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Bounded end-to-end delay with Transmission Power Control techniques for rechargeable wireless sensor networks

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ABSTRACT

Due to sporadic availability of energy, a fundamental problem in rechargeable wireless sensor networks is nodes have to adjust their duty cycles continuously. On the other hand, the energy harvested from surrounding environment usually is not enough to power sensor nodes continually. Therefore, the nodes have to operate in a very low duty cycle. These unique characteristics cause packet delivery latency is critical in Rechargeable WSNs. At the same time, energy storage device of a node is always limited. Hence, the node cannot be always beneficial to conserve energy when a network can harvest excessive energy from the environment. In this work, we introduce a scheme by improving transmission power of nodes to bound E2E delay. We provide an algorithm for finding the minimal sleep latency from a node to a sink by increasing minimal h number of nodes whose transmission power improved. For bounding E2E delay from source node to the sink, we propose an E2E delay maintenance solution. Through extensive simulation and experiments, we demonstrate our delay bound maintenance scheme is efficient to provide E2E delay guarantees in rechargeable wireless sensor networks.

1. Introduction

Wireless Sensor Networks (WSNs) are comprised of a large number of low-cost, low-power, small size, and multi-functional sensor nodes with finite battery life that can sense and process data and communicate with each other over a short distance. They are usually deployed in remote or dangerous areas that render servicing impossible or impractical. This means sensor nodes must operate for a long period of time in order to be useful. To this end, in recent years, researchers have paid much attention to WSNs have been a topic of much interest to researchers due to their wide-ranging applications. For example, they have been used in military applications [1], environmental applications [2], health applications [3] and home applications [4], to name a few.

A fundamental problem in WSNs is the limited lifetime of sensor nodes. To this end, a significant amount of work has been carried out across the protocol stack to prolong the lifetime of WSNs. Examples of which include energy-efficient Medium Access Control (MAC) protocols [5], duty-cycling strategies [6], energy efficient routing [7] and topology controlled mechanisms [8]. Other examples can be found in [9,10] and references therein. An interesting approach to extend the lifetime of sensor nodes is to equip them with rechargeable technologies [11], which convert sources such as body heat [12], foot strike [13], and finger strokes [14] into electricity. Assuming energy neutral operation [15], a sensor node can operate perpetually if the harvested energy is used at an appropriate rate. Note, a harvesting node is said to achieve energy-neutral operation if the energy used is always less than the energy harvested, and the desired performance level can be supported in a given harvesting environment.

In these so called energy harvesting or Rechargeable WSNs (R-WSNs), although their lifetime is less of an issue, the available energy on nodes varies dramatically over time owing to the varying environment conditions. For example, a node that relies on the sun will extract more energy on sunny days as compared to when it is cloudy and extract no energy at night at all. For instance, when a node lies in direct sunlight, the energy harvesting rate can reach 15,000 μm/cm^2, while during cloudy days, the energy harvesting rate only reaches 150 μm/cm^2 [16]. Given these characteristics, nodes must regulate their activities accordingly to ensure energy neutral operation.

To regulate energy consumption, nodes adapt their duty cycle according to available energy or application requirements. For example, in burst and high-traffic load scenarios, the duty cycle of nodes can be increased to meet QoS requirements, such as low latency and high reliability [17]. That are node's wake-up more

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frequently to reduce end-to-end delays. The tradeoff here is that a high duty cycle leads to significant energy expenditure. Hence, duty cycles of around 1–10% are typical in order to maximize energy saving and minimize latency [18]. The mechanisms used to adapt the duty cycle of nodes are significantly different to those used in conventional WSNs. Due to environmental factors that lead to sporadic availability of energy, a node must adjust its duty cycle continuously.

Duty cycling leads to high packet delivery latency or sleep delay [5]. Sleep latency is the duration from the moment a packet is ready at the sender to the moment the destined receiver accepts the packet [19]. The key contributor to delay is the fact that if a node wants to communicate with a neighboring node, it has to wait for the corresponding neighbor to wake up. Sleep latency is usually in the order of seconds, which is much longer than other delivery latencies, such as, processing delay, transmission delay, and propagation delay. The End-to-End (E2E) latency is the sum of sleep latencies along the path of data delivery.

In many applications, E2E latency guarantee is required for sink-to-sources and sources-to-sink scenarios. For example, sources will have to actively communicate with the sink in order to inform it of sensed data so that in turn the sink can issue new commands [20,21]. In these operations, an E2E delay bound is usually required. Henceforth, in this paper, we address the delay bound problem. Specifically, we seek to reduce the delay of all E2E paths using the least amount of energy expenditure. In a nutshell, we propose a distributed Transmission Power Control (TPC) algorithm to bound the E2E delay for sink to sources, and sources-to-sink communications in R-WSNs. To the best of our knowledge, this is the first generic work that studies the use of TPC to bound End-to-End delays in R-WSNs.

The remainder of this paper is organized as follows: In Section 2 we present a number of existing E2E latency guarantee solutions, while in Section 3 specify the network model and assumption, Section 4 we present our method and design. Section 5 contains experimental results. Conclusions are presented in Section 6.

2. Related work

Dynamic duty cycle schemes are widely adopted to lower latencies in WSNs. Various protocols for providing delay guarantees have been proposed; e.g., [22–25]. Demand Wakeup MAC (DW-MAC) [18] introduces a low-overhead scheduling algorithm that allows nodes to wake up on demand during the sleep period as traffic loads increases, which allows DW-MAC to achieve low latency delivery. Adaptive Scheduling MAC (AS-MAC) [26] allows nodes to change the length of the awake duration in each operation cycle dynamically and be adaptive to variable traffic load, which enabling AS-MAC to schedule data transmission in the sleep period to reduce E2E delay resiliently. Lu et al. [27] show that E2E delay can be reduced significantly by choosing multiple wake-up slots carefully for each node when given a duty cycle budget in tree and ring topologies. Wang et al. [28] propose DutyCon, a control theory-based dynamic duty cycle controlling approach, which decomposes the end-to-end delay guarantee problem into a set of single-hop delay guarantee problems along each data flow in the network. In DutyCon, the authors control the single-hop delay of each packet to meet the delay requirement by adjusting the receiver's sleep interval dynamically. These schemes encounter critical tradeoffs between network lifetime and data delivery latency. In R-WSNs, the lifetime is not the main problem which can be maximized by operating in an energy neutral mode for nodes.

By considering the dynamical energy supply for sensor nodes, Noh et al. introduces a duty-cycle-based low-latency geographic routing for asynchronous R-WSNs [29]. They propose D-APOLLO, an algorithm that periodically selects an appropriate duty cycle of each node to achieve minimum latency, which base on the currently estimated energy by predicting energy consumption and energy expected from harvesting device. Sun et al. [30] present an algorithm to reduce delivery delay that allows a sensor with packets to be sent dynamically selects a forwarder from a forwarding sequence set, in which potential forwarders are sorted in the order of their wake-up time. Gu et al. [31] introduce a method to increase duty cycle by strategically adding wake-up slots to nodes to reduce end-to-end delay to within a given bound. Gu et al. [32] further to present Energy Synchronized Communication (ESC) to synchronize the harvested energy at an individual node to minimize communication delays by shuffling and adjusting the working schedule of a node under different rates of energy harvest further. However, more energy will be consumed, and collision will be serious in these protocols.

The transmission power determines the range over which a packet can be received correctly. Therefore, Transmission Power Control (TPC) techniques are widely utilized to achieve high link reliability [33,34], high-throughput [35,36], and efficient energy utilization [37,38]. To address these issues, various protocols have been proposed for WSNs. In [33], the transmission power of a node is increased to improve the reliability of a link when it is below a certain threshold. In [35], TPC techniques are used to decrease the amount of collisions during channel contention. By using a higher transmission power, the bandwidth can be increased in the presence of heavy workloads, or decrease to maximize energy-saving [37].

In order to evaluate how the transmission power affects latency and energy consumption in WSNs, Ammari et al. [39] provides an analytical model and shows that the delay decreases in the cost of higher-energy consumption if the transmission power at each node is increased, and vice versa. TPC techniques have to be used seriously to reduce delay because of fixed and limited energy supply in WSNs. However, in R-WSNs, TPC techniques for reducing energy consumption are not always to save energy in R-WSNs which is different to that in WSNs to save energy for a longer network lifetime. In R-WSNs, TPC techniques can utilize the energy sufficiently when a network can harvest excessive energy from the environment since energy storage devices are usually limited.

Different from earlier works, which either focus on static battery-powered network or minimizes delay under energy constraints, in this work, we present a delay maintenance algorithm satisfying E2E delay bound by controlling transmission power of nodes in R-WSNs. In summary, on observing the lack of TPC technique's consideration for bounding communication delay in existing power management protocols, we introduce the first generic delay maintenance algorithm with TPC in R-WSNs. To the best of our knowledge, there was no prior work studying the problem of bounding delays using TPC.

3. System model

Consider a static rechargeable wireless sensor network modeled as an undirected graph $G=(V,A)$, where V is the set of n rechargeable sensor nodes and sink nodes within the network. A is the set of links, $A=\{A|(i,j)\in A,\ i,j\in V\}$. G consists of a finite nonempty vertex set V and edge set A of ordered pairs of distinct vertices of V. At any point of time t, there are two states for any sensor node with duty-cycle: active and dormant. In the active state, a sensor node can generate data after sensing its surrounding environment, transmit the data to its neighbors or receive data from its neighbors. While a sensor node is in the dormant state, it turns off all its modules except for a timer to wake itself up.