2019 15th International Conference on Distributed Computing in Sensor Systems (DCOSS)

Energy harvesting and smart management platform for low power IoT systems

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***Abstract*—Advances in Micro-Electro-Mechanical Systems (MEMS) and energy scavenging technologies are now able to provide viable solutions based on different application environments. In particular, rechargeable battery-operated Wireless Sensor Networks (WSN) can now be set upon a new basis that targets both ambient energy harvesting and wireless charging technologies in different forms and scales. Hence, the assumption of finite energy budget (that may also affect the system's performance) can be over-passed by potentially unlimited energy supply.**

The presented platform is able to effectively power a low power IoT system with processing, sensing and wireless communication capabilities. It embeds an advanced energy management IC that allows extremely high efficiency energy harvesting, suitable for low-power and miniaturized energy generators. Unlike other systems it not only supports a variety of power supply options, but also a hybrid energy storage scheme. This paper aims to provide a description of the system's design, the embedded intelligence and the performance in terms of energy autonomy.

***Index Terms*—energy harvesting, IoT, smart sensing, low power**

I. Introduction

Wireless sensor networks, day by day make their presence more intense and indispensable in modern life. Concepts as IoT, smart cities and industry 4.0 have as a cornerstone the wireless sensor networks to get all the necessary information and build intelligent systems for safety, pre-maintenance procedures, improving quality of life and many other applications. In this new situation, we are called to face a number of challenges, one of which is how these systems can be energy autonomous but also perform to a satisfactory level.

In general, energy harvesting can be divided into two large classes: a) use at once harvested energy b) includes a storage module for potential future use. For the first case, the node is powered directly by the harvester which means that the system remains operational as long as sufficient amount of energy is available. The main drawback of this approach is that the sensor node may oscillate between ON and OFF states. In contrast to the first, the second class includes a storage component to store harvested energy and power the system later on when the conditions are such that harvesters are deactivated. Capacitors and rechargeable batteries can play that role, while two stage storage structure can be adopted. Such implementations offer a secondary storage battery as backup when the primary storage is out of energy. As primary storage usually capacitors are used that can potentially offer a large number of charging/discharging cycles compared to batteries.

Our contribution. Here we present the results of our work in an attempt to build a platform that will render sensor motes autonomous regarding energy. We develop a power supply board which can fuel low-power systems and combine the following innovations in an all-in-one system:

- supports different energy harvesting technologies (solar, piezoelectric, vibrations, RF harvesting, electromagnetic)
- integrates features such as temperature, overcharge, deep discharge protection
- introduces a hybrid solution regarding energy storage by combining rechargeable and non-rechargeable batteries

This work was supported by the General Secretariat for Research and Technology (GSRT), the Hellenic Foundation for Research and Innovation (HFRI) and SAFE STRIP (Safe and green sensor technologies for self-explaining and forgiving road interactive applications) project which has received funding from the European Research Council (ERC) under the European Union's Horizon 2020 research and innovation program (Grant Agreement n 723211).

2325-2944/19/$31.00 ©2019 IEEE
DOI 10.1109/DCOSS.2019.00075

- implements a hierarchical energy management scheme to make more efficient use of available energy and prolong system's lifetime.
- enhances battery charging rate
- prototypes a custom-built energy harvesting and management hardware module that enables the above characteristics

Roadmap of the paper. The rest of this paper is organized as follows. Section 2 elaborates on the related works in algorithmic approaches, designs and hardware solutions. Our system overview, functionality goals, challenges are explained in Section 3. Section 4 presents the hardware design and implementation and other details. Finally, in Section 5 we present the outcomes of the evaluation both in simulator environment and lab experiments, while in Section 6 we summarize the subject of the work and present our next steps for its further development.

II. Related work

In the most recent state of the art we can find works that are fully aligned to the current one, concerning hardware designs and energy harvesting implementations. In particular, [1] describes a new kind of piezoelectric energy harvesting devices that can potentially be applied in wearable devices and aim to provide high power output at low frequency. In [2] a design procedure of flexible dual band rectenna along with a solar cell is presented. As wireless power is one of the most emerging technologies there is a very intense activity on the research area. In [3] the authors propose a hybrid source switch-based RF Wireless energy harvesting technique which adaptively switches between high power RF sources, while in [4] the authors proposed a solution to the problem of battery constraints on the user's device that uses a resonant coupling-based wireless power transfer. To conclude our references to wireless power transfer, we wish to include some algorithmic approaches on this topic such as [5] and [6] in which algorithms are presented to further increase the maximum power fueled to a wireless power transfer network. As rf harvesting co-exists with electromagnetic radiation, the last years we see more and more research works on this particular topic. Some of them include scheduling techniques to control radiation ([7]) or even ways to find low radiation path to move when multiple radiation sources are active ([8]).

Similarly to this work, in [9] an efficient multiple energy sources platform is proposed. The interest of this design is that it is flexible and extends to different energy sources by using a plug-in mechanism. The system is validated in a monitoring application using WSNs. In [10], Sparrow energy harvesting wireless sensor node is presented, which aims to be both a truly energy autonomous development platform and an efficient energy harvesting module. In [11] the authors deploy a multi-transducer platform for photovoltaic and piezoelectric energy harvesting either for outdoor or indoor scenarios.

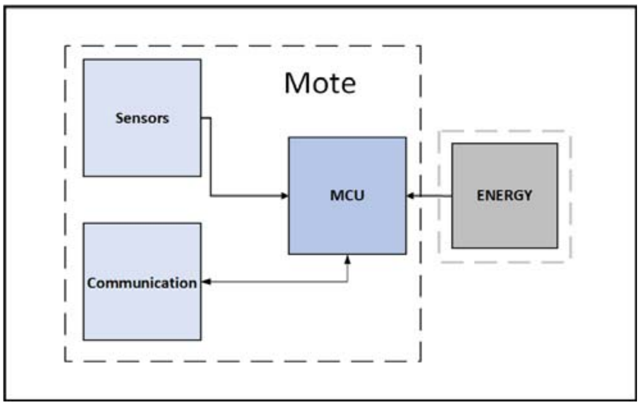


Fig. 1: High level schematic of a mote including sensors, MCU and communication. The connection with the energy part is also depicted.

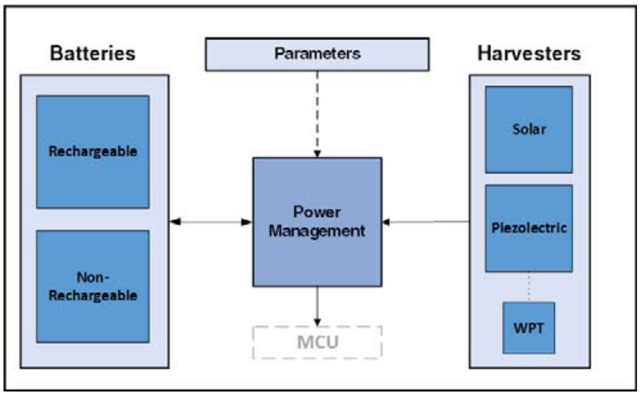


Fig. 2: Abstract schematic of the mote's energy module. Power management submodule has dual input (Harvesters and Batteries) single output and accepts parameters for its operation.

III. Energy Management

In our approach to deal with the upcoming challenges (support a variety of harvesters, enable intelligence regarding the most efficient energy usage coming from available sources, support primary and secondary energy storage modules, etc.) we conduct a study upon the design of an energy management board that supports potentially multiple energy harvesting modules, so that a novel outcome could be resulted, incorporating new emerging technologies and techniques. The model that we follow, relies on the well-known mote definition which is a device that incorporates sensing, communication and processes capabilities. Thus, a power supply solution is required to perform the above tasks efficiently in terms of energy and power (Fig. 1).

A. Energy management design

Our proposed energy management and supply system includes three main components which are illustrated in Fig. 2;

a) the energy harvesters that scavenge ambient energy b) the energy management module that is responsible both to implement stable DC output power supply, battery charging and discharging process and a prioritization scheme that enables the efficient exploitation of available energy and c) the energy pool that stores the harvested energy for future use. The implementation currently does not affect the operating state of the connected sensing and communication system, yet it provides useful input for better awareness and use of the available energy resources. Thus, in the application layer, energy oriented data can be used towards a more energy efficient performance from the side of the MCU.

B. Energy harvesting sources

As we have already mentioned, industry is in a position to provide us with a wide variety of energy harvesters in the low-power scale that is between μW and mW. Harvesters such as solar, piezoelectric, vibration, RF, thermoelectric and electromagnetic can be selected and connected to our system. For this case, we select the harvesters below, motivated by a potential road infrastructure deployment. In particular, a sensing and communication IoT device is installed on the road surface with the appropriate packaging. The system provides useful information both to road infrastructure and the drivers regarding ambient conditions, speed and lane positioning.

Solar energy source. Solar is one of the most viable solutions in terms of energy harvesting due to a list of advantages; a) solar cells offer energy harvesting in small form for varying light intensity that may include either indoor or outdoor applications, b) high energy conversion that can reach up to 21%, (c) easy integration and low cost. Hence, solar can sufficiently both charge batteries and power a low-power system in typical light conditions and even more in road physical systems.

Piezoelectric energy source. Piezoelectric harvesters are very popular because they have the ability to convert mechanical strain energy to electrical. The mechanical strain can be originated from various sources, some examples are: a) Vibrations, b) Human motion, c) Object pressure. Their generated power is in a few milliwatts scale, which is enough for low power system applications.

RF energy source. We finally, integrate Powercast P2110B RF harvesters ([12]) that the enable wireless charging concept. This particular technology, decouples the dependency between ambient conditions in a location of interest and the energy source. Different approaches exist such as a) collecting ambient rf radiation coming from routers, cell towers etc. or b) include dedicated devices, called rf chargers that transmit electromagnetic waves in a specific area. Here, we implement the second case, in which by using the corresponding rectenna we achieve wireless power charging.

IV. PROTOTYPE IMPLEMENTATION

In this paper, a specific energy harvesting system that combines multiple sources simultaneously is presented, to exemplify our approach in a given application context. It includes three products from Analog Devices, LTC3331[1], LTC3335[2] and LTC4071[3]. A typical example of the LTC3331 usage, along with the user selectable pins can be seen in the Fig. 3. The LTC3331 offers a battery charger and an output named V_{OUT} to a system using harvested energy in a single IC. The battery charger provides eight configurations through the pins FLOAT[1:0] with LBSEL for different thresholds about when to stop using, start using and stop charging the rechargeable batteries. The IC has 8 different user selectable voltage output options through the pins OUT[2:0] ranging from $1.8V$ to $5V$ and the input harvester can be configured through pins UV[3:0] to work on certain windows, meaning that the IC can be optimized to operate each harvester near

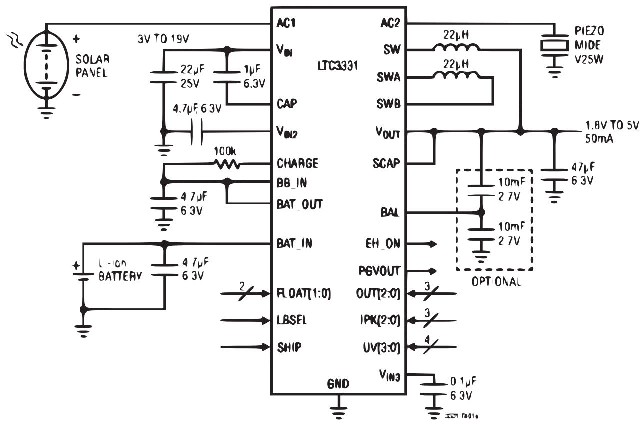


Fig. 3: Typical application of the LTC3331 ([13]) using a solar panel and a piezo energy harvester to provide 1.8 to 5V to the output and charge a single cell Li-Ion battery.

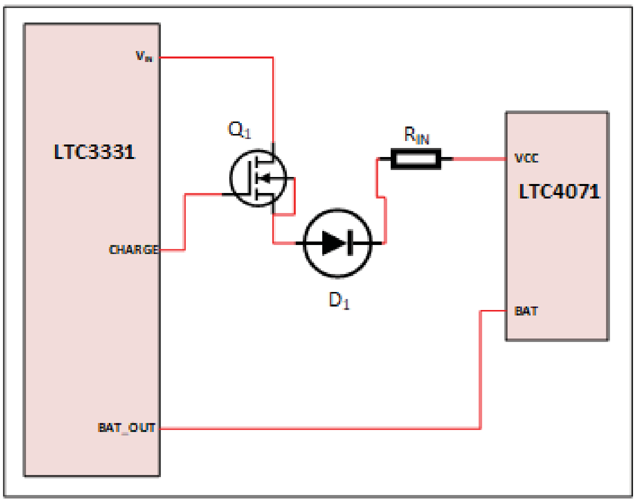


Fig. 4: LTC3331 combined with LTC4071 to allow more charging current to the rechargeable batteries.

[1]https://www.analog.com/en/products/ltc3331.html
[2]https://www.analog.com/en/products/ltc3335.html
[3]https://www.analog.com/en/products/ltc4071.html

the peak power point without the need to use different energy adapters for the majority of energy harvesters. Together with the internal bridge rectifier, it makes an ideal solution for both AC or DC output energy harvesters since it can potentially accept 1 AC or 2 DC harvester input (on pins $AC1$ and $AC2$) without the use of an external circuitry.

The integrated battery charger offers only a small portion of the harvested energy towards the rechargeable batteries even when the load on the output is very small. Hence, a great part of the harvested energy remains unused. For this reason, we also integrate LTC4071 in our design, which implements a shunt battery charger. We connected the external charger as shown in Fig. 4, between the harvester input rail and the charging input for the battery named V_{IN} and BAT_OUT. Charging process is controlled by the pin named $CHARGE$ which enables the charging of the battery when the V_{OUT} is in regulation and harvested energy is available. This configuration helps us to provide up to $50mA$ to charge the batteries instead of the $10mA$ that the LTC3331 is restricted to.

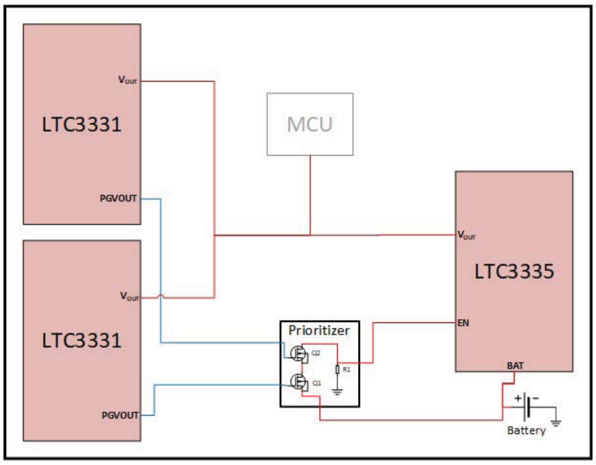


Fig. 5: Priority is given to harvested energy and rechargeable over non-rechargeable batteries utilizing the PGVOUT signal of each LTC3331.

We also use LTC3335, a buck-boost DC/DC converter with non-rechargeable batteries. A simple yet effective low level prioritizer (Fig. 5) is implemented using the digital pin from the LTC3331 named $PGVOUT$ that changes its state depending on whether the V_{OUT} is in regulation or not, to activate or deactivate the LTC3335. The $PGVOUT$ pin drives the MOSFETs that control the EN pin of LTC3335, tying it HIGH to battery or LOW to $ground$. The prioritizer activates the LTC3335 only when harvested energy is not available and the rechargeable batteries energy level is not sufficient to support the connected system's power demand. In Fig. 8 we provide the corresponding flow chart that is implemented via the prioritizer. The last case can also happen if the temperature is above the threshold of the rechargeable batteries protection limit. In general, primary batteries have a wider temperature operation range compared to the secondary. This is mainly the reason that our design also incorporates non rechargeable batteries option.

The proposed configuration can prolong the system's operational time even when harvested energy is not available for long periods of time. We use two LTC3331 with external charger in order to enable more energy harvesters and connect them both to the same battery pool. This implementation enables quicker charging of the batteries when all the harvesters are generating power. It also eliminates the chance of one of the IC's to stop working because its batteries are completely discharged and its harvester cannot provide enough power at the time. Fig. 6 illustrates the proposed energy management module.

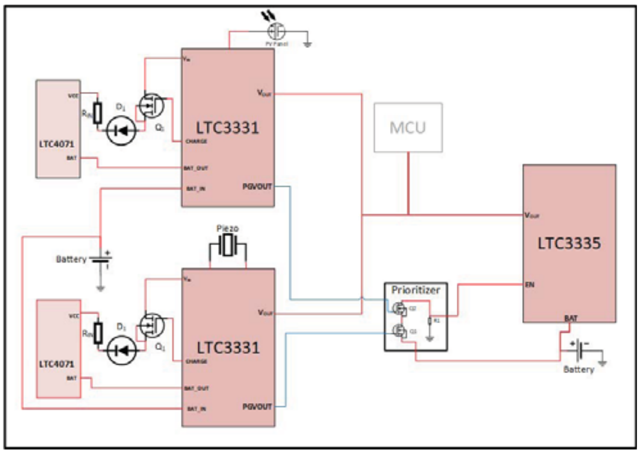


Fig. 6: High level schematic of our proposed energy management module. It contains the two LTC3331 with the LTC4071 as the external charger, the LTC3335 and the prioritizer we implemented.

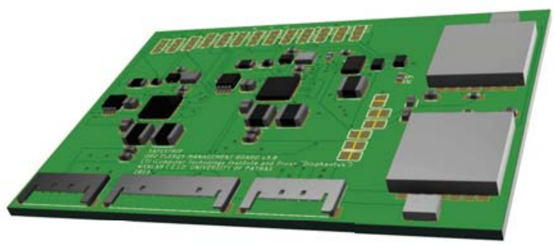


Fig. 7: 3D model of the PCB we designed for our proposed circuit.

V. EVALUATION

In this section we describe the test and evaluation process of our board considering both performance and functionality

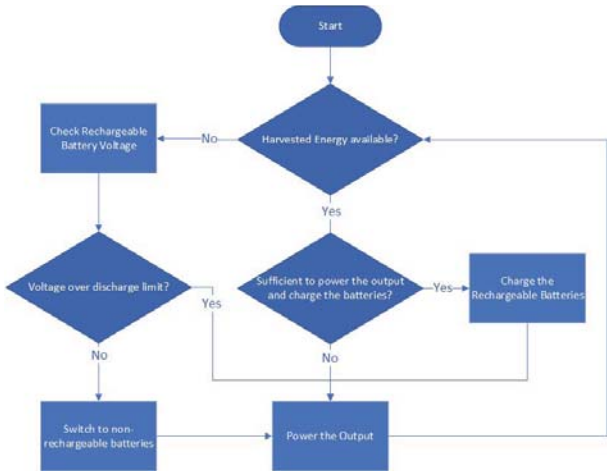


Fig. 8: Flowchart that depicts the hierarchy scheme of the harvested energy over batteries and the corresponding priority of the rechargeable batteries over non-rechargeable.

criteria. Both simulations and lab experiments have been conducted to achieve maximum robustness and reveal any hidden insights of this implementation. Below is provided a comparative illustration of the two evaluation processes together with verification checks for various features that are supported.

A. Simulation

We performed a transient analysis on the combination of LTC3331 and LTC4071 for a period of $500ms$. The circuit we used for the simulation is shown on Fig. 9. We used a $3.2mF$ capacitor with $3.5V$ starting voltage in the place of our rechargeable battery as the energy storage. In the place of the harvester we used a model for solar cell consisting of a current source, a resistor and a diode. The source was configured to generate a pulse of $50mA$ with $250ms$ period, $1ms$ rise and fall times and 40% duty cycle. Finally, a 200Ω resistor is acting as a continuous load of $18mA$ at $3.3V$ on the output of LTC3331. The LTC3331's configuration is to provide $3.3V$ to the output, charge the capacitor until it reaches $4.2V$ and disconnect it when it reaches $3.2V$. The window for the harvester is also set to demonstrate the switch to batteries when the harvester's voltage falls below $6V$ and switch back to harvested energy when it goes over $7V$. The buck-boost regulator is configured to ramp up the inductor current to $250mA$.

As can be seen on Fig. 10a, at the beginning of our simulation the output voltage remains at $0V$ until the harvester's voltage exceeds $7V$. At this point it begins to rise until it reaches the regulation point of $3.3V$. The battery level remains the same until V_{OUT} is in regulation, where it begins to charge. The charging process continues until the batteries reach the $4.2V$ limit where they float. After $100ms$ the harvester's voltage begins to fall until $0V$ value. Then the capacitor starts to provide power to V_{OUT}, which remains in regulation. In Fig. 10b and Fig. 10c we observe after the first $20ms$ where our system is initialized, the current flowing through the BAT_IN pin, where the capacitor is connected, starts from $0mA$ until the V_{OUT} reaches $3.3V$. Then begins to move to the negative side until it reaches $-30mA$, where it remains until the capacitor is charged over $4V$ and is slowly increased to $0mA$. After $100ms$ where the harvester's voltage falls below $6V$ we can see that the value of the current is over $0mA$ but is unstable. That is the result of our configuration for the buck-boost regulator of the LTC3331, the current ramps up to a point where it is sufficient to provide power to the output and then falls down to $0mA$ to ramp up again. Every $250ms$ the process is repeated.

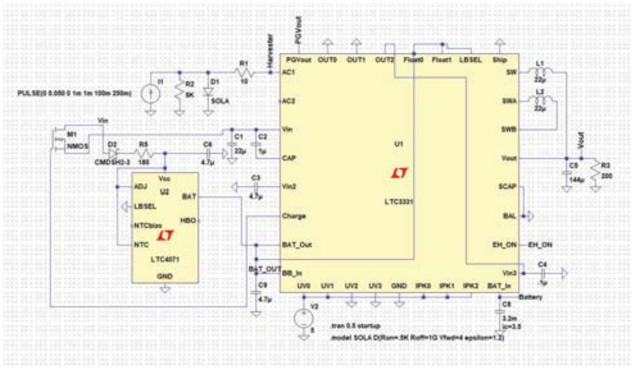
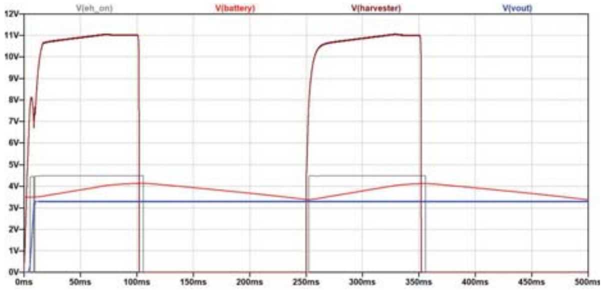


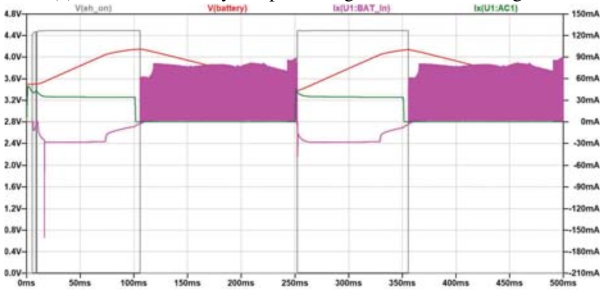
Fig. 9: Schematic from the simulation of the combination of LTC3331 with the LTC4071 to increase the charging current for the rechargeable batteries.

B. Experiments

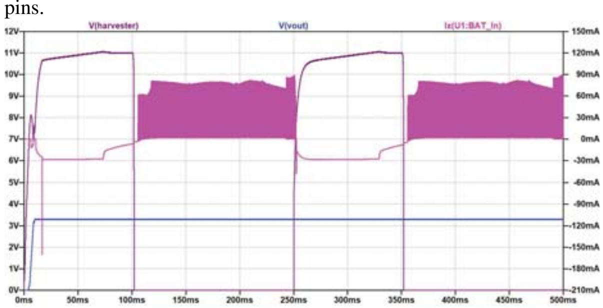
For the experiments conducted for this paper, the below setup is followed (Fig. 11). For energy harvesting, we chose the AMORTON 5902 solar cells from Panasonic, at $150mW$ nominal power per cell. We used 4 cells of $150mW$ nominal power each connected by 2 in parallel and then in series, ending up with a total power of $600mW$. We use four LIR2032 rechargeable batteries at $160mAh$ total capacity and four RENATA CR 2430 non-rechargeable batteries at $1200mAh$ total capacity. The LTC3331 is configured to provide 3.3V in the output, activate harvested energy when the harvester's voltage goes over $6V$ and enable batteries when it goes under $5V$. They were also configured to charge the rechargeable batteries until they reach $4.2V$ and disconnect them at $3.2V$. As a system load, a sensor mote with ambient sensors and BLE communication was placed. Mote's specifications include a continuous current draw of $4mA$ and peak current draw during transmission of $18mA$ at $3.3V$. The transmission occurs once every second and has a duration of $3.71ms$. A microcomputer was programmed to measure the harvester's voltage according the luminosity, the rechargeable and non-rechargeable batteries voltage and track every transmission the sensor mote made. The data collected is saved to CSV formatted file with each



(a) Harvester, battery, output voltage and EH_ON signal.



(b) Battery voltage and current flowing through $AC1$ and BAT_IN pins.



(c) Harvester and output voltage and current flowing through BAT_IN pin.

Fig. 10: Transient analysis of LTC3331 combined with LTC4071 for $500ms$ duration.

measurement's timestamp. Harvester, batteries and load where connected on a PCB we designed that contained the IC's and the peripheral components needed for their operation. Fig. 7 shows a 3D model of our PCB with all the components and the solder-shorts used to configure the LTC3331.

The experimental procedure lasted for a week and as can be seen on Fig. 12 our board was able to support the load of the sensor mote during the day where energy from the solar cells was available and also during the night from the rechargeable batteries. In Fig. 12a the relation between luminosity and solar panel's voltage is illustrated. Our implementation with the combination of LTC3331 and LTC4071 managed to charge the batteries to their maximum capacity during the time the solar cells generated enough power to both enable output and battery charging. Since the rechargeable batteries didn't fall under the $3.2V$ threshold, the non-rechargeable weren't used. The rechargeable batteries were charging faster when direct sunlight was applied on the solar cells.

Since in our first experiment the non-rechargeable batteries weren't activated, we conducted one more. We disconnected the rechargeable batteries leaving only the harvester and the non-rechargeable battery. Then we proceed to measure the harvester's, output and non-rechargeable batteries voltage. We disconnected the harvester in order to demonstrate the activation of non-rechargeable batteries. The second experiment had a duration of $720s$ and Fig. 13 illustrates the results. As we can observe the voltage of the non-rechargeable batteries remains stable while the harvester is connected. When the harvester is disconnected it begins to fall until the harvester is connected again. The output remains close to $3.3V$ for the whole duration of the experiment.

As in the simulation, we observe in the experiments too, that the IC activates the rechargeable batteries when the harvester's voltage falls under the specified threshold to switch to batteries ($6V$ for simulation $5V$ for experiments). Then, when the harvester's voltage rises above the threshold to switch back to harvested energy, it begins to recharge the batteries while it also powers the output.

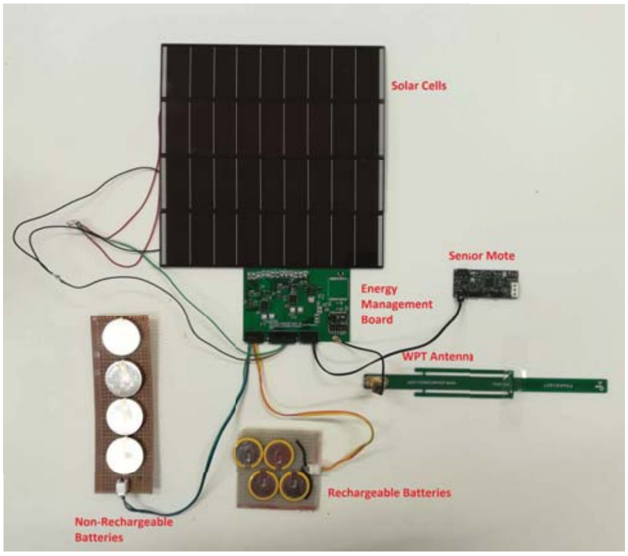
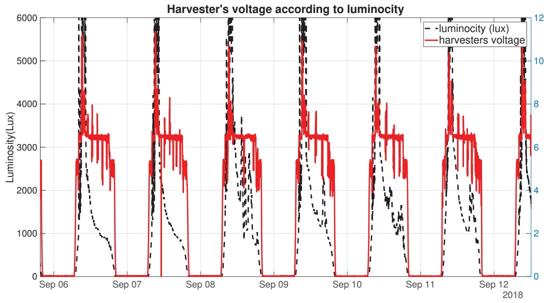


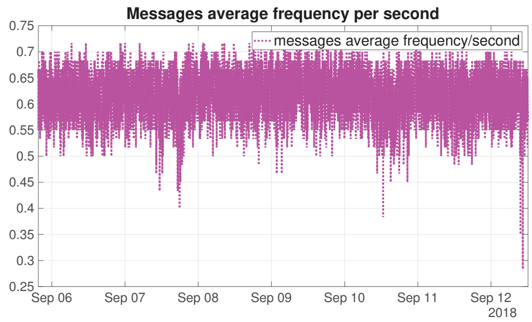
Fig. 11: Lab setup for experiments. Energy Management Board, Sensor Mote, Solar Cells, Rechargeable Batteries and Non-Rechargeable Batteries.

CONCLUSION AND FUTURE WORK

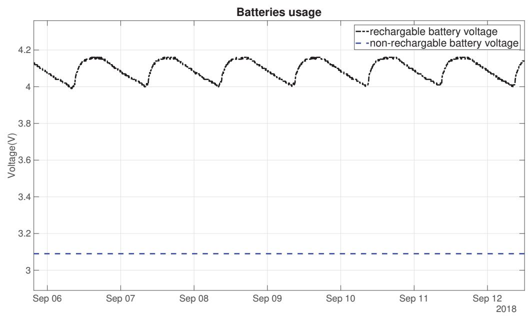
In this work we present an integrated energy platform that combines both energy harvesting technologies, energy store and energy management. Its specifications includes a variety of features such as temperature battery safety, overcharge and deep discharge protection, and improved battery charging rate. We also introduce a smart hierarchical scheme regarding the



(a) Solar cells voltage according to the applied luminosity.

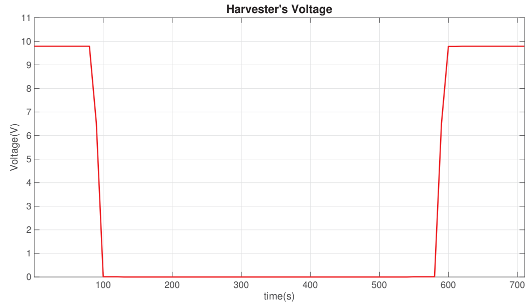


(b) Average rate of received messages per minute from the sensor mote.

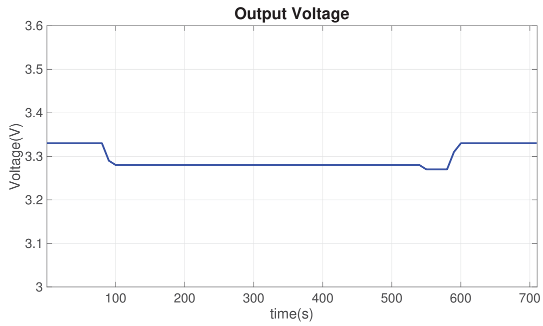


(c) Rechargeable and non-rechargeable battery voltage.

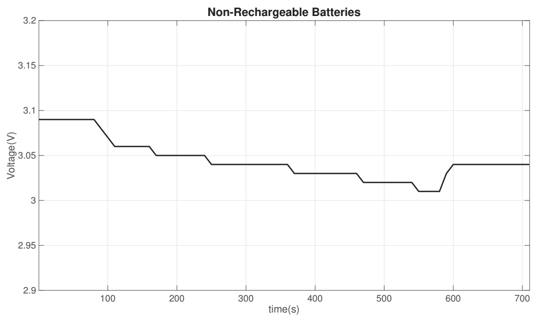
Fig. 12: Results from a seven day evaluation of our energy management board.



(a) Harvester's voltage.



(b) Output voltage.



(c) Non-rechargeable battery voltage

Fig. 13: Results from a short evaluation of our board to demonstrate the robust switch from harvesters to non-rechargeable batteries and vice versa.

source (harvester, primary battery, secondary battery) that fuels the system and enables its use in WSN applications of different deployment environment.

In the future we aim to further improve many of the existing features and adopt even more. As an example we plan to embed a low power micro-controller that can provide all the necessary information regarding consumption, energy storage and harvesting instead of individual signals. Particularly, we wish to optimize the trade-off between redundant hardware and cost, autonomy parameters. Moreover, we target on the exploitation of new emerging technologies that can enable the decoupling of the harvesters and the ambient conditions. It is essential to improve the energy received by the WPT module as we suspect that our design have not reached the maximum of the RF harvester capabilities. Finally, we seek for new energy harvesting technologies for road infrastructure systems.

Acknowledgment

This work was supported by the General Secretariat for Research and Technology (GSRT), the Hellenic Foundation for Research and Innovation (HFRI) and SAFE STRIP (Safe and green sensor technologies for self-explaining and forgiving road interactive applications) project which has received funding from the European Research Council (ERC) under the European Union's Horizon 2020 research and innovation program (Grant Agreement n 723211).

References

[1] Qijia Cheng, Zhuoteng Peng, Jie Lin, Shanshan Li and F. Wang, ”Energy harvesting from human motion for wearable devices,” 10th IEEE International Conference on Nano/Micro Engineered and Molecular Systems, Xi’an, 2015, pp. 409-412.

[2] B. Naresh, V. K. Singh and V. K. Sharma, ”Flexible Hybrid Energy Harvesting System to Power Wearable Electronics,” 2018 Fourth International Conference on Advances in Electrical, Electronics, Information, Communication and Bio-Informatics (AEEICB), Chennai, 2018, pp. 1-5.

[3] A. Obaid, F. Hussain and X. Fernando, ”Adaptive Switching for Efficient Energy Harvesting in Energy Constraint IoT Devices,” 2017 IEEE 86th Vehicular Technology Conference (VTC-Fall), Toronto, ON, 2017, pp. 1-5.

[4] S. Y. Prawiro and M. A. Murti, ”Wireless power transfer solution for smart charger with RF energy harvesting in public area,” 2018 IEEE 4th World Forum on Internet of Things (WF-IoT), Singapore, 2018, pp. 103-106.

[5] Ioannis Katsidimas, Sotiris Nikoletseas, Theofanis P. Raptis, and Christoforos Raptopoulos. (2017). An algorithmic study in the vector model for Wireless Power Transfer maximization. Pervasive and Mobile Computing. 42.

[6] I. Katsidimas, S. Nikoletseas, and C. Raptopoulos, Power efficient algorithms for wireless charging under phase shift in the vector model, 15th International Conference on Distributed Computing in Sensor Systems (DCOSS), 2019.

[7] H. Dai, H. Ma, A. X. Liu and G. Chen, ”Radiation Constrained Scheduling of Wireless Charging Tasks,” in IEEE/ACM Transactions on Networking, vol. 26, no. 1, pp. 314-327, Feb. 2018.

[8] Ioannis Katsidimas, Emmanouil Kerimakis and Sotiris Nikoletseas, ”Radiation Aware Mobility Paths in Wirelessly Powered Communication Networks”, in 2018 Global Information Infrastructure and Networking Symposium (GIIS), Thessaloniki, Greece.

[9] T. N. Le, T. P. Vo and A. V. D. Duc, ”Plug-In Multi-source Energy Harvesting for Autonomous Wireless Sensor Networks,” 2017 International Conference on Advanced Computing and Applications (ACOMP), Ho Chi Minh City, 2017, pp. 105-108.

[10] I. Deaconu and D. . Tudose, ”Sparrow: An energy harvesting wireless sensor node,” 2017 4th International Conference on Control, Decision and Information Technologies (CoDIT), Barcelona, 2017, pp. 0410-0415.

[11] G. Smart, J. Atkinson, J. Mitchell, M. Rodrigues and Y. Andreopoulos, ”Energy harvesting for the Internet-of-Things: Measurements and probability models,” 2016 23rd International Conference on Telecommunications (ICT), Thessaloniki, 2016, pp. 1-6.

[12] https://www.powercastco.com/

[13] https://www.analog.com/