The ICARUS Mote: Employing Off-Chip RTC to Attain 22 nA Sleep Current in Duty-Cycled IoT Devices

GIANNIS KAZDARIDIS, University of Thessaly, Greece
NIKOS SIDIROPOULOS, University of Thessaly, Greece
IOANNIS ZOGRAFOPOULOS, University of Thessaly, Greece
POLYCHRONIS SYMEONIDIS, University of Thessaly, Greece
THANASIS KORAKIS, University of Thessaly, Greece

In this work we demonstrate the ICARUS mote, the first wireless sensor node that features the extremely-low sleep current of 22 nA. To achieve this, we employ an off-chip on-board Real-Time-Clock (RTC) circuit with an ultra-low power consumption profile. The RTC is configured to control the power supply of the under consideration mote, by enabling or disabling its power in a *power-gating* fashion, while it is the only module that remains powered during sleep, hence the overall mote's consumption is substantially diminished. The proposed principle can be adopted by any *IoT* mote, in order to extend the life expectancy of battery-powered applications, by pushing sleep currents an order of magnitude lower.

CCS Concepts: • **Hardware → Circuits power issues**; **Sensor devices and platforms**; *Wireless devices*; **Platform power issues**.

Additional Key Words and Phrases: Power Management, Sleep Current, Low Power Design, IoT, Sensor Networks, RTC

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1 INTRODUCTION

A major research concern in the domain of Wireless Sensor Networks is the energy efficiency of the sensor nodes. In most real-world applications, sensors are battery operated, with their power profile and the network's load determining the lifetime of the sensor network. Commonly, sensor devices follow a *duty-cycle* fashion in order to save as much energy as possible, since overhearing and idle listening are major sources of energy wastage [16]. To this end, sensor nodes are configured to enter a low-power mode, the so-called *sleep-state*, during their inactive periods. The sleep state is interrupted by short, burst events, where sensors sense, process and propagate data.

It is worth noting that the power consumption in *sleep-state* is usually in the order of a few *μA*, while in active-state sensors dissipate roughly few tens of mA. Despite it seeming reasonable to neglect energy consumption in the sleep state, typical sensor applications operate at quite low *duty-cycles* ranging from *0.01 %* to *1 %* [3], which suggests that both states account for the systems' power budget expenditure [10]. Notably, the power consumption of the widely-used *MicaZ* [11] and *TelosB* [12] motes are *15 μA* and *8.8 μA* respectively on a *3.3 V* supply, when in sleep mode. Even the moderns prototypes of the *Opal* [4] and the *Storm* [1] feature *8.9 μA* and *13*

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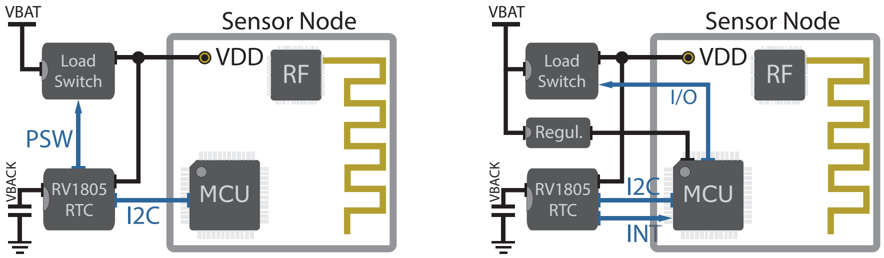


(a) Proposed PSW Architecture Diagram (b) Proposed Interrupt Architecture Diagram

Fig. 1. Proposed Architecture Diagrams

μA respectively in this state, which is undoubtedly, an expensive energy budget to spend during inactive periods. The only motes that present power draw close to 1 μA is the *eZ430* [2] and the *Waspmote* [15], as well as our previous work [7] that employes a an ultra-low power timer to provide the external stimulus. To this end, we remark that it is essential to minimize the power draw of sensor nodes in sleep phase, in order to extend the lifetime of networks.

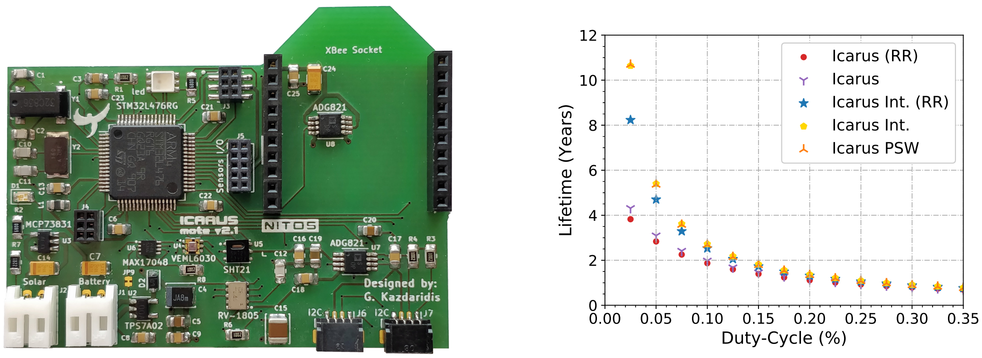
In our work we present the ICARUS prototype mote that employs a novel principle to drop the power draw in sleep state to as low as 22 nA, while the same circuit block can be adopted by any commercial or prototype sensing device.

2 NANO POWER CONSUMPTION SYSTEM IMPLEMENTATION

In this work, we propose the employment of an on-board, off-chip *RTC* module with an ultra-low power profile, to manage the *go-to-sleep* and wake-up phases of battery powered *IoT* nodes. To this aim we employ the *MicroCrystal RV1805-C3* [13] *RTC*, which features the extremely low consumption of 22 nA at 3.3 V power supply. Moreover, the selected RTC supports a time accuracy of *2 ppm*, which allows the formation of synchronized wake-up schemes for duty-cycled sensor networks. Lastly, the *RV1805* communicates with the host node through an I2C port for the appropriate configuration. We propose two different topologies for utilizing the proposed *RTC*, each one with different trade-offs.

PSW Topology: In the *PSW* (*Power SWitch*) case we employ a *load-switch* along with the *RTC*, to completely power-off the under-consideration sensor node adopting the *power-gating* [14] method, as illustrated in Fig. 1(a). Practically, the only component that remains powered in sleep-state is the RV1805, while the host node is powered via the load-switch Evidently, the inevitable trade-off when applying this method is the additional time required for the sensor to enter an active state, since the cold-boot time is notably longer than the respective wake-up time from any other sleep-state. However, when considering modern MCUs, the average cold-start time is roughly 1 ms, which is an acceptable cost to pay in most scenarios, especially when considering low duty-cycled applications. Notably, a typical active duration of a sensor node is 200ms [3], which also suggests that cold-start time is a negligible overhead.

Interrupt Topology: On the other hand, in the *Interrupt* (*INT*) configuration the MCU remains constantly powered even in sleep-state, while the RV1805 is employed to provide waking signals to the the host *MCU*. Moreover, we apply the *power-gating* principle in the remaining electronics and peripherals of the IoT node by employing a *load-switch* to eliminate any leakage or quiescent power when asleep. The architecture is illustrated in Fig. 1(b). Despite the fact that in this scenario the overall power draw is notably higher compared to the *PSW* case, it still remains in the order of a few *nA* when considering modern MCUs, such as the MSP430 and the STM32L families. Apparently, an essential advantage of this approach is the fast wake-up time. Moreover, this



(a) The ICARUS Prototype Mote (b) ICARUS Lifetime vs Duty-Cycle (0.025%-0.35%)

Fig. 2. ICARUS mote & Expected Life Duration

scheme is able to support RAM retention, since the *MCU* remains powered, which is of crucial importance when considering sophisticated application scenarios.

The *ICARUS* mote [6], illustrated in Fig. 2(a), features the ultra-low power STM32L476RG which is an ARM Cortex-M4 32-bit RISC core MCU operating at a frequency of up to 80 MHz. It embeds high-speed Flash memory of 1 MB and an SRAM of 128 KB. The mote integrates an XBee-footprint socket for plugging-in wireless interfaces, such as LoRa, ZigBee, BLE, etc., Moreover, it embeds a *SHT21 temperature & humidity*, a *VEML6030 light intensity* and a *MAX17048G+ battery gauge* sensors, while extra sensing modules can be interfaced through the available *I2C* and *I/O* ports. Of course, the *ICARUS* also integrates the *RV1805 RTC*, which, along with the ADG821 load-switch, is used to switch the power of the mote entirely on or off, or to alternatively serve as an interrupt source for waking-up the host *MCU*. An extra *ADG821* is employed to control the power rails of the wireless interface and of the attached sensors and peripherals. Notably, each *ADG821* features two internal switches. The *ICARUS* exhibits roughly *22 nA* power draw in sleep state, exploiting the proposed mechanism.

3 EVALUATION

In this section we characterize the performance of the proposed scheme, evaluating the power consumption profile and the expected lifetime when our principle is applied versus the standard operation.

3.1 Power Profile

In our implementation the selected RTC is configured in a specific mode (RC) in which it auto-calibrates itself every 50 sec, in order to attain high timing accuracy, while drawing only a few nA. Apparently, in this mode it is not trivial to measure its power profile in order to characterize the power draw of the overall system. To this aim, we rely on our high-fidelity monitoring tools [5, 8, 9], which support a dynamic shunt resistor switch that alternates depending on the flowing current, which eases the process of measuring the power profile of the *RV1805*. The measured consumption of the RV1805 along with the ADG821 over a single auto-calibration period when powered at 3.3 V is 22 nA, which is also the overall system's consumption when the PSW topology is applied.

3.2 Lifetime Evaluation

Our principle substantially drops the power consumption of a sensor system when in sleep state, expecting to extend the lifetime of a sensor node as much as possible. Therefore, it is essential to evaluate the lifetime of a sensor node under various duty-cycles. We assume a scenario in which the ICARUS mote is powered via a battery of an available capacity of *360 mAh* and that the average power draw of the ICARUS in active state is 14 mA. Moreover, we estimate that the power draw of the ICARUS mote if our principle is not applied is 7 μA in sleep state, considering the on board components and STM32L476's draw with the on-chip RTC active. We note also that a typical active time for a sensor device is *200 ms* [3]. According to the above, Fig. 2(b) plots the calculated life expectancy of the ICARUS mote when our principle is applied versus the standard operation, under various duty-cycles. Undoubtedly, our principle substantially extends the lifetime of the ICARUS mote when the PSW topology is applied while the same is also true when the Interrupt topology is utilized, both with and without RAM retention capabilities.

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