Tempo: an Energy Harvesting Mote Resilient to Power Outages

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***Abstract*—We present the design of the Tempo mote that operates on ambient energy harvested from the environment. Equipped with a ultra low-power timing module that acquires Coordinated Universal Time (UTC) information from a long-range radio transmitter, Tempo can persistently access the global time and is thereby resilient to power outages. A prototype implementation of the Tempo mote shows that it achieves millisecond level accuracy at 100 μA current draw. We argue that one can more generally leverage the access to global time across all nodes of a wireless sensor network to overcome the challenges related to the very tight energy budget that is inherent with harvesting ambient energy.**

I. Introduction

Recent efforts have demonstrated the feasibility of powering wireless sensor network (WSN) nodes through energy harvesting [1–3]. The importance of harvesting energy from the environment rises with the size and the duration of WSN deployments, as the monetary and environmental cost of using batteries increases. At the same time, nodes that operate using ambient energy have to confront with the non-deterministic and time-varying availability of energy. In response, previous attempts [1] have focused on using larger solar panels and energy containers that are inherently bulky and expensive, and the goal is to avoid the complete depletion of the energy container, in which case the mote will remain powered off until enough energy is collected.

In this work, we present the design of the Tempo mote, which utilizes a new and inexpensive generation of energy harvesting devices [4]. These new modules come with their own set of challenges: limited ability to produce and store energy. Given the limited energy reserves, it is likely that a mote will experience multiple power outages during its lifetime, and the mote will lose its time state after waking up from each outage. Therefore, we build a low-power timing module that is resilient to power outages, to recover the time state after each outage. Alternatives such as GPS, RTC and FTSP-like protocols [5] are not feasible due to the aforementioned energy constraints and power outages. Also, RTC exhibits cumulative timing errors due to frequency drifts.

While important, recovering time state is only one step in confronting the challenges of limited and unpredictable energy reserves. Others include rethinking low-power network protocols and sensor sampling strategies.

II. Architecture

While low-power disconnected operation is relatively easy to achieve, addressing corruption of time state due to clock drifts and power outages is much more challenging; if not impossible without some sort of communication. For example, a GPS receiver can extract very accurate time and location information from satellite signals, but its prohibitively high energy consumption and high cost renders it impractical within the tight budget of energy harvesting sensor nodes. Fortunately, there exist other time signals that allow the corresponding receiver modules to combine low power with low cost. One such time signal is transmitted from the WWVB radio station located in Colorado that covers North America [6]. The time information encoded in the WWVB signal is derived from a set of atomic clocks and each one-minute frame of WWVB encodes the UTC time and therefore the reception of a frame suffices to extract the global time. Similar to GPS, WWVB is generally available outdoors, while we experimentally found that it is also available in some indoor environments. Low-power and low cost ($\sim$\$2) receiver chips that can decode the WWVB signal became recently available [7].

A. Timing module

We designed and built a timing module that utilizes the low-power CME6005 [7] chip to receive the WWVB signal and extract the WWVB bits. The extracted WWVB bits flow into a PIC16LF1827 micro controller. The PIC checks the timing and validity of the bits, decodes the global UTC time, and outputs the UTC time information as an NMEA (National Marine Electronics Association 0183) date and time message through a UART interface at 9600 baud rate.

The CME6005 consumes less than 100 μA, while the PIC consumes 800 μA at 4 MHz and only 600 nA at 32 kHz. Fortunately, due to the ultra-low bit rate of the WWVB signal ($\sim$1 bps), the PIC needs to operate at 4 MHz only when a bit arrives, and can safely switch to 32 kHz after the calculation is done. Given this PIC duty cycle, the overall average current draw of our timing module is less than 100 μA. Note that after decoding one frame, the global UTC time is available and therefore the timing module can be safely powered off. We deployed nine such timing modules in an outdoor environmental monitoring site for over one week. Approximately 80% of the broadcasted WWVB frames were

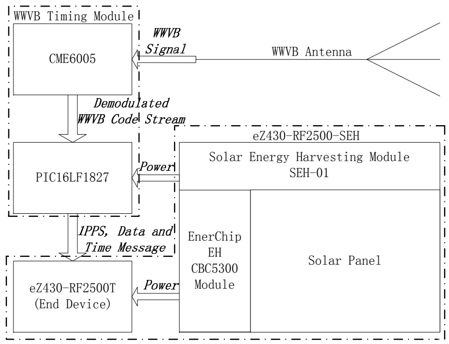

Fig. 1. Architecture of the Tempo mote.

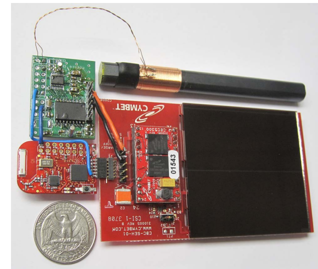

Fig. 2. The Tempo mote. The green board (located at the top left corner) is the timing module. The other two red boards and the solar panel comprise the Solar Energy Harvester module.

successfully decoded and the resultant timing accuracy was in the order of one millisecond.

B. Tempo Mote

The design of the Tempo mote relies heavily upon the robust low-power timing module. This module provides consistent access to accurate global time and thus greatly simplifies the recovery process from a power outage. For example, an essential activity of an environmental monitoring node is to collect and timestamp scientific data. Without the timing module, each node would rely on its local clock to timestamp the measurements. These timestamps are translated to the global timebase using a time reconstruction protocol. Running this protocol requires the network be connected, which is likely to be violated if neighboring nodes also happen to be in the middle of a power outage. Moreover, the translation needs to happen before the start of the next power outage, otherwise the measurements collected between the two outages will not have valid global timestamps and will therefore be unusable.

The traditional approach in designing solar harvesting motes advocates for using large solar panels and rechargeable batteries to prevent or minimize the frequency of outages. On the other hand, the ability of the timing module to efficiently recover access to global time reduces the impact of power outages and allows us to select energy harvesting components more aggressively for the Tempo mote.

The prototype Tempo mote uses an off-the-shelf eZ430-RF2500-SEH Solar Energy Harvester (SEH) from TI to demonstrate the feasibility of building an efficient yet robust energy harvesting mote for various environments [4]. The solar panel has a small footprint (2.25 in $\times$ 2.25 in) and can output 350μW (100μA at 3.5v) with ample indoor lighting (1000 lux). Figure 1 details the architecture of the Tempo mote. The timing module and the SEH are the two major components. Figure 2 shows the footprint of the Tempo mote.

The SEH is equipped with a CC2500 2.4 GHz transceiver that draws up to 20 mA (RX mode) or 22 mA (TX mode), which is far higher than the maximum output current from the solar panel. To accommodate this high current, the SEH incorporates two thin-film batteries with a total capacity of 100 μAh and a 1 mF capacitor. The batteries charge the capacitor and the capacitor delivers the high amplitude pulse current for radio activities. When discharged at 30 mA, the capacitor can last for 20 ms, which is enough for the transmission of only a few radio messages. The extreme scarcity of available energy also means that running a time synchronization protocol is not a viable option. Using the state-of-the-art FTSP protocol [5] as an example, when running on top of low-power-listening (LPL) with a probe interval of one second, a node needs to continuously send packets for a little over one second in order to deliver just one packet, far exceeding the capacitor's limit. Supercapacitors that are bigger than 1 mF might help, but we note that when charged in full, according to the datasheet, the two batteries can support 400 packets in total which are insufficient for LPL-like MAC protocols that send long preambles. On the other hand, given the access to global time that Tempo provides, we envision that TDMA-based protocols will not only provide an energy efficient alternative, but will also be easier to implement.

III. Summary

The prototype Tempo mote is a low-power solar-powered device. The access to global time via the timing module makes Tempo robust to power outages. One immediate application is to employ Tempo as a special time service node for systems such as Phoenix [8]. Equipped with appropriate sensors, Tempo can serve as a full-fledged sensor node.

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