DC-DC Switching Converter as On-Field Self Energy Meter

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***Abstract*—A DC-DC switching converter, originally included to reduce the power consumption of a Wireless Sensor Networks (WSN) node, has been proposed as the core of an on-field self-energy meter. In this paper we present a method and circuit that improves the electronics proposed by previous work by conditioning the signal from the switching converter that is connected to the microcontroller's counter. A software module that allows a WSN node to measure its own charge and current consumption was also implemented. The proposed method allows to measure the current consumption in a wide range, from 0 to $30mA$, is highly linear and is ultra-low-power (the maximum current consumption is $8\mu A$). Finally, we present a case study in which the proposed method is used to power profile a WSN node. Results show that a time-based estimation (Energest) overestimates the Clear Channel Assessment consumption for more than 10%.**

***Index Terms*—Wireless Sensor Networks, Low-Power design, DC-DC converter, Energy measurement, Contiki OS**

I. Introduction

Real-time on-field power consumption measurement has proved to be a powerful tool in the Internet of Things (IoT) and particularly in Wireless Sensor Networks (WSN). Performing adaptive sampling [1], assessing on the fly the energy efficiency of communication protocols [2], predicting the remaining battery charge for routing decisions [3] and performing hardware diagnosis for detecting subsystems faults or unusual power consumptions [4], [5] are just a few examples of its potential.

Several approaches have been proposed for estimating or measuring real-time on-field power consumption, both software [6] and hardware based. Hardware approaches have been proposed as an external add-on [5] and as a circuit that enables self-metering power consumption. Within the latter, the main measurement methods are based on a shunt resistor [4], switched capacitors [7], DC-DC switching converters [8] or combined methods [9].

Nowadays, off-the-shelf DC-DC switching converters achieve efficiencies that permit significant reductions in power consumption by the only effect of reducing the supply voltage [10]. Accordingly, they are increasingly being adopted in devices that require low-power operation, like WSN nodes.

In this context, the DC-DC switching converter approach seems to be a very interesting real-time on-field self-metering power consumption method. Firstly proposed by Dutta et al. [8], it takes advantage of the fact that the inductor pulses are limited to a fixed charge, then the total energy transferred from the input to the output is quantized, and the switching frequency varies linearly with the output power (since the output voltage is constant, a linear increase in current represents a linear increase in power). According to [8] by connecting (by means of a simple wire) the inductor output to a microcontroller counter pin, the total energy consumed at any point in time can be recorded. This method has two drawbacks. Firstly, in many platforms the power consumption of the microcontroller counter prevents its usage to register the sleep-state power consumption. Therefore this method is not suitable for applications where the power consumption is dictated by the sleep-state. Secondly, depending on the desired precision, it can be necessary to make an initial calibration of the frequency-output current characteristic of the DC-DC converter. Besides, additional calibration can be required because this method is sensitive to external fluctuations (temperature and input voltage). Despite these drawbacks, its savings in terms of size, part count, and power consumption make it a very interesting trade-off for real-time on-field self-metering power consumption.

In [8] it is claimed that this method is "for free" because only one wire has to be added. In fact, this approach does not respect the maximum absolute rating of the microcontroller counter pin and may cause permanent damage to the device. In this work we propose a circuit and a method for real-time on-field self-meter power consumption, inspired in [8], that solves this problem and is "almost free". The findings of this work were done in the framework of a microclimate monitoring application where temperature and air humidity are measured with WSN nodes every 15 minutes, and transmitted in a multihop mesh network to a sink node that saves the information in a database. The WSN node uses the remaining battery charge estimation to dynamically change the sampling and reporting frequency of the sensors. The remaining charge is calculated by subtracting the charge measured by the proposed method from the nominal initial battery charge. In addition, the proposed measurement method has proved to be useful to detect inconsistencies in a software-based energy estimation method.

II. Sensor node design

The WSN node is based on the CC2538 System-on-Chip (SoC) manufactured by Texas Instruments, which combines an ARM Cortex-M3-based microcontroller with an IEEE

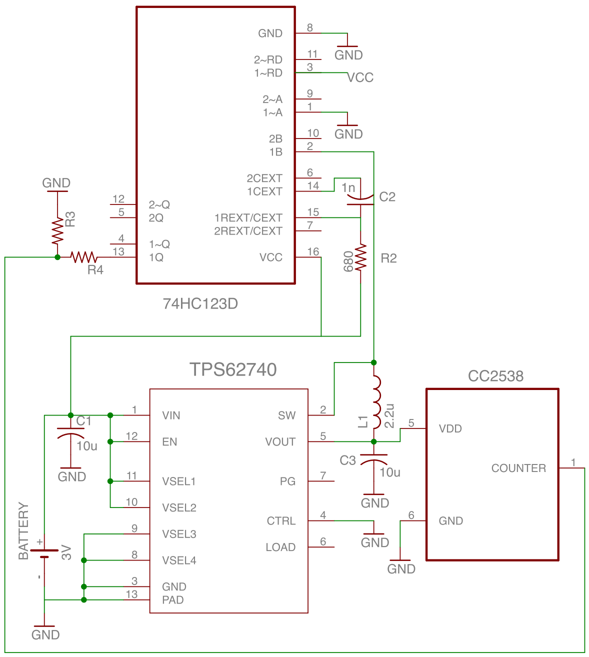

Fig. 1: Schematic of the node (only relevant parts are included).

802.15.4 radio. The node supports analog and digital sensors, for which it includes auxiliary circuits such as switches (for controlling and isolating the different sensor's power supplies), interfaces and sensor connectors. The node is powered by two AA lithium-ion batteries in series, supplying a nominal voltage of $3.0V$. The most power consuming element of the node is the CC2538, but its power consumption can be reduced by using an efficient step-down DC-DC converter to lower the voltage supply from the battery to $2.1V$ (near the minimum supported). We adopted the TPS62740 converter, which achieves efficiencies greater than 90% for a current draw as low as $10\mu A$, guaranteeing power savings even during low-power modes.

We experimentally measured the current drain at different voltages, to confirm that the node average power consumption in our application can be reduced by 20%, as it is stated in [10].

A. Hardware design and implementation

The basis of the proposed measurement method is the affine transfer of the DC-DC converter which is used as a charge meter. The switching frequency of the converter is affine with its output current, so each switch or pulse of the converter corresponds to a fixed amount of charge or *charge quantum*.

Fig. 1 shows the complete schematic of the node, including the CC2538, the DC-DC converter and the auxiliary circuit to implement our measurement method.

The switching signal of the DC-DC (identified as the pin SW of the TPS62740 in Fig. 1), needs some signal conditioning to be used to measure the charge consumption. Fig. 2 shows the switching pulses (upper trace, channel 2). This

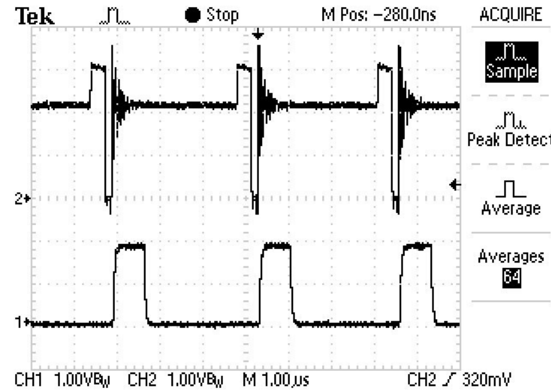

Fig. 2: DC-DC converter switching pulses: a) signal at pin SW (CH 2), b) signal at pin Counter of the CC2538 (CH 1).

signal SW has a baseline value equal to the output voltage V_{out} of the converter, in this case $2.1V$. Each time the converter switches, the switching signal steps up to the input voltage V_{in} for $390ns$, in this case around 3.0 V, then goes down to ground for $150ns$, to finally stabilize at the baseline voltage after some ringing (due to the effects produced by the inductor).

This signal cannot be connected directly to a microcontroller due to two reasons. Firstly, the microcontroller is powered by the the output voltage V_{out} of the DC-DC converter, and since the maximum absolute rating on any pin is $V_{DD}+0.3V$, feeding SW may cause permanent damage to the device. Secondly, the oscillations around V_{out} may generate spurious pulses leading to wrong read-outs.

The switching signal is conditioned using a multivibrator monostable, 74HC123 from NXP Semiconductors, and a simple resistive divider formed by R_3 and R_4 to reduce the pulses amplitude to be connected to the microcontroller. The capacitor C2 is chosen so that the pulse duration is $750ns$ to ensure a proper operation in the desired current range (up to 1 MHz, corresponding to $I_{out} = 30mA$). Fig. 2 shows the resulting signal (lower trace, channel 1) that is connected to the microcontroller. These pulses are counted using an internal timer/counter without the need of the microcontroller intervention.

The increase in the power consumption due to the proposed method is negligible compared to the overall system power consumption. The main contribution for this increase is the multivibrator monostable, which has a maximum static consumption of $8\mu A$.

B. Software design and implementation

Contiki is an open source, event-driven operating system oriented to WSN and IoT applications using constrained hardware. The Contiki distribution includes the network protocols' stack most widely used in WSN. Contiki also includes the Energest module, which implements a software-based energy estimation mechanism. This module measures the accumulated time the sensor node spends in each of the following states: ON, LPM, Tx and Rx, corresponding to CPU active, low-power mode, transmission and reception respectively [11]. The

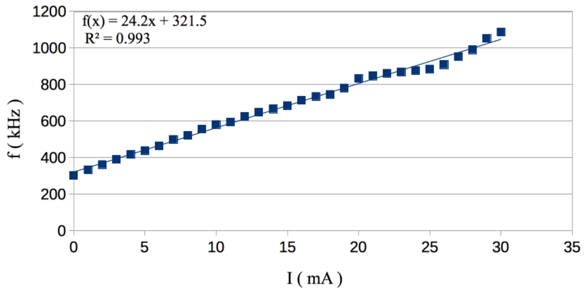

Fig. 3: TPS62740 characteristic: switching frequency vs. output current

mechanism runs directly on the sensor nodes and provides information for estimating the average current energy consumption based on the current consumption of each state.

For our experiments and further analysis, we added another state to the Energest module, to separate the time measurements of the Clear Channel Assessments (CCA) from the reception state. The CCA turns the radio transceiver on every $125ms$ (by default) to check for activity in the radio channel, so the charge consumption associated the CCAs represents much of the total power consumption. This makes that an error in the estimation of the charge consumption of the CCA would make a considerable impact in the estimation of the overall charge consumption.

In order to include the charge and current measurement to a sensor node, a new software module was created and integrated to Contiki to measure the charge by counting pulses. A 16-bit timer/counter configured as a counter with external clock source is configured. The counter register corresponds to the lower part of the 32-bit charge counter. The upper part is incremented when the counter register overflows. This new module replicates the Energest register that counts time, to count pulses of charge corresponding to each of the different states.

III. Experimental results

A. Relationship between output current and switching frequency

The curve of the output current of the DC-DC converter as a function of the switching frequency was found using an evaluation module of the TPS62740 converter, a current source (HP 3245A) to control the output current of the converter and an oscilloscope to measure the switching frequency (Tektronix TDS1001B). The input voltage of the DC-DC converter was set to $3.0V$, and the output voltage of the converter was configured to $2.1V$. Results are shown on Fig. 3.

We can observe from Fig. 3 that, as mentioned in Section II, the output current is affine ($R^2 > 0.993$, where R^2 is a statistical measure of how close the data are to the fitted regression line) with the switching frequency in the studied current range ($0 - 30mA$). Then, the switching frequency can be represented by Eq. 1.

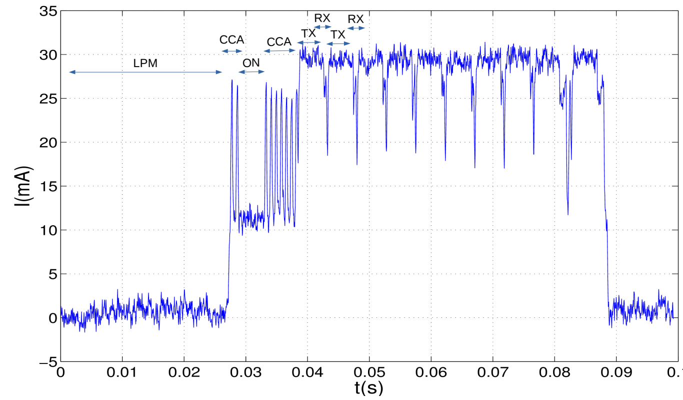

Fig. 4: Current profile, labeling the different states

TABLE I: Average current consumption in different states.

State	$I_{avg}(mA)$
ON	11.23
TX	29.64
RX	24.17
CCA	21.64

$$f(I) = \frac{1}{\Delta Q} \cdot I + f_{offset} \tag{1}$$

where $1/\Delta Q$ is the slope curve, I is the output current, and f_{offset} is the switching frequency for zero output current (no load). $\Delta Q = 41.3nC$ and $f_{offset} = 321.5kHz$ were determined by calculating a linear regression.

B. Current consumption measurements in the different node states

We measured the current consumption of the system in each of the different states to establish a baseline of comparison. A shunt resistor was placed between the output of the TPS62740 and the input of the CC2538, and the voltage drop was measured using an oscilloscope and acquired by a computer for further processing. Fig. 4 shows an example of a capture of a WSN node current profile. Table I shows the measured average current consumption in each state.

Note that the CCA average current consumption differs from the RX average current consumption. This is explained by the fact that for a CCA, the radio is turned on just to assess activity in the channel, while in the case of a packet reception the radio also performs digital processing.

C. Pulse count in the different node states

As stated in section II, the switching frequency can be computed by dividing the number of pulses by the elapsed time. The pulses and time are measured and accumulated for each state. The average current in each state can be calculated from Eq. 1 as:

$$I = \Delta Q \cdot \left(\frac{N_{state}}{t_{state}} - f_{offset} \right) \tag{2}$$

TABLE II: Data obtained with the proposed method, including differences with oscilloscope measurements.

State	$t(s)$	N	$I(mA)$	$Difference(\%)$
ON	64.64	37,066,400	10.80	-3.8
TX	33.95	36,625,900	31.29	5.7
RX	16.37	14,587,800	23.54	-2.7
CCA	9.50	8,138,500	22.13	2.3

where $\Delta Q = 41.3nC$ and $f_{offset} = 321.5kHz$. We ran an experiment over 20 minutes where the WSN node reported data every two seconds. The measured times and pulse count in each state are shown in Table II. This table also shows the computed average current consumption and the relative difference with the oscilloscope measurements presented in Table I. It can be observed that the difference in every state is below 6%.

Running these experiments we detected an inconsistency that Energest performs in the charge consumption estimation of the CCA, which is presented in the following subsection.

D. Analysis of CCA charge consumption

One of the most widely used methods for estimating the charge consumption in nodes that run the Contiki operating system is to measure the time the node spends in each state with the Energest module and multiply it by the nominal current of each state. The first drawback of this method is that a calibration is needed in order to know the nominal current of each state. It is also assumed that the current consumption in each state is constant, and equal to this calibrated value.

Previously in this section we observed that the measured average current consumption in RX state was $24.17mA$ while the measured average current consumption doing a CCA was $21.64mA$, about 10% lower. The Energest module does not differentiate the CCA mechanism from the reception of a radio packet, so when we multiply by the average current of the RX state, we are overestimating the charge consumption in about 10%. Our method allows us to measure the power consumption of this new state without the need of laboratory instruments.

IV. Conclusion and Future Work

DC-DC switching converters are increasingly included in WSN nodes to reduce power consumption. In this work a DC-DC converter is proposed as the core of an on-field self-energy meter. We introduced some improvements to the electronics proposed by previous work to avoid permanent damage of the microcontroller that processes the signal from the switching converter. We also combined the charge measurements with time information to compute the average current in different states.

The proposed method allows to measure the output current of the switching converter in the range of 0 to $30mA$, corresponding to pulse frequencies from $300kHz$ to $1MHz$, where the R-squared coefficient of the transfer curve is above 0.99. The maximum static consumption of the introduced hardware to condition the signal, dominated by the multivibrator monostable, is $8\mu A$.

We detected in Energest an overestimation of the CCA charge consumption by more than 10%.

Results show that the proposed method can accurately measure the current consumption of the system within the WSN node. In our future work, this will allow us to use this information for several applications, such as self-diagnosis for detecting hardware faults (short-circuits, sensors malfunctions, etc.). Additionally, the remaining battery lifetime information enables the node to take autonomous decisions. For example, it can be used by the network protocols to implement energy aware routing or to dynamically change the CCA frequency.

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