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A DEPENDABLE WIRELESS SENSOR NODE WITH SOLAR CELL HARVESTING FOR HARSH ENVIRONMENTS

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Abstract - Wireless sensor networks are nowadays used in many industrial and automotive applications for distributed sensing and instrumentation. This paper presents the design of a dependable wireless sensor node for the application in automotive engine test beds. The sensor node is autonomously powered by means of a solar cell harvester module, which allows for the continuous operation of the sensor even in periods of low ambient light conditions. The measurement module features a Pt1000 based low power evaluation circuitry for temperature monitoring and a circuitry to determine the available input power for energy budget estimation. Experimental results obtained under laboratory conditions and in an automotive testbed are presented to demonstrate the applicability of proposed design.

Keywords: Wireless sensor nodes, ambient energy harvesting, solar energy, automotive engine test bed

1. INTRODUCTION

Automotive powertrain and engine testing is an inherent part of the automotive development cycle and requires test setups with a large number of distributed sensors to monitor critical parameters (as e.g. temperature, vibrations, etc.). The sensors are typically connected by means of tailored wiring harnesses, which require high maintenance effort and which are difficult to handle in case of a failure. Driven by the industries needs for a flexible and easy-to-adapt measurement infrastructure, the research towards wireless sensor nodes for automotive test environments is of interest. E.g., the Europe’s FP7 funded project ’Dependable Embedded Wireless Infrastructure’ (DEWI) aims to foster the integration of wireless technology into industrial and automotive applications.

For the design of energy constrained wireless sensor nodes (WSN), energy harvesting concepts are a key enabler to overcome the limitations of battery based devices. A single battery supply will result in a limited node life span as the batteries discharge over time. In automotive environments, the sensor node is typically exposed to higher temperatures, e.g. in particular if mounted in the vicinity of the combustion engine or the exhaust system. Hence, the increased self-discharge of the batteries would lead to a further decrease of the available mission duration.

In this paper we propose the design of a dependable wireless sensor node based on ambient light harvesting for temperature monitoring in automotive engine test beds. The sensor node is intended to continuously operate for the duration of a complete engine test cycle (up to 10 hours) and should remain operative also in periods with limited or no harvesting capabilities.

The available power budget is strongly dictated by the environmental conditions. Typically, automotive test environments provide a rich well of solar energy due to the presence of high-power artificial light sources. However, in order to increase the node life span, the transmission and measurement rates of the WSN have to be adjusted according to the available power. Therefore the sensor node features a power management unit, which determines the delivered power from the solar cells.

Work towards the design of solar cell based WSNs has been proposed e.g. in [1] and [2]. In [2] a hybrid solution based on ambient light and thermal energy harvesting for indoor applications is discussed. A sensor node for vibration sensing measurement and energy scavenging capability based on a piezoelectric element for automotive applications is described in [3]. However, the feasibility of using a WSN based on ambient light harvesting in the challenging environment of engine test beds has not been reported so far. Hence, the work in this paper investigates the applicability of the harvesting principle and reports experimental results from field tests.

The paper is structured as following. Section 2 describes the architecture of the sensor node and highlights aspects of the circuitry design. The following sections investigate the energy budget with respect to the measurement rate. Section 4 describes a laboratory test setup and provides experimental results.

2. ARCHITECTURE OF THE SENSOR NODE

The system design of the sensor node prototype is depicted in Figure 1. The sensor node supports energy harvesting from different types of ambient energy sources and features an RF system on chip (SoC) module to establish a 2.4 GHz RF communication link to a base station. The sensor node architecture can be partitioned into the following two main building blocks:

- A power management unit comprising a harvesting module, measurement circuitry for monitoring the harvesting conditions and energy storage components.

- A low power RF module and a conditioning circuitry for a Pt1000 temperature sensor.

In the following, both sub-systems are briefly described. Further circuitry aspects of the harvesting subsystem are presented in the following sections and are discussed with respect to application constraints.

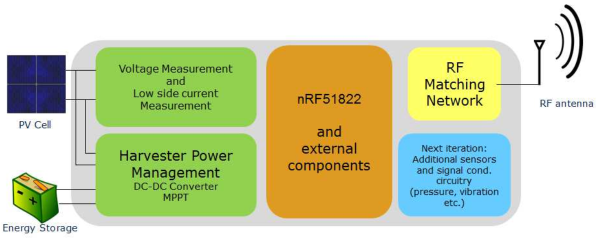


Fig. 1. Block diagram of the wireless sensor node with ambient light harvesting.

2.1. Description of the Power Management Unit

The central component of the power management sub system is an energy harvesting module, which performs the necessary DC-DC conversion while providing maximum power point (MPP) tracking. We use the device BQ25570 from Texas Instruments, which also accepts other ambient energy sources (e.g. thermal, piezo-generator etc.). An integrated step-up converter charges a super capacitor, if the photovoltaic (PV) cells provide a sufficiently high voltage level at the input. When reaching a pre-defined voltage level at the super capacitor, an output voltage of 1.85 V is generated by means of the integrated step-down converter. This is the supply voltage for the RF module and the measurement circuitry. To power the WSN, we use the solar cell AM-1417 fabricated from amorph silicon with an effective cell area of 3.5 cm^2.

In order to control the power consumption of the device (e.g. by changing the transmission rate), the power management unit requires information about the harvesting conditions. Therefore, the measurement unit depicted in Figure 2 is implemented, which provides signal conditioning for the following signals of interest:

- Voltage of the solar cell ('V_SOL').

- Voltage at the super capacitor ('V_SCAP').

- Current delivered by the solar cell. This current is measured by means of the shunt resistance 'R_SHUNT' in a low-side measurement configuration. The voltage drop across 'R_SHUNT' is amplified and provided as signal 'V_OUT' to the ADC.

The measurement signals are then processed by the micro controller core to estimate the available input power.

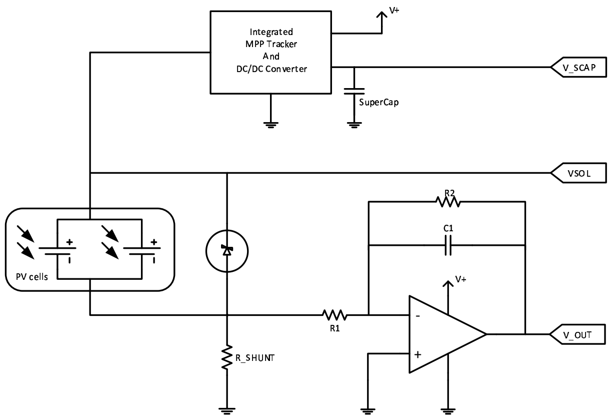


Fig. 2. Measurement circuitry to determine the harvesting conditions.

2.2. Description of the Measurement Sub-System

The 2.4 GHz RF module consists of a micro controller (μC) device based on the nRF51 family from Nordic. The RF antenna is implemented as printed circuit board (PCB) antenna and is connected through an impedance matching network to the RF module of the μC. The sensor node facilitates an interface circuitry to determine the temperature dependent resistance of an external Pt1000 element (compare Figure 3).

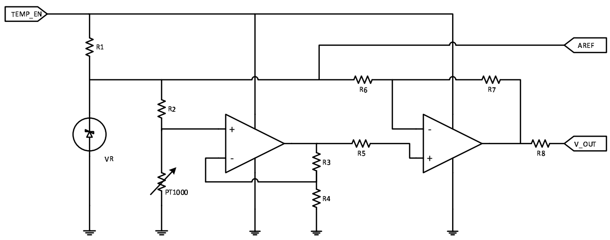


Fig. 3. Low power circuitry to measure the temperature dependent resistance of an external Pt1000 element.

The circuitry is enabled by means of the μC signal 'TEMPEN'. The analogue supply voltage 'AREF' is stabilized by means of a 1.25 V shunt voltage reference, which exhibits low power consumption and low temperature drift. The signal 'AREF' is also used as reference signal for the internal ADC of the μC. The temperature dependent voltage drop across the Pt1000 element is adjusted by means of the operational amplifier circuitry to exploit the full scale range of the internal ADC. The circuitry covers a temperature range from -40 °C up to 130 °C with a resolution of 0.17 °C. The peak power consumption for the temperature measurement amounts to 160 μA.

Together with the data provided by the external Pt1000 sensor, the measurement data is transmitted to the base station depending on a defined update rate (refer to section 3). The protocol development is based on the proprietary Gazell protocol from Nordic and implements a framework to manage the communication between the host and up to 8 sensor nodes.

2.3. Sensor Node Implementation

Figure 4 depicts a photo of an assembled sensor node. The outline dimensions of the sensor node (including the interface circuitry for the external Pt1000 element) amount to 45 mm x 20 mm x 8 mm. The solar cells are mounted on the bottom side of the printed circuit board (PCB), thus no additional space is required to accommodate the solar cells. The assembled PCB (except the antenna section) can be encapsulated (e.g. by means of molding) to provide a rugged assembly.

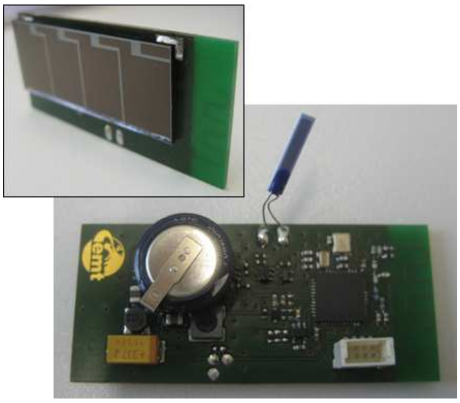


Fig. 4. Photography of the implemented sensor node. The solar cells can be mounted on the bottom side of the PCB.

2.4. Summary of Performance Figures

Based on a lab characterization, the performance of the harvesting subsystem has been investigated under different light conditions. The results of this study are summarized in Table 1. According to the building blocks of the harvester module, the data is grouped into the following sections:

- Data of the μC and the measurement circuitry.
- Choice and dimensions of the energy storage element.
- Delivered output power of the solar cells at different ambient light conditions.

For the calculations, a sensor update rate (measurement cycle and data transmission) of 0.1 Hz has been assumed. The corresponding averaged power consumption amounts to 12.6 μW. In this mode of operation, the sensor node can be powered by means of PV cells and can continue its operation for a period of more than 10 hours of darkness (i.e. in the absence of ambient light).

3. TRADING SENSOR UPDATE RATE VS. POWER CONSUMPTION

This section studies the impact of the sensor update rate on to the power consumption of the sensor node. The following system parameters are considered:

Table 1. Performance figures for the implemented prototype sensor node.

Description	Value
μC and Measurement Unit	
Sensor update rate	0.1 Hz
Supply voltage	1.85 V
Current consumption in active phase	3.5 mA
Efficiency of DC/DC converter in active phase	91 %
Duration of active phase	3.8 ms
Current consumption in passive mode	4 μA
Efficiency of DC/DC converter in passive phase	75 %
Required amount of electrical power	12.57 μW
Energy Storage Device	
Required buffer time	10 h
Efficiency of the energy storage unit	90 %
Required amount of stored energy	139.63 μWh
Super Capacitor	
Charging voltage	5.4 V
Shutdown voltage	2 V
Nominal Capacity	40 mF
Solar Cell	
Charging duration (harvesting period)	14 h
Efficiency DC-DC-PV	80 %
Required amount of energy during harvesting period	394.46 μWh
Required amount of electrical power	28.18 μW
Power per cell area - weak illumination (cloudy, no direct sunlight)	3.24 μW/cm^2
Total cell area / length	8.70 cm^2 / 2.95 cm
Power per cell area - good illumination (direct sunlight)	30 μW/cm^2
Total cell area / length	0.94 cm^2 / 0.97 cm

- Sensor update rate: the update rate determines the number of active phases per time. The active phase contains the μC wake-up time period, the measurement cycles and the duration for the data transmission to the base station.
- Required buffer time: this parameter refers to the longest time period the sensor should stay alive without solar cell harvesting. I.e. during this time period, the energy is only drawn from the backup storage element (super capacitor).

For the calculations, additional overhead due to fault tolerant communication schemes has not been considered. E.g. the number of re-transmissions in the case of missing or erroneous data packets increases the power consumption as well as protocol measures in the presence of electromagnetic disturbances (e.g. channel switching).

Figure 5 illustrates the relationship between the required solar cell power, the harvesting period and the sensor update rate, respectively.

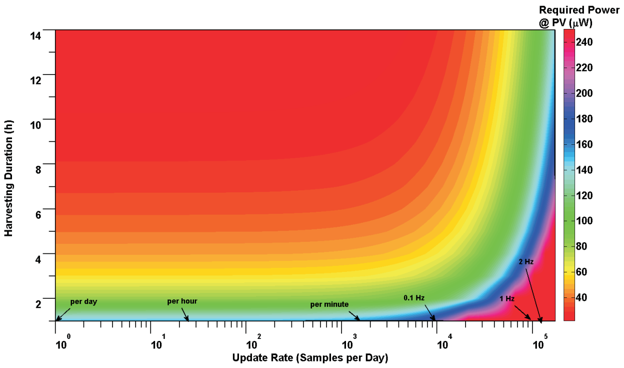


Fig. 5. Required power delivered by the solar cell for a buffer time of 10 h vs. update rate.

The harvesting duration denotes the time period in which the sensor node is able to harvest energy from ambient light. The results are plotted for a selected buffer time of 10 h. For sake of simplicity, an equal distribution of harvested energy vs. time is assumed. Although the real ambient light characteristics will not follow a linear relation, the required solar cell area can be roughly estimated based on this data.

4. EXPERIMENTAL SETUP AND RESULTS

Figure 6 sketches the implemented lab setup for the experimental characterization of the sensor nodes. The measurement data from the sensor nodes is collected by a base station and further processed by an attached host PC. For the experiments, five sensor prototypes equipped with solar cells have been assembled. Based on these experiments, a suitable configuration of PV cells and energy storage components is tested prior to the actual installation within a productive test bed.

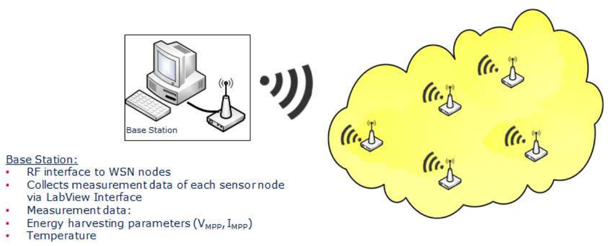


Fig. 6. Lab setup consisting of several sensor nodes and a central host.

4.1. Power Consumption Measurements

This section summarizes results obtained from laboratory experiments. Figure 7 depicts the measured current consumption of the sensor node in the active phase. Note that the immediate wake-up phase of the μC (power up of RF module, settling time of RF clocks) is not shown in Figure 7. The power consumption of the passive device in sleep mode amounts to 4 μA.

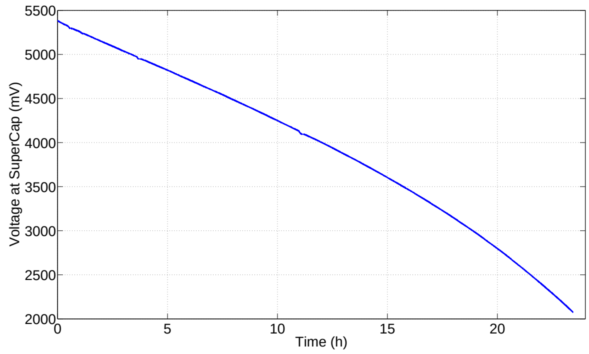


Fig. 8. Measured discharge curve of the super capacitor without solar cell (C= 0.47 F, 2 Hz sampling rate).

Figure 8 depicts the measured discharge curve of the super capacitor for a sensor node operating without solar cell harvesting, i.e. the solar cells have been detached to emulate a certain buffer time. The measurement data is transmitted with an update rate of 2 Hz. As can be seen the buffer time for the chosen super capacitor value equals almost 23.5 hours before the turn off voltage of about 2.1 V is reached.

4.2. Laboratory Experiments

In order to demonstrate the functionality of the sensor nodes, long term experiments in a laboratory environment have been performed. The main purpose of these tests is to validate the autonomous operation of the sensor nodes under different ambient light characteristics and to assess the network stability. During the experiments, each of the five prototype nodes continuously monitors the available solar cell power and the voltage level at the super capacitors. Both parameters provide an indication about the current harvesting conditions as well as the remaining life time during periods with little to no harvesting capabilities. In the following, measurement data of individual sensor nodes are discussed.

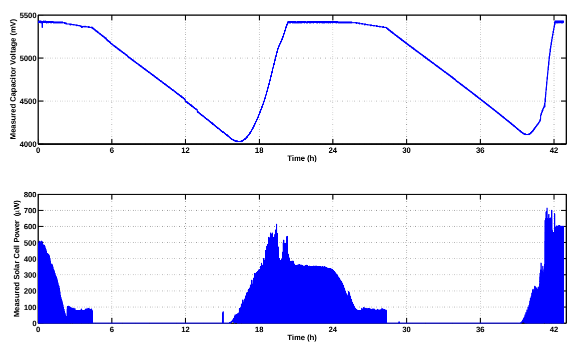
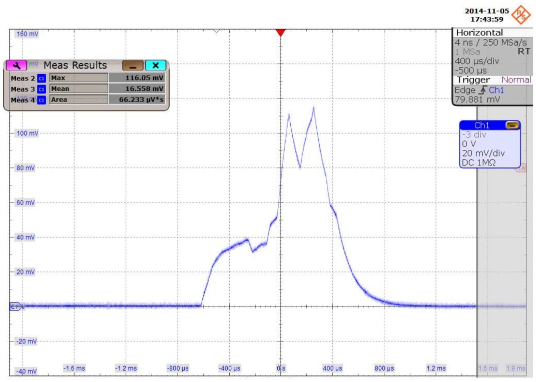
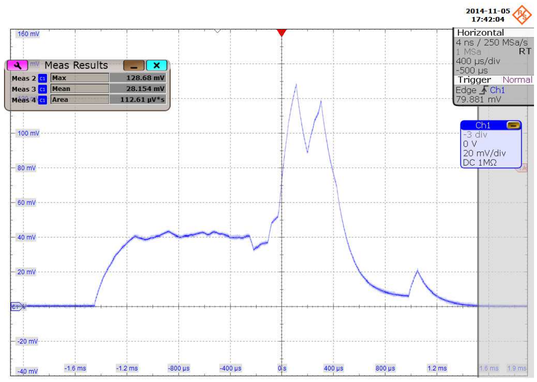


Fig. 9. Laboratory experiment with a duration of 43 hours using an update rate of 2 Hz at indoor light conditions.



(a)



(b)

Fig. 7. Current measurement with a shunt resistance of 10 Ω with (a) disabled measurement circuitry and (b) with active measurement circuitry.

Figure 9 presents measurement results obtained from a sensor node with an update rate of 2 Hz. The sensor is exposed to different ambient light conditions within a typical lab environment. As can be seen, the harvested energy provides a safe margin to continuously operate the sensor node also during night. With the presence of ambient light, the super capacitor is recharged within a period of few hours.

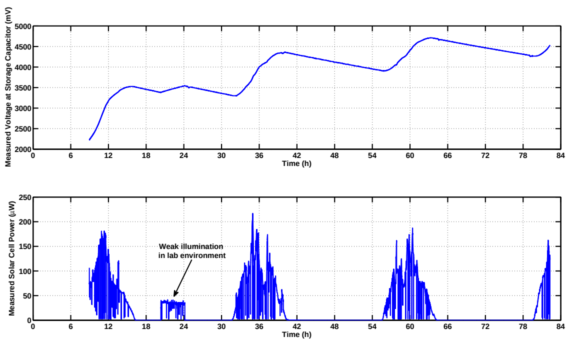


Fig. 10. Laboratory experiment with a duration of 82 hours at an update rate of 0.1 Hz at low illumination conditions.

Figure 10 presents the measurement results of a long term experiment for a period of more than 80 hours. Here, the update rate of the sensors has been set to 0.1 Hz. The sensor is exposed to ambient light arising from cloudy weather conditions (no direct sunlight). Therefore, the recharging process of the super capacitors during periods of positive energy balance requires more time. However, the sensor nodes still provide continuous operation with a safe margin. The super capacitor has been completely discharged at the beginning of the experiment. Therefore, the harvester module has to charge the super capacitor first in order to reach the turn-on voltage of the step down converter. When this voltage level is reached, the sensor node automatically connects to the base station for data transmission.

4.3. Automotive Testbed Experiments

This section reports the results of experiments conducted within an automotive engine testbed.

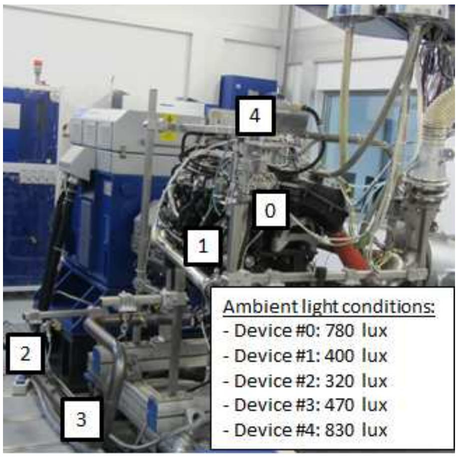


Fig. 11. Experimental setup in an automotive engine testbed. The sensor nodes are installed at different positions at the engine and at the exhaust pipe section. The illumination strengths measured at the beginning of the experiment are shown. Photo courtesy of [4].

Figure 11 depicts a photo of the setup showing the installation positions of the nodes. The experiment aims at demonstrating the continuous operation of the nodes under the illumination characteristics of a testbed environment. Furthermore, the harvesting conditions with respect to the time of day are assessed by means of the node measurements. During the experiment, no engine tests have been performed. I.e., temperature effects and electromagnetic influences have not been observed during the experiment. Figure 11 summarizes the illumination strengths measured with a luxmeter at each device position at the beginning of the experiment. The illumination strengths are rather low and range from 320 lux for positions in the bottom area up to 800 lux on the topmost location. Based on

these measurements, three devices (labeled with IDs 0 to 2) have been equipped with 2 solar cell panels of type AM-1417 connected in parallel. This corresponds to a total cell area of 980 mm^2 and should provide enough power also under low light conditions (compare Table 1). The remaining devices are powered from a single cell array with an active cell area of 490 mm^2.
In order to characterize the harvesting conditions, the sensor nodes continuously monitor the available input power by means of the measurement unit presented in section 2.1. As changes in illumination occur rather slow, the measurement rate has been set to 1 Hz. Five consecutive measurements are bundled to a data packet and transmitted to the host system. Figure 12 depicts the measured solar cell voltage and the delivered cell current of the solar cell in the maximum power point for the complete experiment duration of about 22 hours. The maximum power point is automatically tracked by the energy harvesting module.

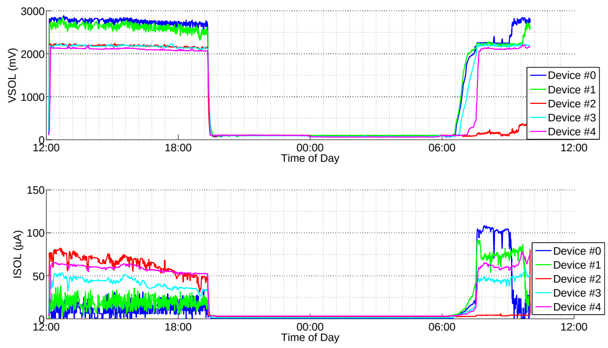


Fig. 12. Measured solar cell voltage ('V_SOL') and current delivered by the solar cell ('I_SOL') in the maximum power point. The measurement data is processed by means of a moving average filter with a filter length 20. Therefore, fluctuations of the observed cell voltage due to the power point tracking operation are smoothed.

The available energy budget of each sensor node can be assessed by means of the measured capacitor voltage trend (compare Figure 13). After the shutdown of the testbed, the capacitor voltage slowly decreases as the energy is solely provided from the super capacitor (for a time period of about 10 h). With the presence of ambient light, the harvester module restarts operation and again charges the capacitor. The harvesting module of device 2 shows a delayed operation as it has been partially shielded by a mistakenly placed testbed equipment. However, all sensor nodes have remained active during the experiment.

5. CONCLUSION

This work presents the design of a self-sustaining wireless sensor node for distributed temperature monitoring in harsh environments. The sensor node is autonomously powered by means of ambient light energy scavenging and

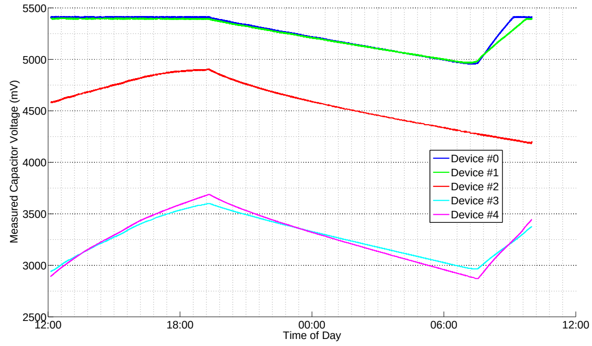


Fig. 13. Measured voltage at the super capacitor ('V_SCAP'). The harvesting modules are able to recharge the capacitors even after longer durations with litte to no ambient light.

features a power management unit in order to determine the harvesting conditions. The continuous operation of the sensor node has been successfully demonstrated in an automotive engine testbed.

ACKNOWLEDGMENTS

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