Experimental Modeling of the Residual Energy of a Rechargeable Battery-Powered Node in Wireless Networks

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Abstract: *This paper proposes an effective method for experimental modeling of the remaining energy in terms of State Of the Charge (SOC) of a battery-powered node in a wireless network. The SOC of a battery is used to accurately determine the remaining energy of the battery. For experimentation, three practical applications (i.e., loads) were allowed to run on the Ni-MH rechargeable battery. The real-time variations in the battery terminal voltage are captured using IC INA219 fuel gauge and an empirical equation is derived from this captured data for each application. These empirical equations are used on a node as a programmable model to experimentally verify the SOC of the application discharge curves. The developed model randomly runs the application for a random duration of time and then computes the SOC of the node. The effectiveness of the randomness in the developed model has been analyzed and found to be practically worth. The proposed work can be scaled up to any number of nodes in a wireless network. This work can benefit the researchers and the academicians working in the area of wireless networks.*

Keywords: *Node modelling, state of the charge, fuel gauge, wireless mobile networks, discharge-curves.*

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1. Introduction

Effective utilization of the available battery charge or energy remains a major concern and a challenging task in the battery-powered nodes of a wireless network. This concern aggravates when more and more functionalities are added to the node. The researchers are making efforts to address this issue through their studies involving different battery chemistries under various environments. One such area of study involves the nodes of the Wireless Mobile Network (WMN) powered by batteries. The WMN is an infrastructure-less and highly dynamic network. The nodes of a WMN are typically battery-powered. The energy of the battery in each node becomes very important for improving the lifetime of the overall network. The nodes of a WMN are energy-constrained, and efforts are needed to optimize the consumption of the available battery energy. The residual energy or remaining energy of the battery is a function of the parameters such as State of the Charge (SOC), Depth Of Discharge (DOD), open circuit voltage and temperature.

The SOC is a battery metric that defines the remaining charge of the battery, which can be estimated by applying mathematical models [5]. The energy of a node not only depends on the radio transmission hardware but also on the processes and applications that run on it. Barboni and Valle [1] have experimentally found that processing and sensor data sampling are mainly responsible for the depletion of the battery rather than the radio transceiver. The work presented in this paper proposes an empirical modeling approach towards estimating the SOC of Nickel-Metal Hydride (Ni-MH) rechargeable battery chemistry. The authors of the proposed work claim that the applications running on the node are the significant factor in the determination of the lifetime of the WMN. It is further asserted that the above opinion is justified and validated through the implementation of a cost-effective experimental test-bed.

Remainder of this paper is structured as follows. The section 2 discusses related work primarily focusing on characterization of a rechargeable battery and modeling of SOC in WMN. The construction detail of the experimental setup is discussed in section 3. Section 4 discusses the application of the empirical model on a node and analyses the effectiveness of the application's randomness. Finally, the conclusion and future work of the presented work is given in section 5.

2. Related Work

This section discusses the related work. The work presented in this paper requires interdisciplinary research approach; hence for convenience the discussion is categorized in the following subsections.

2.1. Rechargeable Battery Modeling

The concept of battery modeling is very important in the estimation of the remaining lifetime of a portable device or a node in the WMN. A battery in this article refers to the rechargeable battery chemistry. The primary battery models can be classified as the data model, first principle model, surrogate first principle model, and hybrid model. In this paper, the proposed method considers and applies the empirical model. The empirical model belongs to the data modelling technique, in which battery characterization is done using equations that are derived based on the data [19].

2.2. Characterization of Rechargeable Battery-An SOC Perspective

The behaviour of the battery based on the time-dependent currents and behaviour of the rechargeable metal hydride chemistry can be easily predicted [17] under a constant current ripple. The experiment in [17] ascertains the requirement of a controller to mitigate the current pulse effect on the SOC if the battery is subjected to the pulsed current. An analytical model is proposed in [15] considers the temperature and the effect of the cycle of aging for predicting the remaining charge in the Li-ion battery. The model presented in [15] is validated using simulation results. The accuracy in predicting the charge of the remaining battery can be improved by measuring both current and voltage of a battery. There are significant benefits of applying a voltage and current integration method at higher SOC as described in [Work Book on Challenges and Solutions in Battery Fuel Gauging, Texas Instruments Incorporated, 2004] for estimating remaining charge of a battery. Nowadays combined voltage and current-based fuel gauge ICs are available that can improve SOC characterization of a rechargeable battery [20].

An improved Gaussian Process Regression (GPR) model is proposed in [13] for estimating the state of the health of the Li-ion battery. The data of the improved GPR model is compared with the sets of the Li-ion battery data from Aeronautics and Space Administration (NASA) to prove its accuracy. A method to implement a battery model for SOC indication system is described in [12] and the novel method adopted has shown improvement in the accuracy of the SOC indication for Li-ion battery chemistry. The parameters related to the battery such as Electro-Motive Force (EMF) and over-potential can also be measured and are used for modelling the SOC. These parameters are fed to a SOC algorithm to predict the remaining run-time of the portable applications. This paper proposes to use the fuel gauge IC to estimate the remaining charge in terms of SOC for the Ni-MH rechargeable battery.

2.3. Battery Modeling in WMN

It is learned from the related literature that the work in the direction of SOC modeling has progressed to a considerable extent but the application of the same in the modeling of the node in WMN is limited. An experimental analysis in [11] describes the battery discharge characteristics in Wireless Sensor Networks (WSN) and its related non-trivial implications in selecting the power control strategies. An analytical and experimental node energy model is presented in [18] for WSN. A detailed process for predicting the battery's state of health in wireless sensor applications is presented in [5]. The process has been validated experimentally by connecting the rechargeable battery to Telsob motes [8]. Snajder *et al*. [16] have constructed a measurement based wireless node model for data-intensive communication. The energy consumption in ZigBee motes and application of the Wi-Fi units for the transmission of a high-resolution image was analyzed with varied data rates. A mechanism is proposed in [3] to reduce the consumption of the average energy based on the application of the load balancing in the wireless network. A different strategy is used in [21] by exploiting the sleep period to increase the capacity of the battery. The simulation results of the proposed Battery Recovery Effect aware Connected Dominating Set (BRE-CDS) algorithm shows improvement in the network lifetime. An experimental validation of the analytical battery model called as Kinetic Battery Model (KiBaM) for WSN is presented in [14]. Based on the correctness of the model parameters, the KiBaM can be used to estimate the battery lifetime within the WSN context. A detailed comparative analysis of three Adhoc NETwork (MANET) routing protocols i.e., Ad Hoc On-Demand Distance Vector (AODV), Dynamic Source Routing (DSR), and Dynamic MANET On-demand Protocol (DYMO) under residual life estimator battery model is presented [4]. The work primarily focused on simulation studies using QualNet 5.0 considering the DURACELL-AA battery. Two models to evaluate the remaining lifetime of a battery are proposed in [7]. The first one is an analytical model which can be used with a network simulator and the second an empirical one to be used for the real test-bed. A set of experiments based on Advanced Configuration and Power Interface Basic Input-Output System (ACPI BIOS) measurements to evaluate energy consumption in IEEE 802.11 wireless network interface (a model of ad-hoc mobile terminals) is described. A routing method based on the prediction of node residual energy and minimum hop count is proposed [2]. Considering the example of AODV routing protocol, the simulation results have clearly shown significant improvement in terms of number of dead nodes, energy-efficiency, Packet Drop Rate (PDR) and normalized control overhead.

In summary, analytical or empirical battery models are widely used for modeling the energy source of a node. But, the energy consumption of the node depends on varying needs such as transmitting/receiving power, the number of applications running, sleep/wakeup power. The related work lacks in considering these varying needs in modeling the energy source. The proposed work is an effort to model the energy source of the node considering varying needs such as applications running on a WMN node.

2.4. Important Terms Related To Rechargeable Batteries

There are various metrics related to the characterization of battery performance. Important or most widely used metrics are good enough to characterize a battery. Hence, only the required metrics are defined below:

- A rechargeable battery consists of more than one cell arranged in a particular way to obtain the required current and voltage.
- Ampere-hour: Ampere-hour is the amount of current a battery can deliver for an hour before the voltage reaches the end of its life point.
- C Rate: The rate, at which a battery discharges relative to its maximum capacity, is defined as C rate. For example, 1C means discharging the entire battery in an hour.
- State of the Charge (SOC): is defined as the percentage of the present battery capacity to the maximum capacity.
- Depth of Discharge (DOD): is defined as the discharge expressed as a percentage of maximum capacity.
- Terminal voltage: is defined as the voltage across the battery terminals with load and the open circuit voltage is defined as the voltage across battery terminals without the load.

3. The Experimental Model

This section discusses experimental modeling of a rechargeable battery-powered node. The battery chemistry under consideration is Ni-MH and rated 3.6V, 600m AH. This model is generic and can be customized as per the requirements involving different battery chemistries and applications. The methodology adopted is known as fuel gauge method of measuring the SOC of a battery. All the experiments were carried out at room temperature. The specifications of the experiments are tabulated in Table 1. In terms of SOC, three applications are selected for practical modelling based on the node energy consumption. The applications are the combination of Direct Current (DC) motors and a 100K Ohm (1/2Watt) resistor. It is preferable to choose the applications that are easy to replicate owing to the fact that they are less time consuming and whose experimental model can be developed within a short period of time. The next part of this section describes a simplified methodology to construct an experimental model for a wireless node.

Table 1. Notations and meaning.

Battery Chemistry /Application	Voltage Rating(V)	Current Rating (mAH)	Remarks
Ni-MH	3.6	600	Variations are observed in the multi-meter measurements.
Application-1 (DC Motor)	3.2	60	Inductive load.
Application-2 (2 DC Motors)	3.2	60	Inductive load.
Application-3 (2 DC motor ,100K ohm)	3.2	60+100KOhm	Inductive+Resistive load.

3.1. SOC Modeling of Ni-MH Rechargeable Battery

Figure 1 shows a simplified view of the block diagram for SOC modeling having only one application. The fuel gauge-INA 219 (from Texas Instruments) sensor is used as the key element in determining the instantaneous voltage and current drawn by the load (or application). The microcontroller reads voltage and current from the INA 219 sensor. With a view to developing an empirical model, the application is run till the battery drains to a minimum value or until the application stops. The INA 219 can also read shunt, bus, and load voltages. These parameters are acquired for further analysis and modeling. Because of a particular load, the SOC can be determined by capturing variations in the terminal voltage or instantaneous voltage and the current drawn or any of these combinations.

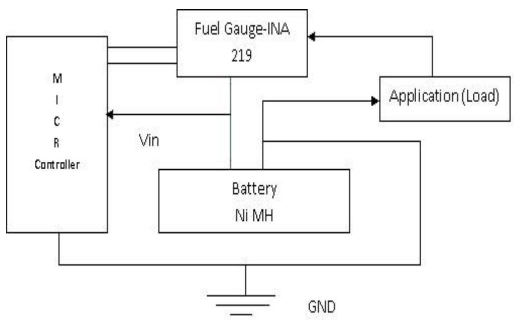

Figure 1. Block diagram of SOC modeling of a node having one application.

The work presented in this paper captures variations in the terminal voltage to determine the SOC of the battery with different applications (i.e., loads).

Figure 2 shows an integrated view of the model for determining the SOC of a battery having three different applications. Referring to Figures 1 and 2, *Vin* is the terminal voltage of the battery that is read directly by the microcontroller with respect to the ground.

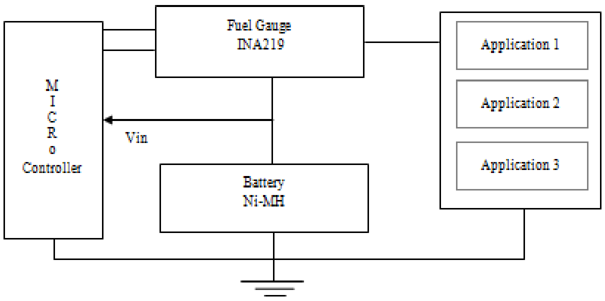

Figure 2. Block diagram of SOC modeling of a node having three applications.

For SOC modeling, it is assumed that at any given instant of time only one application is allowed to run for the duration as decided by the node (Microcontroller).

The duration of operation for each application or load depends on the type of load. The load may be resistive, inductive or capacitive as indicated in Table 1. The responses or load discharging curves are obtained from the acquired readings and are as shown in Figures 3 and 4.

3.2. SOC Empirical Modeling

The regression fitted responses for variations in the battery terminal voltage for application 1 (refer Table1) are shown in Figure 3. The response (discharging curve) in the blue colour is from the acquired data as per the block diagram of Figure 1. The response shown in the red colour is regression fitted response with an initial battery voltage of 4.22V. Even though the battery under consideration is rated 3.6 V, after every charge-discharge cycle it is found that the battery terminal voltage remained around 3.9V and sometimes above 3.9V.

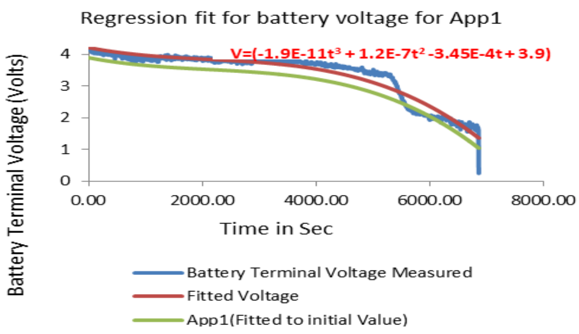

Figure 3. Regression fit response for application-1.

The battery initial readings always varied after each recharge-discharge cycle and, hence a method is devised for modeling the initial value of each application. After acquiring data for three applications under consideration, it was finally decided to fit the readings to a new initial value of 3.9V. The response shown in the green color is fit for application-1 with an initial value of 3.9V.

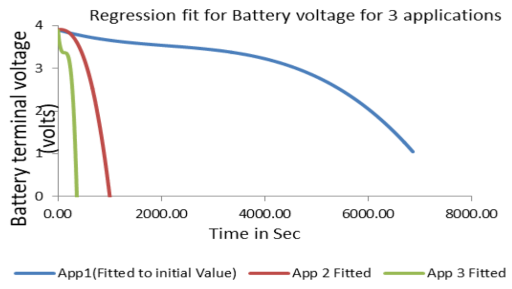

Figure 4. Regression fit responses for three applications with an initial value of 3.9V.

Figure 4 shows the regression responses for three applications with an initial value of 3.9V. From these responses, it is apparent that application 3 consumes the highest battery charge and application 1 consumes the least battery charge. This is in certain agreement with the values of Table 1.

A set of empirical equations is derived from the obtained responses. The battery terminal voltages are fitted as a function of time. The Equations (1), (2), and (3) are used to characterize the rechargeable Ni-MH battery behaviour with respect to the application.

$$V1 = (-1.9*10-11 * t3) + (1.20*10-7 * t2)- (3.45*10-4 * t)+3.9 \quad (1)$$

$$V2 = (-1.55*10-11 * t3) - (8.5*10-8 * t2)+ (0.00005 * t)+3.9 \quad (2)$$

$$V3 = (-1.99*10-9 * t3) + (3.87*10-8 * t2)- (0.0025 * t)+3.9 \quad (3)$$

Table 2 gives the initial and final voltage readings across the battery terminals without load (i.e., measured when the application stops). Sparse variations are observed in the measured final values of the battery terminal voltage. In this work, these values imply that the battery has reached the end point of its rated capacity or the application has stopped. The variations observed are obvious due to the battery performance that depends on many factors including temperature.

Table 2. Battery terminal voltage without load.

Battery Chemistry (Ni-MH)	**Multi-meter Reading**	
Load/Application	***Initial***	***Final***
Application-1 (DC Motor)	3.83	3.33
Application-2 (2 DC Motors)	3.87	3.30
Application-3 (2 DC motor ,100K ohm)	3.92	3.33

4. Application of the Empirical Model

This section discusses the application of the empirical equations in modeling a WMN node. The said equations are used to model the SOC of a node. The practical applicability of this approach is also briefly described at the end of this section.

4.1. The SOC Programmable Model

As the empirical equations depend on time, a programmable model (i.e., algorithm) is developed to determine the SOC at any instant of time with the random application running on a node. The programmable model should select an application randomly and run for a random duration. The randomness in the selection of the running time and the application give realistic modelling of the battery-powered nodes.

Figure 5 gives the average (of five trials) response for battery terminal voltage variations as a function of time. The response is shown for a random runtime duration ranging from 30 to 60 seconds. From the response, it is observed that battery behaviour is not constant except at the beginning. The response in the middle shows a gradual drop and at the end, the response is abrupt. This approach is more realistic and it gives a better strategy in evaluating the performance for WMN nodes.

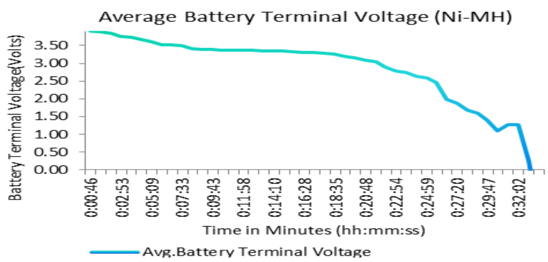

Figure 5. Average battery terminal voltage as a function of time (Ni-MH).

4.2. Analysis of Randomness of The SOC Programmable Model

The randomness factor involved is a very important metric in assessing the developed SOC model. It is necessary in the selection of the application and the duration to run on a node for the real world implementation.

It is evident from Figure 6 and Table 2 that application-3 has consumed the largest portion of the total charge. The analysis also shows that the maximum difference of the runtime duration considering all applications is approximately 2 minutes only. This is a very small difference indicating that randomness in the developed programmable model is very effective. If the effect of randomness is analyzed on the duration of the runtime of the applications, it is noticeable that the duration of the average random application remains the same for the three applications in the experiment (refer to Table 3).

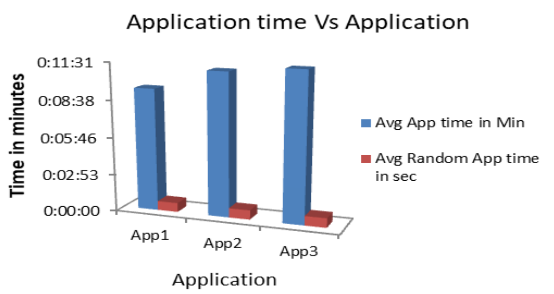

Figure 6. Application Time verses applications and average random time.

The randomness in selecting the application also shows that applications-2 and 3 ran for 15 times each and application-1 ran for 13 times. Thus randomness in selecting an application by the programmable model proves the effectiveness of the proposed methodology.

Table 3. Average application runtime analysis.

Parameter	Application 1	Application 2	Application 3
Average Application time in *min*	9.30	11.03	11.28
Average Random Application time in *Sec*	43	44	44
Average number of time the application runs	13	15	15

4.3. Examples of Applicability of the Proposed Empirical Model

The proposed empirical model considering the Ni-MH battery is experimented with practically by constructing a four-node test-bed. The SOC-based residual energy empirical model is used in [9, 10]. These papers show the elegant use of the proposed empirical approach for both Wireless Sensor Networks (WSN) and wireless Mobile Ad-hoc NETworks (MANETs). Further, this empirical model of the Ni-MH battery can be added to the NS3/NS2 tool and other simulators. Improvements in the performance evaluation of the MANET protocol can be made with this addition. Also, the concept of heterogeneity in energy in the WMN can be applied if other rechargeable battery empirical models such as mentioned in [6] are developed and incorporated in the simulators.

5. Conclusions and Future Work

A method for experimental modeling of the energy of a wireless node is proposed and implemented to determine the state of the charge of Ni-MH battery based on the application (i.e., load) discharge curves. It is evident that Ni-MH rechargeable battery behaviour is acceptable until a sudden drop starts to affect the performance of the battery. The randomness analysis corroborates the practical viability of the proposed model as shown in [9, 10]. The developed empirical model can be used to estimate the remaining energy or time of a battery based on the terminal voltage. This work can be extended to the Wireless MANETs, WSN and any kind of wireless network having any number of nodes and evaluate the performance. Further characterization of these models is determined by the nature (rechargeable or non-rechargeable) of the battery used. However, the selection of the type of battery depends on the deployment scenario of a WMN.

The presented SOC model can be used to construct an experimental wireless network test-bed involving a number of nodes. In future, the developed empirical model will be used to model nodes of a wireless network and also it is intended to derive similar empirical models for different rechargeable battery chemistries. The temperature factor is significant for accurate estimation of the SOC in a battery. Hence, in future, the effect of temperature on the proposed model will be incorporated to improve the effectiveness of the proposed model.

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