Thermoelectric energy harvesting system for
demonstrating autonomous operation of a wireless
sensor node enabled by a multipurpose interface

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Abstract. This paper demonstrates the autonomous operation of a wireless sensor node exclusively powered by thermoelectric energy harvesting. Active operation of a wireless sensor system is demonstrated successfully by means of an on-line programmable emulation kit that enables various thermoelectric energy harvesting scenarios. Moreover, this emulation kit accomplishes autonomous wireless sensor node operation by interfacing a small-scaled thermogenerator via a CMOS integrated autonomous multipurpose energy harvesting interface circuit performing maximum power point tracking.

1. Introduction
The extremely large number of sensors in todays means of transportation such as automobiles, aircrafts, or trains require the reduction of the size of these sensor systems as well as the power drawn from the battery. Therefore, autonomous wireless sensor networks composed of self-sufficient tiny sensor nodes need to be applied [1].

In order to increase the sensor network energy efficiency, low power radio transmission protocols are necessary which ensure reliable and proper operation with respect to established specifications such as given by the automotive industry [1].

Thermoelectric energy harvesting is an attractive candidate for successfully meeting the powering challenge since various temperature gradients arise during transportation. Moreover, thermoelectric energy harvesting is suitable for real world applications because very small scaled off-the-shelf devices which provide high power densities such as Micropelt® thermogenerators (TEGs) allow efficient and miniaturized wireless sensor network solutions [2–4].

The reliable operation of wireless sensor nodes by means of energy harvesting requires interface circuits which optimize the ambient energy extraction and which manage the wireless sensor node powering. Furthermore, the storage of excessive harvested energy has to be controlled by these interfaces [4–7].
This paper presents the programmable thermoelectric energy harvesting emulation kit outlined in Figure 1 which is composed of a thermoelectric energy harvester, a CMOS integrated circuit (IC) for efficiently interfacing the energy harvester, and a wireless sensor application designed for automobile safety systems [1, 3, 6]. This emulation kit allows setting of a defined temperature difference across the thermoelectric energy harvester and triggering of wireless data transmissions. Autonomous sensor node operation is established by the CMOS integrated energy harvesting interface circuit that enables maximum power point (MPP) tracking (MPPT) [6].

Section 2 describes the applied thermogenerator while the interface is covered in Section 3. Section 4 details the emulation kit and autonomous wireless sensor node operation is verified in Section 5. Finally, in Section 6 the paper draws a conclusion.

2. Thermoelectric energy harvester
The used thermoelectric energy harvester is the TGP-751 thermogenerator from Micropelt® [3]. This energy harvester can be modeled by a DC voltage source in series to the internal resistance $R_{\text{TEG}}$ as shown in Figure 2 [4]. The open circuit voltage $V_{\text{TEGoc}}$ is generated because of the Seebeck effect and $R_{\text{TEG}}$ is the total series resistance of the thermoelectric legs.

Figure 1. Overview of the programmable thermoelectric energy harvesting emulation kit that enables various thermoelectric energy harvesting scenarios and the autonomous operation of a wireless sensor node by means of a multipurpose interface circuit.

Figure 2. Equivalent circuit model of the thermoelectric energy harvester.
The thermogenerator delivers maximum power $P_{\text{max}}$ when the load resistance $R_{\text{load}}$ matches the internal resistance $R_{\text{TEG}}$. The terminal voltage $V_{\text{TEG}}$ at the maximum power point ($V_{\text{MPP}}$) is therefore 50% of $V_{\text{TEGoc}}$. Hence, the maximum electrical load power $P_{\text{max}}$ can be given as

$$P_{\text{max}} = \frac{V_{\text{MPP}}^2}{R_{\text{TEG}}} = \frac{V_{\text{TEGoc}}^2}{4R_{\text{TEG}}} = \frac{(\alpha \Delta T)^2}{4R_{\text{TEG}}},$$

where $\alpha$ is the Seebeck coefficient and $\Delta T$ is the temperature difference across the harvester [4].

The Seebeck coefficient provided by the TGP-751 is specified to be 110 mV/K and the value of the internal resistance is specified to be 300 $\Omega$. Both characteristics are declared by the datasheet for an ambient temperature of 25 $^\circ$C [3]. Measured load power characteristics for different temperature differences across the applied thermogenerator are shown in Figure 3 and obviously the maximum power point occurs at a load resistance of around 300 $\Omega$.

3. Multipurpose energy harvesting interface

Figure 1 illustrates the applied self-sufficient multipurpose CMOS integrated energy harvesting interface circuit which is detailed in [6] and Figure 4 shows the prototype chip micrograph. This interface allows optimal electrical energy output of the thermogenerator by means of maximum power point tracking. In [6] this interface is applied for highly efficient energy harvesting with electromagnetic kinetic energy transducers that deliver AC voltages.

In contrast to that, this paper proposes the use of the same interface for DC sources such as thermogenerators. Thus, a multipurpose interface is introduced enabling the use of different physical principles with a single interface chip and the storage of the harvested energy in the energy buffer $C_{\text{buf}}$ as depicted in Figure 1. Using the harvested energy, a wireless sensor node connected to the interface as outlined in Figure 1 can be operated autonomously and reliably by the stabilized output voltage $V_{\text{stab}}$ regulated by the multipurpose energy harvesting interface.

Figure 4. Micrograph of the prototype interface chip fabricated in a 0.35 $\mu$m CMOS process [6].
4. Thermoelectric energy harvesting emulation kit

Figure 5 shows a photograph of the experimental emulation kit that is schematically shown in Figure 1. It is composed of a demonstrator board, peltier elements, thermogenerators, a wireless sensor node, and a radio base station.

The demonstrator board comprises the multipurpose energy harvesting interface IC and a microcontroller evaluation board (EFM32TG-STK3300 [8]). Two peltier elements and three identical thermogenerators (Micropelt® TGP-751 [3]) are sandwiched as shown in Figure 6. This sandwich allows defined temperature differences by cooling and heating the peltier elements accordingly via an on-off control. This control consists of a microcontroller implementation, the thermogenerator $\text{TEG}_{\text{temp}}$ (Figure 1) for sensing the current temperature difference, pushbuttons ($\text{P}_{\text{heat}}$ and $\text{P}_{\text{cool}}$) for setpoint programming and a power MOSFET used as actuating element.

The thermogenerator $\text{TEG}_{\text{har}}$ is the actual energy harvesting device and $\text{TEG}_{\text{MPP}}$ in conjunction with $R_{\text{MPP}}$ is used to track the maximum power point dynamically (Figure 1) [6, 7].

A sensor network for automobile safety systems as described in [1] is exemplified by the radio base station and the wireless sensor node. The pushbutton $\text{P}_{\text{sensor}}$ emulates the glass break sensor needed for the intrusion detection of this safety system and triggers radio transmissions.

Figure 7 presents the final emulation kit comprising the experimental kit that cooperates with a controller area network (CAN) [1]. The shown car window is monitored by the above mentioned automobile safety system and an intrusion indicated by the emulated glass break sensor is displayed on the computer screen completing a remote intrusion monitoring system.

Figure 5. Photograph of the experimental thermoelectric energy harvesting emulation kit.

Figure 6. Sandwich of peltier elements and thermogenerators to enable a defined temperature difference $\Delta T$ across the thermoelectric energy harvesting device.

Figure 7. Photograph of the final thermoelectric energy harvesting emulation kit.
5. Autonomous wireless sensor node operation

Figure 8 shows a measured cold start-up from a fully discharged energy buffer capacitor $C_{\text{buf}}$ for a temperature difference $\Delta T$ across the harvester of 9 K. The harvester output voltage $V_{\text{har}}$ is controlled up to the maximum power point voltage $V_{\text{MPP}}$ by the autonomous multipurpose interface in order to operate the harvester TEG$_{\text{har}}$ close to its maximum power point.

The stabilized output voltage $V_{\text{stab}}$ is controlled to 2.2 V in order to supply the wireless sensor node. The first voltage drop interval of $V_{\text{buf}}$ encircled in Figure 8 indicates the initialization of the wireless sensor node. Active radio transmission of the sensor node is shown by the next encircled voltage drops. The stabilized voltage $V_{\text{stab}}$ shows negligible influence due to these voltage drops and therefore reliable autonomous operation of the wireless sensor node is demonstrated.

Energy not used by the wireless sensor node or by the interface circuitry is stored in the energy buffer $C_{\text{buf}}$. In order to keep the system within the maximum allowed electrical operation conditions the interface circuit limits the buffer voltage $V_{\text{buf}}$ as shown in Figure 8 [1, 6].

6. Conclusion

Autonomous operation of a wireless sensor node without needing a pre-charged energy storage element is successfully demonstrated by means of the presented on-line programmable thermoelectric energy harvesting emulation kit. The self-sufficient CMOS integrated multipurpose energy harvesting interface circuitry implemented in the emulation kit operates the very small scaled off-the-shelf thermogenerator close to its maximum power point in order to optimize the ambient energy extraction. Moreover, this interface manages the powering of the wireless sensor node reliably and stores excessive harvested energy in an energy buffer.

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References

[1] Thewes M, Li X and Scholl G 2012 Proc. IEEE Int. Multi-Conf. on Systems, Signals and Devices (Chemnitz) pp 1–5
[2] Böttner H, Nurnus J, Schubert A and Volker F 2007 Proc. IEEE Int. Conf. on Thermoelectrics (Jeju) pp 306–309
[3] Micropelt GmbH http://www.micropelt.com/products/thermogenerator_package.php access date: 2013–09–27
[4] Kluge M, Samson D, Becker T, Gavrikov A, Bennemann B and Nurnus J 2010 Proc. PowerMEMS (Leuven) pp 2–3 2
[5] Manoli Y 2010 Proc. IEEE Eur. Solid-State Circuits Conf. (Seville) pp 27–36
[6] Leicht I, Maurath D and Manoli Y 2012 Proc. IEEE Eur. Solid-State Circuits Conf. (Bordeaux) pp 101–104
[7] Brunelli D, Moser C, Thiele L and Benini L 2009 IEEE Trans. Circuits Syst. I, Reg. Papers 56 2519–2528
[8] Energy Micro AS http://www.energymicro.com/downloads/tools-documents access date: 2013–09–27