# An Empirical Study of Harvesting-Aware Duty Cycling in Sustainable Wireless Sensor Networks

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*Abstract*—**In sustainable wireless sensor networks powered by ambient energy harvesting, node operation highly depends on the energy availability and harvesting rate. For them to support existing wireless sensor network applications, duty-cycling schemes need to adapt the nodes' sleep-wake schedules according to energy harvesting and consumption rates. In this paper, we propose a harvesting-aware duty-cycling scheme, perform an empirical study of this scheme over a solar harvesting powered wireles sensor network in a source-relay-sink configuration, and provide some experimental results to illustrate its throughput performance under various light conditions.**

## I. INTRODUCTION

Wireless sensor networks are increasingly being used in various structural health monitoring, intelligent transportation systems and environmental monitoring applications, both indoors and outdoors. In these applications, nodes are not easily accessible after the initial deployment, and they are required to operate untethered for extended periods of time, with little or no human intervention to reset or replace nodes. Hence, energy harvesting capabilities, which enable sustainable wireless sensor network operation, are becoming increasingly important in such applications.

In traditional battery-powered wireless sensor networks, energy efficiency is usually addressed by maximizing network lifetime. In contrast, the design of practical networking protocols for sustainable wireless sensor nodes needs to take into consideration the energy *availability* under different harvesting conditions, based on which the nodes need to adapt their modes of operation or protocol parameters.

As ambient energy availability may be difficult to predict and harvested power remains much lower than the typical power consumed by wireless sensors, nodes cannot afford to listen to the wireless channel for long periods of time, as that would deplete their remaining energy. Instead, nodes can operate in sleep-wake cycles, conserving energy in the sleep mode while harvesting ambient energy, and waking up intermittently in a harvesting-aware manner to transmit data and maintain network connectivity.

In this paper, we perform an empirical study of harvesting-aware duty-cycling for a two-hop wireless sensor network powered solely by solar energy. By varying the duty cycle of the relay node under different solar energy harvesting conditions, we perform measurement studies of the achievable throughput. The rest of this paper is organized as follows. In Section II, we review related work in duty-cycling MAC protocols for battery-operated and sustainable wireless sensor networks. In Section III, we describe our experiment design and our duty-cycling mechanism for the relay node in our 2-hop configuration. In Section IV, we describe the hardware platform we used, our experiment setup and measurement results. We conclude in Section V with a description of our future work.

## II. RELATED WORK

### A. Duty-Cycle MAC Protocols

MAC protocols for duty-cycling wireless sensor networks have been well-studied in the literature. They may be broadly divided into two categories: *synchronous* and *asynchronous* protocols. Synchronous protocols such as S-MAC [1] make use of synchronized sleep-wake schedules to improve on data delivery rates. However, they incur significant hand-shaking message overhead for schedule synchronization, which may be costly for low duty-cycle wireless sensor networks.

On the other hand, asynchronous protocols such as B-MAC [2] and X-MAC [3] do not need to synchronize their sleep-wake schedules. In B-MAC, a node with data to send first transmits a long preamble. When a neighboring node wakes up, it listens continuously until the end of the preamble to determine if it is the intended recipient. Sender nodes need to send preamble packets for a longer duration than receiving nodes' sleep durations, and receiving nodes need to stay awake until the end of the preamble sequence before starting to receive data packets, thus wasting significant energy on idle waiting, despite both nodes being ready to exchange data. In addition, other overhearing nodes waste energy in staying awake to wait for the end of the preamble sequence, only to find that they are not the intended recipient.

X-MAC improves upon B-MAC, where instead of sending a long continuous preamble sequence, the sender node transmits strobed preamble packets containing the intended receiver's address information, with a small listening period in between preamble packet transmissions. When the receiver wakes up and hears a preamble packet that indicates it is the intended recipient, it sends an early-ACK packet, to request the sender node to immediately begin transmitting the data packet. This saves waiting time on both the sender and receiver nodes, and allows other awake neighboring nodes to go back into sleep-mode. X-MAC was shown to improve energy efficiency and reduce packet latency over B-MAC.

In [4], the authors address the issue of time uncertainty in duty-cycle MAC protocols, which incurs communication overhead in the form of long preambles, guard bands and synchronization packets. They propose a model of long-term clock drift and design an adaptive algorithm, RATS (Rate Adaptive Time Synchronization), that adapts the resynchronization rate to keep the clock drift error within a user-specified bound, and estimates the time uncertainty at any instance. The authors show that their uncertainty-driven scheme managed to significantly reduce overhead incurred by excessively-large preambles in asynchronous protocols and high resynchronization rates in synchronous protocols, thus significantly reducing transmission energy without affecting packet loss rates.

In [5], the authors presented an asynchronous duty cycle Receiver-Initiated MAC (RI-MAC) protocol, in which the receiver node initiates data transmission, so as to minimize the amount of time both the sender and receiver spend occupying the wireless channel. In addition to reducing overhearing, RI-MAC was shown to achieve lower collision probability and recovery cost, thus out-performing X-MAC and B-MAC in achieving higher throughput and packet delivery under light and heavy traffic loads, and with bursty traffic.

### B. Duty-Cycling in Sustainable Wireless Sensor Networks

While all the above-mentioned MAC protocols focus on energy-efficient and low duty-cycle operation to maximize network lifetime, they assume full control of nodes' duty-cycles, with the on-board batteries providing a consistent energy source. This assumption does not hold for energy-harvesting wireless sensor networks, for which network protocols need to be aware of the *availability* of the ambient energy-harvesting conditions and adjust their protocol parameters accordingly, in order to ensure sustainable operation. A variety of transmission and duty-cycling strategies have been proposed for energy harvesting wireless sensor networks, and a detailed survey can be found in [6]. In this section, we highlight some representative approaches.

In [7], the authors used a stochastic model for the energy harvesting process, a linear battery model with a relaxation effect to model the capacity recovery process, and a finite-state Markov chain to model channel fading. A queuing analytical model was developed, based on a multidimensional discrete-time Markov chain, to analyze different sleep-wake strategies, and the model was validated by simulations. A game-theoretic Nash bargaining model was formulated and a direct search on the Pareto-optimal solutions was performed to obtain the optimal sleep-wake strategy, which provides a trade-off between packet dropping and blocking probabilities.

In [8], the authors presented an extensive study of power management in energy harvesting wireless sensor networks by addressing the maximum rate at which energy can be used. *Harvesting theory* was used to formulate analytic models to characterize the energy availability and to align the sensor network workload allocation with different energy availabilities across nodes. This was applied to dynamically adjust duty-cycles to adapt to node energy measurements for periodic and event-driven monitoring applications, to ensure *energy-neutral* operation (*i.e.*, energy consumption would not exceed available supply from energy harvesting and energy buffers.)

In [9], the authors used adaptive control theory to formulate a linear-quadratic optimal tracking problem for maximizing task performance while maintaining minimal duty cycle variations under energy-neutral operation. A gradient-descent approach was used to estimate the coefficients of the linear system dynamics model, which were used by an optimal control law to adapt the duty-cycle to energy harvesting conditions. The proposed approach is model-free and is especially suitable for event-monitoring applications, as a consistent wake-up probability would help to minimize packet delivery latency.

The above-mentioned studies generally make use of actual measurements of environmental energy (e.g., solar) to drive the design of efficient and low duty-cycle protocols, which are then verified via simulations. In contrast, we perform empirical studies on an existing integrated energy-harvesting wireless sensor platform, characterize the achievable performance under different harvesting conditions, and design a harvesting-aware duty-cycling protocol. Thus we provide a more detailed treatment of the practical issues and constraints commonly encountered in protocol implementation on actual devices.

## III. DATA DELIVERY OVER SUSTAINABLE WIRELESS SENSOR NETWORKS

### A. System Model

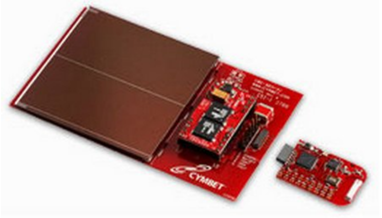

Fig. 1. Texas Instruments eZ430-RF2500-SEH Solar Energy Harvesting Development Kit

In this empirical study, we set up a two-hop sustainable wireless sensor network testbed that comprises a source, a relay, and a sink. The source node senses and delivers sensor data, via the relay, to the sink, which collects data for processing. The sink is always on; the relay and the source are powered by solar energy. We use the Texas Instruments eZ430-RF2500-SEH platform, shown in Figure 1. Each platform consists of a target board with a MSP430 microcontroller, a CC2500 radio transceiver, and a SEH-01-DK solar energy harvesting board.

The output voltage from the solar harvester, $V_{out}$, which can be measured using the Analog-to-Digital Converter pin on the MSP430 chip, can be used to estimate the energy available. The default radio settings provided in the Texas Instruments Sensor Monitor with Solar Energy Harvesting demo application (http://www.ti.com/litv/pdf/sprt506) is used. The transmit power is set to 0dBm, which consumes 21.2mA during signal transmission at 250 kbps. In receive mode, the radio consumes between 15mA to 19 mA, depending on the strength of the input signal.

### *B. Harvesting-aware Duty-Cycling Mechanism*

Duty-cycling mechanisms (c.f., Section II), where nodes follow a sleep/wake cycle, are commonly used for data dissemination in wireless sensor networks. In traditional battery-powered networks, the duty cycle is usually minimized so as to conserve energy. However, this strategy may not be efficient for environmentally-powered networks as excess energy supply may only go to waste due to limited energy buffer capacity and leakage. A better strategy is to maximize the duty cycle subject to energy availability constraints. We therefore design a simple harvesting-aware duty-cycling scheme that dynamically adjusts the sleep time, and hence the duty cycle, based on available energy. We maximize the duty cycle by increasing it when the harvesting rate is higher, and decreasing it when the harvesting rate is lower.

In our proposed scheme, nodes enter a low power mode and wait for energy to become available during the SLEEP phase, and perform sensing and data delivery tasks when they are awake[1].

The state diagram for the relay node is shown in Figure 2. The relay node goes into SLEEP upon startup. While in SLEEP, the radio is switched off and the node checks for available energy by sampling $V_{out}$ once every $t_{check}$; once $V_{out}$ exceeds a threshold $V_{run}$, the node goes into LISTEN. While the node is in LISTEN, the radio is switched on and it listens for incoming packets for time $t_{listen}$. If it does not receive any packets after $t_{listen}$, it goes back to SLEEP. When it receives a data packet from a previous hop, it immediately forwards the packet to the next hop and enters the SLEEP state again.

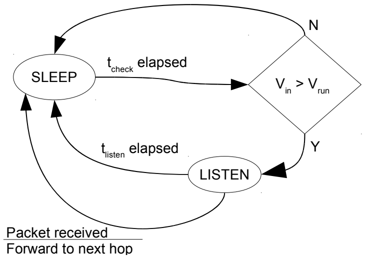

Fig. 2. Relay node state diagram

The source follows a similar cycle, as shown in Figure 3: first it goes into SLEEP, and when enough energy becomes available, it sends a single packet and goes back to SLEEP.

The harvesting-aware duty-cycling mechanism is illustrated by the timing diagram in Figure 4 as well as an oscilloscope trace in Figure 5 obtained by monitoring $V_{out}$. During $t_{sleep}$, the node is in SLEEP state and is periodically checking $V_{out}$. We can see that $V_{out}$ rises during this time; the tiny downward spikes within $t_{sleep}$ indicate the times when the node is sampling $V_{out}$. The interval between successive samples, $t_{check}$, is shown by the time between the spikes. When $V_{out}$ has reached $V_{run}$, there is a drop in voltage indicating that the node is listening for packets.

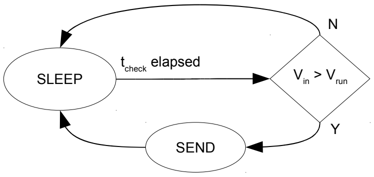

Fig. 3. Source node state diagram

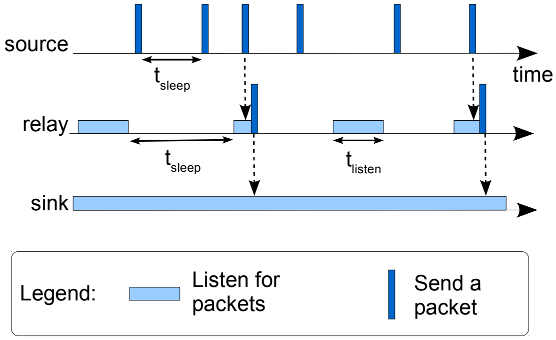

Fig. 4. Protocol timing diagram

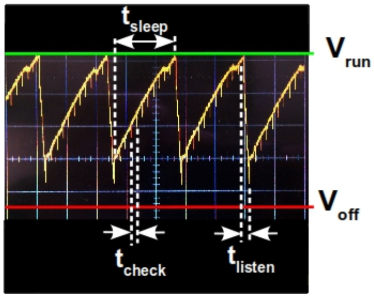

Fig. 5. Node in steady-state with voltage always above $V_{off}$

### *C. Choice of Protocol Parameters*

There are three design parameters for our proposed harvesting-aware duty-cycling protocol: $t_{check}$, $t_{listen}$, and $V_{run}$.

- **Choice of $t_{check}$:**
  When $V_out$ reaches $V_{run}$, the node should wake up as soon as possible. The lag time between $V_{out}$ reaching $V_{run}$ and the node waking up can be minimized by sampling the voltage at an appropriate interval, $t_{check}$. Since sampling consumes some energy, there is a trade-off between

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[1] The MSP430 and CC2500 chips each provide several low-power operating modes to support the SLEEP state in our design. When a node is in SLEEP state, the MSP430 is put into Low Power Mode 3 and the CC2500 into power-down mode, during which the MSP430 consumes 900nA of current and the CC2500 consumes 400nA

sampling at a high frequency, which is wasteful, and sampling too infrequently, which results in a high lag time and increases $t_{sleep}$[2].

- **Choice of $t_{listen}$:**
  The parameter $t_{listen}$ specifies the *maximum* time that the relay stays awake to listen for incoming packets. As illustrated in Figure 4, if the relay receives a packet before $t_{listen}$ has elapsed, it will go to sleep. This simplifies the energy budgeting since we know the maximum energy consumption of the relay for a single cycle: it consumes the most energy when it receives a packet and forwards it just as the node is about to exit the LISTEN state.
  Ideally, $t_{listen}$ should be chosen such that the relay is guaranteed receive a packet from the source every time it wakes up. However the value of $t_{sleep}$ for the source is variable and depends mainly on the harvesting rate. To increase the chances of the relay receiving a packet from the source, we measure the average interval between packets sent by the source at the lowest light conditions. This gives us an approximate worst-case interval between packets. Then $t_{listen}$ is set to be slightly greater than this interval. Thus, the relay can expect to receive a packet from the source whenever it is awake.
- **Choice of $V_{run}$:**
  $V_{run}$ must be high enough to cater for the maximum energy consumption of the node for a single cycle. For the source, this is simply the energy required to send a packet. For the relay, it is the energy required for the LISTEN state and the energy required to send a packet. We note that since source and relay have different maximum energy consumptions, it is possible for the source to have a lower $V_{run}$ than the relay. However for simplicity, we set $V_{run}$ to be the same for both.
  In addition, empirical measurements indicate that when $V_{out}$ falls below a threshold, $V_{off}$, the node will shut down and remain inactive until the target board is manually disconnected from the harvester and the former allowed to re-charge, as illustrated in Figure 6. To avoid this situation, the value of $V_{off}$ is measured experimentally and $V_{run}$ is set such that $V_{out}$ never falls below $V_{off}$.

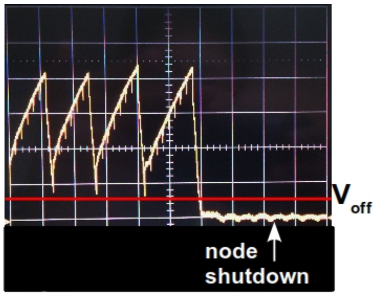

Fig. 6. Node shutting down when voltage drops below $V_{off}$

## IV. EXPERIMENTAL RESULTS

In our experiment, we place the source and relay under a table lamp and vary the illuminance by adjusting their distance from the lamp. A light meter is used to measure illuminance. The source sends 32-byte packets for a duration of 500s. Routing is static and set as source → relay → sink. Nodes are assigned addresses and operate in non-promiscuous mode, discarding packets not addressed to them. We record the throughput at the sink over the experiment period.

We set $t_{check}$ to 20ms and to pick $t_{listen}$, we conduct a simple one-hop experiment where the source sends directly to the sink, at a light intensity of 5000lux. We record the average interval between successive packets received at the sink and find it to be 90ms. Hence we set $t_{listen}$ to 100ms as a worst-case, providing a 10ms buffer to cater for variations in the packet arrival rate.

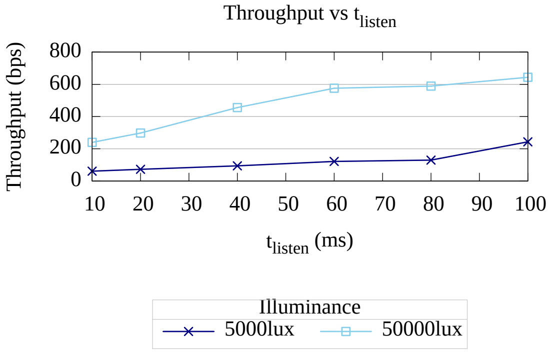

Fig. 7. Throughput vs $t_{listen}$

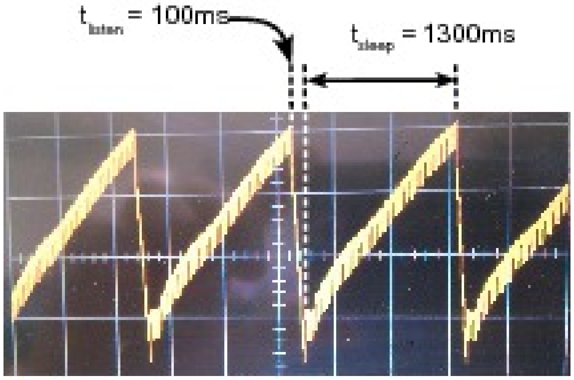

Fig. 8. Relay's voltage level, source turned off

To examine the effect of $t_{listen}$ on the throughput, we vary $t_{listen}$ and measure the throughput at 5000lux and 50000lux. The results are shown in Figure 7. At both values of illuminance, we observe that throughput increases with $t_{listen}$, due to the relay having a higher chance of receiving a packet from the source when it listens for a longer interval. In addition, once a packet is received, the relay goes back to sleep and $t_{sleep}$ of its next cycle is reduced.

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[2] Note that $t_{sleep}$ is not a design parameter; it is a multiple of $t_{check}$ and depends mainly on the energy harvesting rate and is affected, to a small extent, by the value of $t_{check}$.

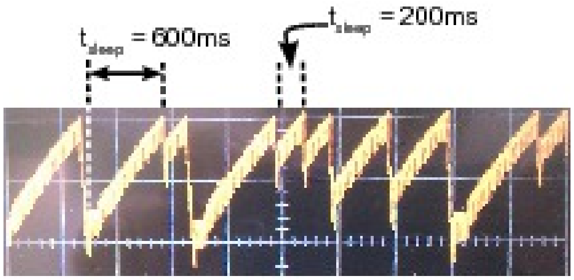

Fig. 9. Relay's voltage level, source turned on

In Figures 8 and 9, we show $V_{out}$ of the relay with the source turned off and on respectively. When the source is turned off, the duty cycle is constant, since the harvesting rate is constant and there are no incoming packets. The relay simply listens for 100ms and goes back to sleep to recover and reach $V_{run}$. This takes about 1300ms. However, when the source is turned on, the duty cycle changes because once the relay receives and forwards a packet, it goes back to sleep. In the worst case, if it does not receive anything after listening for 100ms, it will take 1300ms to recover. If it receives a packet after listening for 40ms, then less energy is consumed and it takes only about 160ms to recover. Hence the protocol is able save energy if packets are received earlier on during the listen period and it is better to have a value of $t_{listen}$ to cater for the worst-case sending interval from the source.

To choose an appropriate value of $V_{run}$, we choose the minimum value of $V_{run}$ so that $V_{out}$ does not go below the cutoff $V_{off}$. To measure $V_{off}$, we charge the capacitors to maximum capacity, disable the energy harvester using one of its jumpers, allowing the node to draw power until it reaches $V_{off}$ and shuts down. This gives us a value of around 1.6V. Next, we find a value of $V_{run}$ that ensures that the nodes will not go below 1.6V in steady-state by setting $V_{run}$ to 3.5V, observing the bottom value using an oscilloscope, and decreasing $V_{run}$ until the bottom value is just above 1.6V. We obtain a value of 3.2V using this method.

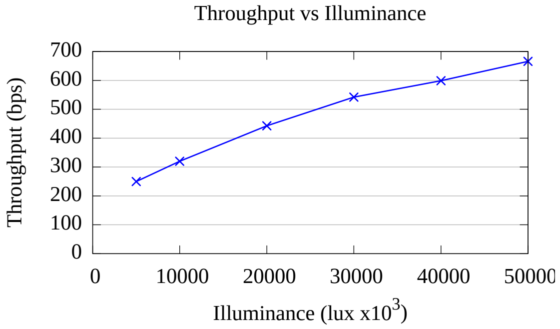

Fig. 10. Throughput vs Illuminance

The results for our experiment are shown in Figure 10. $V_{run}$ is set to 3.2V, $t_{listen}$ is set to 100ms, and $t_{check}$ is set to 20ms. From the results we observe that the throughput increases with illuminance. As illuminance increases, the harvesting rate increases and leads to a higher duty cycle, allowing the relay to wake up more often and increasing the throughput. With a 2-hop network, a throughput of about 660bps can be achieved at 50000lux illuminance.

## V. CONCLUSION

In this paper, we have described the design and implementation of a two-hop source-relay-sink configuration for a wireless sensor network powered solely by solar energy. We introduced a simple harvesting-aware duty cycling scheme which allows nodes to adapt their duty cycles to the harvesting rate of a solar harvester. We also provided experimental results to estimate the throughput that is achievable under various conditions.

As part of future work, we will extend the number of hops and work on a multi-hop data delivery scheme to improve performance over 3 or more hops. We will continue to perform more detailed measurement studies of the energy harvesting process to fit them into analytic models that can be used in transmission strategies, such as [10], to make harvesting-aware decisions on the duty-cycles of energy-harvesting nodes or to change their MAC protocol parameters.

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