Self-energy meter in duty-cycle battery operated sensor nodes

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***Abstract*—Reduced levels of energy consumption is one of the major goals in Wireless Sensor Networks (WSNs), making the design of a sensor node a challenging task. On-field real-time measurement of the energy consumption of sensor nodes could have a major impact on developing wireless networks. It could be applied to predict the remaining battery charge or to asses the energy efficiency of communication protocols. However, designing such a system presents many challenges that will be discussed in this work. Moreover, 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. SEM is a novel approach focused in solving the problem of covering a dynamic range of five decades in duty-cycle battery operated sensor nodes. Experimental results show that SEM has very low power consumption, ensuring an almost negligible impact in the battery lifetime, is highly linear, presents a very low temperature drift, and is almost independent of the power supply.**

***Index Terms*—power measurement, energy consumption, WSN, self-energy meter, low power.**

I. Introduction

Wireless sensor networks (WSNs) embed computation and sensing in the physical world, enabling an unprecedented spectrum of applications in several fields of daily life, such as environmental monitoring, cattle management, elderly care, and medicine to name a few. A WSN comprises sensor nodes, which sense, process the acquired data and communicates information wirelessly to other sensor nodes. The design of a sensor node face specifications that can be contradictory, as they are expected to be small, reliable and low cost, resulting in an extreme scarcity of resources, including energy, computation power, memory and communication bandwidth.

Reduced energy consumption is one of the major goals in WSNs, since it determines the lifetime of sensor nodes when they are powered from batteries, and dictates severe requirements on the harvesting system when the node scavenges scarce energy from the environment. In this context, real-time measurement of the energy consumption of sensor nodes in the field could have a major impact on developing wireless networks. The energy-profile information, available readily to nodes, enables novel interesting applications, that range from predicting the remaining battery charge to asses on the fly the energy efficiency of communication protocols.

Typically a WSN node has two distinct consumption levels corresponding to different operation modes: active and sleep. In the active mode, the node is performing computations, and may also be transmitting or receiving data through its radio. In this case, the current normally varies from a few milliamperes to tens of milliamperes. In the sleep mode, the current is roughly constant and can be as low as a few microamperes [1]. Usually these two consumption levels are used to define a duty-cycle (DC). Such a high dynamic range in the node current consumption is one of the most challenging requirements for on-board energy measurement.

Early efforts focused on measuring the energy consumption were limited to laboratory operation [2]–[4]. In [2] a coulomb counter was implemented by switching a pair of capacitors, while one capacitor is feeding the device, the other is charging. In this case, the consumed charge is the number of times that the capacitor switches multiplied by the charge. This method has some disadvantages, like the output ripple. In [3] a voltage to frequency converter (VFC) was presented for the same purpose. This approach has a negligible ripple, as the current sensing is done in a shunt resistor, but it does not have the temporal resolution of the first method if the current is too small. Finally, the roughly constant energy consumption associated to different states has been exploited in order to estimate the energy consumption by measuring the elapsed time in each state [5], [6]. These methods allow sensor nodes reporting or processing estimated values of their own energy consumption during operation time. However, the error could be significant [7], for example due to temperature or battery voltage variations. The extension and application of these methods to on-field operation was first proposed in [8].

In this work we propose a method and a circuit (namely self-energy meter or SEM) to add to a sensor node the capability of measuring its own on-field energy consumption, featuring negligible power consumption, five decade dynamic range, easy integration and low resource requirements.

The remainder of this paper is organized as follows: Section II presents our proposal, Section III presents the experimental results, and Section IV contains concluding remarks and research directions.

II. System description

On-field energy measurement of very low power battery operated devices presents many challenges. First, the limited energy available prevents adopting previously proposed methods, designed for laboratory operation. The energy consumption due to the measurement should be kept as low as possible to maintain the battery lifetime of the sensor node virtually unaltered (e.g. above 95% of the original duration without the measurement plug-in). Second, the measuring cost should not be significant. Third, the measuring method should be almost non intrusive, large data manipulation or calculations should be avoided to obtain the measured data. Furthermore, the measure has to be precise and reliable under harsh conditions. In particular, sensor nodes are exposed to a wide temperature variation, thus the measuring device should not be affected by temperature changes. Finally, one of the most challenging requirements is the five decades dynamic range, as the current varies from a few microamperes to tens of milliamperes.

The method proposed by this work is based on measuring the sensor node current consumption through the voltage drop across a shunt resistor. This voltage is fed into a voltage-to-frequency converter (VFC). The value of the shunt resistor is limited by the maximum permissible voltage drop, resulting from the maximum current consumption, the minimum device operating voltage and the battery voltage drift. However, 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. To overcome this shortcoming, we propose a novel approach in order to measure the current consumption in the full range of operation (preliminary results were presented in [9]), while the active current is directly measured using the aforementioned VFC method, the sleep consumption measurement is based on feeding the device from a charged capacitor. The accumulated sleep consumption measurement is performed when the node wakes up, measuring the charging current of the capacitor.

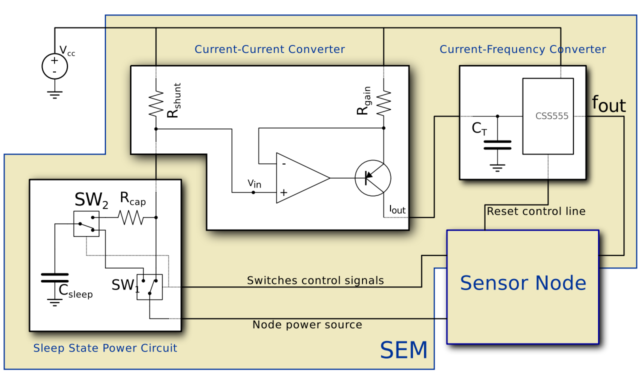

Fig. 1. Block diagram of the SEM showing the integration with the sensor node.

Fig. 1 presents the block diagram of the SEM and how it is integrated with the sensor node. The first block is a resistor (R_{shunt}) in series with the sensor node that 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 times smaller than the original (Iout). The third block takes that current and repeatedly charges and discharges a capacitor C_T from ground to a certain threshold voltage V_{REF} (established by means of a voltage reference chip). The output of the last block responds to this charge/discharge behavior generating a square wave signal (f_{out}) ready to be used by the sensor node. The frequency of f_{out}, namely $f(I)$, is presented in Eq. 1.

$$f(I) = \frac{1}{\frac{V_{REF}.R_{gain}.C_T}{I.R_{shunt}} + t_d^*} \tag{1}$$

where I is the current drained from the batteries, and R_{gain}, R_{shunt}, C_T and V_{REF} are the components previously described. The transfer function is non linear because of the t_d^*, the propagation delay of the timing circuit (CSS555).

The square wave signal (f_{out}) is fed to a general purpose timer/counter module in the micro-controller in the sensor node, where each count represents a fixed amount of charge consumed by the sensor node (a *charge quantum* Q). Considering that the charge quantum Q is I/f and $f < 1/t_d^*$ we obtain the following expression:

$$Q(f) = \frac{V_{REF}.R_{gain}.C_T}{R_{shunt}} \frac{1}{1 - f.t_d^*} \tag{2}$$

In addition to fulfilling the design criteria described above, R_{gain}, R_{shunt}, C_T and V_{REF} should be sized in order to meet that $\frac{V_{REF}.R_{gain}.C_T}{I.R_{shunt}} \gg t_d^*$ (this can be easily met taking into account the low values of I involved in the application), thus:

$$f(I) = \frac{R_{shunt}}{V_{REF}.R_{gain}.C_T} I \tag{3}$$

and,

$$Q = \frac{V_{REF}.R_{gain}.C_T}{R_{shunt}} \tag{4}$$

Before the sensor nodes is set in sleep state, SEM is also set in standby, to reduce power consumption. In order to measure the energy consumed during the sleep state a capacitor (named C_{sleep}) is used as a buffer. When the active state is reached, the sensor node power supply is switched from C_{sleep} to the batteries (V_{CC}), and the capacitor is switched in order to be recharged and be ready for the next cycle. In this scenario, the charge consumed during the sleep state is measured when recharging C_{sleep}.

The measuring current range with the proposed configuration is reduced from five decades (from micro to tens of miliampers) to only two decades (miliampers to tens of miliampers). This is achieved measuring the sleep state energy consumption in the wake-from-sleep event, during the C_{sleep} charge.

SEM uses two switches to implement the aforementioned changes between the consumption measurement modes. Fig. 2 shows two switches used to configure the circuit as follows: switch SW_1 connects the device to the batteries (V_{CC}) or to the buffer capacitor C_{sleep}, and switch SW_2 connects the C_{sleep} capacitor to the device or to the batteries. The resistor

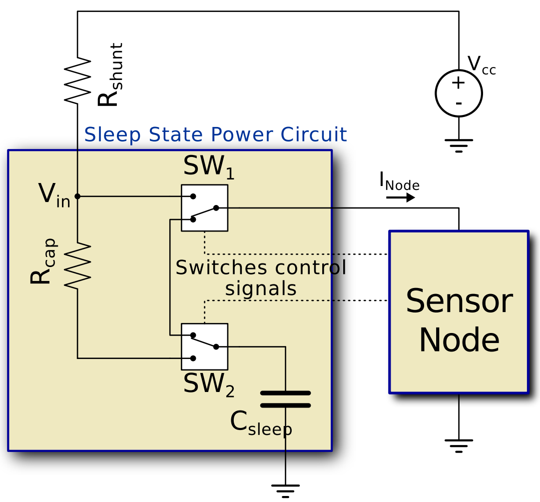

Fig. 2. Generic WSN node with the VFC and the sensor node included. Sleep State Power Circuit operation.

R_{cap} limits the charging current of C_{sleep}, so it fits within the maximum range of SEM.

The time line diagram in Fig. 3 shows the sensor node states and the measuring phases. During the interval I, the node and SEM are in active state and powered by batteries. The current consumption is measured directly and in real-time. During interval II, the node and SEM are both in the lowest power consumption state. The power is taken from the buffer capacitor. There is no current through R_{shunt} during this interval. When the node wakes up, first measures the sleep consumption. Because this would cause a delay every time the node resumes from sleep, the node wakes up earlier— interval III— and controls the switches to set SEM to measuring state, switching its own power supply from Csleep to the batteries, and connects Csleep to be recharged. During interval IV, the node is in sleep state again, but the current through R_{shunt} is now the sum of the currents of the supply to the node and the recharging current of C_{sleep}, and thus is the actual consumption of the device in interval II, III and IV. So during this last interval, the consumption of the whole sleep state plus a very small rise of consumption of interval III, is measured. This rise is negligible in comparison to the other current/time pairs.

Despite the fact that longer sleep periods can be achieved by increasing the capacity of C_{sleep}, two aspects should be taken into account. First, recharge time depends on the value of C_{sleep} as the recharge current is limited by R_{cap}, so the recharge current fits in the linear range. And second, charge losses of the actual capacitor (due to temperature change, or leakage currents), should be maintained small. This is achieved if temperature varies slow, and self discharge of the capacitor is negligible compared to one sleep cycle.

The minimum duration for the active period is determined by the resolution of the current to frequency converter. It should be at least twenty pulses of SEM in the shortest active period. The reason for this constraint is because a whole pulse maybe lost during the transition of active measurement to sleep of SEM, and thus a loss of information.

The interruption of the sleep cycle, namely Interval III, is part of the measuring cycle. It does not affect the overall power consumption as occupies very few instruction cycles. The figure is exaggerated to clarify the concept.

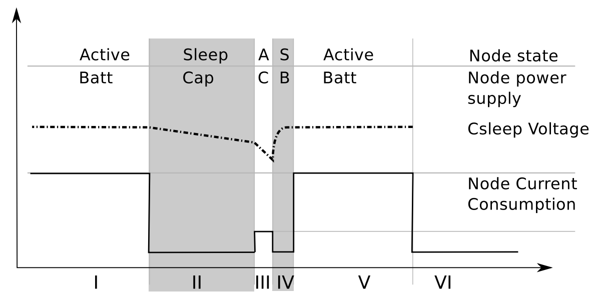

Fig. 3. Timing diagram of the measuring cycle. Active state is denoted by A, Sleep state by S. When the device is powered from the batteries it is marked as B and when it is powered from the buffer capacitor it is denoted as C. The axes scales are exaggerated for illustrative purposes.

III. Results

A. Transfer characteristics

The characterization of SEM was made measuring the output of the current-frequency converter. Measurements were performed at nominal conditions (25^oC and $3V$ power supply), then these were repeated varying temperature and power supply voltage.

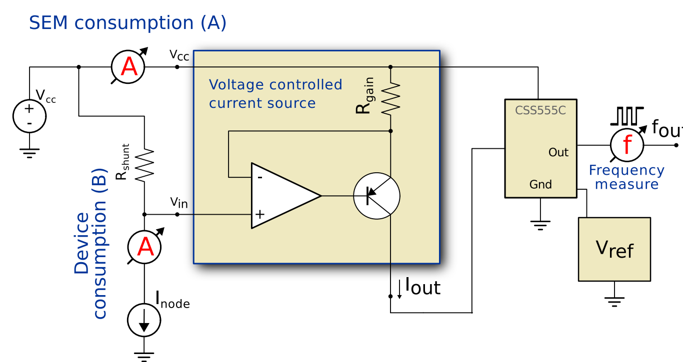

Fig. 4. Measurement setup circuit.

Fig. 4 depicts the setup circuit. The current at points A and B were measured with two Fluke 45 multimeters, and the output frequency was registered with a Tektronix TDS220 oscilloscope. The voltage supply, V_{CC}, was obtained from a Tektronix PS280 regulated power supply and the temperature was varied by means of a custom temperature-controlled oven.

The energy consumption of a typical sensor node in active state was simulated using a standard current source I_{Node} (a resistor feeding a Wilson current mirror). The current was varied from $0.2mA$ to $100mA$.

Fig. 5 shows the relationship between the output frequency of the current-frequency converter and the instantaneous current consumed by the sensor node. When the power source is set to $2.1V$ (curve plotted with red dots) it can be seen that for currents greater than $15mA$ the frequency obtained is lower than the expected. This happens because the voltage reference chip is failing to maintain its output.

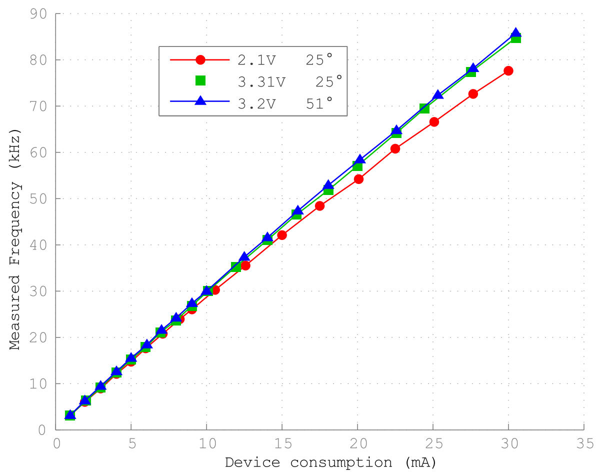

Fig. 5. Output frequency vs sensor node current consumption.

In Fig. 6 it is possible to see that the charge quantum is almost constant. The very slight difference is caused by the fact that the relation between the output frequency and the current is not exactly linear (as was shown in Eq. 1 y Eq. 2).

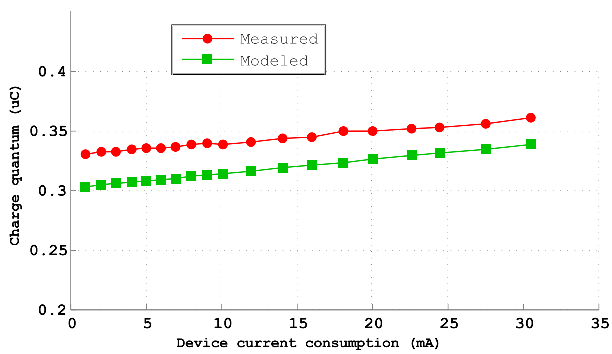

Fig. 6. Charge quantum prediction and measurement.

In Fig. 7 SEM current consumption is introduced. There it can be seen that this current is negligible compared to the one consumed by the sensor node. This ensures that the use of SEM does not affect significantly the battery lifetime.

B. SEM validation in a real sensor node

In order to validate the system, SEM was integrated in the WSN node *TelosB* [1]. A PCB was fabricated and a software module was developed over Contiki OS [10]. The current was measured over a minute of operation using both, a TrueRMS amp-meter (UNI-T E60) and SEM. The current average was taken and compared. The result of this comparison is shown on Table I.

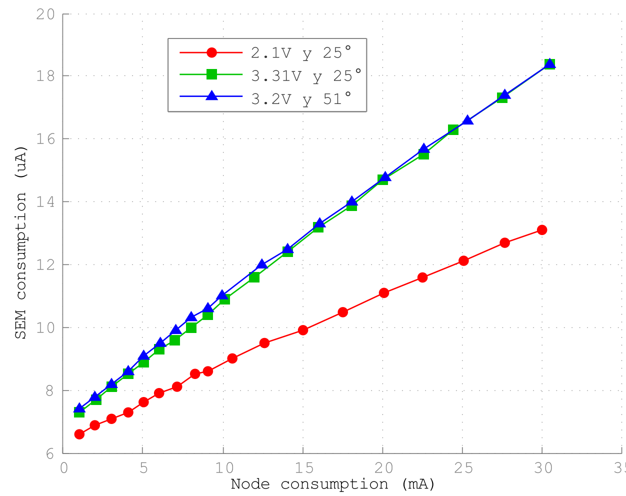

Fig. 7. Current consumption of SEM.

TABLE I
COMPARISON BETWEEN SEM AND A TRUE RMS AMP-METER IN A TELOSB.

Method	Current (mA)
SEM	1.01 ± 0.01
True RMS amp-meter	1.04 ± 0.04

IV. CONCLUSIONS

We proposed a system called SEM that allows a WSN sensor node to measure in real-time its own energy consumption in the field, with good linearity, temperature stability, independently of the battery voltage drop over time, and without significantly affecting the battery lifetime. In Table II the main characteristics of SEM are introduced.

The main contribution of the SEM is that overcame the problem of handling a dynamic range of five decades by proposing a novel method of current measurement that combines a VFC and a capacitor used as buffer.

Future work could include a comparison between SEM and estimation methods such as ContikiOS's Energest [5]. Moreover, long term deployments should be done in order to exploit the advantages of energy measurement on every node of the WSN.

TABLE II
MAIN CHARACTERISTICS OF SEM.

Parameter	Min	Typ	Max	Units
Current Consumption	6.6	-	18.4	μA
Power Supply	2.2	-	5.0	V
Frequency	3.0	-	84.6	kHz
Linearity	-	-	2.6	$\%FS$
Resolution	-	0.35	-	μC
Precision	-	1%	-	-

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