Power Management Scheme of a Photovoltaic System for Self-Powered Internet of Things

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***Abstract*—Energy efficiency is especially important for many Internet of Things (IoT) devices, such as prototyping boards and Bluetooth Low Energy (BLE) beacons. In this paper, we design and implement the power management of a photovoltaic system for a solar-powered BLE beacon, using discrete components. The main goal is to increase energy efficiency and extend the lifespan of the beacon that contains a battery and a solar cell as power sources. The introduced design can be further implemented in a printed circuit board with optimal components to increase energy efficiency and provide a reliable power supply system.**

***Keywords*— Self-powered Internet of Things; Power Management; Photovoltaic System.**

I. Introduction

Most of the devices that are connected to the Internet everyday, are devices that have at least one sensing element, creating great opportunities for more direct integration between the physical world and computer-based systems [1]. This is the idea behind the Internet of Things (IoT), a development of the Internet in which everyday objects have network connectivity, allowing them to send and receive data.

The interconnectedness of all things is continuously expanding with the ultimate goal to improve quality of life. The aim is to have every person connected with their surroundings, whether it be at home, at work, or in public spaces. Although most of these devices have minimal energy requirements, their energy efficiency can greatly affect their overall performance and adaptation [2]–[4]. Energy harvesting techniques can alleviate the problem [5]–[10]. Self-powered devices can extend their lifetime while they can also improve their performance. Solar-powered IoT devices are a promising approach [11], [12].

In this work, we propose a power management scheme of a photovoltaic system for self-powered IoT devices. The proposed scheme is implemented and tested with Bluetooth Low Energy (BLE) beacons. Two experiments are conducted to compare the performance of the proposed scheme with a conventional implementation, in order to assess the improvement in energy efficiency.

The rest of this paper is organized as follows: Section II describes the solar-powered system. The introduced power-management scheme is discussed in Section III followed by the implementation and experimental results is Section IV. We conclude this work in Section V.

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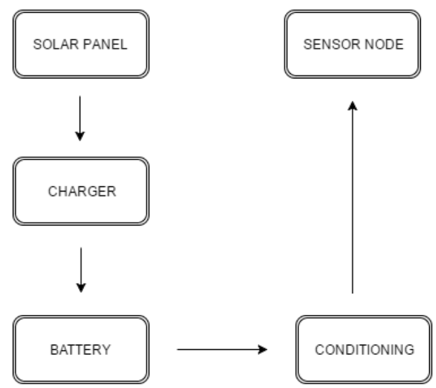
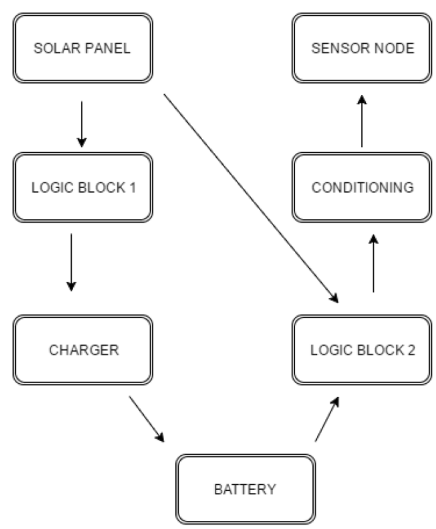


(a) Conventional system.



(b) Proposed system.

Fig. 1: Solar powered management systems.

II. Solar-Powered System

Solar-powered systems are a popular solution for energy-constrained wireless sensor nodes that are placed outdoors. Traditional approaches use the solar cell to charge the battery. The battery is then responsible to power the node, based on the implemented conditioning, as shown in Fig. 1a.

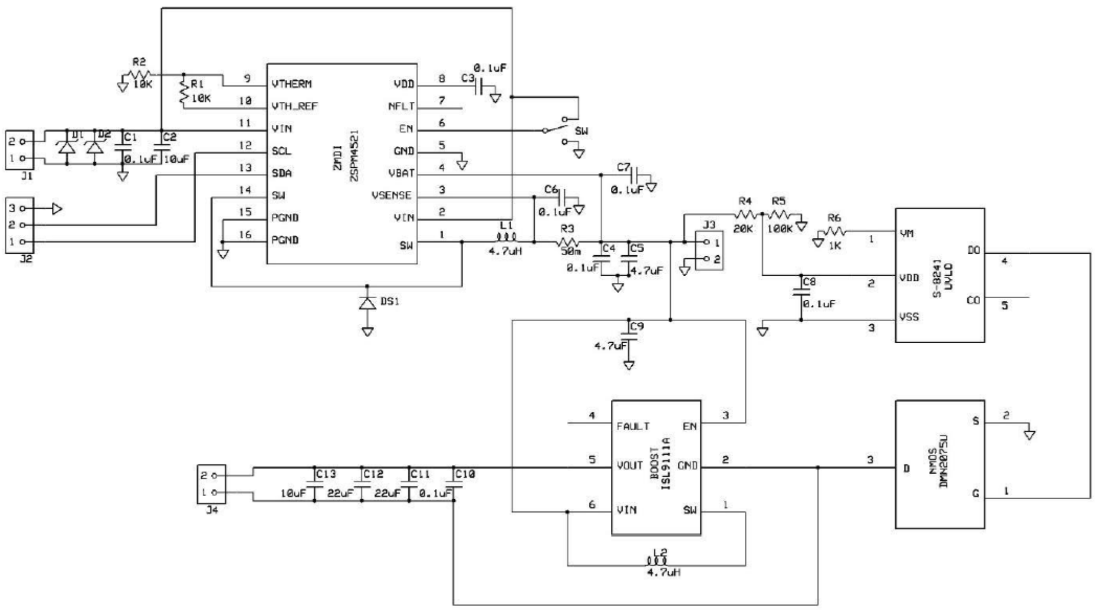


Fig. 2: Schematic of the conventional board.

In our previous work [13], we suggested an improvement of the traditional powering systems used in Wireless Sensor Networks (WSNs). It was noticed that in periods when the radiant power received by the solar cell is not enough to recharge the battery or in periods when the battery is fully charged, the system does not take advantage of the extra power from the solar cell. Hence, the overall performance of the network decreases. However, the performance can be improved by reconfiguring the connections of the energy sources of the sensor node.

Using the approach of [13], there are three possible modes for powering a sensor node:

i. In the first mode, the power supplied by the solar cell is larger than a high threshold, making the system able to power the sensor node and recharge the battery at the same time.
ii. In the second mode, the power supplied by the solar cell is not large enough to recharge the battery; however, the power can be used to supply the sensor node without depleting the battery.
iii. In the third mode, the power supplied by the solar cell is not enough to power the sensor node, so the battery is used.

Based on this configuration, the system can operate for an extended period of time than for the conventional approach, thereby increasing the energy efficiency and lifespan of the sensor node.

To implement the three modes above, a novel power management scheme is proposed. The block diagram is shown in Fig. 1b, and it includes two logic blocks that reconfigure the energy sources. Logic Block 1 is designed to determine if the battery should be recharged or not, while Logic Block 2 selects the battery or the solar cell for powering the node.

III. Power Management Scheme

As a starting point, the conventional board schematic shown in Fig. 2 was used. This design implements a charger for solar cell (ZMDI), an interlock system (UVLO and the NMOS) that prevents battery problems such as over discharge, and a converter that steps up the battery voltage to drive the sensor (boost converter). Additionally, the input/ output pins J1 to J4 implement the following functions. J1 is connected to the solar cell, J2 is used to program the ZMDI board, J3 is connected to the battery, and J4 is the output that supplies power to the system.

As it can be seen in Fig. 2, the DC-DC converter that supplies power to the output at the appropriate voltage level receives power from the battery and it is enabled only if the battery is charged (i.e. it operates only if a charged battery is connected to pin J3).

In order to implement the proposed scheme, the solar cell should be able to power the sensor directly in some situations. The needed modifications include the connection of the battery and also the interlock system (i.e. UVLO and NMOS), which is replaced by Logic Block 1 and Logic Block 2 that are designed to correctly evaluate if the battery level. The changes in the board schematics are shown in Fig. 3, which is the introduced board design after the addition of Logic Block 1, shown in Fig. 4 and Logic Block 2, shown in Fig. 5.

A. Logic Block 1

Logic Block 1 is responsible to check if the solar cell should be connected to the battery charger. The solar cell should only be connected to the charger if the solar cell power is enough to charge the battery and sensor at the same time (i.e.

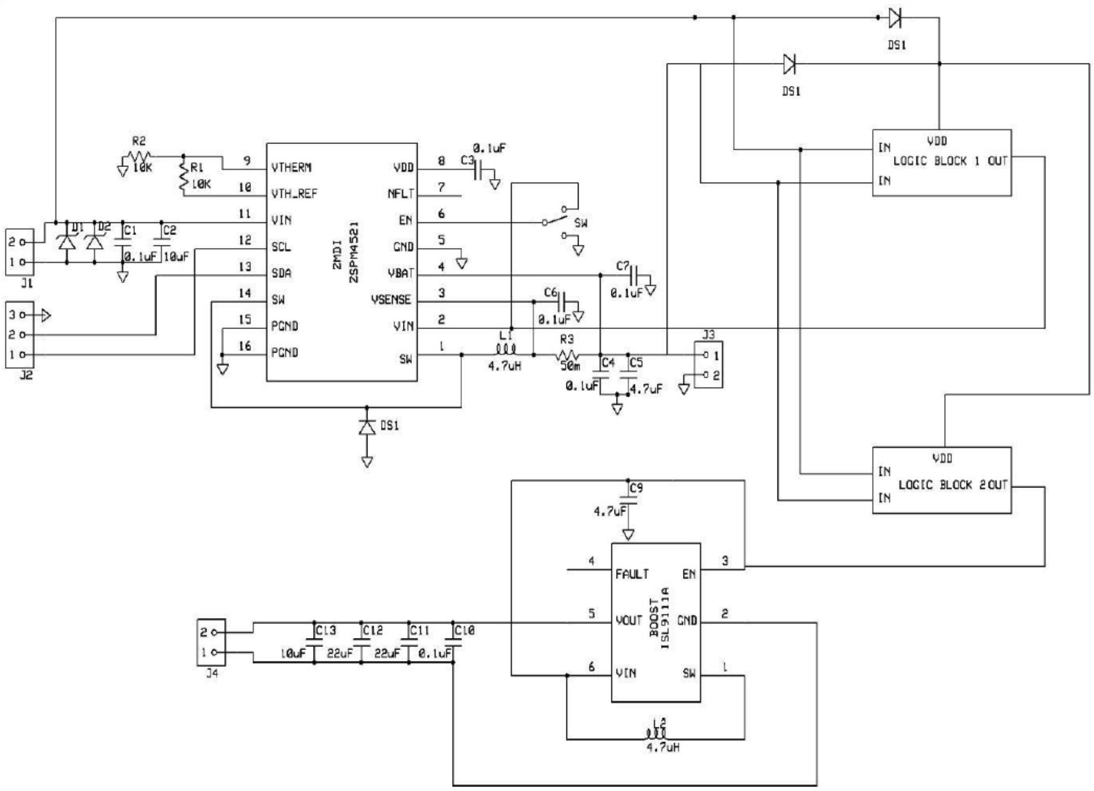


Fig. 3: Schematic of the proposed system.

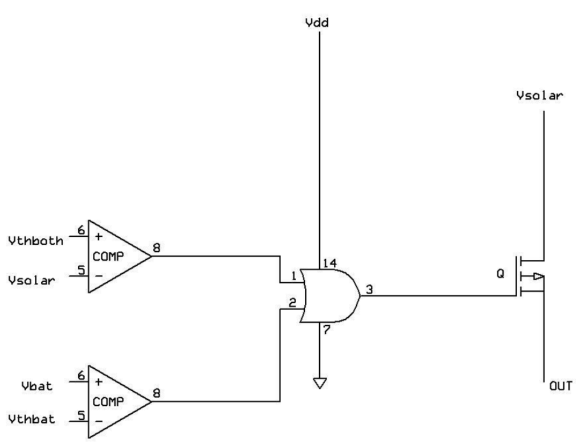


Fig. 4: Components of Logic Block 1.

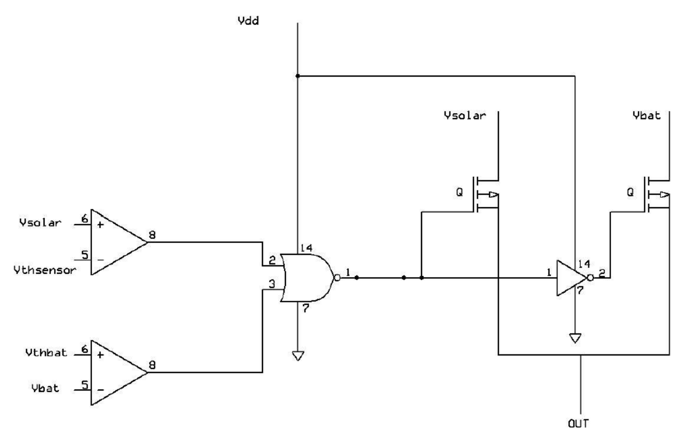


Fig. 5: Components of Logic Block 2.

mode i). The block was designed using two comparators, one OR gate, and one PMOS switch. The comparators drive the corresponding switches to be closed (logic 0) or open (logic 1) if the input voltages are higher or lower than predetermined threshold levels. In the first comparator, if the solar cell voltage is higher than the threshold V_{thboth}, which indicates a voltage level enough to power the sensor and recharge the battery simultaneously, the comparator gives a logic 0; otherwise, it outputs a logic 1. In the second comparator, if the voltage of the battery is lower than the threshold V_{thbat}, indicating that the battery needs to be recharged, the output is a logic 0; while if the battery has enough voltage, the output is a logic 1. When both comparators give a logic 0, the PMOS switch is closed and the solar cell is connected to the battery charger; in any other case, the energy of the solar cell is not used to recharge the battery. The schematic of the logic described is shown in Fig. 4.

B. Logic Block 2

Logic Block 2, shown in Fig. 5, is responsible for selecting the power source that powers the sensor. This block was

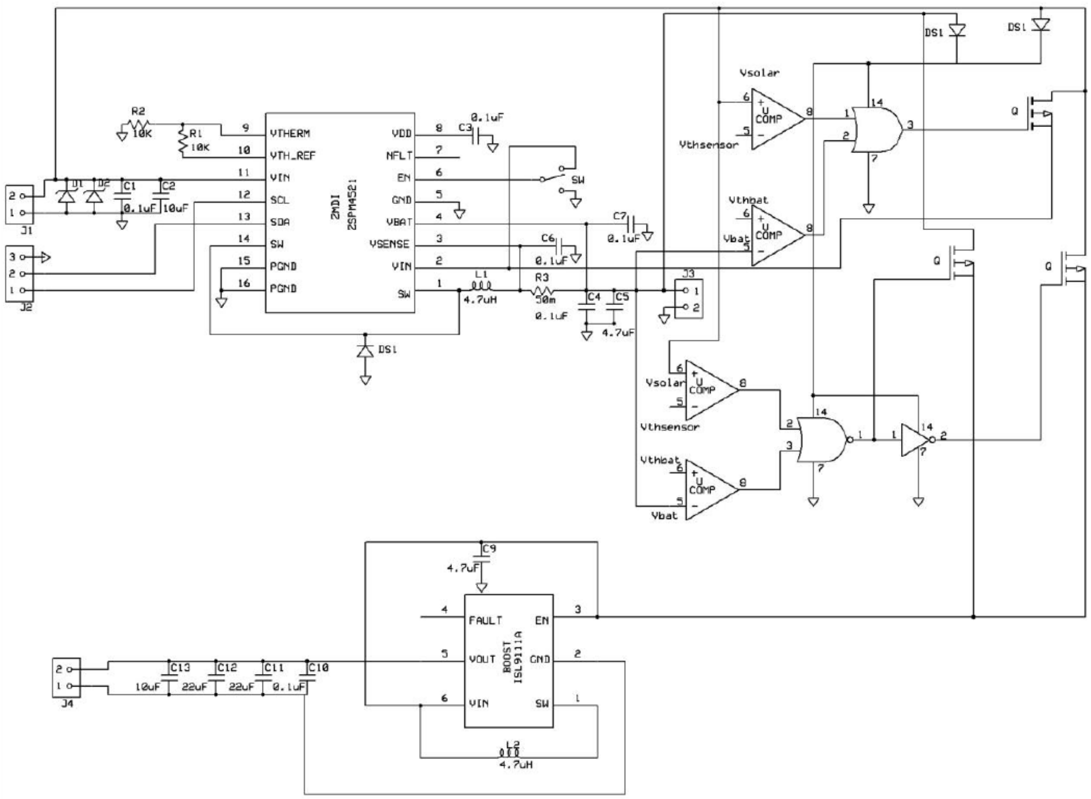
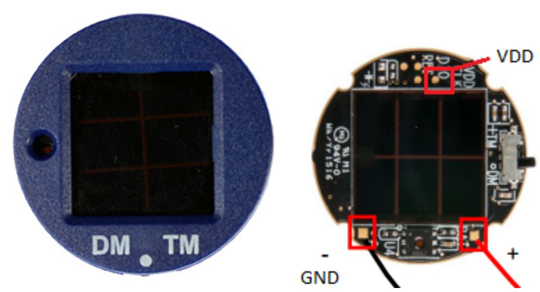


Fig. 6: Schematic diagram with introduced components.

designed with two comparators, one NOR gate, one OR gate, and two switches. The comparator on the top is responsible for comparing the voltage from the solar cell to a threshold that indicates if there is enough power to charge the sensor only. If the voltage is higher than the threshold, this comparator gives 1; otherwise, it gives 0. The other comparator is responsible for checking the voltage in the battery. If the voltage in the battery is higher than the threshold that indicates the battery is too low, the comparator outputs 0; if not, it outputs 1. Both outputs of the comparator are connected to a NOR gate, which controls the PMOS connected to the solar cell, and a signal with opposite logic to the NOR output is connected to the PMOS switch controlling the connection to the battery. Using this configuration, only one of the switches is closed. The final design with all components can be seen in Fig. 6.

IV. Implementation and Experimental Results

To validate the system, two experiments were made using discrete components and providing power to the Cyalkit-E02 Solar Powered Beacon [14], [15], shown in Fig. 7.



(a) Cyalkit-E02 (b) Board

Fig. 7: Solar powered beacon.

A. Experiment 1

Experiment 1 was intended to verify that the logic operated correctly. The thresholds were set to $V_{\mathrm{thbat}} = 3.3$ V (threshold that indicates that the battery needs to be charged and there is enough available power from the solar cell to power only the sensor), and $V_{\mathrm{thboth}} = 5$ V (threshold which indicates there is enough power in the solar cell to recharge the battery and to power the sensor at the same time). Two voltage sources of 3.3 V and 5 V were used to generate the reference thresholds, while two others voltage sources were used to emulate the solar-cell voltage and the battery voltage inputs. The system was emulated with a 2.2-kΩ load resistor. In Experiment 2, this circuit was modified to be able to drive more current, is connected to the boost converter and verifying that it can, in fact, power the sensor.

Experiment 1 was made setting the battery voltage to predetermined values and changing voltage of the solar cell. Figures 8 and 9 show the behaviour of the system when the battery is above the threshold. Figure 10 shows the behaviour when the battery voltage equals to the threshold, and Figs. 11 and 12 show the behaviour when the battery is below the threshold.

As shown in Figs. 8 to 12, Logic Block 1 presents output voltage different than zero only when the battery voltage is low—indicating that it needs to be recharged—and the solar cell voltage is high enough—showing that it can recharge the battery and power the system at the same time. For Logic Block 2, the solar cell is responsible to power the system if it has a voltage larger than the V_{thsensor} threshold. When the solar cell voltage is below V_{thsensor}, if the battery is higher or equal than the threshold, the battery powers the sensor (Figs. 8, 9, and 10); if the battery voltage is low, the system is always powered by the solar cell (Figs. 11 and 12). In this way, Experiment 1 shows that the logic was correctly designed. However, it is important to notice that the voltage of Logic Block 2 will be used as input for the boost converter, which will limit the power fed to the sensor. In Experiment 2, additional switches provide enough current to drive the sensor and, in fact, the experiment shows that the system can be added to the board.

B. Experiment 2

A voltage source was used to generate the reference threshold voltages $V_{\text{thsensor}} = V_{\text{thbat}} = 4.8$ V, while two others voltage sources were used to emulate the solar-cell voltage and the battery voltage inputs. The output of the designed system was connected to the dc-dc converter on the original board via J3 pins, which was used by the battery, and the output of the board was connected to the sensor. Components that perform the same functionality of the PMOS switch were added in parallel to make the system able to provide enough current for the boost converter. The results are shown in Table I, II, and III.

As shown in Table I, II, and III, the logic works after the integration of the system with the boost converter. When the battery is charged, the solar cell powers the system if it has high voltage; otherwise, the battery provides power to the sensor. If the battery is not charged, the system is supplied by the solar cell at all points.

In Table III, it is possible to see that when the voltage of the solar cell is too low, the interlock system stops the dc-dc converter and the sensor is turned off. This operation can be changed by adjusting the level of the threshold. Further improvements can be achieved by using components with reduced losses.

V. Conclusion

Logic Block 1 and Logic Block 2 were successfully designed and the functionality of the control logic of a prototype system was tested. The proposed power-management scheme can increase the energy efficiency and extend the lifespan of the beacon powered by a battery and a solar cell. The introduced design can be further implemented in a printed circuit board with optimal components to increase energy efficiency and provide a reliable power supply system.

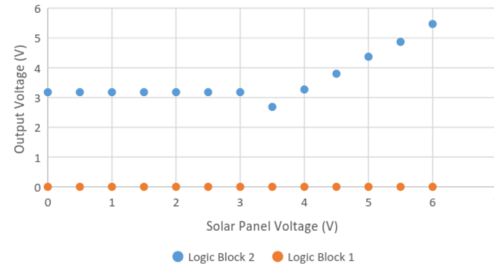


Fig. 8: Battery Voltage = 3.7 V.

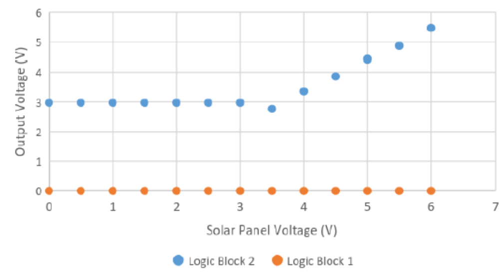


Fig. 9: Battery Voltage = 3.5 V.

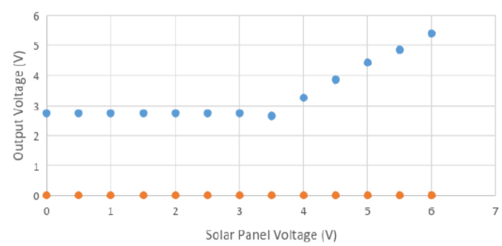


Fig. 10: Battery Voltage = 3.3 V.

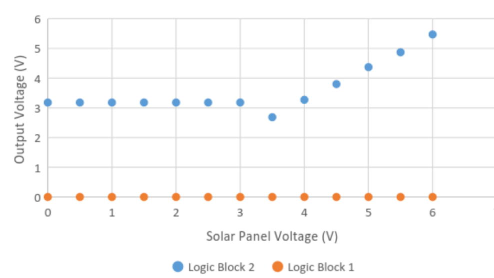


Fig. 11: Battery Voltage = 3.1 V.

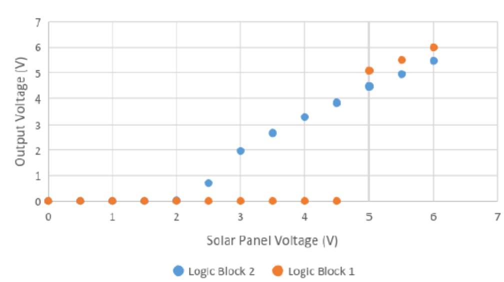


Fig. 12: Battery Voltage = 2.9 V.

Solar Cell Voltage (V)	Sensor Voltage (V)	Solar Cell Current (mA)	Battery Current (mA)	Sensor Status
6	4.95	70	0	ON
5.5	4.95	90	0	ON
5	4.94	110	0	ON
4.5	4.94	0	80	ON
4	4.95	0	80	ON
3.5	4.95	0	80	ON
3	4.95	0	80	ON

TABLE I: Values for battery voltage = 5.1 V.

Solar cell Voltage (V)	Sensor Voltage (V)	Solar Cell Current (mA)	Battery Current (mA)	Sensor Status
6	4.95	70	0	ON
5.5	4.95	90	0	ON
5	4.94	110	0	ON
4.5	4.95	0	90	ON
4	4.95	0	90	ON
3.5	4.95	0	90	ON
3	4.95	0	90	ON

TABLE II: Values for battery voltage = 4.8 V.

Solar cell Voltage (V)	Sensor Voltage (V)	Solar Cell Current (mA)	Battery Current (mA)	Sensor Status
6	4.95	70	0	ON
5.5	4.95	90	0	ON
5	4.94	110	0	ON
4.5	4.93	150	80	ON
4	3.4	0	220	ON
3.5	2	0	50	OFF
3	1.3	0	0	OFF

TABLE III: Values for battery voltage = 4.5 V.

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