.