Self-powered Heat-Sink SoC as Temperature Sensors with wireless interface: design and validation

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***Abstract*—We present the design and the proof of concept of a self-powered System-on-Chip temperature sensor with wireless communication interface integrated in the shape of a heat-sink. The proposed solution is based on a thermo-harvesting module that scavenges the energy required to operate from the target device under monitoring. The heat-sink provides optimal thermal dissipation while the SoC underneath provides feedback on the temperature. The thermal gradient between the chip and the environment is converted into electrical energy that supplies the wireless interface to send a beacon message to a receiver. The packet rate is directly related to the temperature of the target device by means of the efficiency curve that characterize the thermo-harvesting module. We designed the proposed SoC architecture and we proved the concept using commercial devices. We validated our approach comparing simulated results with real experiments. The prototype system has been proven effective to measure the temperature on the package of a general purpose ARM CPU in the range $40°C$ to $70°C$.**

I. INTRODUCTION

Electronic systems are becoming more and more compact and new features are integrated on single chips. Although the powering issues are very critical, also the cooling of such devices is crucial. This is particularly critical with new generation embedded systems, where high performance processors are arranged in very small devices. In such a scenario, it is not always possible to deploy a sufficient number of integrated temperature sensors to monitor the thermal performance of the whole platform, or of particular components (FPGAs, DSPs, GPUs, ...). In addition to the traditional evaluation and computing of complex thermal models to safeguard the integrity and tuning the performance of the target system, we propose the design of an active heat-sink to achieve both dissipation and monitoring simultaneously. The proposed self-powered thermal sensor, with wireless interface, can be shaped to meet specific requirements (dimensions, temperature range, ...) and can be deployed in a distributed fashion to realize a Wireless Sensor Network embedded into a specific electronic platform.

To extend the battery lifetime of embedded systems, harvesting techniques are generally used to convert an environmental energy to electrical energy that supplies the node or recharges its batteries [1]. In an outdoor environment, solar energy generally represents the most reliable power source, and solar panels exhibit the higher scavenging performance and efficiency with respect to other techniques [2]. However, only few tens of milliwatts can be recovered from harvesting solar, or vibrational energy, in an indoor environment. To overcome the reduced energy availability in an indoor environment, solutions that combine hybrid sources have been proposed [3]. The lack of renewable energy sources in indoor environment drives us to recover energy from waste. In this work we present a device that scavenges electrical energy from the thermal energy wasted by a CPU. The amount of heat dissipated by a CPU is relatively small, but it is almost continuously available as long as the CPU is turned on [4]. Other systems that harvest heat wasted by microprocessors have been presented in the literature [5]. It has been demonstrated that the amount of harvested energy is not sufficient to recharge the battery of the system from which the energy is scavenged [6]. Nevertheless, using CPU heat as energy source and adopting advanced techniques for embedded systems power management, allows us to design an almost perpetual device integrated into a Wireless Sensor Networks.

Generally, energy harvesting techniques are used to recharge the batteries of embedded systems to extend the device lifetime [7]. In our work, we designed a harvesting circuit able to supply the system only with harnessed energy, so that the circuit does not require batteries. The low-power features of the sensor device allows us to build an energy neutral wireless sensor node. To demonstrate the feasibility of an energy neutral thermometer embedded in an heat-sink, we build a test-bed with commercial components, and performed a characterization of the architecture.

This article is organized as follows. In Section II we describe the features of the proposed SoC sensor. Section III presents the test-bed specification. In Section IV we discuss the performance of the system we obtained by measurement on our test-bed.

II. SYSTEM DESCRIPTION

The proposed SoC temperature sensor is depicted in Fig. 1. The bottom layer of the heat-sink embeds a circuit composed of a Thermo-Electric Generator (TEG), the conditioning and storage components, and a microcontroller with a radio transceiver. Possibly, the system can be extended to include external sensors for environmental monitoring. The TEG lies in the middle of the heat-sink to facilitate the placement over the hot-spot of the thermal source, and to collect the maximum amount of thermal energy. Fig. 2 represents a detailed functional schematic diagram of the proposed system together with the connection to a Wireless Sensor Node. We refer to the combination of thermal-electric generator, conditioning circuit and storage unit with the term TERS, which stands for Thermal Energy Recovery System. The electrical energy generated by the TEG is conditioned and stored in capacitors. A comparator is used to read the amount of harnessed energy. Once enough energy has been collected, the capacitor is

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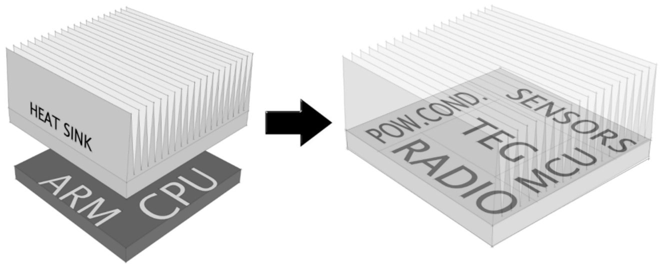

Fig. 1. Proposed SoC Design

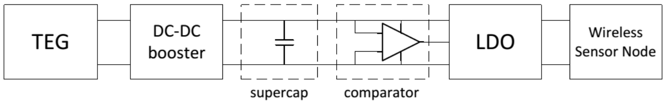

Fig. 2. Functional diagram of the proposed SoC implemented in a test-bed framework based on commercial devices for the proof of concept

discharged toward the device via a low dropout voltage (LDO) regulator to power the microcontroller and the transceiver. This system can be scaled to fit many different monitoring scenarios (given the current advances in CMOS technology) starting from few cm^2, which is the lower limit to realize an optimal thermal dissipation with a heat-sink. The lack of wires improves flexibility and reconfigurability while the wireless interface provides the digital interface.

III. PROTOTYPE EVALUATION

We realize a test-bed system made of commercial devices to validate the proposed conceptual design. The diagram in Fig. 3 illustrates the energy flow that logically links together the test-bed components. We used an ARM A15 CPU as target heat generator chip and we built a custom thermo-harvester made of two stacked Peltier cells (used in Seebeck configuration [8]) connected in series with a heat-sink on top. The output power has been conditioned and stored in capacitors and then used to power a wireless microcontroller to send radio beacons.

We characterize the efficiency of the TERS by studying the output current relative to the thermal gradient. Fig. 4 shows the data collected (blue dots, labelled “dataset”) and represents the empirical characteristic curve that models the input-output relation (ΔT vs. power) of the harvesting and storage system. The resulting model is a composite piece-wise continuous function of the temperature. The non linearity of the input output relationship is due to the variation of the efficiency of the TEG that depends on the thermal gradient (ΔT), and the efficiency of the conditioning circuit, especially the DC-DC booster. Therefore, the curve is composed of an initial exponential segment between 5° C and 20° C ofΔT, followed by a polynomial segment between 21° C and 31° C. For temperature over 32° C the input-output relation exhibits a linear behaviour. We do not model the system for temperature higher than 40° C since we never exceed this value with the proposed experimental setup.

We designed and built a thermal energy recovery and storage circuit (TERS) to supply a WSN node. The thermo-electric generator is made of two 40×40 mm^2 PE1-12706AC Peltier cells arranged in stack, and connected in series. The thermoharvester is placed on the CPU of a Samsung Exynos Arndale board[1] equipped with an Exynos 1.7 GHz dual-core ARM Cortex A15 processor with 2 GB DDR3 RAM @ 800 MHz that runs Linux Kernel version 3.10. A 2 mm thick Aluminum layer that acts as a heat spreader is placed in between the CPU package, and the hot-side of the bottom Peltier cell. A common heat-sink lies on top of the thermal harvester to facilitate thermal exchange to the cold-side of the top Peltier cell. We placed thermal glue in between each different component to guarantee a good thermal contact, and placed a 0.1 mm aluminum spreader between the two Peltier cells.

An electronic circuit manages, and stores the electric

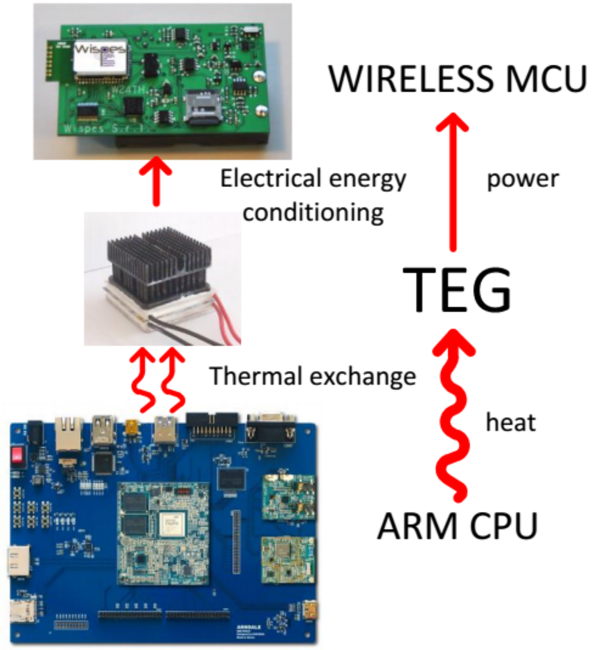

Fig. 3. Framework for the test-bed proof-of-concept system evaluation

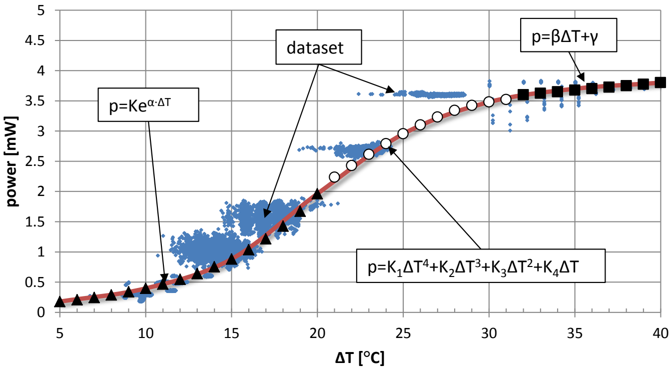

Fig. 4. Empirical characteristic of the thermoharvesting module. Knowing the energy required to transmit one single beacon packet and the frequency of transmission, it is possible to evaluate the energy harvested in a specific time interval and derive the temperature on the target chip surface by inverting this relationship.

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[1] Arndale Board [Technical Reference], “http://www.arndaleboard.org/wiki/-index.php/WiKi”

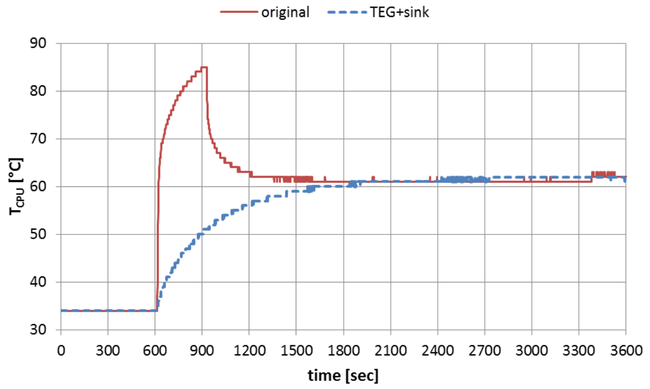

Fig. 5. Comparison of the CPU temperature with and without the proposed prototype

energy scavenged by the thermoelectric generator, and supplies the wireless node. The conditioning circuit is made of a cascade of a DC-DC boost converter, storage capacitors, a comparator, and a DC output voltage regulator (LDO). The LDO output is connected to the node power supply connectors. The boost converter is an electronic circuit able to provide at the output a voltage greater than its input voltage [9]. These circuits are widely used in harvesting applications, since harvesting generators produce an output voltage lower than the voltage required to supply embedded devices. A comparator is used to monitor if the amount of charge stored in the supercapacitors is enough to supply the wireless node. The comparator upper threshold is set using ladder components to $V_{max} = 2.48$ V, that is sufficient to power the micro-controller. The comparator digital output is monitored by an embedded system responsible to actuate the relay that opens and closes the connection from the capacitors to the sensor node according to the amount of energy present in the storage capacitors, thus controlling the WSN node activity. Once the stored energy crosses the V_{Max} threshold, the relay creates a path from the supercapacitors to the node power connectors. The storage circuit must be properly dimensioned to fit the power consumption of the wireless node. In this experiment we used three 3 F supercapacitors connected in series resulting in a 1 F storage unit. Thanks to the low internal resistance of the supercapacitors, it is possible to sustain the current peak required to supply the wireless node during its operation.

The WSN node is a W24TH produced by Wispes s.r.l.[2]. It is based on the powerful JN5148 microcontroller unit (MCU) from NXP-Jennic[3], which embeds a 32 bit MCU and a IEEE 802.15.4 compliant radio transceiver with its antenna. We configured the node to use a simple network protocol, built on top of the IEEE 802.15.4 MAC layer. Once the device is switched on it transmits a radio beacon to a sink node. Since the device activity depends on the amount of energy stored, which is directly related to the thermal gradient to which the thermoharvester is exposed to, the number of radio packets that the node can send is proportional to the temperature.

Before running our experiments, we make sure that the presence of the TERS on top of the CPU package does not cause CPU overheating. Figure 5 shows the temperature measured with the integrated sensor of the CPU when the Arndale switches from the Idle state to 100% load at clock frequency $f_{CLK} = 1.5$ GHz. With the standard package the temperature runs so high that the DVFS governor of the embedded systems scales down the clock frequency after 5 minutes to prevent damages. Our system guarantee to operate within the safe temperature region, since the CPU temperature never exceeds 62° C.

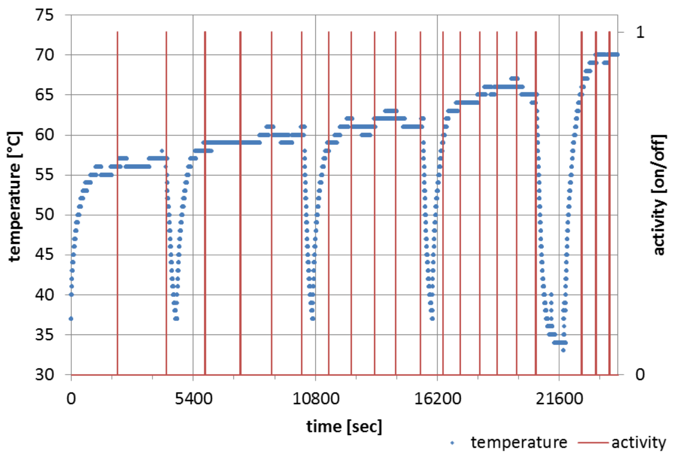

Fig. 6. Simulated beacon transmission frequency using a fixed load and a range of temperature profiles. The closer the vertical lines (beacons) the higher the frequency, hence the higher the temperature.

IV. RESULTS

We run both simulations and real tests. Firstly we evaluated the beacon transmission frequency using a fixed load, in place of the wireless transceiver, made of a $40\ \Omega$ resistor which resulted in an approximate 140 mW power consumption for 1 second activity. Results are shown in Fig. 6. In this case we selected a computationally intensive task (100% load) that was executed in the ARM CPU at different clock frequencies, each one for approximately 1 hour and half, that led to the temperature profile depicted. Accordingly, the beacon transmission frequency, depicted as a two-state sequence (activity-1/sleep-0), increases with the temperature as expected.

Fig. 7 presents the results of the simulated beacon frequency based on a generic input temperature sequence; Fig. 8 presents the results obtained with the real test-bed exposed to the same temperature profile. Results show a correlation between simulated and real performance. We achieved a 5-minute beacon interval with the non-optimized test-bed in case of $\sim 70°$ C ($45°$ C ΔT $+23°$ C of the environment) and 13 min. interval with $\sim 40°$ C. Considering the dimension and the power optimization achievable by SoC integration, we expect to increase the feedback frequency by at least one order of magnitude (30 s @ 70° C).

System characterization have been carried out with the Arndale working at a settled clock frequency ranging from 1.3 GHz up to 1.7 GHz, with 0.1 GHz steps. During the whole experiment, the Arndale performs a multi-thread mathematical application at 100% work load.

Tab. I summarizes a selection of the results shown in the pictures. Immediately, we can notice that the ARM CPU

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[2] Company website: http://www.wispes.com

[3] http://www.jennic.com/products/wireless_microcontrollers/jn5148

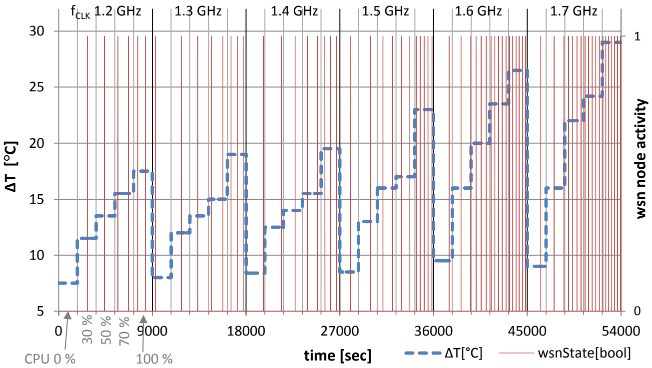

Fig. 7. Simulated beacon transmission frequency based on a generic input temperature sequence and the model of Fig. 4

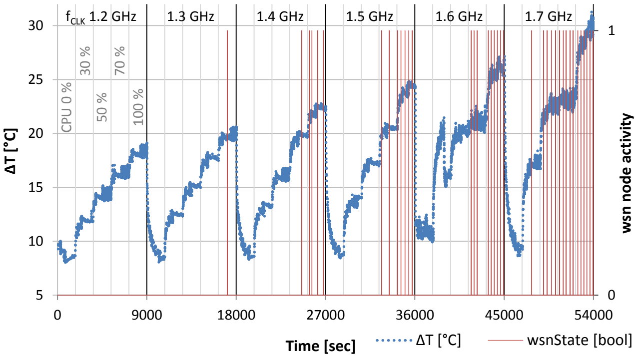

Fig. 8. Proof of concept, the real results on beacon transmission frequency obtained by reproducing the simulation test using the prototype harvester with supply to the wireless node

reached higher temperatures during the tests with fixed load than in real WSN case but the time interval between activities is longer. We evidently overestimated the power consumption of the real node to perform few operations and send the beacons. Actually, the node average consumption during activity is close to 50 mW. Another observation is that simulated and real results are close to each other, evidence that the model extracted for the prototype thermoharvester is valid. Fig. 9 depicts the sustainability curve of the prototype WSN node supplied with the prototype thermoharvester. The curve, obtained with empirical data clarifies the expected performance since the higher the ΔT the lower the frequency of transmitted beacons packet (monitoring interval in the picture).

V. CONCLUSION

We described the concept of an energy neutral wireless sensor supplied by the electric energy recovered by the heat dissipated by CPUs. We designed the system using commercial components to demonstrate the feasibility of the idea. The resulting proof-of-concept allows the Wireless Sensor Node to activate every 5 minutes. However, our future work is aimed to optimize the storage and step-up converter stage of the system and to realize a circuit embedded in the heat sink. We expect to achieve better performance with the integration and refinement of the circuit dimensioning.

TABLE I. COMPARISON BETWEEN SIMULATION RESULTS AND REAL EXPERIMENTS OF THE INTERVALS OF BEACON TRANSMISSION AT DIFFERENT CPU TEMPERATURES AND AT 100% WORKLOAD USING DIFFERENT OPERATING FREQUENCIES.

Test	T_{CPU} [°C] 1.5GHz	t [sec]	T_{CPU} [°C] 1.6GHz	t [sec]	T_{CPU} [°C] 1.7GHz	t [sec]
Fixed Load	62	1015	66	822	70	618
Simulation	50	372	52	307	57	284
Real WSN	50	380	52	310	57	300

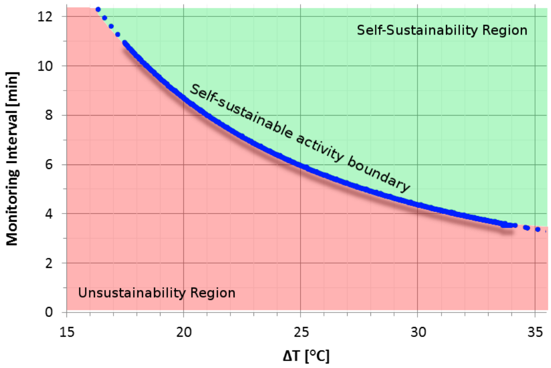

Fig. 9. Sustainability curve of the WSN powered by the harvester prototype.

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