

Procedure for Selecting a Transmission Mode Dependent on the State-of-charge and State-of-health of a Lithium-ion Battery in Wireless Sensor Networks with Energy Harvesting Devices

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ABSTRACT

Diverse methods and considerations have been proposed to manage the available energy in an efficient manner in Wireless Sensor Networks. By incorporating Energy Harvesting Devices in these type of networks it is possible to reduce the dependency of the availability of the Energy Storage Devices, particularly the lithium-ion battery. Recently, the State-of-Charge and State-of-Health of the battery have been considered as inputs for the design of the Medium-Access-Control protocols for Wireless Sensor Networks. In this article, different guidelines are proposed for the design of Medium-Access-Control protocols used in Wireless Sensor Networks with Energy Harvesting Devices considering the State-of-Charge and State-of-Health as indicators for the estimation of the transmission time of the sensor node. The proposed guidelines consider different currents used during the transmission to estimate the State-of-Charge and State-of-Health of the battery. The incorporation of these indicators aim to improve the decision-making process of the sensor node when transmitting.

1. INTRODUCTION

Traditionally, Wireless Sensor Networks (WSNs) have used batteries to provide the required energy to the sensor node. Batteries have a limited lifetime, which results in energy efficiency being one of the most studied factors in WSNs. Many of the techniques proposed in the literature to improve energy

efficiency have focused on Medium-Access-Control (MAC) protocols. MAC protocols are designed to conserve energy because they control the communication process of the sensor node, process of a vast energy consumption.

The addition of Energy Harvesting Devices (EHDs) has made possible to have flexibility on the energy requirements, since it has a greater amount of available energy that can be used to power the sensor node or recharge the battery. The EHD has originated a change of guidelines in the design of the MAC protocols to maximize the performance and the network lifetime (Nguyen et al., 2014). MAC protocols for WSN should operate in the Energy Neutral Operation state, i.e., the sensor node has to operate in a condition where the energy consumption is less or equal to the energy harvested. In addition, they need to consider the battery behavior, the energy consumption of the sensor node and the energy available according the type of EHD (Karthi, Rao, & Pillai, 2015). These four criterion are used to implement dynamic Duty Cycle in MAC protocols for EH-WSN.

In the sensor networks that incorporate EHD, the batteries have an important role in supplying power to the network in the time periods when the EHD cannot do so. Therefore, it is important to understand the behavior of batteries. Two indicators used for this purpose are the State-of-Charge (SOC) and State-of-health (SOH) (Lajara, Solano, & Pelegri-Sebastia, 2018). The SOC is used to know the percentage of energy available in the battery, while the SOH indicates the percentage of degradation, i.e., the amount of energy that can be stored and delivered with respect to its nominal value. Both indicators require to be estimated, since they cannot be measured directly, and information from variables such as dis-

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charge current, voltage, temperature, internal impedance, life cycle, capacity degradation rate, is used (Pola et al., 2015). Nowadays, these indicators are being incorporated more frequently in the design of MAC protocols. For example in (Castagnetti, Pegatoquet, Le, & Auguin, 2014) the authors propose a Duty Cycle control strategy based on the SOC. In (Mokrenko, Vergara-Gallego, Lombardi, Lesecq, & Albea, 2015), the SOC is related with the remaining battery capacity and the estimation of the SOC is used to apply a Model Predictive Control (MPC). Another example is presented in (Lajara et al., 2018) where the authors proposed a SOH estimation methodology.

The Prognostics and Health Management (PHM) systems use the battery's SOC and SOH as indicators regarding the usage and operating decision-making process (Dong, Chen, Wei, & Ling, 2018). For example, the SOC provides information about the amount of available energy in the battery aiding the decision-making process in the short term to determine if the device has enough energy to execute a specific activity or requires to enter the charging mode. In similar way, it is possible to know how degraded a battery is through the SOH. This indicator is used to quantify how much lifetime the battery has. Currently, different methods have been proposed to estimate the battery SOC and SOH (Rezvanizani, Liu, Chen, & Lee, 2014) (Han et al., 2014). The selection of the method will depend on the characteristics of the application and the precision and accuracy required of both indicators. The methods based on battery modeling are used more frequently because they allow on-line estimation. Examples of these methods are Fuzzy Logic, Neural Networks and Bayesian inference (Xu et al., 2014). Regardless of the selected method to estimate the SOC or the SOH, the information provided by these two indicators assists the MAC protocols to adjust their activity or sleep times, thus prioritizing the functions of each of the sensor nodes (Castagnetti, Pegatoquet, Belleudy, & Auguin, 2012).

This work develops the necessary guidelines for the design of MAC protocols for EH-WSN using the SOC and SOH of a battery. These indicators can improve the decision-making process of the MAC protocols by providing more accurate information of the battery status. According to these indicators, MAC protocols decide the best transmission current, the best periods to charge the battery, and which device has transmission priority. This paper is organized as follows: the first section describes the proposed methodology to develop the guidelines for design of MAC protocols using the SOC and the SOH. The second section details the results obtained by evaluating various scenarios. In the last section we present the conclusions.

2. METHODOLOGY

This section describes the methodology used to establish the required guidelines for the design of MAC protocols for EH-WSN considering the information provided by the SOC and SOH. The first consideration of the methodology is that each sensor node has a CC2500 transceiver, which has been designed for low-power wireless networks (Instruments, 2013). Table 1 shows some characteristics of this transceiver, specifically the currents used in different operating modes of the sensor node.

Table 1. Currents Characteristics - CC2500

Operating Mode	Currents
Transmission	22 mA (0 dBm output power)
Transmission	15 mA (-6 dBm output power)
Transmission	11 mA (-12 dBm output power)
Reception	14 mA
Idle	1.5 mA
Sleep	900 nA

The second consideration is to define the type of EHD to be used. In this work, it is assumed that each sensor node is provided with a solar panel of 5.5×7 cm. In addition, the periods in which the EHD can harvest energy are determined based on the data of sunlight hours for Santiago of Chile for the year 2017. An average of 10 hours of sunlight is available during each day. Moreover it is considered that during the periods of light the EHD is capable of supplying the necessary current to charge the battery at one-half the nominal current (22.5 mA for the LIR2032 battery), see Figure 1.

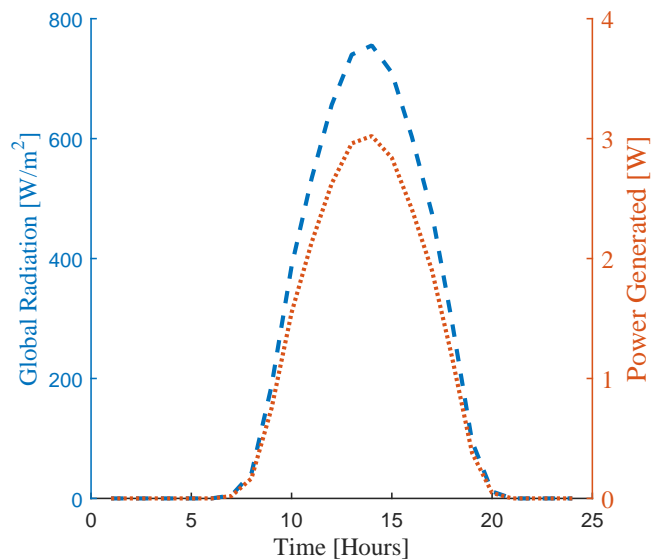


Figure 1. Global Radiation and Power Generated

The proposed algorithm requires a model that characterizes the battery discharge behavior of a Li-ion battery. In this work, the state-space model presented in (Pola et al., 2015) is used to describe the discharge process. This model defines two states: the first state is an unknown parameter associate to the internal impedance of the battery and the second state corresponds to the SOC estimation. The measurement equation represents the battery voltage at time k . The data used to characterize the discharge process was obtained by discharging a Li-ion type LIR2032 (45 mAh, 3.6 V) battery at one-half of the nominal current (0.5 C) and constant ambient temperature, as presented in (Quintero, Estevez, & Orchard, 2017). Figure 2 shows the voltage obtained during the discharge process with its corresponding current profile, which is a combination of two current values. These currents describe two operating modes: transmission mode (22 mA) and reception mode (14 mA).

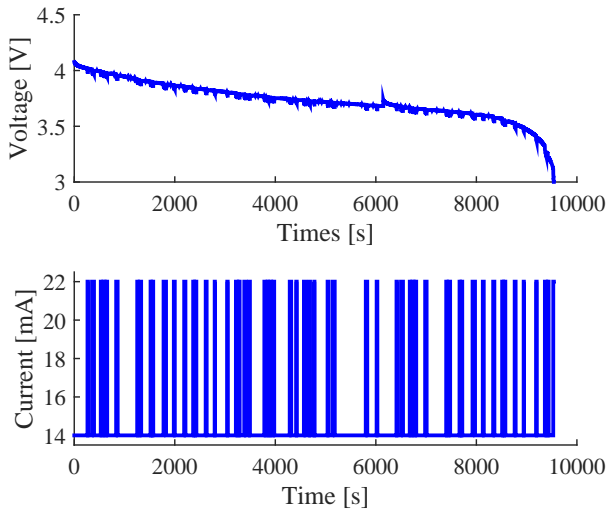


Figure 2. Current and Voltage Discharge

2.1. SOC Estimation and Prediction

Initially the SOC estimation is made to establish the point at which the algorithm will begin the prediction of the SOC. In this paper, the SOC estimation and prediction is based on particle filter. Two case studies are presented to evaluate the discharge time of the battery under different current profiles. The first case of study uses an aggressive profile, that is, where the sensor of the node is constantly transmitting, see Figure 3. The second case of study employs a conservative usage profile where the sensor node presents time periods in which no activity is used to evaluate their impact on the discharge process, see Figure 4. This second profile attempts to establish a guideline on how the sensor node should operate at night when it depends exclusively on the energy available in the battery.

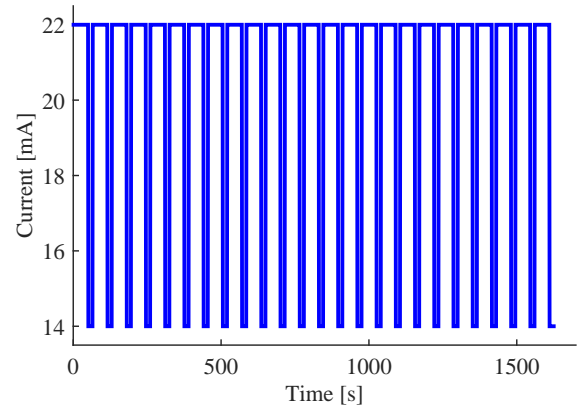


Figure 3. Current Discharge

Subsequently, for each of the proposed scenarios, three transmission currents (11 mA, 15 mA, and 22 mA) are used to evaluate their impact on the discharge process. Additionally, the prediction of the SOC starts when the SOC has reached approximately 80%. This condition is established through a random number generator.

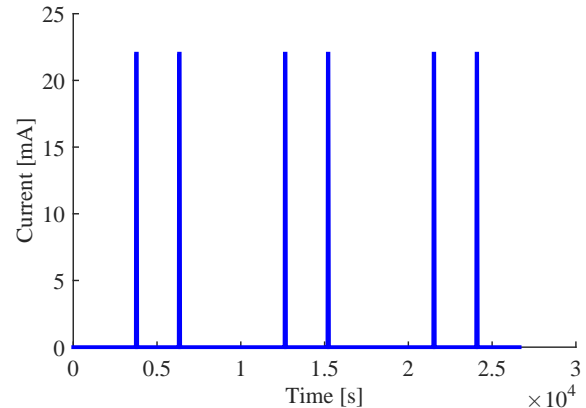


Figure 4. Current Discharge

2.2. SOH Estimation

In this subsection, the objective is to analyze the degradation suffered by the battery. To implement this step it is necessary to define an operation cycle. In this work, an operation cycle is fulfilled when the $SOC = 0.75$. The conservative current profile is used to evaluate the battery behavior. To evaluate the degradation suffered by the battery, the method proposed in (Pérez et al., 2017) is used. This method uses the concept of Coulombic efficiency to determine the degradation of the battery. Likewise, this method contemplates the use of SOC-swing (SOC-s) and swing range (SR) concepts. The SR indicates the range of start and end of the discharge, while the SOC-s indicates the total variation of the SR. In this case in

particular the SR is equal to the SOC interval between 75% and 100%, while the length of the SOC-s is equal to 25%. In addition, the advantages and disadvantages of applying this methods in the design of MAC protocols for EH-WSNs are analyzed.

3. RESULTS

The first part of the results obtained corresponds to the estimation and prediction of the SOC of the battery. In the first scenario, the sensor node is constantly transmitting, without resting times. In this case it can be clearly seen that when the transmission current decreases, the transmission time increases by 1/3. This behavior is shown in Figure 5.

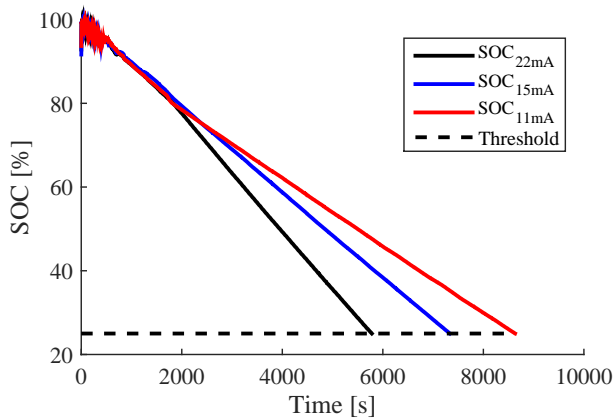


Figure 5. SOC Prediction - Scenario 1

Under the second scenario, the sensor node includes resting times, which conserves energy, emulating a more realistic approach. Figure 6 shows that the SOC does not decay rapidly but remains constant for an instant of time, which coincides with the periods of inactivity of the sensor node. Under this scenario, the typical behavior of the Open Circuit Voltage (OCV) curve of the battery can be observed more clearly, having a 20% drop at the beginning and then entering the linear area defined by the $0.25 \leq SOC \leq 0.70$.

Through the analysis of the results obtained in Figures 5 and 6, it is possible to establish the first guidelines to be considered in the design of the MAC protocols for EH-WSNs. This guideline is focused on the way in which the sensor node should transmit at night time. For aggressive profiles it is advisable to transmit to the minimum current allowed by the transceiver, while for profiles, such as the one in Figure 4, operating ranges can be established. Table 2 shows one example of different operating currents according to the SOC of the battery, when a cycle is defined using a SR of (100%-25%).

The ranges of values shown in Table 2 are reflected in Figure 7, where the use of combined currents for transmission

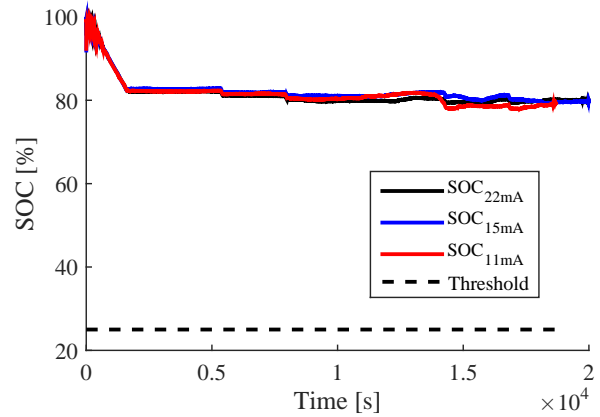


Figure 6. SOC Prediction - Scenario 2

Table 2. SOC operating Ranges

SOC Ranges	Currents
$SOC \geq 0.65$	22 mA
$0.25 \leq SOC < 0.65$	11 mA

is exemplified. When executing the algorithm in this way, it is observed that the transmission time is increased, which improve the operation of the sensor node. In other words, switching to a lower current once the SOC reaches 65%, the battery can deliver energy for nearly 30 minutes more, when undergoing an aggressive usage profile.

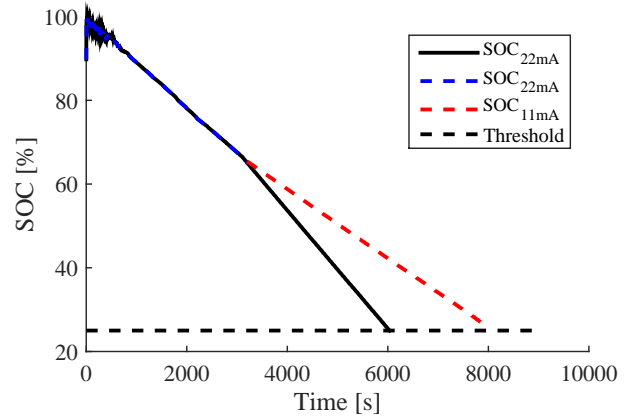


Figure 7. SOC Prediction

To study the degradation suffered by the battery, the algorithm is executed with the conservative current profile during the daylight hours to study the battery charging and discharging processes. Figure 8 shows a portion of time of one of the performed realizations, where the black line represents the 22 mA current, while the blue and red refer to the cases of 15 mA and 11 mA, respectively. The main intention of this figure is to illustrate how the battery operates on a daily basis

for the three discharge currents. In this article, every time the SOC reaches a value of 75% a cycle is accounted since the algorithm is designed to allow a normal operation of the sensor node above this value. Once the SOC is less than 75% the battery enters its recharging period, and a new cycle begins. This cycle definition is different from the one described in Table 2, since the SR is different. Figure 9 shows the histogram obtained for the total working time of the sensor node required to complete an operating cycle for the 22 mA transmission current.

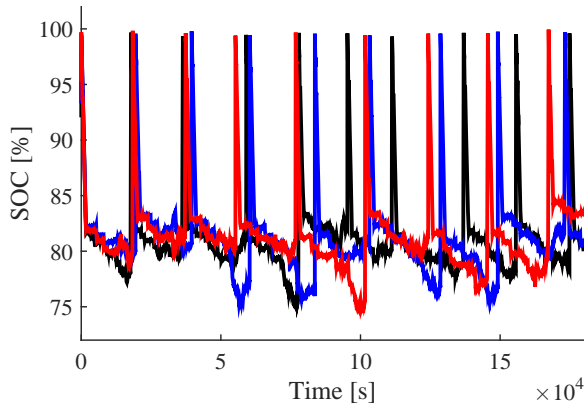


Figure 8. SOC Prediction

Using the information from the datasheet of the LIR2032 battery, the number of the operating cycles and the percentage of degradation suffered by the battery were obtained. The methodology proposed in (Pérez et al., 2017) is used to determine the Coulombic efficiency using a SR (100–75%), being this $\eta_k = 0.9995752629$. Using the Coulombic efficiency it is determined that after 25 operating cycles the capacity of the battery has degraded in 0.0017%. The methodology proposed in (Pérez et al., 2017) allows to determine an approximate percentage of degradation suffered by the battery but it does not manage to distinguish when discharging the battery with currents other than 22 mA. Although an important issue to consider is that during the same amount of simulated time, the total cycles reached by the 11 mA profile was 23, meaning that the battery degraded less as expected. Furthermore, we can be aware of the maximum degradation that the battery can suffer, since using the current of 22 mA is transmitting at maximum power, which would be the worst case scenario in terms of energy efficiency of the sensor node.

The following guidelines obtained from the results improve the design of the MAC protocols for EH-WSN. Depending on the type of EHD available in the sensor node it is important to have knowledge of its periods of use, to determine the number of hours in which the sensor node will depend exclusively on the battery. Upon this knowledge the MAC Protocol, with the assistance of the SOC information, must be able

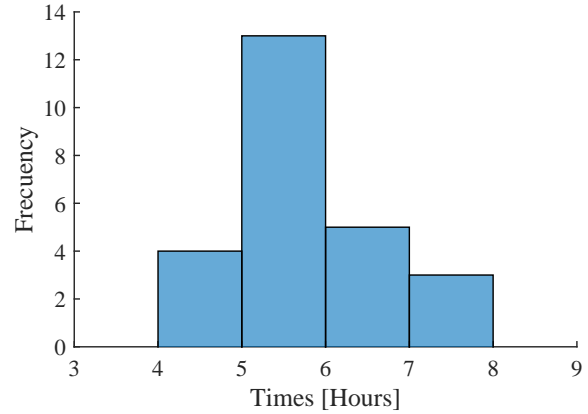


Figure 9. Duration of Each Cycle

to adjust the transmission currents. Incorporating information regarding the battery degradation process aids the sensor node to make timely decisions about the transmission times and about the network lifetime. The design of MAC protocols with SOC and SOH information represents a real challenge for the scientific community because the required tools to estimate both the indicators must be implemented without causing a considerable increase in the energy consumption of the network. On the other hand, it is important to experiment with methods that allow the assessment of the impact on the health status of the battery produced by the combination of different transmission currents.

4. CONCLUSION

Some guidelines were presented to be considered in the design of MAC protocols for EH-WSN that consider SOC and SOH information of the battery. First of all, using different currents in the transmission process helps to increase transmission times and presents the opportunity to select different current combinations to maximize the transmission time when high demand scenarios are present. Second, with inclusion of the SOH is possible to quantify the degradation process, allowing the search for the best usage profile, that is, the one that causes less degradation in the battery and extends the lifespan of the battery. The incorporation of both estimators entails a great challenge in WSNs, since its implementation has to be done using as less current as possible, although the information provided by both indicators contribute an improvement on the accuracy in the estimation of the transmitting times of each sensor node.

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NOMENCLATURE

EHD	Energy Harvesting Devices
EH-WSN	Wireless Sensor Network with EHD
ESD	Energy Storage Devices
Li-ion	Lithium-ion
MPC	Model Predictive Control
OCV	Open Circuit Voltage
PHM	Prognostics and Health Management
SOC	State-of-Charge
SOH	State-of-Health
SR	Swing Range
WSN	Wireless Sensor Network

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BIOGRAPHIES

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