Towards a Perpetual Wireless Sensor Node

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***Abstract*—We report our experimental findings on a perpetual wireless sensor node. Our perpetual node is based on the integration of a wireless sensor node that runs IEEE 802.15.4e technology on TI's MSP430 with a solar energy harvesting module that is based on TI's bq25504 modules. We show that by default running the time synchronized channel hopping (TSCH) MAC layer draws more power than the harvester is able to provide. To close that gap, enhancements that improve the power efficiency of TSCH protocol are described and results are presented. The enhancements proposed consist of shared slot suppression, slotframe skipping, and connection setup time reduction. It is shown that even with these enhancements consumed power is still greater than harvested power. We provide future directions on how to further reduce consumed power at the node.**

I. Introduction

Wireless sensor networks are increasingly available in home and industry automation applications for monitoring and control applications. Nodes in these networks are characterized by having limited processing capabilities, computing resources, and energy reserves. These characteristics stem from the nodes being battery powered but still requiring long operation times.

The use of battery-powered wireless sensor nodes eases network deployment. However, inefficiencies associated with medium access control (MAC) protocols as well as battery energy limits, result in these nodes, or their batteries, needing to be replaced more often than initially expected. Thus, network lifetime is greatly impacted. To address this problem, sensor nodes can be powered from harvesting energy in the environment during runtime, from sources such as wind, solar, thermal, vibration, and radio frequency (RF), to name a few[1].

Energy and its relationship to sensor networks is a critical subject and has garnered much interest from the research community. In [2], the authors propose a distributed framework that learns about the energy environment and uses this information in tasks such as load balancing, leader election for clustering techniques and ensures energy-aware communications. Experience with hardware design for ZebraNet has been reported in [3]. The sensor node designed in [3] consists of TI MSP430F149 microcontroller and GPS sensors mounted into collars of zebras. The GPS sensors take location reading and propagate them to the base station. Among the problems pointed out in this research is the high power consumption of GPS processor, selection of a suitable microcontroller, noise and crosstalk, as well as limitations of the energy scavenging approach used. In [4], the authors report analysis, design choices, and tradeoffs involved with the design of an efficient solar harvesting systems. The analysis consider solar cell characteristics, energy storage technologies, harvesting circuit design, hardware selection, and protocol/software implementation. Integration of energy-harvesting leaf nodes and battery-powered sensornet trees has been investigated in [5]. The study shows that leaf nodes that are smaller in size compared to battery-powered sensors, can still harvest enough energy to transmit data every minute, even in poor lighting conditions. However, as pointed out in [5], scaling this platform up to larger networks will take new networking protocols.

Apart from the design choices and experiences given in these papers [2]-[4], as mentioned in [5], implementation of the networking stack for wireless sensor nodes is important. To ensure that the desired quality of service is provided in the network and to increase system efficiency and lifetime, the implementation of different layers, not just the protocol/MAC, is of paramount importance. These protocols have to take into consideration that the wireless sensor network consists of energy-harvesting nodes and this information needs to be shared across all layers: application, routing, MAC, PHY, etc. Studies have been done to improve scheduling for low power wireless sensor networks [6], where the authors propose to use different MAC protocols on the same network based on the conditions and locations of the nodes and the fact that different areas experience different and changing load conditions. An investigation of IEEE 802.15.4e time synchronized channel hoping (TSCH) protocol is reported in [7], where authors also propose a novel scheduling scheme that is based on traffic awareness. Thus, investigations on energy harvesting sensor nodes are using proprietary protocol solutions, while investigations on standardized protocols do not consider energy harvesting sensor nodes. Furthermore, standardized solutions that are based on IEEE 802.15.4e[8], [9] and WirelessHART[10] were not designed with energy harvesting sensor nodes in mind.

In this paper, we investigate the design of a perpetual wireless sensor node, where the power that enables node communications is obtained via a solar power harvester module. The node runs the IEEE 802.15.4e TSCH protocol on the Contiki real time operating system[11]. Contiki is designed for sensor nodes that have limited computational capabilities, limited memory, and limited energy. The sensor node uses Texas Instruments MSP-EXP430F5438[12] hardware platform with the CC2420[13] radio transceiver. The harvester module is based on TI's bq25504[14] solar harvesting power module. We show that enhancements to the TSCH protocol are needed to close the gap between consumed and harvested power. Even then, further optimization are required to realize a perpetual wireless sensor node.

The remainder of the paper is organized as follows. In Section II we describe the system under investigation, where we describe in detail the energy harvesting node as well as TSCH protocol. Evaluation and results obtained using

978-1-4673-4642-9/13/$31.00 ©2013 IEEE

the energy harvested node are shown in Section III and we conclude our findings in Section IV.

II. System Overview

Next, we describe the sensor node module and the TSCH protocol that enables communications.

A. Energy Harvesting Node

The sensor node is depicted in Figure 1, while the connections between modules is shown in Figure 2. The MSP-EXP430F5438 experimenter board is an evaluation board for the MSP430F5438A family of microcontrollers [12]. The board provides many peripherals that can connect to a number of external components that enable various functions. Connection to the CC2420 radio is done using the CC-EM headers, which is simply an SPI interface to CC-EM modules. The CC2420 radio is compliant with IEEE 802.15.4/ZigBee.

Fig. 1. Energy harvesting wireless sensor node that uses an MSP430 and solar energy harvester module based on the bq25504.

TI's bq25504 is a highly efficient boost converter that is targeted towards wireless sensor network nodes that have stringent power requirements [14]. The way it operates is that it extracts power from low voltage harvesters and stores it in some type of energy storage element. The storage elements can be either a re-chargeable battery, super capacitor, or a conventional capacitor. The board also indicates to the attached microprocessor when the voltage in the storage element reaches a desired level or has dropped below a pre-set critical level. Since the system load has large transients, using a large buffer capacitor along with a battery can help with brief current surge needs.

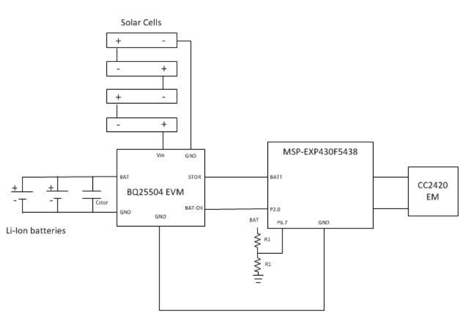

Fig. 2. Circuit diagram for the perpetual sensor node. Note the capacitor in parallel with the Li-ion batteries to handle sharp changes in load current.

The solar cells are IXYS SLMD121H04 cells based on monocrystalline silicon technology [15]. Their efficiency is about 22% and it is suitable for charging various battery powered and handheld devices. Its power peak is 89.2 mW at 2.0 V. Eight of these solar cells are connected in our energy harvesting (EH) sensor node. Figure 3 shows the irradiance levels in log-linear scale over a week period in different offices [5]. While the irradiance level is sufficient during the day to collect enough energy to power wireless communication, at night virtually nothing is collected. We use a rechargeable battery to store energy and using it during the time that the energy harvested from ambient light is not sufficient for communications.

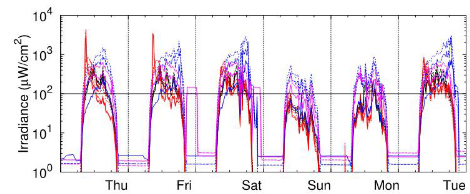

Fig. 3. Irradiance over a typical week in four offices according to [5].

The batteries used for the sensor node are Panasonic MLI220 lithium-ion rechargeable batteries which have a nominal voltage of 3 V and 17 mAh capacity[16]. To ensure at least a day of normal operation for the energy harvesting node, two of these batteries are used. The number of batteries required to power the node for one day was found experimentally with the node transmitting at one message per minute.

B. IEEE 802.15.4e: Time Synchronized Channel Hopping

TSCH is one of the MAC features proposed in IEEE 802.15.4e[8] and mostly based on WirelessHART[10]. The way it operates is illustrated in Figure 4.

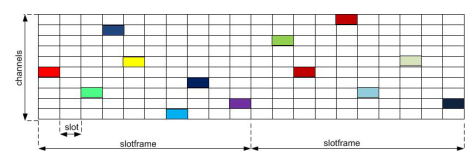

Fig. 4. Time synchronized channel hopping illustration.

Time is divided in slotframes, and slotframes are split into slots of length 10 ms. All of the nodes in the network are synchronized to the slotframes. In the case that the wireless sensor network has a coordinator, the coordinator sends periodic beacons and schedules transmission among nodes. Beacons are used for synchronization and conveying information about beacon slots, shared slots where all nodes can compete for transmissions, and dedicated slots where pairs of nodes can communicate directly without interference. To actively participate in the network, nodes need to be awake to receive beacon frames, listen during shared slots if there is any transmission dedicated for them, and during the dedicated slots either for transmission or reception of data frames. At all other dedicated slots, the nodes can be asleep and save energy. Also, to improve reliability and defend against external interference, TSCH uses multiple channels for communication and changes channels following a predetermined schedule.

While TSCH is an improvement compared to legacy IEEE 802.15.4 MAC protocol[17], it is still power inefficient since the nodes still need to receive beacons and also listen during shared slot times. As we show in the next sections, this greatly impacts the power consumption at the nodes.

III. Evaluation and Results

Figure 5 shows the network under investigation. It consists of a coordinator node, two intermediate nodes and an EH sensor node. The coordinator node sends the beacon frames and schedules transmissions among the nodes. Intermediate nodes also send beacon frames, however, they forward all scheduling requests to the coordinator. When a node, for instance the EH node in this scenario, wants to join the network it listens to the beacon frames (from the intermediate node) to learn about the shared slots as well as the slotframes and timing alignment. During a shared slot, the joining node sends an association request to its intermediate node, which in turn forwards it to the coordinator node. The coordinator then sends an association response that contains information on the dedicated links between the EH node and its intermediate node. Thus, a dedicated link is established between the EH node and its intermediate node for data transmission.

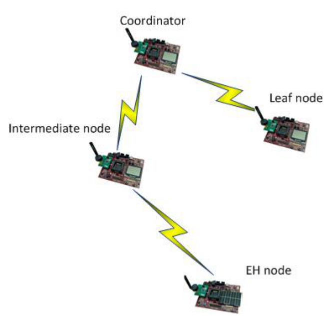

Fig. 5. Investigated network diagram. The coordinator and intermediate nodes both send beacons, allowing the leaf and energy-harvesting nodes to connect to either node.

Figure 6 shows the average power for the node when running the default TSCH protocol, average harvested power for low light environment, and average harvested power when better illuminating lights are used. The EH node has an average power draw of 395 μW when operating, and given a maximum harvested power of 88 μW (for high light power), enhancements to the TSCH protocol are required to swing the balance towards harvested power. One potential solution would be to increase the size of the solar cells; however, that makes the EH node size not attractive.

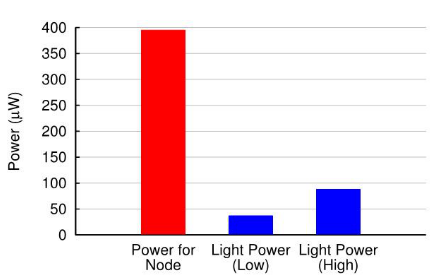

Fig. 6. Average node power and harvested power.

Another approach would be to look at protocol optimizations. While the TSCH protocol was designed for low power sensor nodes, further enhancements are required to make the protocol energy harvester friendly. One of the problems with TSCH protocol can be observed in Figure 7. It shows the time taken by the EH sensor node from when it initially boots to when it hears a beacon. As one can see, the time required to receive a beacon can regularly be about 40 s or more. These beacon reception times were determined with the radio on continuously. Given that radio in receive (Rx) mode operates at about 20 mA, that is a large amount of power consumed just on connection setup compared to the data communications and synchronization maintenance portion. The large value to receive a beacon is due to the fact that beacons are not sent at fixed channels and there are 16 channels available in 2.4 GHz Industrial, Scientific, and Medical (ISM) band at which the beacon can be sent.

One method we implemented to try to mitigate this high startup cost is to select a fixed number of channels for beacon transmissions. In our experimental measurements the maximum connection setup time was reduced from more than 120 seconds to below 10 seconds when a limited number of beacon channels were used.

Once connected, a typical leaf node in TSCH must periodically wake up to receive future beacons, check for broadcast transmissions in shared slots and check for unicast transmissions in dedicated slots. The radio wakeups, and the required radio guard times for these slots is another significant drain on an EH node's energy reserves. To reduce these effects we proposed and tested a mechanism which allows the EH node to skip beacon slots, shared slots, or entire slotframes. The extend to which the EH can skip wakeups depends on node's application and real time clock capabilities.

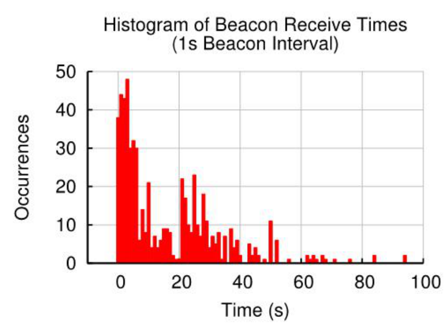

Fig. 7. Beacon receive times histogram.

Figure 8 shows the improvement in terms of radio and CPU duty cycles as we add different enhancements to the node. There are a few optimizations options that are shown in this figure.

- Fixed beacon channels: instead of searching for a beacon over 16 channels, we limit the number of beacon channels to 3 known channels.
- Shared slot suppression: the EH node decides to skip listening to shared slots when it has no data to transmit.
- Slotframe skipping: the EH node is asleep during entire slotframes when it has no data to transmit.
- Sampled scan: during scan, the EH node chooses to scan for a particular interval as opposed to the whole time till it receives a beacon.

As the number of beacon channels are fixed, the duty cycle for both CPU and radio reduces; however, the reduction is minimal. This is because although the startup cost is significantly reduced, when averaged over a long runtime of the network the average savings is minimal. When slotframes are suppressed (i.e., the node is not awake for every slotframe), the CPU and radio duty cycles reduce from about 2.7% for both to 0.75% and 0.35%, respectively. This is due to the fact that the node is awake for fewer slotframes, hence the reduction in duty cycle. The impact of additional slot skipping of shared slots is minimal, since slotframe suppression is larger in terms of time units. The same can be said for sampled scan enhancements, where the node chooses to scan for 100 ms and sleep for 100 ms during connection setup. Note that, although sampled scan does not reduce the duty cycles significantly, it has profound effect on the energy harvester node when beacon channels are not fixed. This is due to the fact that having the radio on for long duration of time (e.g., longer than 120 seconds) depletes a significant portion of the energy reserves while allowing virtually no recharging to occur.

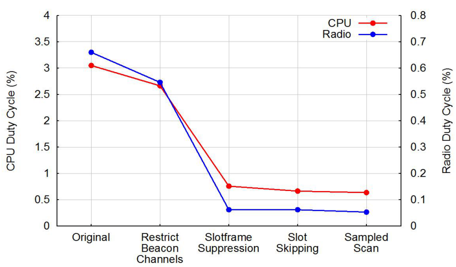

Fig. 8. Radio and CPU duty cycles with enhancements.

Even though the average power of the EH sensor node using these enhancements is reduced by a factor of more than 6, the power harvested for low light environment is still lower than the power required for the node to start (i.e., establish a connection setup). Thus, the harvested power is not adequate for the power required for the node in steady state (see Figure 9). To further reduce the power of the node required in steady state, the following approaches can be investigated:

- Microcontroller sleep power - the use of microcontroller that uses lower sleep power current can increase EH sensor node lifetime and reduce its power consumption. This is the case for applications that require infrequent data transmissions.
- Reducing software stack size for EH node - since the node is a leaf node and does not forward packets to other nodes, then, a lighter version of the software stack can be used.
- Radio Tx/Rx power - reduction of Tx/Rx power can further reduce power required for connection setup and can lower the average consumed power. The impact is higher for applications that require more frequent data transmissions.

Our next step is to investigate the power consumed by the EH sensor node with lower sleep power microcontroller.

IV. Conclusions

In this paper, we showed the design and reported experimental findings on the perpetual wireless sensor node. Findings indicate that harvested energy from the solar panels is not

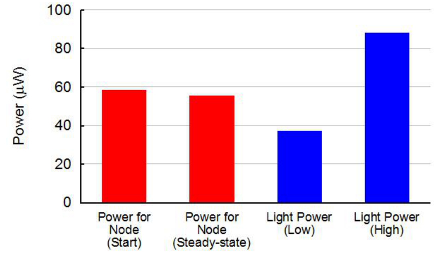

Fig. 9. Average node power for start and steady-state as well as harvested power.

sufficient to realize the perpetual sensor node. Optimizations implemented to make TSCH protocol more power efficient still could not bridge the gap between the consumed power and the harvested one. Further enhancements are required in radio design to lower the consumed power from the perpetual wireless sensor node.

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