Low-Power Self-Energy Meter for Wireless Sensor Network

Carlos Fernández, Diego Bouvier, Jorge Villaverde, Leonardo Steinfeld, Julián Oreggioni
Instituto de Ingeniería Eléctrica
Facultad de Ingeniería UdelaR
Montevideo, Uruguay
Email: carafer@adinet.com.uy, {dbouvier, jvillav, leo, juliano}@fing.edu.uy

Abstract—**Real-time measurement of the energy consumption of wireless sensor network nodes in the field has many interesting applications that range from predicting the remaining battery charge to the energy efficiency assessment of communication protocols. However, designing such a system presents many challenges. In this work we present a measurement method and circuit, named Self-Energy Meter (SEM), that easily adds to a sensor node the capability of measuring its own energy consumption. The SEM developed has very low power consumption, ensuring an almost negligible impact in the battery lifetime. It also solves the problem of handling a dynamic range of five decades. Results from simulations show that the SEM is highly linear, with a coefficient of determination of 0.996, presenting a very low temperature drift, and is almost independent of the power supply.**

I. INTRODUCTION

A lot of efforts have been made in order to measure or estimate the energy consumption of a wireless sensor network (WSN) node, almost all of them for laboratory usage. In [1] is presented an interesting analysis of some of these efforts. It also points out the main motivations for measuring the energy consumption, such as predicting battery lifetime of a single node or the entire network, or allowing optimization of the communication protocols.

A sensor node comprises a microcontroller, a packet radio, and at least one sensor. Hereafter, we will refer to the microcontroller and the transceiver, without distinguishing if the node is implemented using a SoC (System on a Chip) or a separate integrated circuit for the microcontroller and the transceiver. Typically a WSN node has two distinct consumption levels corresponding to different operation modes. In the active mode, the node is performing computations, and may also be transmitting or receiving data through its wireless radio. In this case, the current normally varies from a few miliamperes to tens of milliamperes. In the sleep mode, the current is roughly constant and can be as low as a few microamperes (as shown in [2]). Usually these two consumption levels are used to define a duty-cycle (DC).

Different approaches were taken to measure energy consumption. In [3] a coulomb counter is implemented using a pair of capacitors to support programming and debugging tasks (at the lab in development time). This method was also applied to real-time operation in the field [4]. Although this method is very efficient from the point of view of energy consumption, it has some drawbacks, e.g. the introduced ripple when switching the feeding capacitor. In [5] a voltage-to-frequency converter (VFC) is presented for the same purpose. As the current sensed is a shunt resistor, this approach can achieve a negligible ripple, but presents a poor temporal resolution if the current is too small.

Continuous measurement of energy consumption in very low power battery operated devices presents many challenges. The first and most important is the energy cost of the measuring method itself. Adding hardware means more power consumption, so the first requirement is to maintain the battery lifetime of the device under test (DUT) unaltered (e.g. above 90% of the original duration without the measurement plug-in). The second limitation is the scarce resources available in the sensor node to process the measured data. Large data manipulation or calculations should be avoided. In the third place, as many WSN nodes are deployed in open fields exposed to harsh conditions, they are exposed to a wide temperature variation, thus the measuring device should not be affected by temperature changes. One of the most challenging requirement is the dynamic range, as the current varies from a few microamperes to tens of milliamperes. Moreover, good accuracy and adequate temporal resolution are fundamental for measuring different operation states of the node, e.g. sleep, computing, radio transmission and reception. In this work, the resolution was selected to be one tenth of the charge consumed during a CCA (Clear Channel Assessment), since represent the least consuming activity of interest of a sensor node. And last but not least, the measurement circuit should be simple (pursuing low cost) and easy to integrate to the sensor node.

In this work we propose a method and a circuit to add to a sensor node the capability of measuring its own energy consumption, to be used in the field, with good linearity, temperature stability, independently of the battery voltage drop over the time, and without significantly affecting the battery lifetime.

II. SELF-ENERGY METER

Our method is based on measuring the DUT current consumption through the voltage drop across a shunt resistor. This voltage is fed into a voltage-to-frequency converter.

Ideally, the output frequency is proportional to the current through the resistor. This technique has an inherent drawback, the limited measurement range [5]. In one hand, this method is limited by the maximum acceptable voltage drop in the shunt resistor, resulting from the maximum current consumption, the minimum node operating voltage and the final battery voltage. In the other hand, for very low current values (i.e. sleep current) the voltage drop across the shunt resistor is below the circuit noise level, preventing its measurement. We propose a novel approach to overcome this shortcoming for measuring a sensor node consumption in the full range of operation. The active current, above milliamperes, is measured using the aforementioned method. The sleep current, in the microamperes range, is measured by feeding the node from a charged capacitor. In previous works that used this principle [3] [4], the measuring is based in switching a pair of capacitors -while one capacitor is feeding the device, the other is charging- and counting the number of capacitor full discharges. Since a switching control is required, the associated current draw prevent using this method during sleep mode. Instead, we reused the method adopted for the active mode to measure the accumulated sleep consumption.

The SEM core consists of three blocks. Fig. 1 presents a block diagram of the SEM and showing its integration with the DUT. The first block is a shunt resistor (R_{shunt}) in series with the DUT, which is used as a current-to-voltage converter. In order to maintain a low power operation, the second block converts the voltage across R_{shunt} to a current one thousand smaller than the original (we call this scaling factor α). The third block takes that current and repeatedly charges and discharges a capacitor C from ground to a certain threshold, generating a square wave signal. This signal is feed to a counter in the sensor node (each pulse correspond to a *charge quantum*).

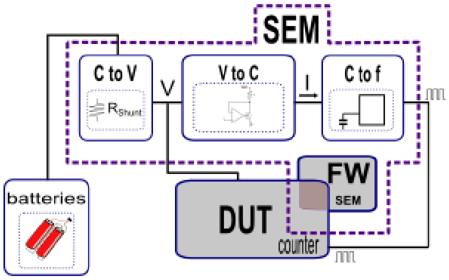

Figure 1. SEM block diagram showing the integration with a WSN node.

To measure the full range of energy consumption, in particular the two distinct states of sleep and active, SEM also uses two states. The idea is to use a capacitor as a buffer (named C_{sleep}) for the energy consumed during the sleep state. When the active state is reached, the DUT power supply is switched from C_{sleep} to the battery, and the capacitor is switched from DUT to a point where it is recharged and prepared for the next cycle. In this scenario, charge consumed during sleep is measured when recharging C_{sleep}. A time diagram is presented on Fig. 2.

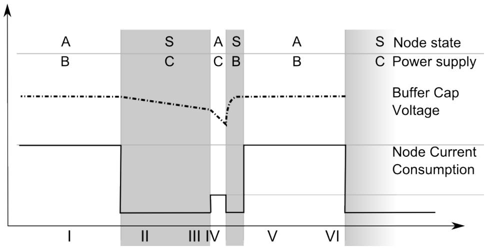

Figure 2. Timing diagram of the measuring cycle. Active state is denoted by A, Sleep state by S. When the node is power from the battery is marked as B and when the buffer capacitor is connected is denoted as C. The axes scales are exaggerated for illustrative purposes.

Two switches are used to change between the measurement modes, and to switch between different power sources. Fig. 3 shows a diagram with the described components: the switch (SW_1) connects the DUT to the battery or to the buffer capacitor C_{sleep} and the switch (SW_2) connects the C_{sleep} capacitor to the DUT or to the battery through a pair of resistors. These two switches are controlled by only one control line of the DUT.

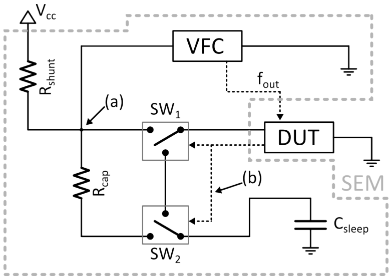

Figure 3. Generic WSN node with the VFC and the DUT included. Current sense point (a) and analog switches control lines (b) are shown.

The resistor R_{cap} limits the charging current of C_{sleep}, so it fits within the maximum range of SEM. During the last phase of sleep state measure, the battery powers the DUT and the current through R_{shunt} is the sum of the current recharging C_{sleep} and the DUT in sleep. In interval III (Fig. 2) it is possible to see that the DUT is consuming more energy than in intervals II and IV. This is necessary as the microcontroller of the DUT must be active for a very short period of time to switch the power supply from C_{sleep} to the battery. This small rise in the current -that will be measured as sleep consumption because we have C_{sleep} as power source- can be neglected, as it is very small compared to the other current/time pairs.

The measuring current range with the proposed configuration is reduced from five decades (from micro to tens of milliamperes) to only two decades (milliamperes to tens of milliamperes) as there is no need to measure the consumption in sleep state. This consumption is measured in the wake-from-sleep event, during the C_{sleep} charge.

Assuming that the current is constant during each state, and that there are many pulses in each state, then the capacitor is charged with constant current, and thus it holds:

$$f(I) = k \cdot I \tag{1}$$

where $f(I)$ is the frequency of the output signal, I is the current drained from the battery, and k is a constant determined by system components. The parameter k is in $coulombs^{-1}$, and is equivalent to the inverse of the charge of each pulse from SEM. In Eq. (2) is shown the value of k after disregarding some terms, where C is the timing capacitor, α is the current scaling factor, and V_{ref} is the voltage reference to which C is charged.

$$k = (\alpha \cdot C \cdot V_{ref})^{-1} \tag{2}$$

III. RESULTS

SPICE simulation results are promising, data showed that nodes could have an accurate measurement of energy consumption. Fig. 4 shows the relationship between the output frequency of the current-to-frequency converter and the instantaneous current consumed by the DUT. This relationship is shown for three different temperature values when the node is powered with battery at their nominal voltage. It is also shown an approximation using linear regression (dashed), which has a coefficient of determination of 0.996. Finally, a curve at nominal temperature but with decreased battery terminals voltage (2.4 V) is also shown. It is worth to remark the fact that the approximation is forced to pass through zero.

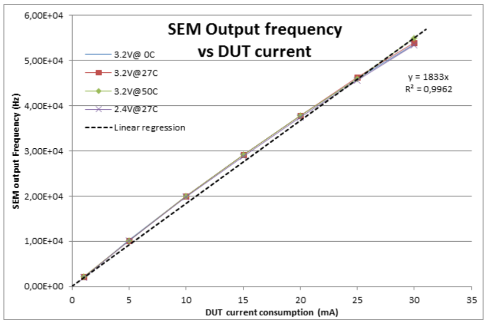

Figure 4. Output frequency versus current consumed by the DUT.

Fig. 5 shows the voltage on C_{sleep} terminals and the output signal during the time C_{sleep} recharge that occurs when the node returns the minimum power state. Consumed charge is recovered in this period, which is less than the time in sleep. This fact is always true as the recharge current is many times the discharge rate.

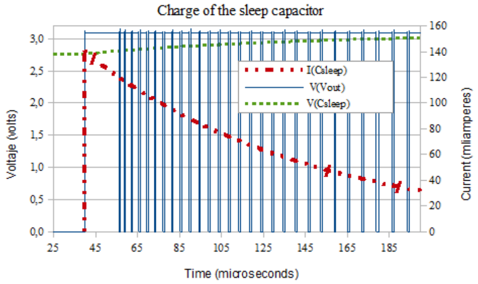

Figure 5. Simulation of the output signal during the switch from sleep state to active state

IV. CONCLUSIONS

We proposed a system called SEM that allows a WSN node to meter in real-time its own energy consumption in the field. The SEM overcame the problem of handling a dynamic range of five decades and a theoretical calculus shows that the consumption overhead of this method is less than 1% for a TelosB with a duty-cycle above 0.3%. Results from simulations show that the SEM is highly linear, with a coefficient of determination of 0.996, has a very low temperature drift, and is almost independent of the power supply.

In order to complete this on-going research, the SEM has to be built and tested in the field. Moreover, a future work could include a comparison between the SEM and estimation methods such as ContikiOS's Energest [6]. Long term deployments should be done to exploit the advantages of energy estimation on every node of the WSN.

REFERENCES

[1] A. Hergenroder and J. Furthmuller, "On energy measurement methods in wireless networks," in *IEEE International Conference on Communications (ICC)*, 2012, pp. 6268–6272.

[2] J. Polastre, R. Szewczyk, and D. Culler, "Telos: enabling ultra-low power wireless research," in *Proceedings of the 4th international symposium on Information processing in sensor networks*. Piscataway, NJ, USA: IEEE Press, 2005.

[3] J. Andersen and M. Hansen, "Energy bucket: A tool for power profiling and debugging of sensor nodes," in *Third International Conference on Sensor Technologies and Applications (SENSORCOMM)*, 2009, pp. 132–138.

[4] J. Oreggioni and L. Steinfeld, "Automedida de consumo en dispositivos portables," in *Proceedings of the XIX Iberchip Workshop, Cusco, Peru*, 2013. [Online]. Available: http://iie.fing.edu.uy/publicaciones/2013/OS13

[5] X. Jiang, P. Dutta, D. Culler, and I. Stoica, "Micro power meter for energy monitoring of wireless sensor networks at scale," in *Proceedings of the 6th international conference on Information processing in sensor networks*, ser. IPSN '07. New York, NY, USA: ACM, 2007, pp. 186–195.

[6] "Contiki the open source os for the internet of things," april 11th 2013. [Online]. Available: http://www.contiki-os.org/