Durable Solar Energy Harvesting from Limited Ambient Energy Income

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***Abstract*—Typical wireless sensor network applications in the domain of environmental monitoring require or profit from extended system lifetime. However, restrictions in sensor node resources, especially due to the usage of capacity limited batteries, forbid these desired lifetimes to be reached. As opposed to batteries, energy harvesting from ambient energy sources enables for near-perpetual supply of sensor nodes, as the utilized energy source is inexhaustible. Nevertheless, the supply from ambient energy sources is rate-limited, wherein this supply-rate is mainly defined by the system deployment location. On the other hand, the attached sensor node has a consumption-rate, which has to be supplied to guarantee continuous node operation. In this paper, we address the matching of supply-rate and consumption-rate in solar energy harvesting systems at locations with limited insolation. The focus lies on the reduction of harvester energy overhead, which in low-duty cycled system easily reaches similar or higher consumption levels than the load it supplies. We suggest and present two harvester architectures [1], that have their main design consideration on simplicity. The individual modules of the architectures are tested and verified in laboratory measurements and we evaluate the fully implemented systems in an outdoor deployment. Based on the laboratory results, implementation choices for the architecture modules have been made. Whereas both harvesting architectures continuously supplied the attached load during the deployment period, we were able to compare their behavior with each other and present individual advantages and drawbacks.**

***Keywords*-energy harvesting; environmental monitoring; wireless sensor networks; energy sources; node lifetime**

I. Introduction

According to general believe, Wireless Sensor Networks (WSN) have the possibility to revolutionize the way we perceive and interact with our environment [2]–[4]. Combining sensing, control, processing and communication capabilities in relative small and inexpensive measurement systems, allows sampling at large-scale with high temporal and spatial resolution. This in turn offers advantages in a plethora of different application domains, increasing efficiency of existing applications and enabling a set of completely new functions.

In Environmental Monitoring, as one of these application domains, WSNs offer distributed and autonomous measurements with automatic data acquisition possibilities. Large areas of interest can be observed with a scalable number of sensing stations and flexibility in their positioning, while not demanding increased human interaction. Furthermore, connectivity through the network infrastructure allows sample transfer from all sensor nodes to a desired gathering point and remote access and control of these nodes.

Table I
Typical energy harvesting sources and power levels available in outdoor environments [8], [9]

Energy source	Power density	Condition
Solar	$100\,\mathrm{mW\,cm^{-2}}$	direct sunlight, outdoors
Wind	$100\,\mathrm{mW\,cm^{-2}}$	$9\,\mathrm{m\,s^{-1}}$, $10\,\mathrm{m}$ altitude
Ambient RF	$< 1\,\mathrm{\mu W\,cm^{-2}}$	unless close to emission source
Thermo-Electric	$60\,\mathrm{\mu W\,cm^{-2}}$	at $5\,^{\circ}\mathrm{C}$ temperature difference

Nevertheless, application setup and deployment can require considerable amount of time and money [5]–[7], especially when numerous sensor nodes are involved. Therefore, lifetime and maintenance demands become an important issue, defining economical feasibility of this technology. Ideally, system operation should be indefinitely, uninterrupted and without requiring human involvement.

As an active electronic system, one primal requirement for system autonomy is the constant supply of power. Due to the typical inaccessibility of a fixed power infrastructure, energy storage devices - usually in form of batteries - are used as power sources. Though, as energy storage capacity of these devices is limited, autonomous lifetime of the systems these devices power, is inevitably limited as well.

As a result, energy harvesting attracts increasing attention in research involving Wireless Sensor Networks. Harnessing available ambient energy, such as from wind, sun, vibrations or temperature gradients, energy reservoirs in storage devices of limited capacity can be recharged on a regular basis. Because these ambient energy sources are not limited in their energy capacity (i.e., they are inexhaustible), but only in their supply rate, matching their supply rate with the load consumption demand enables perpetual energy supply.

Table I provides an overview of expectable power densities for different ambient energy sources, typically available to outdoor environmental sensor networks. While power densities can be quite high, it is strongly depending on deployment location and environment.

Solar energy harvesting is the most frequently used form of energy harvesting in outdoor Wireless Sensor Networks, which might find explanation in several of its properties. (i) Its conversion technology is rather mature and low-cost, because of the use in macro-scale energy production. (ii) Power densities are often sufficiently high. (iii) Available energy spreads over a wide area and conversion rate is easily scalable, and (iv) conversion does not require mechanical parts, leading to higher maintenance requirements.

Nonetheless, also for solar energy harvesting, achievable conversion rates are highly location specific. This means while there are locations providing good harvesting possibilities, there are also those where solar radiation is limited and insolation unequally distributed over the year. Research targeting micro-solar energy harvesting systems for the former case is documented plentiful in literature. Opposed to that, systems addressing low solar radiation environments are strictly limited.

In this paper, we address the issue of limited irradiation conditions for solar energy harvesting based outdoor sensor networks. The general architecture of solar energy harvesting power supplies is presented and analyzed towards limitations for use in low irradiance situations. Design considerations are made to allow the sufficient conversion of light into electricity for powering sensor sample-and-send sensor nodes in Environmental Wireless Sensor Networks, while at the same time avoiding lifetime limitations due to battery storage devices. Herein, the focus of the system lies on providing sufficient energy levels, guaranteeing uninterrupted operation at all times, opposed to optimization towards efficient energy conversion at times of strong irradiation.

The remainder of the paper is organized as follows. The next section summarizes a subset of existing related work in the area of solar energy harvesting systems. After that, Section III provides theory on general solar energy harvesting system architecture, location influence and application requirements, leading to the design considerations of solar power supplies for the intended scenario. Section IV will present measurement and evaluation setups, followed by measurement results, resulting system architecture and its evaluation in Section V. Finally, Section VI will conclude the results obtained.

II. Related Work

Plenty of work has been done in Wireless Sensor Networks for Environmental Monitoring, as typical applications in this domain gain from measurement capabilities this technology can provide. To mention only a small subset of the work presented in this area, applications include monitoring of bird nesting behavior [2], observations of glacier movement [10], monitoring of volcano activity [5] and analysis of rainforest environments [11].

Nonetheless, while usually large-scale deployments with numerous sensor nodes are expected, most deployments are at a proof-of-concept stage with limited coverage and amount of sensing stations. Likely reasons for this are high cost for system setup and maintenance. In turn, a major part in maintenance is the replacement of depleting energy storage devices, limiting the period of unattended sensor operation.

Energy harvesting has gained more attention, as it can replenish energy reservoirs from ambient energy sources. Types of energy sources cover a broad area, including solar, wind, water flow, vibration, temperature difference and even pH differences in trees [12]–[15]. While the availability of the energy source is highly application dependent, in outdoor environments (i.e., the typical deployment location for environmental monitoring applications) solar energy is almost ubiquitous.

Existing solar energy harvesting systems are presented amongst others in [16]–[19]. Distinction exists between implemented storage devices, charge circuitry and system management (i.e., mainly hardware vs. software control). Typical energy storage devices include Nickel-Metal Hydride (NiMH) batteries, Lithium-Ion (Li-Ion) batteries and Electrochemical Double Layer Capacitors (EDLC), coming each with their advantages and disadvantages.

Systems embedding NiMH batteries include the ones introduced in [17], [20], [21], while Li-Ion based systems are presented in [19], [22]. Due to the limitation of charge cycles, several solutions resulted, combining rechargeable batteries with EDLCs (also known as supercapacitors or ultracapacitors), leading to extended system lifetime [16], [23]. A set of systems, purely relying on Electrochemical Double Layer Capacitors as their storage type, is demonstrated in [1], [18].

Relating to energy extraction, a topic of discussion is Maximum Power Point Tracking (MPPT) for the solar panel. Reference [24] provides a broad overview of different MPPT techniques, whereas not all of them are applicable in micro-solar energy harvesting systems due to energy overhead concerns. Most often used are methods such as *perturb-and-observe*, *hill-climbing*, as well as *fractional open-circuit voltage* and *fractional short-circuit current*.

Micro-solar energy harvesting systems comprehending MPPT techniques are those in [18], [21], [25]. However, some of the methods used yield only limited performance. Arguments against the use of Maximum Power Point Trackers, especially in applications with low power output, are raised in [26].

Work concerning low irradiation conditions is very limited. Reference [11] mentions problems regarding restricted solar availability due to shading in their deployment. Moreover, in [26] limited power income is a major design consideration, but the application addressed is indoors and therefore energy availability is more predictable and constant.

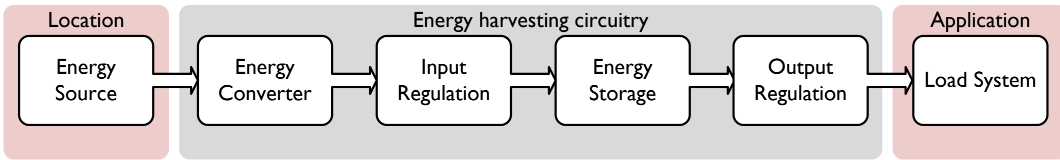


Figure 1. Modular structure of a general energy harvesting system

III. Theory

The underlying architecture of micro solar energy harvesting systems contains modules for energy conversion, energy storage, as well as energy management. While the existence of these modules is conventional, the way of implementation and necessity of additional circuitry varies between systems. Typical differentiation is made between storage types, charge circuitry, energy conditioning, as well as general system complexity. These different design considerations are mainly based on application and location constraints, i.e., expected conversion and consumption rates.

In this section, we will analyze the general architecture of micro solar energy harvesting systems and introduce application and location limitations in our system scenario. Based on these design constraints, we will suggest two harvester architectures.

A. Solar Energy Harvesting

Solar energy harvesting is one of the most common ways of employing ambient energy sources, supporting or replacing battery power supplies in distributed sensor networks. Figure 1 depicts the typical modular structure of an energy harvesting system. While the ambient energy source itself and the load system can be considered as external modules, both have a strong influence on system operation. In turn, energy source availability is depending highly on the system location, as well as load system demands are based on the application. As these factors have considerable impact on the system performance, a more detailed analysis will follow.

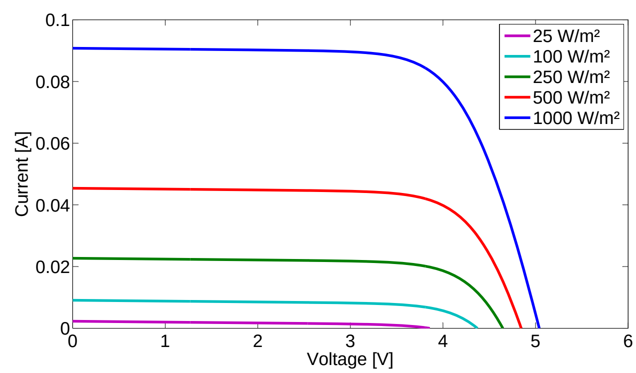
The energy harvesting circuitry itself acts as an intermediate module between energy source and load. It contains a conversion module, an energy buffer, as well as typically some sort of input and output regulation.

1) Solar Energy Conversion: Solar cells are used to convert sunlight into direct electrical current, using the photovoltaic effect. In micro solar energy harvesting for distributed sensor systems, size and cost are typical constraining factors. Depending on load system consumption, number of nodes and deployment location, typical solar panels in use rate between hundreds of milliwatt and a few watt.

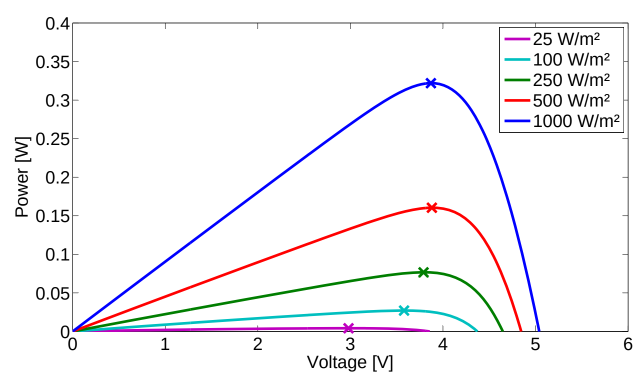
The output current of a photovoltaic cell is mainly dependent on its terminal voltage and the light intensity, irradiating the cell. This relation is typically described with a solar panel's IV-curve, such as depicted in Figure 2a. The higher the quality of the solar panel, the more its IV-curve will match a rectangle. This is described in the fill-factor of a solar panel, describing its maximum performance in relation to its theoretical maximum performance. The fill-factor is defined as

$$FF = \frac{P_{mpp}}{V_{oc} \cdot I_{sc}} , \quad (1)$$

with P_{mpp} being the maximum extractable power, V_{oc} the solar panel's open-circuit voltage and I_{sc} its short-circuit current. The operating point of maximum extracted power is the solar panel's maximum power point (MPP). However, the maximum power point will change with varying irradiance levels, thus being an irradiance dependent maximum power point function. The maximum power points of the solar



(a)



(b)

Figure 2. Typical relationships of (a) – current and voltage (IV-curve) and (b) – power and voltage (PV-curve) of a small scale solar panel under different irradiance levels

Table II
OVERVIEW OF MAIN CHARACTERISTICS FOR DIFFERENT STORAGE TYPES; BASED ON [28]

Type	Voltage [V]	Energy Density [$\mathrm{W\,h\,kg^{-1}}$]	Self-discharge [%/month]	Cycles [#]	Toxicity
Lead-Acid	2	30-50	5	200-300	high
NiCd	1.2	40-80	20	1500	high
NiMH	1.2	60-120	30	500	low
Li-Ion	3.6	100-150	< 10	1000	low
DLC[1]	2.5-5.5	1-5	several/day	>500000	low

panel underlying Figure 2a are marked in its PV-curves in Figure 2b.

2) Energy Storage: In systems, where the load should be supplied continuously, an energy buffer is necessary. This is, to supply the load from a reservoir at times of insufficient energy income from the ambient energy source. For solar energy harvesting, this typically occurs in a daily cycle. However, impact of the daily cycle itself can be depending on an additional seasonal cycle. The desire is, what in [27] is called energy-neutral operation. At any moment in time, available energy should be greater or equal to the required energy for supplying the load. That is,

$$P_{solar}(t) + P_{store}(t) \geq P_{load}(t) + P_{loss}(t)\,, \qquad (2)$$

where P_{solar} is the power extracted from the solar panel, P_{store} the extractable power from the energy storage, P_{load} the load power consumption and P_{loss} represents storage and conversion losses.

Different types of storage elements have been implemented, with the most common choice being rechargeable batteries. However, alternatively also electrochemical double layer capacitors are used. An overview of properties of typically used technologies is provided in Table II. While rechargeable batteries offer higher energy densities and lower self-discharge rates, leading to be more suitable for long-term storage applications, their overall lifetime and number of recharge cycles is strictly limited. On the other hand, DLCs have long lifetimes and can be charged easily and fast, though their low energy density and high leakage circumvent long-term storage.

3) Input Regulation: The input regulation module usually fulfills two tasks in solar energy harvesting. On the one hand, it adjusts the energy input to meet requirements for further use. On the other hand, it allows to alter the operating point of the solar panel, to extract maximum power.

While input adjustment mainly depends on output levels of the solar panel and the respective storage technology in use, it can be found to some extend in almost all system architectures. Typically implemented functions include reverse-current protection, charge management for the storage device, as well as voltage level adjustments. Opposed to this, Maximum Power Point Tracking (MPPT) is an optional function and its effectiveness in micro solar energy harvesters is not always clear. This is, due to the rather high energy consumption of the tracking solution itself compared to the efficiency gain it will lead to. As the energy consumption of the tracker does not scale down well, systems with low energy harvesting might reduce efficiency when using MPPT [25].

4) Output Regulation: As opposed to the input regulation, the output regulation usually only provides one function which is the adjustment of the harvester's output voltage to an appropriate level for the attached load system. The necessity and the form of implementation purely depends on the energy storage device used in the harvesting system. While systems based on Li-Ion batteries typically do not require voltage adjustments, most of the other storage implementations do. In the majority of cases a step-up regulator which boosts the voltage of the energy buffer is involved. In some cases, implementation of these regulators can be avoided by raising the storage voltage due to the series connection of several storage cells. However, this, in turn, will lead to an increase in both cost and size of the harvester.

The boost operation of the step-up regulator can be formulated as

$$V_{out} = V_{bat} \cdot \frac{I_{bat}}{I_{out}} \cdot \eta\,, \qquad (3)$$

where V_{out}, V_{bat}, I_{out} and I_{bat} are the voltages and currents of the battery and the regulator respectively, and η is the conversion efficiency which typically is a function of the previous parameters. Important dimensioning factors for the use in these applications are, on the one hand, the power consumption of the regulator itself and, on the other, the conversion efficiency. As the latter can vary significantly, a regulator with high efficiencies for the expected input and output parameters should be selected.

B. Application Considerations

As mentioned previously, the application parameters have a considerable influence on the energy harvester design. This is, because energy supply from the ambient source which is rate-limited and the consumption of the load have to match to guarantee continuous operation. As the application determines the sensor nodes tasks and thus their energy demands, the application has to be considered in the design of the harvesting system.

The typical applications that are in focus of this work involve Environmental Monitoring Wireless Sensor Networks. In particular, we consider applications which gather data from a large-scale area in a time-driven manner. As a result of this, the sensor nodes in the network follow a periodical work scheme which is determined by the desired sampling rate of the gathering application. Therefore, the workload of the sensor nodes is predictable which allows for relatively accurate estimation of their power consumption.

Figure 3 depicts a typical network organization in these types of applications. The architecture is organized hierarchically in a cluster-star topology. This leads to a great number of simple sensor nodes, while only a smaller subset of sensor nodes is involved in a multi-hop backbone network. These clusterheads, in turn, are usually equipped with more resources to balance their increased workload. In addition, the backbone network is connected via a gateway node to a server which stores the collected data and allows for remote access to the network. As there is usually a distance between the deployment site and operator, the communication link between the gateway and server involves remote communication technology (i.e., typically long-range RF, satellite or GSM/GPRS).

Because of the large number of sensor nodes that are expected in these types of applications, maintenance of each individual sensor node in the network is not feasible. The sensor node lifetime should thus be as long as possible to allow for extended data collection periods. Based on the periodical workload of the sensor nodes, duty-cycling is an efficient way to reduce their overall power consumption. The sensor nodes thus follow a defined schedule of active and inactive periods which enables for estimation of their average power consumption according to

$$P_{avg} = \delta \cdot P_{active} + (1 - \delta) \cdot P_{inactive}\,, \quad (4)$$

$$0 < \delta < 1\,. \quad (5)$$

In this case δ is the duty-cycle rate and P_{avg}, P_{active} and $P_{inactive}$ are the respective power levels in average, in active state and in inactive state.

Additionally, equation 4 can be broken down to power levels and time intervals which are typically involved, so that

$$P_{avg} = \frac{P_p \cdot t_p + P_c \cdot t_c + P_s \cdot t_s + P_i \cdot t_i}{T_{sample}}\,, \quad (6)$$

where P_p, P_c, P_s, P_i, t_p, t_c, t_s and t_i are power levels and time intervals for processing, communicating, sensing

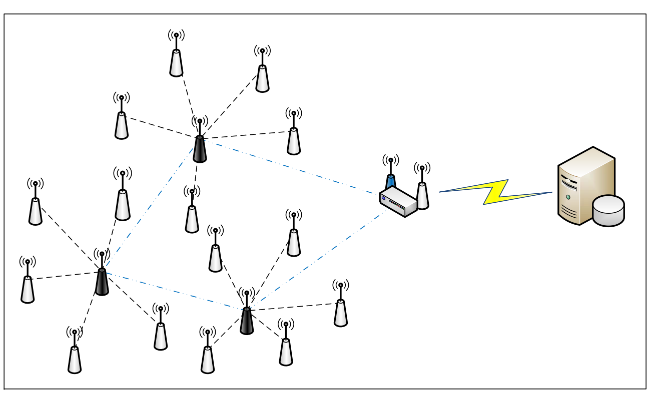


Figure 3. Possible network architecture of data gathering applications in environmental wireless sensor networks under scope

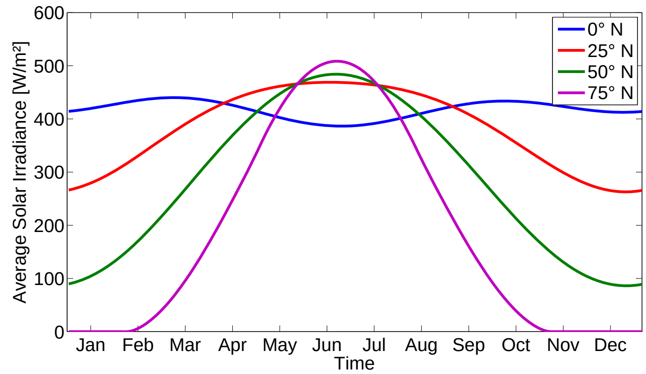


Figure 4. Overview on estimated solar irradiation on top of earth atmosphere at different latitudes (data obtained from [29])

and when inactive respectively, and T_{sample} is the sample interval of the sensor nodes.

Based on the, usually in environmental monitoring found, low sampling rate and the low power consumption in the idle state of the system, the resulting average power consumption is also low.

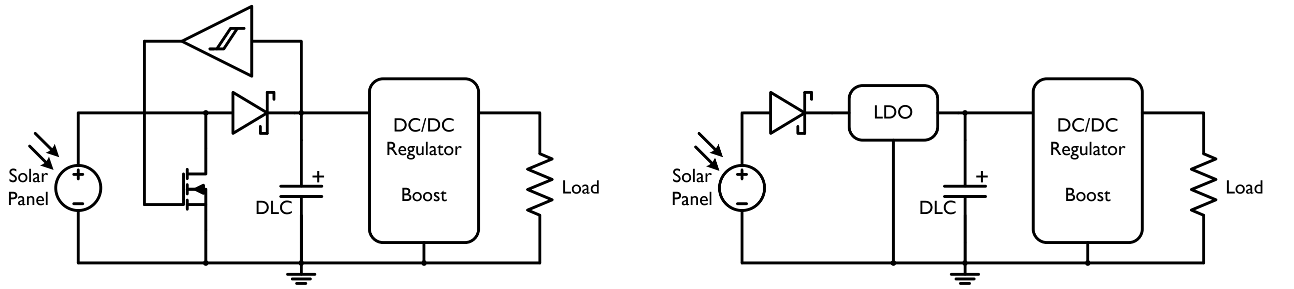
C. Location Dependency

The second external parameter which influences the harvester operation is the location the final system is deployed in. This is mainly because of varying availability constraints of incoming solar irradiation with changing deployment location. Figure 4 shows changes in estimated solar irradiation over the year at different latitudes in the northern hemisphere. Moving north from the equator, two observations can be made which have to be considered in the usage of ambient energy sources at different locations. These observations are

1) With increasing latitude, one typically has to deal with a decrease in solar intensity (e.g., a decrease in average yearly solar radiation).
2) With increasing latitude, variation of solar irradiation during the year increases which leads to periods of high and low solar radiation.

While the first constraint alone does not pose such a big problem, the combination with the latter constraint is what requires an additional design consideration. Certainly, a reduced average solar radiation leads to a lower supply rate from the ambient energy source, which limits the permitted energy demands of the load system. However, for low power systems, such as Wireless Sensor Nodes, this often is not an issue. Furthermore, the reduction in the supply rate could easily be compensated with an increased solar panel.

As opposed to that, the variable solar irradiation over the year forms some limitations the harvesting system has to deal with. As there are time intervals with high solar radiation, as well as intervals with low solar radiation, ideally an energy balancing is desired. Because of the rather long timescales involved, this balancing requires long-term



(a) (b)

Figure 5. Simplified circuit diagrams of the suggested solar energy harvesting architectures - (a) direct input coupling and (b) LDO input regulation

storage of energy and requires, thus, typically battery storage technology. In contrary, if energy balancing is not an option, the system design is determined by the period of lowest energy income. This means, the harvesting unit is designed for the worst case scenario of the deployment location.

In addition to this *global* location dependency, a *local* location dependency can influence the harvesting behavior and outcome. Typical influences are due to obstacles which change the intensity and direction of incoming solar irradiation. The amount of influence in these situations is difficult to predict, but the influence might be classified into generally open or generally shaded locations. Nonetheless, the effect of these obstacles usually is an overall reduction of solar income or short-term variations, as opposed to long-term variations of global location dependency.

D. Suggested Architectures

In this work, we mainly target systems that should be capable of operating from solar energy even at locations with limited solar radiation, as described previously. Furthermore, the one main design goal is the durable and continuous energy supply to the load system. Thus, the two solar energy harvesting architectures presented, are built upon a Double Layer Capacitor (DLC) energy buffer which allows long system lifetime, but provides only short-term energy storage in the order of days.

The two suggested architectures are presented in simplified form in Figure 5. While the basic structure of the two systems is the same, there is a difference in the implementation of the input regulation. Because of the usage of DLCs as the harvesters' energy buffer and the resulting low energy storage capacity, these harvesting systems are vulnerable to short-term variations in irradiation conditions. This means that the systems have reduced capability of balancing changes in available ambient energy, compared to systems using battery buffer technologies. Thus, these architectures must work sufficiently with the available energy income at any time, except of short bridging periods covering e.g. nights.

Based on this, the system is designed for the worst-case scenario of solar irradiance during the year. As the available energy at these irradiance levels is very limited, harvester simplicity is the key to the successful operation of the system. The smaller the amount of available energy is, the more important becomes the own power consumption of the harvesting module (further referred to as the harvester's energy overhead). For continuous operation, the available energy E_{in} has to be large enough to supply the load system at any moment in time, such as

$$E_{in} \geq E_{oh} + E_{load}\,, \tag{7}$$

where E_{oh} is the energy overhead of the harvester and E_{load} the energy demand of the load. Keeping E_{oh} low allows to supply the load with less E_{in}. It should be noted, that while the load consumption in this application typically is an average consumption resulting from duty-cycled sensor node operation, the overhead consumption occurs continuously.

In addition to the common storage technology, the two presented systems use the same output regulation module. This module consists of a DC-DC regulator of boost topology. As DLCs typically have a rather low nominal voltage and this voltage further decreases tremendously with the discharge of the capacitor, for most sensor nodes a voltage level adjustment is required. For implementation a Texas Instruments TPS61070 was chosen, because it has a low power consumption and offers high conversion efficiencies.

The difference between the two architectures lies in their input regulation. Figure 5a depicts an architecture with direct coupling of solar panel and energy buffer, while in the architecture shown in Figure 5b a Linear Dropout Regulator (LDO) is integrated for input regulation.

Direct coupling of solar panel and storage element means that, on the one hand, the solar panel operating point is determined by the charge state of the DLC, on the other, the charge voltage of the energy buffer is only limited by the open-circuit voltage of the solar panel at any time. In result, the power output of the solar panel depends on the current charge state of the storage element. With a double layer capacitor of the type implemented [30], these operating points will typically be between 1 V and 2.5 V according to Figure 2b. Additionally, due to risk of performance reduction or damage, the DLC has to be protected from over-charging. Over-charge occurs when the capacitor voltage exceeds its nominal voltage which can result in reduced lifetime and eventual destruction [31]. A typical way of over-voltage protection is the introduction of a Zener diode. However, as Zener diodes do not have ideal behavior, losses around the breakdown voltage are immense. The typical behavior of a Zener diode is depicted against the ideal behavior in Figure 6. As it can be seen, with this choice, harvesting losses of tens of milliampere close to the breakdown voltage have to be accepted. As this is an intolerable level in most situations, the over-voltage protection in the suggested architecture consists of a combination of hysteresis comparator and MOSFET. This combination replaces the Zener diode by implementing an almost ideal Zener diode behavior. The comparator observes the DLC voltage and triggers the MOSFET to disconnect the solar panel from the energy storage device once the nominal voltage is reached. In this way losses below the breakdown voltage are limited to the operating consumption of the comparator, while all energy is diverted from the DLC as soon as the breakdown voltage is reached. Implementing this protection circuit with a low-power hysteresis comparator, such as a Maxim MAX9017, these losses are limited to a few microampere.

In the second architecture, an input regulation based on an LDO regulator is implemented. As opposed to direct coupling, this means that solar panel and double layer capacitor are only indirectly connected with each other. The implementation of this regulator comes with mainly two advantages for the harvester. Firstly, the regulator makes an over-voltage protection mechanism obsolete, and secondly, ambient energy availability periods are used more efficiently. The former originates in the regulated output of the LDO regulator which, as long as its input is high enough, provides a constant, predefined voltage at the output. In this case, this constant voltage should be chosen in accordance to the nominal voltage of the double layer capacitor. This means that, the DLC will be charged to its nominal voltage only, but never higher. Additionally, the regulator will hold the capacitor at its nominal voltage as long as the input to the LDO allows this. This results in the second advantage of this architecture, because the DLC just begins discharging when ambient energy availability decreases to an insufficient level. As opposed to that, the directly coupled architecture involves a second charge/discharge condition, which is caused by the hysteresis band of the comparator. However, the implementation choice of regulators in this architecture are limited, based on the internal structure of LDO regulators. The challenge is, that most LDO regulators do not permit the voltage level at the output to be considerably higher than at the input. Because of the energy storage element at the output and the intermittent energy source at the input, however, this is a common situation in energy harvesting applications. This restriction limits the choice of appropriate regulators tremendously, especially when it comes to power consumption constraints. We decided on a parallel structure of two Texas Instruments TPS71525.

In both systems maximum-power-point-tracking is avoided, as the implied additional energy overhead is too high for the relatively low amounts of additionally gained energy extraction in low-irradiance conditions, such as presented in [26].

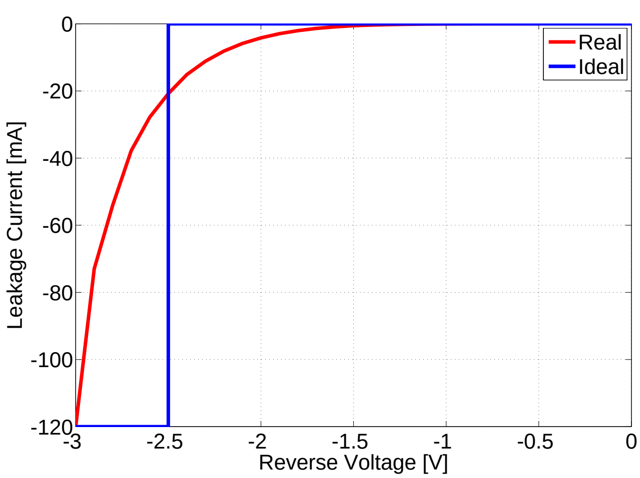


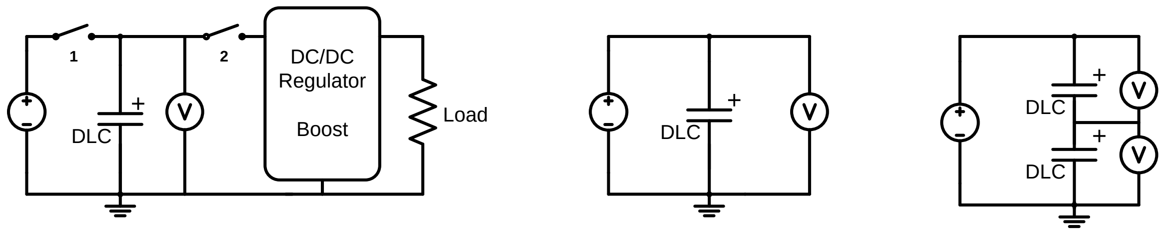
Figure 6. Comparison of ideal and measured current-voltage characteristic of a Zener Diode in reverse connection

IV. Experimental Setup

The evaluation of the architectures is divided into two parts. Firstly, single components and modules of the architectures are analyzed and evaluated in a laboratory environment which describes their behavior and supports the implementation process. Additionally to these measurements, an outdoor deployment of the final architecture implementations is conducted to verify the system behavior in its real application environment.

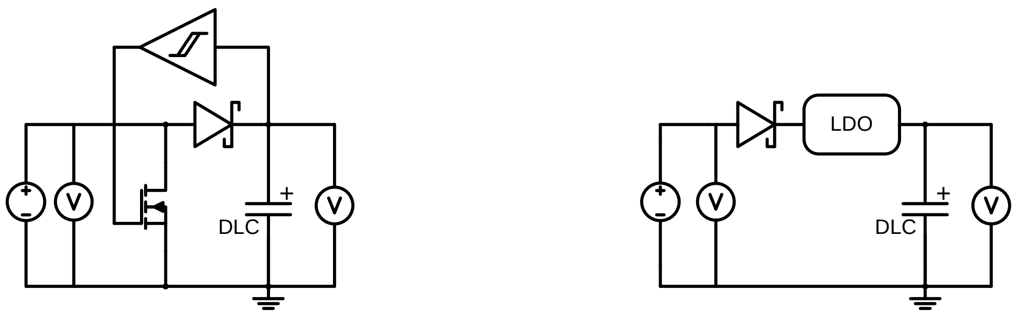
A. *Laboratory Measurements*

In the laboratory measurements, the single components and also combinations of modules are analyzed to determine the behavior of these modules in the final system. Most of the measurements have been performed on the double layer capacitor (i.e., the storage module), as this is the module with most implementation flexibility. The experiments cover analysis of the capacitor's energy storage capability, the influence of its ESR, and the behavior in serial connection of two DLCs.



(a) (b) (c)

Figure 7. Measurement setups of double layer capacitor experiments - (a) Energy storage time analysis; (b) Charge cycle measurement; (c) Evaluation of series connection



(a) (b)

Figure 8. Measurement setups for charge mechanisms - (a) Over-voltage protection measurement; (b) Charge behavior of LDO-based architecture

Additionally to these double layer capacitor tests, evaluation of the charging mechanisms for both architectures have been conducted. This means, for the directly coupled architecture, the over-voltage protection mechanism has been validated, whereas for the LDO-based architecture the whole charging process is evaluated.

The measurement setups are depicted for the capacitor and charge management experiments in Figures 7 and 8 respectively. As DC source in all setups a Hameg HM8143 Programmable Power Supply is used. Furthermore, for voltage measurements in setups 7a and 7b we used an Agilent 34410A Digital Multimeter, whereas a National Instruments NI USB-6008 data acquisition tool is integrated for measurements in 7c, 8a and 8b.

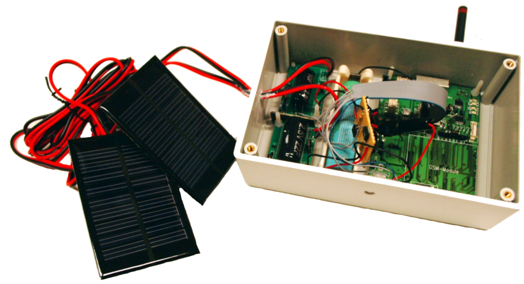
In order to compare the energy storage capabilities of the double layer capacitors, we use a setup according to Figure 7a. The boost-regulator in this setup is a Texas Instruments TPS61070 and DLCs with different capacities from Cooper-Bussmann [30] are implemented as storage device. As system load we employ a typical bi-modal consumer, which is programmed on a Sentio-e^2 node [32]. Changes in the consumers duty-cycle allows for analysis of different load consumptions. In the beginning of this experiment, the switch number one is closed to charge the capacitor to its nominal voltage, while the load is disconnected. Once the DLC is fully charged, the source is disconnected, whereas the load is connected. The voltage level during discharge and the discharge time is logged.

With the measurement setup depicted in Figure 7b, the charging cycle of the double layer capacitor is analyzed. In particular we evaluate the impact of different equivalent series resistances (ESR) in this experiment. Thus, we implement two DLCs of same capacity, but different voltage and ESR ratings. The Hameg HM8143 is used for charging at constant rate and its integrated electronic dummy load (EDL) allows for controlled discharge.

The last DLC experiment conducted, evaluates the behavior of double layer capacitors in serial connection and its setup is shown in Figure 7c. For the measurement two double layer capacitors of same type and capacity are connected in series and collectively charged to the double nominal voltage. Once charged, they are discharged over the EDL of the Hameg HM8143. This procedure is repeated several times, while the individual voltages of the capacitors are logged.

Figure 8a illustrates the experimental setup of verifying the over-voltage protection mechanism. The protection circuit consists of a MAX9017 hysteresis comparator with internal voltage reference and a ON Semiconductor N-channel MOSFET [33]. In the measurement, the double layer

(a)



(b)

Figure 9. Implementation of the deployment system - (a) Direct coupling harvester circuit board; (b) Complete system integration

capacitor is charged with a DC source of higher voltage than the capacitors nominal voltage, while source voltage and DLC voltage are monitored.

The LDO-based charge mechanism is analyzed with the setup depicted in Figure 8b. The LDO used in this setup is a Texas Instruments TPS71525. Furthermore we use a Fairshild Semiconductor Shottky Diode [34], which protects the source from reverse currents. During charging in this experiment voltages at the input and output are logged.

B. Deployment Evaluation

After the evaluation of single modules, the full architectures have been implemented and deployed in an outdoor environment. The architecture implementation occurred according to Figure 5. For the solar panels a commercially available 4.5 V-100 mA type was chosen, because this panel will provide voltages, high enough to fully charge a 2.5 V DLC, even under low irradiation conditions. The physical size of this panel is 94×61 mm^2, thus comparable to dimensions chosen in other systems. As storage element DLCs with capacities of 10 F and 22 F have been chosen.

The load system is implemented with a Sentio-e^2 node platform [32]. This node is designed especially for environmental monitoring applications in mind. It is based on a Texas Instruments MSP430 microcontroller and a CC1101 low-power radio transceiver operating in the 433 MHz ISM-band. The platform consumes less than 7 µA (19.6 µW) in low-power mode with operating timers, which makes it highly suitable for low duty-cycling operations, such as in environmental monitoring. The node operates on a synchronous TDMA communication protocol, which efficiently reduces active time to a minimum, thus, further reducing energy consumption. The load is set to a bi-modal consumption with an average current draw of 20 µA, which approximately equals one packet transmission per minute.

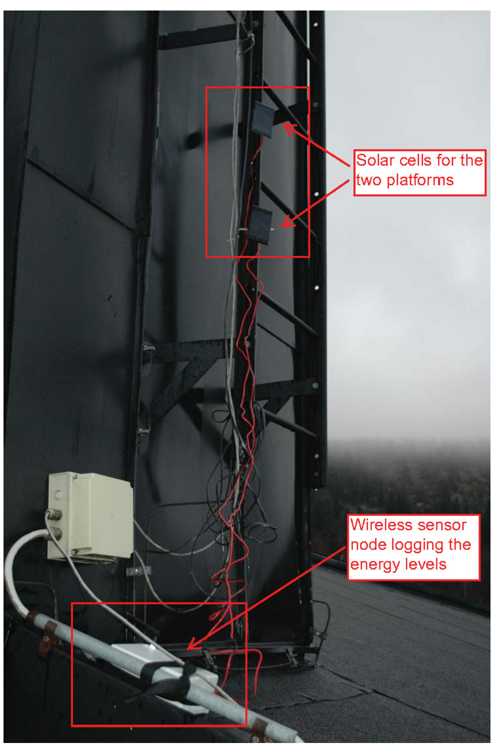


Figure 10. Picture of the deployment setup of a solar harvesting sensor node at the Mid Sweden University campus in Sundsvall, Sweden

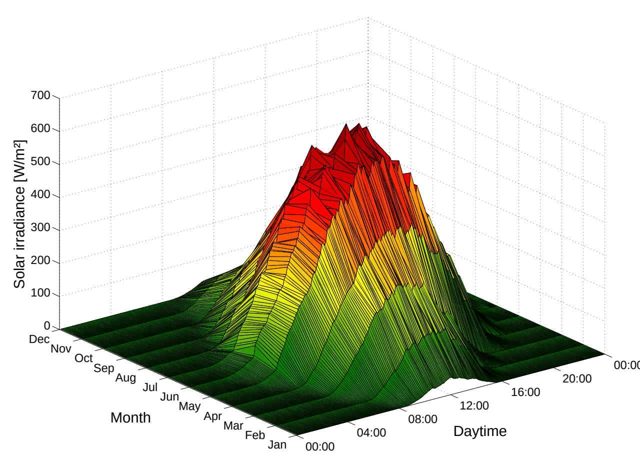
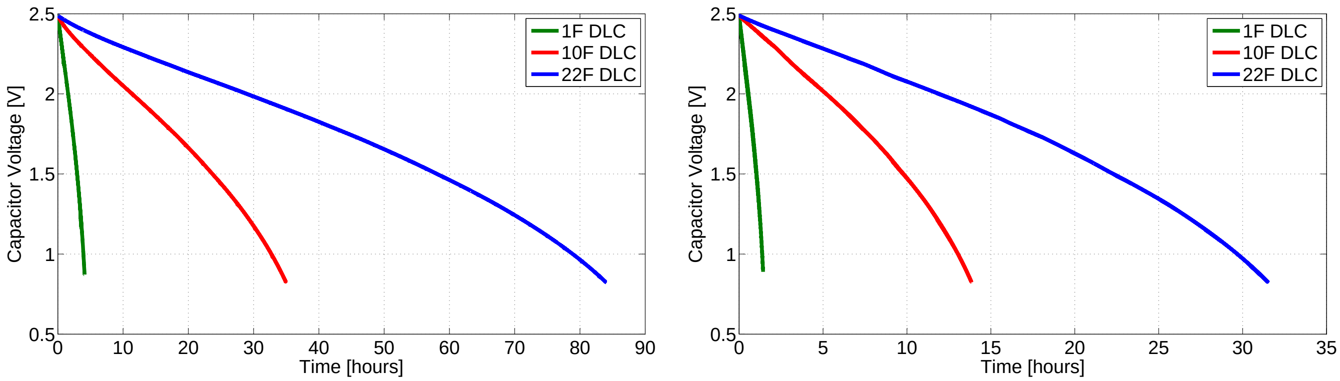


Figure 11. A typical annual insolation profile in Sundsvall, Sweden



(a) (b)

Figure 12. Maximal supply time of fully charged double layer capacitor under bi-modal load - (a) for 20uA average load current; (b) for 100uA average load current

During the deployment, the node system has the function of monitoring the implemented architectures, and additionally measures environmental parameters. While the voltage measurement of the double layer capacitor is performed by the microcontroller's internal ADC, the platform is further equipped with temperature, humidity and solar radiation sensors. For temperature and humidity a Sensirion SHT15 is chosen, whereas a Davis 7821 carries out the solar radiation measurements. The sampling rate of the sensors are 5 min and a Li-Ion battery is provided to allow data collection during times of harvester malfunction.

Figure 9 shows a picture of the implemented system. In 9a the harvesting circuit of the directly coupled architecture is shown, while 9b depicts the complete, deployable system.

The systems have been deployed at the Mid Sweden University campus in Sundsvall, Sweden $(62°24'N, 17°19'E)$. A picture of the deployment setup of one of the deployed sensor nodes is given in Figure 10. The deployment location was chosen to be on a building's roof, to avoid obstacles blocking the insolation to the solar panels. The biggest challenge at this location is the great distance from the equator, which leads to a lower solar radiation and large variations in insolation over the year. A typical solar insolation profile of this location is given in Figure 11, which clearly indicates the short daylight period and low irradiance levels in the winter month. These worst case energy levels will define the maximal load, the harvester can supply at this location. To investigate the system operation under these conditions, the deployment period lasted from November 2009 to January 2010.

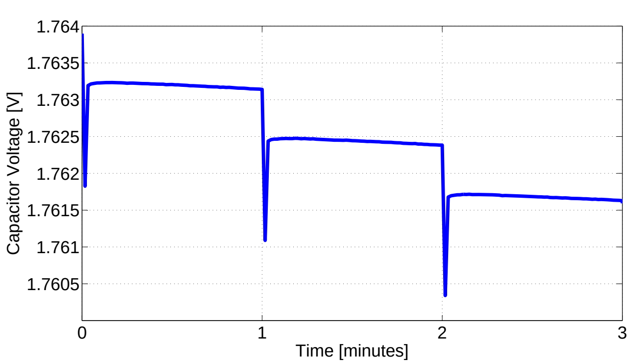


Figure 13. Close-up of the discharge behavior in Figure 12

V. Results

Figure 12 shows the results for the first laboratory measurement, depicted in Figure 7a. The graphs show the discharge from fully charged double layer capacitors of various capacities. The load for this discharge is bi-modal and in Figure 12a the average load current is 20 µA, while the average load current in Figure 12b is 100 µA. The discharge has been continued until the voltage was too low to keep the output regulator operating. The discharge time is a good indicator for how long a dark-period is allowed to be, without the system failing. It is noticeable that the 1 F double layer capacitor lets the output regulator stop at a higher input voltage than the 10 F or 22 F capacitor. This is due to the limited energy stored in the capacitor and the bi-modal load. While in Figure 12 the discharge curves appear constant, the influence of the bi-modal load can be observed in a close-up, shown in Figure 13. The high current peaks, occurring periodically every minute, result in a voltage drop depending on the ESR of the respective DLC. This voltage breakdown relaxes after the current pulse is over. However, the low voltage level for a short moment in time, might stop the output regulator. As the capacitor with smaller capacity has a higher ESR, also the voltage drops are higher.

The ESR of the double layer capacitors also influence the charge-discharge behavior of the device. The measurement of two double layer capacitors of same capacity (i.e., in

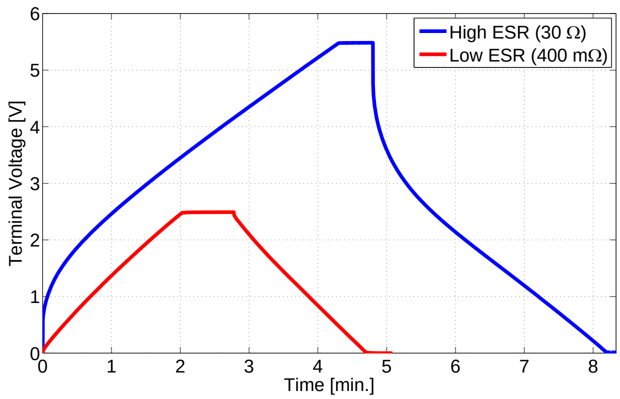


Figure 14. Effect of the ESR on the charge-discharge behavior of DLCs

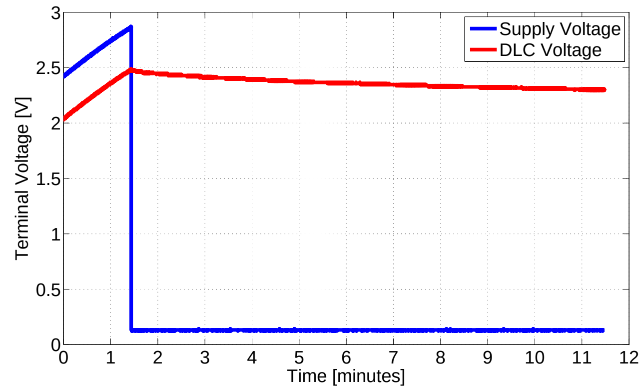


Figure 16. Evaluation of the over-voltage protection mechanism in the directly-coupled harvesting architecture

this case 1 F), but different nominal voltages and ESRs, is depicted in Figure 14.

Figure 15 shows the results of using two double layer capacitors in a serial connection. In the graph it can be observed that charging and discharging does not occur at the exact same rate, even for capacitors of same type. This results into unequal distribution of voltage for the two DLCs. As there is no balancing between the two double layer capacitors, the resulting voltage difference will increase over time. In turn, this means that although the charging voltage might not exceed twice the nominal capacitor voltage, a single capacitor can be charged higher than expected and thus be damaged. Therefore, even with a series connection of capacitors, over-voltage protection is needed.

The results of evaluating the presented over-voltage protection mechanism, presented previously, is depicted in Figure 16. As it can be seen in the graph, the power supply is disconnected from the storage capacitor when the capacitor

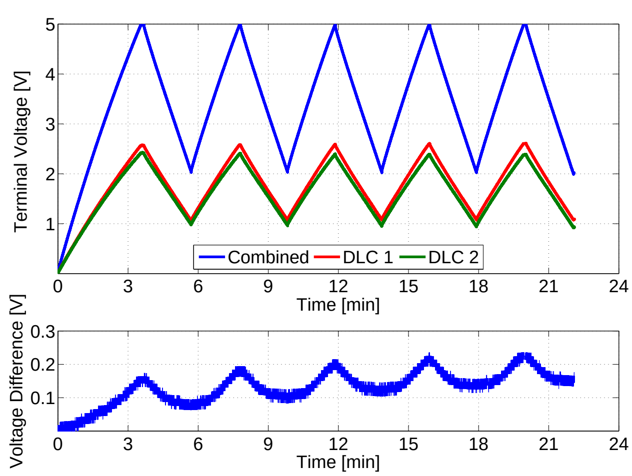


Figure 15. Measurement of charge-discharge behavior of double layer capacitors in a serial connection

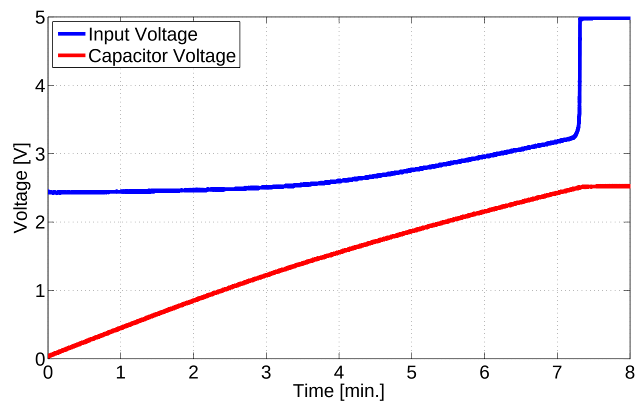
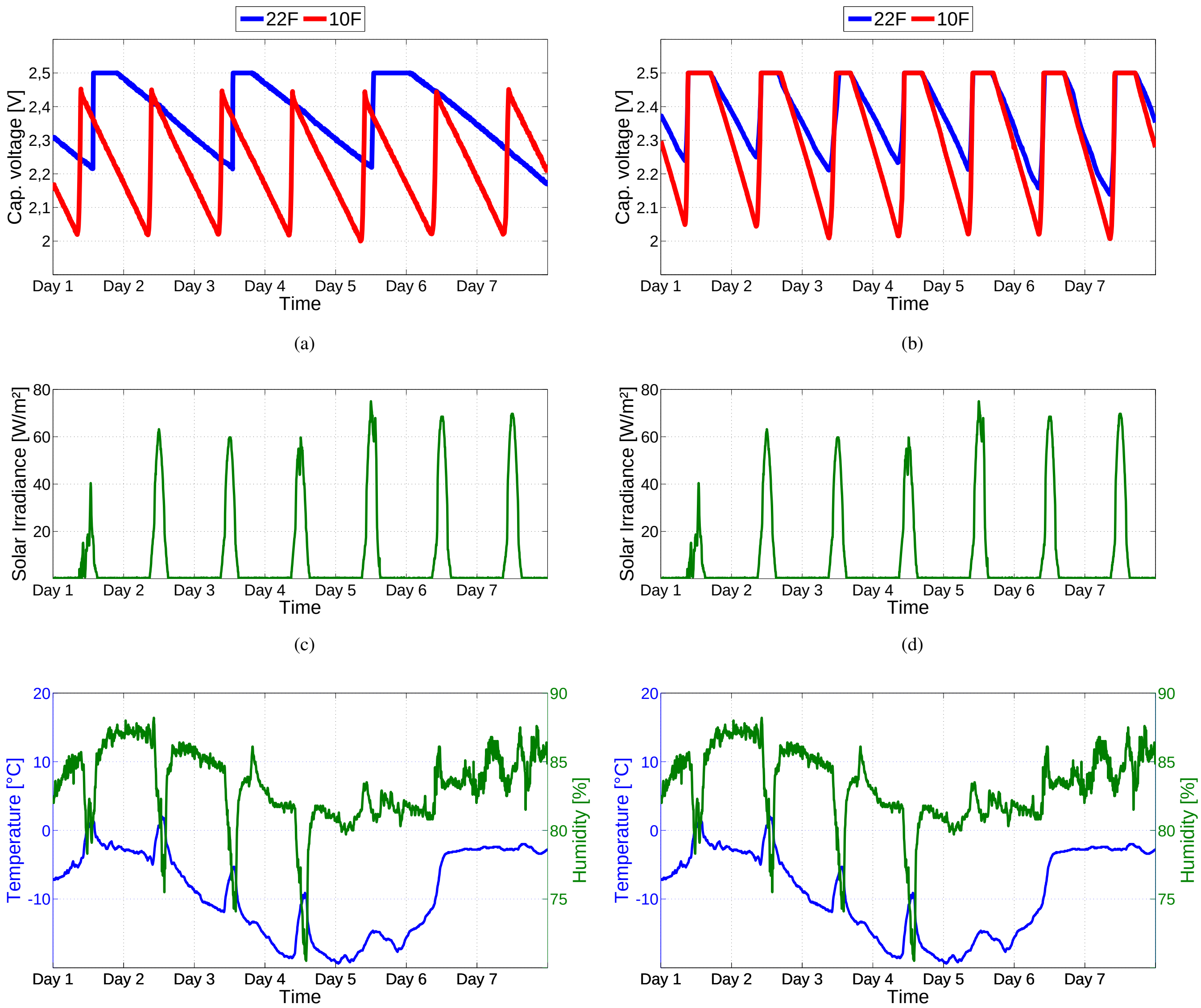


Figure 17. Charge behavior with the LDO regulated harvesting architecture

voltage reaches its nominal voltage. While the power supply is then shorted, the double layer capacitor is discharged until its voltage will cross the lower hysteresis level, connecting the power supply back to the DLC.

In Figure 17, the analysis of the charge behavior in the LDO-based harvesting architecture is shown. It can be observed, that the input voltage is linked to the output voltage of the regulator. While charging the capacitor the input voltage is pulled down to a voltage close to the regulator's output voltage. Only when the DLC is fully charged and does not draw a current from the source any longer, this relation releases and the input voltage raises to its defined level. This behavior is expected to be based on the internal architecture of the used linear dropout regulator. For the solar energy harvesting architecture this means, that the operating point of the solar panel will be between 2.5 V and 3 V, which provides higher power output then the coupled operating point in the directly-coupled architecture.

Finally, results from the fully implemented architectures, obtained in the outdoor deployment, are given in Figure 18. The graphs show one week of data in the deployment period



(a) (b) (c) (d) (e) (f)

Figure 18. System behavior of two solar energy harvesting architectures during one week of deployment – (a),(b) capacitor voltage levels for directly-coupled architecture (left column) and LDO-based architecture (right column); (c),(d) irradiance conditions during the week; (e),(f) temperature and humidity during the week

and include the DLC voltages for both architectures with two different capacity sizes respectively. Additionally, the temperature, humidity and the solar irradiance during the period are provided as reference. As visible in Figures 18a and 18b, the voltage levels in the double layer capacitors follow the daily insolation variations. An exception to this is the directly-coupled architecture, which uses a 22 F DLC. The reason for this is the hysteresis of the over-voltage protection mechanism in this architecture.

While the LDO-based architecture only has one charging condition (i.e., the current insolation), the hysteresis band of the comparator in the directly-coupled architecture adds a second charging condition. This means, the DLC in the directly-coupled architecture does only charge when two conditions are fulfilled. (i) the solar irradiance level is high enough to lead to charge the capacitor and (ii) the lower hysteresis level has been crossed at least once since the last crossing of the higher hysteresis level.

Furthermore, the over-voltage protection leads to a discharge of the double layer capacitor as soon as the comparator voltage (i.e., ideally the nominal voltage) has been crossed. This is independent of external parameters, which means that even when enough solar energy is available, the stored energy will reduce. As opposed to this, the LDO-based architecture charges the storage and holds the DLC at full charge level as long as there is sufficient ambient energy.

In addition, one can observe external influences on the analog over-voltage protection in Figure 18a. Although hysteresis levels have been set to fixed levels, these levels vary depending on the device and external conditions. It is for example clearly visible, that the higher hysteresis level (i.e., the over-voltage trigger level) differs from its preset value. For the $10\,\mathrm{F}$ DLC a trigger voltage of $2.45\,\mathrm{V}$ was measured and for the $22\,\mathrm{F}$ DLC a voltage of $2.55\,\mathrm{V}$, whereas both voltages were set to $2.5\,\mathrm{V}$. Due to a measurement range limitation of the internal ADC of $2.5\,\mathrm{V}$, this is not visible for the $22\,\mathrm{F}$ DLC in the graph.

In Figure 18b the flat tips of the graph do not result from the same measurement range limitation, but occur, because current insolation holds the storage at full charge level. Comparing the discharge rates in Figures 18a and 18b, a higher discharge rate can be observed in the LDO-based harvesting architecture, which results from the higher consumption overhead of this architecture.

VI. Conclusions

Wireless sensor networks offer a number of advantages in the domain of environmental monitoring applications, including the autonomous observation of physical, chemical and biological values at large scale. In addition to area coverage, wireless sensor networks can provide great resolution within this area and deliver their samples to a designated collection point. Additional strength of this technology include the possibility to operate them remotely, which reduces the amount of human invasiveness to the monitored site.

On the other hand, environmental monitoring applications require wireless sensor networks to operate over a long period of time. This results from the typically slow processes being observed and the rather high effort of deploying the network in the environment. In contrast to this requirement, wireless sensor nodes are traditionally powered by batteries and thus have a limited energy resource. Reducing the energy consumption leads to more efficient use of the resource, but cannot alter the fact that the energy capacity is finite.

Energy harvesting provides an alternative supply method, which has the capability to power sensor nodes indefinitely. Solar energy harvesting, as one of these supply methods, offers high availability coverage and generally high energy levels. Furthermore, the conversion technology used in solar energy harvesting is low cost and can easily be scaled to different power level requirements.

However, a problem in solar energy harvesting is the dependency on external factors, particularly the location the final system is deployed in. In this paper we addressed the use of solar energy harvesting at locations with long distance to the equator. These systems have to deal with two main influences. (i) Annual solar radiation decreases with distance to the equator, and (ii) the variation of insolation levels increases.

We suggested two architectures for solar energy harvesting, which address these challenges by their system simplicity. This reduces the energy overhead spent by harvesting, which can easily reach similar magnitudes as the average load consumption of low-duty cycle sensor nodes. We further analyzed the behavior of these architectures in laboratory measurements, which resulted in our implementation choices. After that, the fully implemented architectures have been evaluated in an outdoor deployment in Sundsvall, Sweden ($62°24'N, 17°19'E$) during winter 2009/2010.

The laboratory experiments allowed us to get a feeling of the energy storage capability of double layer capacitors and thus to choose appropriate devices. We could further determine that a serial connection of double layer capacitors can not eliminate the need for an over-voltage protection circuit, even though the input supply voltage is lower than the combined nominal voltages of the used double layer capacitors. Finally, the laboratory measurements also enabled for the verification of the charge mechanisms in both architectures.

Comparing the two architectures, the system deployment showed that both architecture were capable of supplying sufficient power to the load during the whole deployment period. Nevertheless, there are some differences in their operation. While the directly-coupled architecture provides lower energy overhead, and therefore has a slower discharge period, it is affected by the additional charge/discharge condition, introduced by the hysteresis of the over-voltage protection. In addition, the low-power components used in the over-voltage protection module are easily influenced by external factors and thus show strong variations. While it will increase the stress on the double layer capacitor, in future deployments a lower hysteresis band is recommended, which should reduce the impact of these restrictions.

In contrast to this, the LDO-based architecture does not have this additional charge condition, which means charge/discharge behavior is only dependent on available ambient energy at any moment in time. While this utilizes the available energy more effectively, the stress on the double layer capacitor is larger and the overall energy overhead of the architecture is increased. Furthermore, the dimensioning decision for the input regulator, such as the maximum allowed current, limit flexibility of this architecture. This means that one implementation might not be usable for various application conditions (e.g., different solar panel power requirements).

Whereas both architectures come with their individual advantages and disadvantages and proven themselves in the outdoor deployment, once a decision has to be made, we see more advantages in the directly-coupled architecture. While this harvesting architecture shows some limitations due to its second charge condition, the influences of this limitations can be reduced by reducing the hysteresis of its over-voltage protection. Moreover, the system is more flexible to changes in application and location constraints and thus enables for a greater variety of application cases. Finally, its overall lower energy overhead allows for operation during longer dark-periods.

In future work, balancing of annual variations in the ambient energy income is a topic of interest. This can be addressed both, on the hardware and the software level. Furthermore, we will look in more detail into the issue of maximum-power-point-tracking for harvesting from low ambient energy sources.

Acknowledgment

Financial support of the project "Sensible Things that Communicate" by KK-foundation is gratefully acknowledged. Furthermore we would like to thank Torsten Schölzel from Solarwatt AG, Germany, for contributions supporting the work in this paper.

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