Demo: In-situ Power Consumption Meter for Sensor Networks supporting Extreme Dynamic Range

Giannis Kazdaridis*, Ioannis Zographopoulos*, Polychronis Symeonidis*,

Panagiotis Skrimponis*, Thanasis Korakis* and Leandros Tassiulas†

*Department of Electrical and Computer Engineering, University of Thessaly, Greece

†Department of Electrical Engineering, Yale University, New Haven, USA

{iokazdarid,zografop,posymeon,skrimpon,korakis}@uth.gr,leandros.tassiulas@yale.edu

ABSTRACT

Typical wireless sensor devices feature an extreme power consumption range between their active and sleep states, thus requiring different hardware setups for measuring their expenditure with high accuracy. In this demo paper we present the *NITOS dynamic ACM*, an in-situ power meter that exploits auto-ranging methods to support high dynamic currents. Our implementation features 250 kSps of sampling rate, while attaining high precision in both the active and sleep states of the targeted device, by using two different shunt resistors that are alternated automatically with the aid of a high speed comparator. The acquired results indicate the smooth performance of our system as well as the high accuracy attained.

KEYWORDS

Power Consumption Monitoring, Wireless Sensor Networks, Energy Efficiency

1 INTRODUCTION

Power consumption monitoring aims at understanding the behavior and decomposing the energy profile of sensor nodes, in order to aid in the development of energy-efficient protocols. Several works, such as SPOT [5] and iCount [4], present in-situ power meters for extracting power consumption data of embedded hardware. However, sensor and IoT platforms are characterized by sophisticated power management and various operating and sleep modes, thus featuring extreme current dynamics. For instance, a sensor node might consume up to several mA when active, while reaching down to a few uA or even some nA, when asleep. This implies that the power profile of a sensor node exceeds at least three orders of magnitude, requiring high-end tools with wide dynamic range spanning the entire spectrum of possible current draws to ensure sufficient capturing of possible transitions.

The typical principle followed to measure power consumption [7] is the placement of a precise, low-impedance shunt resistor, in series with the supply rail and the *device under test* (DUT). The voltage drop across this resistor is proportional to the current drain, according to Ohm's law, enabling the extraction of power data. The selected shunt plays significant role for the attained accuracy of the entire system. Thus, it must be carefully chosen in order to avoid interference with the operation of the DUT, but at the same time it must provide sufficient input signal, able to drive the pre-amplification circuit and the *Analog-to-Digital Converter* (ADC).

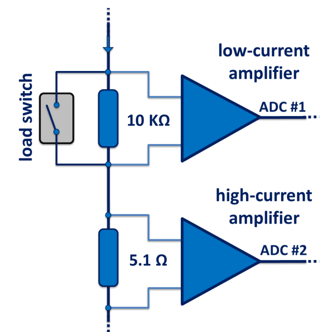


Figure 1: Shunt Resistor Dynamic Circuit

For a desired maximum current of 20 mA, the selected shunt may not be greater than 5 Ω, because it is then already presenting 100 mV voltage drop, which might affect the operation of the DUT. This signal (100 mV) can be easily processed by a pre-amplification circuit that scales the observed voltage drop across the shunt resistor to a full-scale analog signal to ensure accurate sampling by the ADC IC. However, in order to to measure a current as low as 1 μA the selected resistor (5 Ω) will develop a drop as low as 5 μV, which is impossible to prevail over noise and parasitic thermo-voltages. Even if it was to be inflated with an additional gain, the amplified signal would still be quite low to be sampled by the ADC. Therefore, the gain must be generated from the shunt resistor itself. In essence, it is necessary to adjust the shunt resistor during the measurement procedure, without interrupting the operation of the DUT and by constantly measuring even in the transition areas.

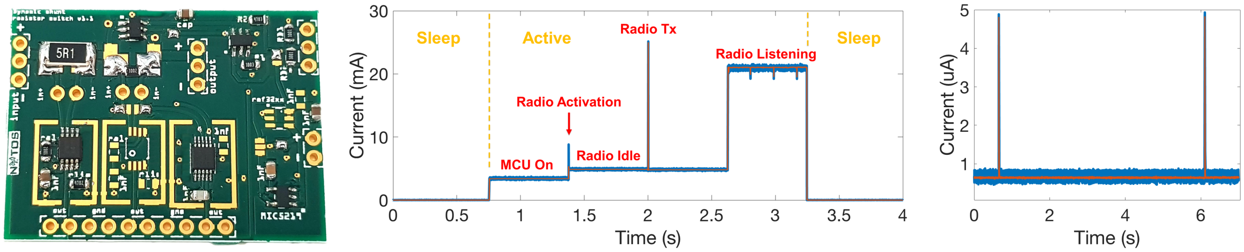
Motivated by Nemo [8] we have developed a dynamic shunt resistor circuit, able to alternate between the shunts with the aid of a high speed comparator. Moreover, we leverage our previous implementation, [6], a high-sampling power meter featuring parallel input channels. The main difference with Nemo is that we constantly monitor the signal generated by both shunts, while Nemo employs a multiplexer circuit to sample only the activated shunt each time, presenting, as a consequence, a loss between the alternations. A similar principle to Nemo is also followed by [3]. In the next section we present the implementation of the proposed power meter and discuss its key features.

The research leading to these results has received funding from the European Union's H2020 Programme under grant agreement no. 687983 (MAZI Project).

WiNTECH'17, October 20, 2017, Snowbird, UT, USA

ACM ISBN 978-1-4503-5147-8/17/10.

https://doi.org/10.1145/3131473.3133331



(a) Developed Dynamic Shunt Circuit (b) Power Consumption Measurements of ez430 Sensing Platform (c) eZ430 Consumption in Sleep State

Figure 2: Developed Dynamic Shunt Switch & eZ430-RF2500 Power Consumption Measurements

2 SYSTEM IMPLEMENTATION

Our implementation is composed of a dynamic shunt resistor circuit and a previously implemented in-situ power monitor device [6]. Briefly, the heart of the power meter is the BeagleBone Black Rev. C [1], which is a low-cost, embedded platform. To convert the analog signal to digital we employed the Texas Instruments (TI) ADS8332 ADC IC, which features 8 input pins allowing for parallel sampling of multiple channels. It supports resolution of 16-bits and high SNR of 91 dB, while performing conversions at 500 kSamples per second (kSps). The overall sampling rate is split among the configured channels. In our implementation we exploit only two of the available inputs, thus we attain a sampling rate of 250 kSps.

The developed shunt resistor circuit board is composed of two shunts, a 5.1 Ω and a 1 KΩ, illustrated in Fig. 2(a), following the diagram depicted in Fig. 1. Both resistors feature a dedicated pre-amplification circuit, formed by a current-sense amplifier, supporting wide Bandwidth range. The output signal of the pre-amplification circuit is fed into the two utilized channels of the ADC IC. Both resistors are placed in series between the power supply and the DUT, but only the *high-current* (5.1 Ω) resistor is constantly activated. The *low-current* (1 KΩ) resistor is connected with a small, single channel load switch which bypasses the path across the resistor. This current switch is controlled by a high-speed comparator that controls the state of the switch. In essence, when the DUT is active only the *high-current* resistor is active, while the *low-current* resistor is bypassed by the load switch. As soon as the DUT enters sleep state the comparator dis-activates the load switch, so as to allow current to flow through the *low-current* shunt as well. In this implementation it is of grave importance to ensure fast alternation between the resistors, exceeding the sampling rate of the ADC IC. To this end, we have utilized an ultra high speed comparator that induces a delay as low as 4.5 ns while the 250 kSps sampling rate implies an interval of 4 μs between the attained measurements. Moreover, the selected load switch features fast activation of 4.5 ns, guaranteeing fast switching when the DUT alternates between the different modes. Furthermore, the comparator IC employs a reference circuit that provides constant voltage utilized to compare the output signal of the *high-current* pre-amplification circuit, in order to detect whether it must activate the low-current resistor.

The developed software supports constant reading by both inputs, thus creating two files during the monitoring procedure. After the completion of this procedure a developed script processes the acquired data and merges the two files into one, filtering out the useless measurements. Lastly, it is worth mentioning that the impedance induced by the load switch does not affect the measurement accuracy of our system, since we only sample the voltage drop across the *high-current* resistor, which is actually a drawback presented in the implementation of Nemo, where there is only one ADC input channel.

3 DEMONSTRATION

To demonstrate the performance of our system we employed a state-of-the-art sensing platform, the eZ430-RF2500 [2]. eZ430 features an MSP430 micro-controller and a CC2500 radio IC. When in sleep state, *Low Power Mode 3* (LPM3), the eZ430 consumes as low as 650 nA, whilst in active state it drains roughly 3-25 mA, thus making it ideal for demonstrating the performance of our meter. Fig. 2(b) plots the power consumption of eZ430. Intuitively, we clearly observe the sleep state, as well as the transition to active state where the eZ430 initializes itself and then propagates a small frame. Next it is configured to radio listening for roughly a second and then it returns back to sleep state. Notably, we artificially introduced delays between the different operations to clearly observe the power drained. Finally, we zoom in on the consumption of the ez430 when asleep, in Fig. 2(c), where we can clearly observe the spikes of the watchdog circuit that remains active in the LPM3 state. To note, those oscillations cannot be captured when using just the *high-current* shunt.

4 CONCLUSIONS

In this work we presented the *NITOS dynamic ACM*, which employs two different shunt resistors that are dynamically switched to accurately monitor the power consumption of sensor nodes in different states. Our device supports fast alternations among different operation states of 9 ns and sampling speed of 250 kSps. Our results indicate the smooth performance and highlight its high accuracy.

REFERENCES

[1] *BeagleBone Black Rev. C Embedded board.* http://beagleboard.org/BLACK.
[2] *eZ430-RF2500 Wireless Development Tool.* http://www.ti.com/tool/EZ430-RF2500.
[3] *M. Riedel and M. Schwarzbach. Current measurement with auto-ranging yields 180dB range dynamics. Retrieved from:.* http://www.imc-berlin.com/.
[4] P. Dutta, M. Feldmeier, J. Paradiso, and D. Culler. Energy Metering for Free: Augmenting Switching Regulators for Real-Time Monitoring. In *IPSN '08*.
[5] Xiaofan Jiang, Prabal Dutta, David Culler, and Ion Stoica. Micro Power Meter for Energy Monitoring of Wireless Sensor Networks at Scale. In *Proc. of IPSN '07*.
[6] G. Kazdaridis, S. Keranidis, P. Symeonodis, P. Dias, P. Gonçalves, B. Loureiro, P. Gjanci, and C. Petrioli. EVERUN - Enabling Power Consumption Monitoring in Underwater Networking Platforms. In *Proc. of WiNTECH '17*.
[7] S. Keranidis, G. Kazdaridis, V. Passas, T. Korakis, I. Koutsopoulos, and L. Tassiulas. Online Energy Consumption Monitoring of Wireless Testbed Infrastructure Through the NITOS EMF Framework. In *Proc. of WiNTECH '13*.
[8] Ruogu Zhou and Guoliang Xing. Nemo: A High-fidelity Noninvasive Power Meter System for Wireless Sensor Networks. In *Proc. of IPSN '13*.