# Demo: Making Batteries a First Class Element in the Design and Evaluation of Embedded Wireless Systems

Laura Marie Feeney
Uppsala University
lmfeeney@it.uu.se

Christian Rohner
Uppsala University
christian.rohner@it.uu.se

Per Gunningberg
Uppsala University
per.gunningberg@it.uu.se

## Abstract

We present a suite of measurement and simulation tools for studying the behavior of non-rechargeable Li-coin cells. These tools will lead to improvements in the design and evaluation of battery-dependent embedded wireless systems.

## 1 Introduction

Achieving long (even multi-year) network lifetimes is essential for the successful deployment of battery-dependent embedded wireless systems. Most of the large body of work addressing this problem focuses on minimizing the total power consumption, which is generally equated with reducing the radio duty cycle and other device activity.

The battery is treated as a simple store of charge (mAh) that is depleted as the device draws $i(t)$ current over $t$ time. This linear model is implicit in both testbed experiments and simulations: In most cases, a sequence of device states is either recorded on the device or generated by a simulator. The battery lifetime is estimated by deducting the charge consumed in each state (based on current values given in hardware documentation) from the initial charge capacity, until it reaches zero. Alternatively, the lifetime is estimated based on direct measurements of current consumption over some short, presumably representative, interval.

In reality, a battery is a complex electrochemical system, with highly non-linear discharge behaviors. Key properties [6] include the rate-capacity effect (low current loads discharge the battery more efficiently), charge recovery (intermittent loads discharge the battery more efficiently than continuous ones), and state-of-charge (SoC) dependence (the same load will have a greater impact on a battery at lower SoC). Other important factors include temperature dependence (low temperatures reduce efficiency) and manufacturing variation among nominally identical batteries. Moreover, a device actually fails when its battery's electrochemical reactions can no longer provide it with the required input voltage in response to an applied load.

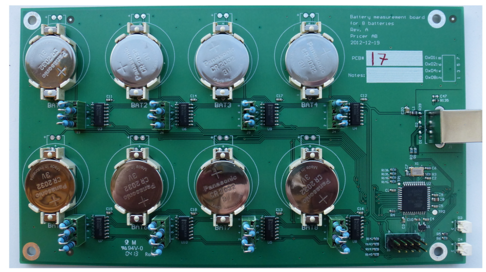

**Figure 1. Measurement hardware.**

A better understanding of battery discharge processes is therefore needed to address three problems:

- Design and evaluation of hardware and software. Systems can use the available battery capacity more efficiently, if battery properties are taken into account.
- On-line SoC estimation. Devices must be able to accurately estimate their own SoC in order to provide status information to the user. SoC data is also needed for load balancing mechanisms, such as battery-aware routing.
- Dimensioning. Given some assumptions about the anticipated load and operating environment, how large a battery is needed to achieve the desired lifetime?

This abstract describes our battery testbed and implementation of the hybrid KiBaM battery model for the OMNeT++/INET network simulator. We highlight how we have built on our earlier work ([1], [2], [7]) to create an integrated environment, where measurement and simulation tools contribute to each other and enable new approaches for improving the performance and predictability of battery-dependent systems. Our work focuses on cheap, non-rechargeable Li-coin cells, which are frequently used in small embedded devices, as well as for personal- and body-area networks.

## 2 Battery testbed

We have developed a low-cost custom testbed [2] that allows us to perform controlled battery discharge experiments on Li-coin cells (CR2032). The test hardware (Figure 1) applies a resistive load (any combination of the four attached resistors) to each of eight batteries and collects output voltage measurements at three instants before and during the

International Conference on Embedded Wireless Systems and Networks (EWSN) 2017
20–22 February, Uppsala, Sweden

ISBN: 978-0-9949886-1-4

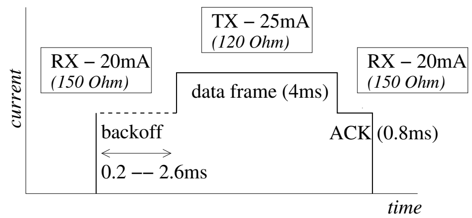


**Figure 2. A synthetic IEEE 802.15.4 packet transmission.**

load. Each load consists of up to ten segments, whose duration can be specified with a granularity of 200$\mu$s. The onboard processor (ATmega16U4-AU) controls the fine grain timing of the load and voltage measurements. A control program running on a RaspberryPi sends load commands to the card and collects the output data.

The control program combines these basic loads to create realistic experiments. For example, loads can be derived from simulation traces or changed dynamically in response to changes in the observed battery voltage. Figure 2 shows a simple synthetic IEEE 802.15.4 transmission, where the duration of the first load segment is randomly generated to reflect the CSMA backoff that precedes each transmission.

Using programmatically generated loads, rather than actual wireless devices, to drain the batteries has two advantages. One, the loads are completely controlled – something that would be impossible to achieve using a large set of devices operating in a shared environment over the full lifetime of their batteries. Two, the testbed is highly scalable, supporting up to 17 concurrent experiments[1] and 136 batteries.

## 3 Battery modeling in OMNeT++/INET

We have also implemented an existing analytic battery model, Hybrid KiBaM [3]. The model takes a sequence of current values as input and provides both the SoC and battery voltage as outputs. The SoC model is based on the Kinetic Battery (KiBaM) model [4], a battery abstraction that captures some of the key behaviors described in Section 1, such as the rate-capacity effect. The voltage model treats the battery as an RC-circuit, whose input voltage and RC time constants depend on the SoC value. Both models are systems of differential equations with closed form solutions, making them fairly lightweight computationally. Because these are analytic models, they must be parameterized based on measurements of the specific batteries in question. Our experience with Hybrid KiBaM, including its parameterization for the CR2032 Li-coin cell, is reported in [7].

The Hybrid KiBaM model has been incorporated into the open source OMNeT++/INET network simulator [5], complementing INET's existing power consumption framework, which provides a simple linear battery model. Implementation details and integration with INET's IEEE 802.15.4 radio model are reported in [1].

## 4 Workflow and use cases

Our testbed and simulations tools create an integrated environment that supports new research directions. To demonstrate how these tools work together, we present results of

[1]Resources permitting, we are happy to run experiments using loads suggested to us by collaborators.

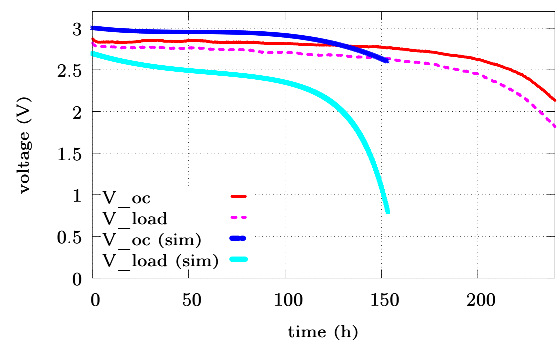


**Figure 3. Measured and simulated output voltage (open circuit and under load) for IEEE 802.15.4 transmissions.**

a recent experiment: IEEE 802.15.4 packet transmissions are simulated using the OMNeT++/INET network simulator, modeling the battery using Hybrid KiBaM. The corresponding testbed load is generated from synthetic packet transmissions, as in Figure 2. Figure 3 shows how the battery output voltage evolves in both the testbed and simulation.

More generally, the testbed allows us to systematically characterize Li-coin cell discharge under a range of conditions. For example, we have shown [2] that these batteries can tolerate high loads (20mA) for short (<10ms) periods. In fact, this is a quite efficient discharge pattern. Such results can be useful inputs for hardware and software design.

Furthermore, experiments that directly measure battery lifetime in deployed networks are logistically hard. Our testbed allows loads from device activity traces to be applied to real batteries under controlled conditions. The testbed also contributes to the design, parameterization, and testing of battery models for use in simulation. Improving the accuracy of these models is important for enabling the development of functionality that depends heavily on battery behavior, such as SoC estimation and battery-aware load balancing.

## 5 Conclusion

We have described our battery testbed and implementation of the Hybrid KiBaM battery model. We plan to demonstrate the key features of these tools and discuss how they can contribute to the development of longer lived, more predictable embedded wireless systems.

## 6 References


[1] L. M. Feeney. Towards a better battery model for INET. In *3rd OMNeT++ Community Summit*, 2016.

[2] L. M. Feeney, C. Rohner, P. Gunningberg, A. Lindgren, and L. Andersson. How do the dynamics of battery discharge affect sensor lifetime? In *11th IEEE/IFIP Conf on Wireless On-demand Network Systems and Services (WONS)*, 2014.

[3] T. Kim and W. Qiao. A hybrid battery model capable of capturing dynamic circuit characteristics and nonlinear capacity effects. In *IEEE Transactions on Energy Conversion*, volume 26, 2011.

[4] J. Manwell and J. McGowan. Lead acid battery storage model for hybrid energy system. *Solar Energy*, 50(5), 1993.

[5] http://www.omnetpp.org.

[6] R. Rao, S. Vrudhula, and D. Rakhmatov. Battery modeling for energy aware system design. *IEEE Computer*, 36(12), 2003.

[7] C. Rohner, L. M. Feeney, and P. Gunningberg. Evaluating battery models in wireless sensor networks. In *11th Int'l Conf. on Wired/Wireless Internet Communications (WWIC)*, 2013.