Energy Harvesting for Wireless Communication Systems Using Thermogenerators

Loreto Mateu, Cosmin Codrea, Néstor Lucas, Markus Pollak and Peter Spies

***Abstract*— The system designed is an energy harvesting circuit that supplies power to a wireless communication module for transmitting sensor data to a receiver. A thermogenerator module (TEG) is employed to harvest energy from temperature gradients between a heat source, e.g. the human body, and the ambient. The output of the TEG is connected to a step-up dc-dc converter to increase the available voltage in order to supply a wireless communication module and to charge an energy storage element. A start-up IC is employed to power-up the switch-mode dc-dc converter. The present prototype employs a temperature sensor for data acquisition. The data transmission rate can be adjusted as a function of the available energy.**

Index Terms: Energy harvesting, thermogenerator, battery and power management, wireless communication.

I. INTRODUCTION

The need for ubiquitous electronics that helps the human being in everyday life, is rapidly growing with increasing features and possibilities of modern mobile terminal devices. One last drawback is the demand for power supplies that allow unlimited operating and stand-by times. A solution to tackle this problem relies on the development of devices and circuits which transform energy from the user's environment or directly from human power into electricity to supply electronic circuits and systems. This paper is focused on energy harvesting from human power. At this point, it is possible to draw a distinction between active and passive harvesting methods. The active powering of electronic devices takes place when the user of the electronic device has to undertake additional actions to generate power. On the other hand, passive energy harvesting assumes that the user is not forced to change his habits in order to generate energy. Thus, the power is harvested from the user's everyday actions [1].

There are several approaches to the energy harvesting scenario. The most common are electromagnetic, thermoelectric, electrostatic or piezoelectric generators. The major challenge of these energy autarkic systems relies in the optimization of the energy harvesting source parameters as a function of the human activity employed. Additionally, it is essential to match the generator to the load and to consume the transferred energy in an economical manner.

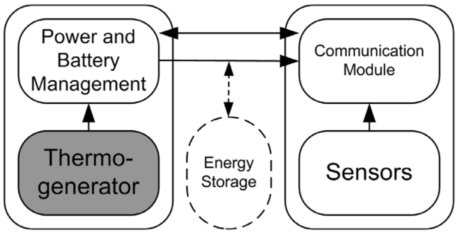

Fig. 1. System overview of the energy harvesting application.

The human body continuously radiates heat. Devices with direct contact to the human body can harvest this wasted energy by means of thermogenerators (TEGs). This valuable technology for self-sustaining power supplies consists of a thermocouple module that employs the temperature gradient between the hot (body) and cold (ambient) side of the thermopair to generate electrical energy. A significant constraint of this solution relies on the relative low temperature gradient in the range of 5 °C-10 °C, or even lower, between the human body and the environment. Therefore, low voltage differences are provided at the output of the TEG. Specific step-up DC-DC converters have to be used by a power management unit to supply an electrical load. Temperature differences, hence electrical energy, are not constant over the operating time, such that two scenarios can be distinguished. On one hand, the electrical load (e.g. a wireless communication module) is supplied only as long as TEG-power is available. On the other hand, accumulators in the form of capacitors or batteries can be employed to ensure continuous power.

In this paper, an energy harvesting application is presented. The energy is harvested from the existing temperature gradient between the human body and the environment employing a thermogenerator. It is used to supply power to a temperature sensor and a power efficient wireless communication module to transmit sensor data to a monitoring station. The employment of an energy storage element is considered as well. A simplified schematic of the application is depicted in Fig. 1. Special care has been taken in optimizing the functionality and the power consumption of the prototype.

The structure of the paper is as follows. Section II shows the state of the art of thermogenerators, as well as the characterization data of the selected TEGs. Section III describes the power management unit, that deals with the conversion of the low output voltage of the TEG to the voltage level required by the consumer electronics. Section IV addresses the selection of the energy storage element and a simplified low-power charging method. Section V focuses on low power design

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considerations for wireless communication. Finally, section VI draws the main conclusions of the paper.

II. ENERGY HARVESTING WITH THERMOGENERATORS

The thermogenerator (based on the Seebeck effect) produces an electrical voltage proportional to the temperature difference between hot and cold junctions. The heat that enters or leaves a junction of a thermoelectric device has two reasons: 1) the presence of a temperature gradient at the junction 2) the absorption or liberation of energy due to the Peltier effect [2]. A thermoelectric module generator basically consists of a thermocouple comprising a p-type and n-type semiconductor connected electrically in series and thermally in parallel. The electrical connection allows to add the voltage obtained at each thermocouple due to the Seebeck effect. Therefore, the output voltage of the TEG is proportional to the number of thermocouples and to the temperature gradient between the cold and the hot side.

The Seiko Thermic watch [3] meant a significant milestone. It uses a thermoelectric generator to convert heat from the wrist into electrical energy. It was the first watch to be powered by the temperature gradient between the body and environment temperature. The thermoelectric generator produces a power of at least $1.5\mu W$ when the temperature difference is in the range of $1\,^{\circ}\mathrm{C} - 3\,^{\circ}\mathrm{C}$.

Applied Digital Solutions [4] developed a miniature thermoelectric generator that converts body heat flow into 1.5V to run a watch or embedded medical applications. The TEG has a surface of $0.5cm^2$ and can generate $40\mu W$ at 3V with a $5\,^{\circ}\mathrm{C}$ difference in temperature. The energy generated is stored in a leading-edge thin-film battery.

Stordeur and Stark [5] developed a small compact thermoelectric generator whose output is compatible to the requirements of microelectronic and micro-matched system loads. The working range of this TEG is around room temperature, and not higher than 120 °C. It provides a power output of 20μW and a voltage of about 4V under load at ΔT = 20 K [6].

A. Design Considerations

Carnot efficiency sets an upper theoretical limit to the heat energy that can be recovered. The human body is a heat source and the temperature gradient between the body and the environment, e.g. room temperature (20 °C), can be employed by a TEG to obtain electrical energy. Starner [7] estimates that the Carnot efficiency at this temperature conditions is 5.5%. In a warmer environment the Carnot efficiency drops while it rises in a colder one. The previous calculations are made assuming that all the heat radiated by the human body can be recovered and transformed into electrical power, so that the obtained power is overestimated. A further issue of interest is the location of the device dedicated to capture human body heat. Starner recommends the neck as a good location for the TEG since it is part of the core region, those parts of the body that always must be warm. Moreover, the neck is an accessible part of the body and the engine can be easily removed by the user without creating discomfort. It is estimated that approximately a power between 0.2W-0.32W could be recovered by a neck brace.

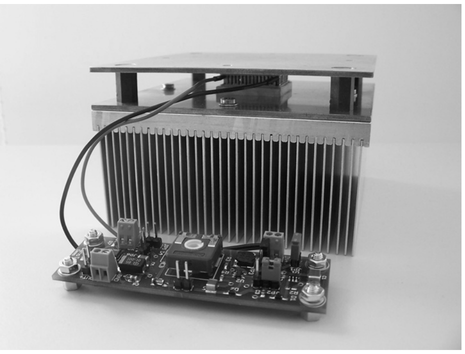

Fig. 2. Employed thermogenerator and the power management unit prototype.

Once the location of the TEG is decided, it is necessary to select the materials employed to fabricate the thermopair. This selection depends on the temperature ranges the thermogenerator must cope with. The conclusions of the work of Altenkirch [8] shows that good thermoelectric materials have large Seebeck coefficients, α, and electrical conductivity, σ, whereas they have low thermal conductivity, λ. These three variables are related with the figure of merit Z, (1).

$$Z = \frac{\alpha^2 \sigma}{\lambda} \tag{1}$$

Another way to define the figure of merit is ZT since Z varies with the temperature. Therefore, the ideal materials for a TEG employed at ambient temperatures should have a large value of ZT under this working conditions. The next step in the design of the TEG is the choice of the dimensions of the thermoelectric module. The maximum power obtained by a thermoelectric generator is proportional to A/l where A is the cross-sectional area and l is the length of a p-n thermoelectric leg couple. The power density is inversely proportional to the leg length. Specific power [W/cm^2] can be increased if the thermoelectric elements reduce their height while maintaining the aspect ratio of the legs. Ryan et. al. [9] predict a specific power around 0.5W/cm^2 for a 10K temperature gradient at room temperature with a figure of merit, ZT, equal to 0.9. Thermoelectric microconverters are expected to have an efficiency of 5-6% and to provide milliwatts of power at several volts. Microconverters can be employed to convert rejected heat into electric power, providing electricity and passive cooling at the same time. Ryan et al. also expound that by manipulating the electrical and thermal transport on the nanoscale it is possible to improve conversion efficiency and thus, ZT is predicted to increase by a factor of 2.5-3 near room temperature.

B. Characterization of the selected TEG

The TEG [10] used to power the wireless communication module was characterized and the results are presented in two different figures. Fig. 3 shows the voltage as a function of current for different ΔT. The value of the internal resistance, m, of the TEG was calculated for every ΔT. Fig. 4 shows

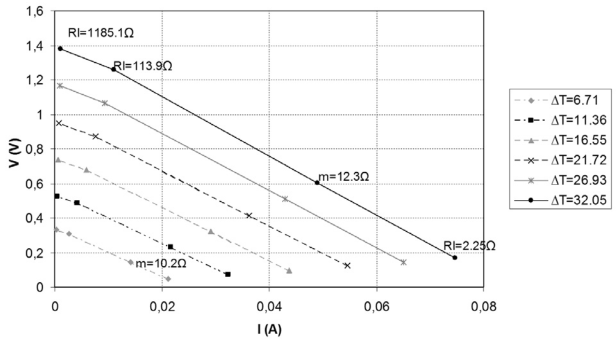

Fig. 3. Measured output characteristic of the TEG employed in the application. Voltage as a function of current for different ΔT. m is the calculated internal resistance of the TEG.

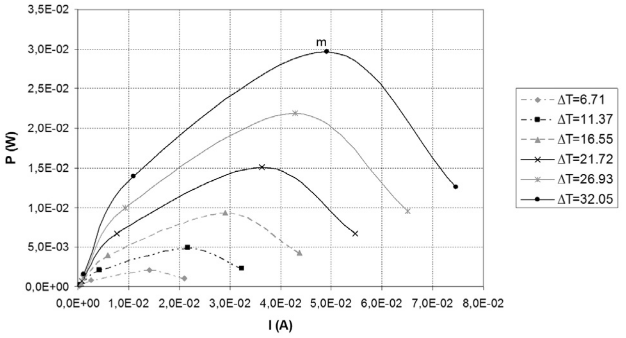

Fig. 4. Power as a function of current for the TEG employed in the application.

the power of the TEG as a function of current for the same values of ΔT. The maximum power is obtained when the output resistance connected to the TEG is equal to m. The TEG together with the power management unit prototype are shown in Fig. 2.

Chavez et. al. [11] and Lineykin et. al. [12] present a SPICE model of thermoelectric elements which makes simulations of the TEG and the power management unit possible. In order to simulate the response of the TEG it is necessary to characterize it in terms of these three parameters: the electrical resistance, m, the Seebeck coefficient, α, and the thermal resistance, Θ. Additional data related with the heat sink and the thermal silicon paste [13] is needed to complete the TEG equivalent circuit.

III. POWER MANAGEMENT UNIT

The power management unit is designed to convert input voltages in the order of few hundreds of millivolts into higher output voltages to supply the wireless communication module and to store the available energy into a storage element like a battery or a capacitor. Conventional step-up converters require input voltages of at least 0.8V to start regulating such that a single converter module cannot perform the specified energy transfer.

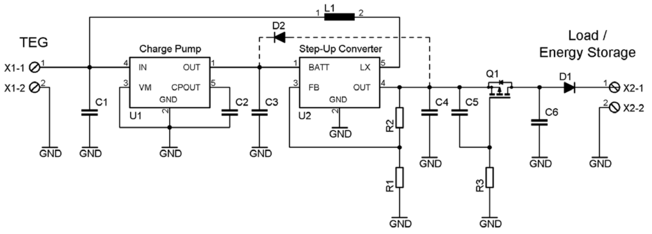

Fig. 5. Power management circuit.

A. Circuit Description

The designed power management circuit is shown in Fig. 5. It consists of a charge-pump [14] in conjunction with a step-up DC-DC converter [15]. The charge-pump delivers the necessary start-up-voltage to the switching circuitry of the step-up-converter which undertakes the energy conversion once activated. A picture of the PCB prototype is presented in Fig. 6.

Starting with input voltages as low as 250mV the charge-pump, $U1$, charges a high value capacitor, $C2$. As soon as it reaches a threshold of 1.8V, an internal transistor turns on and the 1.8V-charge is delivered to the output. Thus, the step-up converter, $U2$, starts switching by means of this available start-up energy. The charge-pump is not designed to supply constant power to a load such that the converter draws energy straight from the low voltage input of the circuit. Once the converter starts regulating and its output rises, it supplies its own control power by feeding the output voltage to the input of its switching circuitry by means of an internal diode, $D2$. Thus, the step-up converter enters stand-alone operation and keeps supplying a regulated output even though the input voltage decreases below the 250mV overall start-up margin. Switching at an input voltage as low as 150mV was recorded.

Care must be taken in the choice of the values of the required energy storage elements, i.e. the capacitor of the charge-pump, $C2$, and the inductor of the step-up-converter, $L1$. A trade-off must be made when dimensioning the value of the charge-pump capacitor. A high value capacitance is required to provide the necessary start-up power of the next stage, while a lower value reduces the start-up time. Thus, the lowest but still functional value was selected ($C2 = 100\mu F$). As the energy source is very restricted, current limitation issues are of no concern for the application. High inductor values may be employed by the step-up converter in order to reduce the minimal start-up voltage and to provide high efficiency as well. Thus a high value inductor was employed ($L1 = 330\mu H$). The output capacitor of the converter, $C4$, is critical as well. If its value is too large, the converter may be prevented from regulating the output with the available start-up energy. Here, a $1\mu F$ capacitance was employed.

A PMOS transistor, $Q1$, is required to delay upon power-up the connection of the converter's output to the electrical load or the energy storage element since at first it can not deliver enough energy for the stand-alone operation and the load. The time delay is set by $C5$ and $R3$ and it is in the order of tens of milliseconds.

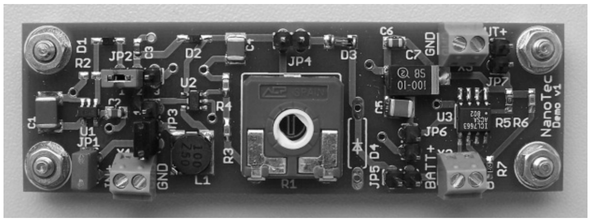

Fig. 6. The PCB prototype of the power management unit.

B. Measurement Results

The power management circuit was first tested at several input voltages under no load condition. An external power supply was employed as input energy source while the output was adjusted to 2.8V. The recorded input currents, I_{in}, are shown in Table I.

TABLE I
MEASUREMENTS OF THE INPUT VOLTAGE AND CHARGE PUMP CURRENT CONSUMPTION.

$V_{in}(mV)$	I_{in}
300	350μA
250	1.5mA
200	3.5mA
150	2.6mA
140	6mA
130	6.4mA

Next, a two-cell NiMH battery pack with an open circuit overall voltage of 1.8V was attached to the output of the step-up converter. Table II shows the charging results with an external power supply. The regulation efficiency, $\eta Regulation$, is calculated with the step-up converter output voltage, V_{out}, whereas the charging efficiency, $\eta Charging$, is calculated with the battery voltage, V_{bat}. The voltage difference is due to the drop over the PMOS transistor $Q1$ and diode $D1$. I_{bat} is the current flowing into the battery.

The external supply was replaced by the TEG introduced in Section II. By means of human body to ambient temperature difference the circuit was powered-up after around 100 seconds providing a regulated output of 2.8V. Upon power-up, the output voltage of the TEG dropped from 350mV to 250mV. The step-up converter kept regulating down to an input voltage of 150mV. Table III shows the measured as well as the calculated efficiency. The data sheet of the regulator [15] shows an efficiency of 70% at an input voltage of 1V and an input current of 10mA which is close to the value obtained with an input voltage around 300mV (see Tables II and III).

IV. ENERGY STORAGE

An energy storage element can be employed for two reasons. On one hand, it permanently accumulates the available energy delivered by the thermogenerator, even though no continuous power is demanded by the electronic application. On the other hand, if excessive power bursts, e.g. upon start-up or during transmission, are required, they can be drawn out of the energy buffer.

A. Accumulator Selection

The output voltage that must be provided by the power management unit depends on the supply voltage range required by the electrical load. The energy storage element must also be selected according to this criterion and the energy requirements of the load as well. Two possible storage elements are batteries and high value capacitors.

- Batteries. For a supply voltage range between 2V and 2.8V two-cell-NiMH [16] or one-cell-lithium-polymer with lithium-titanium-oxide [17] batteries can be taken into account. For higher supply voltages up to 4.2V, typical 3.7V lithium batteries can be selected.
- Capacitors. High value capacitors (Supercaps, Gold Caps, Ultra Caps) can replace the batteries. However, their capacity is generally lower than the one of batteries, they don't have a flat discharge curve and the limited voltage rating has also to be considered. An advantage is the higher power density, such that they can withstand higher current pulses.

B. Battery Management

For the application presented it is not required to make use of a conventional battery charger and thus energy and area can be saved.

A current-limit regulation loop is usually required to avoid overcharging during the fast charging stage of NiMH and lithium batteries [18]. The designed circuit takes advantage of the intrinsic current limiting characteristics of the TEG for charging the battery without the need of dedicated hardware. Additionally, the voltage-limit regulation loop is undertaken by the boost DC-DC converter since it provides the required charging voltage at the output of the power management unit. A battery charger is replaced though by a diode, $D1$, connected between the output of the regulator and the battery. Time-limited charge termination circuitry is also avoided by selecting a regulated voltage slightly below the maximum topping voltage specified by battery manufacturers. This approach is more advisable for lithium-polymer than for NiMH accumulators, since the latter suffer from memory effect degradation when the charging procedure is not completed.

This topology can be enhanced in terms of reliability by placing a Zener diode that limits the charging voltage in case of failure.

V. POWER-EFFICIENT WIRELESS COMMUNICATION AND TEMPERATURE SENSING

The energy that a TEG can harvest from the human body under regular room temperature or outdoor conditions is limited. Hence, an optimized, energy-aware operation of the employed communication module has a significant impact on the functionality and the runtime of the device.

Throughout the development of the presented prototype, a theoretical survey and a practical implementation of TEG powered wireless communication were covered. They are presented as follows.

TABLE II

MEASUREMENTS OF THE INPUT VOLTAGE AND CURRENT, OUTPUT VOLTAGE OF THE SWITCHING REGULATOR, BATTERY VOLTAGE AND CURRENT, AND EFFICIENCY WITH AN EXTERNAL POWER SUPPLY.

V$_{in}(mV)$	I$_{in}(mA)$	V$_{out}(V)$	V$_{bat}(V)$	I$_{bat}(\mu A)$	$\eta Regulation(\%)$	$\eta Charging(\%)$
300	10.33	2.44	2.06	897	70.63	59.63
250	9.8	2.42	2.068	659	65.09	55.62
200	9.35	2.408	2.072	436	56.14	48.31
150	8.8	2.381	2.07	227	40.95	35.6
140	8.66	2.374	2.07	186	36.42	31.76
130	8.45	2.365	2.07	146	31.43	27.51

TABLE III

MEASUREMENTS OF THE TEG VOLTAGE AND CURRENT, OUTPUT VOLTAGE OF THE SWITCHING REGULATOR, BATTERY VOLTAGE AND CURRENT, AND EFFICIENCY WITH A THERMOGENERATOR POWER SUPPLY.

$V_{in}(mV)$	$I_{in}(mA)$	$V_{out}(V)$	$V_{bat}(V)$	$I_{bat}(\mu A)$	$\eta Regulation(\%)$	$\eta Charging(\%)$
265	10.16	2.49	2.13	695	64.28	54.98
254	10	2.476	2.12	645	62.87	53.83
246	9.76	2.43	2.077	646	65.38	55.88
236	9.88	2.489	2.142	550	58.71	50.53

A. Selection of the appropriate communication protocol

ZigBee [19] seems to establish as a de-facto communication standard for Wireless Sensor Networks. However, across-the-board solutions are not always optimal for particular needs [20]. TEG powered transceivers can be more efficiently implemented using the Nordic [21] protocol for small data bursts or the EnOcean modules [22] which are a recently developed proprietary solution for energy autarkic sensing and data transmitting systems.

As ZigBee and Nordic share the 2.4GHz ISM band a direct comparison was made. With Nordic, improvements can be achieved in terms of:

- Radio Efficiency: defined as the ratio between the payload and the gross data rate. ZigBee's framing overhead of 120 bits is acceptable for long bursts. Nordic performs better for frames containing less than 200 bits of payload with its only 56 bits of overhead per frame.
- Time on Air (TOA): the duration of the data transmission has an impact on energy consumption. Nordic transmissions at a given data rate are four times faster than ZigBee (1Mbps vs. 250kbps) as seen in Fig. 7. A shorter TOA reduces also the probability of colliding with other devices emitting in the 2.4GHz ISM band (ZigBee, Bluetooth, WLAN). ZigBee is more prone to retransmissions, having thus a negative impact on power consumption.

The energy requirements of the low-power microcontroller-based Nordic communication module [21] were analyzed and are summarized in Table IV. Taking into account an approximate active periode of 1ms (shared between sensing, digitalization, RF processing and TOA) and an available current around $500\mu A$ (see Table III), a sensing and transmitting task is feasible by means of TEG-power every 40ms.

The Nordic module is designed for flexible, versatile, space-saving data acquisition and transmission. Its capabilities were analyzed here with the aid of a general purpose evaluation platform which is not optimized in terms of power consumption.. In order to take advantage of the outlined module's low power features further board design and optimization work is required. Therefore, for demonstration purpose the EnOcean RF sensor transmitter module was employed with the TEG and the presented power management module.

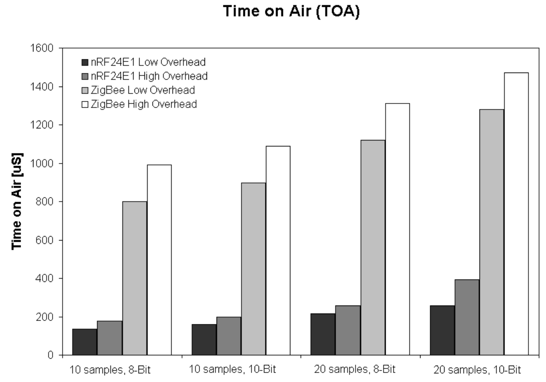

Fig. 7. Time on Air (TOA) for four types of data packets. Low overhead refers to standard framing requirements. High overhead includes transmitter address and burst ID. Nordic data rate is 1Mbps, ZigBee data rate is 250kbps.

TABLE IV

POWER REQUIREMENTS FOR THE NORDIC COMMUNICATION MODULE.

Power supply range	1.9V-3.6V
Current consumption in stand-by	$4\mu A$@1.9V
	140μA@2.5V
Current consumption in Tx mode	∼20mA
Current consumption in Rx mode (reliable only with $V_{DD} > 2.2V$)	∼18mA

TABLE V

Power requirements for the EnOcean communication module.

Power supply range	3V-4V
Current consumption in stand-by	∼25nA
Current consumption in Tx mode	Unknown
Current consumption in Rx mode	∼30mA

B. *Practical Implementation of TEG-powered Communication*

The EnOcean modules are focused on compact ”plug-and-play” solutions for self sufficient applications. The RF sensor transmitter module operates in the 868.3MHz ISM radio channel and has a proprietary telegram protocol. It can sense three analog and four digital inputs and transmit the measured and digitized (8 bit) values every one, ten or hundred seconds. The energy requirements are summarized in Table V. The board is power optimized and consumes 25nA in stand-by. The supply can be applied directly or through a supercap-buffered input.

A complete solution for energy autarkic wireless communication and temperature sensing was build. The EnOcean module is supplied by the presented TEG (see Section II) and the developed power management circuit (see Section III). A common lithium cell was employed as a storage element.

The RF transmitter can be continuously supplied by human power without a storage element. The body heat radiated by the human hand suffices for powering the sensor transmitter such that temperature measurements and wireless transmissions can be performed every second. The temperature was recorded by means of a power optimized NTC-based sensing circuit.

A reduced sensing and transmitting frequency combined with an energy storage element allow applications with lower available thermoelectrical energy, e.g. due to lower body or higher ambient temperatures. Dynamic power management can be applied as well, by adjusting the transmission rate with respect to the available energy.

The system was proven with energy storage elements as well. On one hand, a common lithium battery and on the other a supercap was employed. With both elements, the functionality of the system could be maintained with discontinuous available TEG power.

With the amount of energy harvested and made available by the presented system, no permanent receiver capabilities can be implemented neither with the EnOcean module nor with the Nordic module. The power consumption is too high to implement a continuous Rx-path.

VI. Conclusion

An energy harvesting application using thermogenerators (TEGs) was presented. The temperature gradient between the human body and the ambient was converted into electrical energy that was employed to transmit sensor data by means of a wireless communication module.

In order to dispose of the thermoelectrical energy, a power management unit consisting of a charge-pump and a step-up DC-DC regulator was designed. Thus, the available energy could be employed to supply a wireless communication module and to charge an energy storage element.

Energy-optimized wireless communication and temperature sensing was evaluated and implemented. Hence, transmission protocols and supply requirements of communication modules were analyzed.

A practical energy harvesting system was successfully build. RF transmissions and measurements are performed every second only with the heat radiated by the human body. An energy storage element can be attached as well to guarantee system functionality without permanently available thermoelectrical power

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