Quantitative Evaluation in Embedded System Design: Predicting Battery Lifetime in Mobile Devices

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1 Introduction

In the design process of an (embedded) computer system there are several important attributes the developer has to take care of: first of all, the final product should do the right thing, we then speak of functional correctness. Second, the performance should be adequate, expressed in measures such as throughput, delay or loss probability. Third, when relying on a battery as power source, it becomes increasingly important that the system behaves in an energy-aware manner. We could assess any of the three attributes in isolation, using completely different sets of models and tools. However, since the alteration of one of the attributes most surely also affects the other two, an integrated framework where all aspects can be evaluated and balanced is definitely desirable. We present such an integrated approach, but focus on the evaluation of battery lifetime. The system under consideration is represented by a stochastic workload model which then is combined with a battery model. In doing so, several design alternatives in the behaviour of the system can be compared early in the design process and the optimum with respect to functionality, performance and energy-consumption can be chosen.

2 Stochastic workload models

A stochastic workload model is an abstract model representing the states a protocol or application running on a mobile device can be in. State changes and the residence time in each state are subject to random decisions, capturing uncertainty about the duration or frequency of these events. Depending on the design aspect we are interested in, the term workload becomes different interpretations: as an example, for functional analysis, a state send just states that the protocol is transmitting a message before or after it has done something else. For performance analysis the question is of interest how long it takes to send the message. For energy consumption, we have to define how much power is consumed when sending a message.

We have chosen continuous-time Markov chains (CTMCs) for the modelling of the protocol or embedded system since they are easy to generate from convenient high-level specification languages, have a long and successful history in model-based quantitative evaluation, and there already exists a complete framework for functional correctness analysis. In the following we show how to use an extension of CTMCs with an additional notion of cost (or reward), so-called Markov reward models (MRMs), for the prediction of battery lifetime.

Figure 1 shows an example MRM for a simple battery-powered wireless device. It consists of three states (idle, send and sleep). The residence time in each of the states is ruled by a negative exponential distribution with a parameter depending on the following state. This parameter is assigned to transitions and can be read as the rate at which the model switches to the corresponding state. For each state, the power consumption rate is indicated: \( I_{\text{idle}} = 8 \text{mA}, I_{\text{send}} = 200 \text{mA}, I_{\text{sleep}} = 0 \text{mA} \).

3 Combining a workload with a battery model

The simplest battery model just assumes that energy is provided by a battery in a constant fashion until its charge has been completely consumed. If we take one possible realisation of the workload (a path), and if we know the...
capacity $C$ of the battery, we can easily determine, if the battery is already empty at a given time $t$. For example, if the wireless device first spends 2 seconds in the idle state, then 6 second sending, afterwards 18 seconds idling, 20 seconds in sleep mode and finally again 4 seconds sending, after a total of 50 seconds it has consumed $2 \cdot 8 + 6 \cdot 200 + 18 \cdot 8 + 20 \cdot 0 + 4 \cdot 200 = 2160 \text{mAs} = 0.6 \text{mAh}$.

However, the workload model describes the behaviour of the wireless device as a stochastic process. The exact sequence of states and the time spent in each state is subject to random decisions. The lifetime of a battery with capacity $C$ is therefore no longer a deterministic value but a random variable. For each time $t$ we can indicate the probability that the battery is already empty. For $t = 0$ this probability is zero, for $t \to \infty$ it is one.

**Kinetic Battery Model**

When using a single battery cell, one can often observe the so-called rate-capacity effect: if power is consumed at a high rate, the battery appears to get empty earlier than expected. If it then is allowed to rest for a while the lost charge returns (recovery effect). Both effects can be explained by the electro-chemical reactions inside the battery cell. From these nonlinear effects it follows that not only the total consumed power but also the usage pattern determines when a battery cell is first perceived empty. One model that includes these nonlinear effects is the **Kinetic Battery Model** (KiBaM) [2]. The battery charge is distributed over two wells, the available-charge well and the bound-charge well as depicted in Fig. 2. The available-charge well can directly be accessed by the attached consuming device, the bound-charge well refills the available-charge well. The rate at which charge flows between the wells depends on the difference in heights of the two wells.

The evolution of the model is given by a system of differential equations.

In the basic case we have combined a stochastic workload model with a battery that behaves in a purely linear way. However, we can also attach a stochastic model to the more sophisticated KiBaM. Instead of just accumulating the consumed power we have to keep track of two random variables, i.e. the volumes of the two wells. Thus, we obtain the so-called KiBaMRM which allows for a more precise prediction of battery lifetime. The lifetime (again a random variable) is now defined to be the point in time when the battery is perceived to be empty for the first time. The dashed curve in Fig. 3 shows the probability that the battery is (has been) empty for different $t$.

In comparison to the basic case, the curve is a bit steeper, indicating that the lifetime is, with high probability, shorter. This is the effect of residual charge in the bound-charge well while the available-charge well is already empty. This residual charge can not be used by the device. We can exploit this knowledge in the design of an alternative to the simple protocol, where the battery is always given enough time to recover. This could be achieved by sending packets in bursts leading to longer idle/sleep times in between. A complete survey of the employed methods can be found in [1].

## 4 Conclusions

With the multitude of mobile devices that is used in all areas of social and commercial life it is increasingly important to design systems in an energy-efficient manner. We have shown how stochastic model-based evaluation helps to predict battery lifetime, even if nonlinear intrinsic battery behaviour is taken into account. This approach enables the comparison of different system design alternatives and their impact on battery lifetime already in early phases of the development process.

## References
