A Tutorial on Battery Simulation - Matching Power Source to Electronic System

Manish Kulkarni and Vishwani D. Agrawal
Auburn University
Auburn, AL 36849, USA
mmk0002@tigermail.auburn.edu, *vagrawal@eng.auburn.edu*

Abstract

We use an electrical circuit model to simulate the performance of a battery as it powers the operation of a digital circuit. For a hypothetical electronic system containing 70 million gates implemented in 45nm CMOS technology the problem of finding a suitable battery is analyzed. The proposed three part solution consists of (1) circuit simulation to determine critical path delay and average current as functions of supply voltage, (2) battery simulation to determine its efficiency and lifetime (time between recharges) at various current loads and to find suitable batteries for the electronic system, and (3) derivation of operational modes (supply voltages and clock frequencies) for maximum performance and minimum energy, respectively.

1. Introduction

Most of the work on low power design is focused on designing circuits which consume lower energy and power. As far as the portable electronic devices are concerned, the ultimate aim is to achieve more battery lifetime or, for rechargeable source, perform most operations between consecutive recharges. Optimization of the circuit alone for power and energy may not always result in equivalent optimization of battery lifetime. So a study of the system consisting of battery and the circuit under consideration is required in order to achieve maximum battery lifetime. In general, this lifetime should be measured in terms of the duration of the system operation. A relevant measure is the number of useful clock cycles obtained per battery life or per battery recharge. Size and weight of the batteries are

14th IEEE/VSI VLSI Design and Test Symposium, Chandigarh, India, July 2010

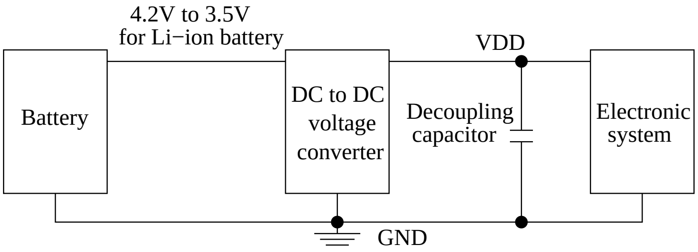

Figure 1. Powering an electronic system.

major design constraints for mobile computing devices. Battery weights are generally proportional to their *ampere-hour* (AHr) ratings. Given an application with its load current requirement, a relevant problem is to find a battery with minimum size and weight to run the application. Since the energy drawn from the battery is not always equal to the energy consumed in the device, understanding battery discharge behavior and its own dissipation are essential for optimal system design. Finding and using a suitable model for a battery is an important part of the problem.

2. Problem Statement

A typical power supply for an electronic system is shown in Figure 1. The primary source of energy is a battery, normally an electrochemical device [5]. The battery can be a *primary* type that is discarded after it is discharged, or a *rechargeable* type. As shown in Figure 1, a fully charged Lithium-ion battery supplies 4.2 volts and when the voltage drops below 3.0 volts it is recharged. The electronic system is supplied a voltage VDD that is close to 1 volt or lower for modern nanometer technologies. A DC-to-DC converter [2, 6] provides the voltage transformation as well as the capability to vary VDD for power management. Because the current requirement of the electronic system is often pulsed and time varying, decoupling capacitors are used to smooth the transient ripples. The decoupling capacitors is, in general, distributed in the power grid of the system.

The size of a battery is specified in terms of the electrical charge it can supply. A Lithium-ion battery of 400mAHr can supply 400mA for one hour. It will supply 200mA for two hours. While 400mA is the rated current for this battery, up to three times the rated current or 1.2A can be drawn for a duration of 20 minutes. However, a discharge rate higher than this can cause noticeable loss in the internal impedance of the battery resulting in heating. This results in a loss of efficiency as defined below.

The time for which a fully charged battery can supply current before requiring recharge is called its *lifetime*. Thus,

$$Ideal\ lifetime = \frac{AHr\ rating}{Load\ current\ in\ Amperes} \tag{1}$$

The end of lifetime is indicated by significant drop in the terminal voltage. Thus, the end of lifetime for a 4.2 volt Lithium-ion battery is indicated by a drop in terminal voltage below 3 volts. In practice a battery can maintain an ideal lifetime for load currents smaller than three times the rated current. Thus, a 400mAHr battery can supply up to 1.2A current. For higher currents, there is generally a reduction in *actual* lifetime due to internal losses. Therefore,

$$Efficiency = \frac{Actual\ lifetime}{Ideal\ lifetime} \tag{2}$$

To avoid loss in efficiency, we must use larger battery. For lithium-ion battery 400mAHr is considered a unit cell. Using multiple cells in parallel enhances the current capacity and lifetime. Thus, a battery size N means a battery consisting of N unit cells. For example, a battery of size $N = 5$ will be rated at 2AHr.

The problems we address in this tutorial are:

1. Determine the minimum voltage supply VDD for a synchronous clocked digital system that will meet the performance (critical path delay) requirement. Obtain the load current for the battery.

2. Determine the minimum battery size (efficiency $\geq 85\%$) for the required load current. The lifetime of the minimum size battery will be 20 minutes. Determine the battery size for given recharge interval. For example, if the minimum battery size is $N = 2$ and the system recharge time is one hour, then we select a battery of size $N = 6$ or 2.4AHr.

3. For the selected size of the battery, we determine a low performance energy saving supply voltage VDD for which the lifetime of the battery in clock cycles is maximized.

3. Battery Model

Analysis of the performance of a battery in a system requires an analyzable model of the battery. Of the three types of models, namely, electrochemical, mathematical and electrical models, we use the last one. Even among electrical models, there are several types. An excellent summary of various kinds of models is given by Chen and Rincón-Mora [4] who also provide the model we have used here. This battery model, as shown in Figure 2, consists of two parts described below:

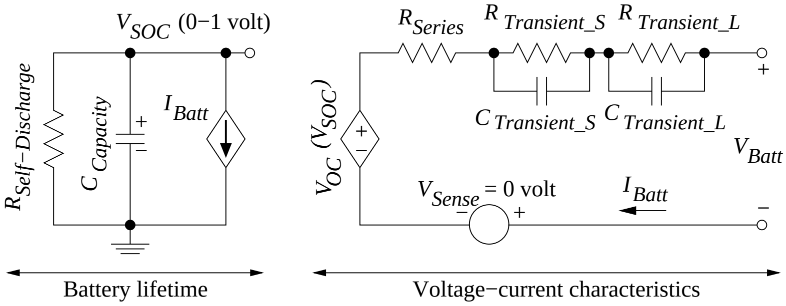

Figure 2. A battery model [4].

(A) Battery lifetime. The *state of charge* (SOC) is defined as 1.0 for a fully charged battery. It is represented by a voltage V_{SOC}, which ranges between 0 and 1 volt. The charge of the battery is stored in a capacitor $C_{Capacity}$ whose value is determined as follows:

$$C_{Capacity} = 3600 \times Capacity \times f_1(Cycles) \times f_2(Temp) \tag{3}$$

where $Capacity$ is the AHr rating of the battery. Thus, $3600 \times AHr$ is the total amount of charge in coulombs. As the battery goes through *cycles* of charging and discharging its capacity to hold charge is affected, reducing the usable capacity. That is represented by $f_1(Cycles)$. Similarly, affects the usable capacity and that is represented by $f_2(Temp)$. For simplicity, we have assumed both factors to be unity in the present discussion. The resistance $R_{Self-Discharge}$ represents leakage when the battery is stored over a long period. For reasonable time between recharge, this can be considered to be large or practically infinite. The current source I_{Batt} represents a source when the battery is being charged or a load when the battery is powering a circuit. In the latter case, it is the current being supplied to the DC-to-DC converter and to the circuit after conversion (Figure 1).

When the model is used to simulate the behavior of a battery that is fully charged, V_{SOC} is initialized to 1 volt.

(B) Voltage-current characteristics. The circuit on the right in Figure 2 emulates the terminal voltage of the battery as it supplies current. This part is linked to the part on the left by *state of charge* (SOC), a quantity in the (0.0, 1.0) range. $V_{OC}(SOC)$ is the open circuit voltage. For Lithium-ion batteries, Chen and Rincón-Mora [4] empirically derive expressions for the circuit components, which all depend on SOC:

$$V_{OC}(SOC) = -1.031e^{-35\times SOC} + 3.685 + 0.2156 \times SOC$$
$$-0.1178 \times SOC^2 + 0.3201 \times SOC^3 \quad (4)$$

$$R_{Series}(SOC) = 0.1562e^{-24.37\times SOC} + 0.07446 \quad (5)$$

$$R_{Transient\_S}(SOC) = 0.3208e^{-29.14\times SOC} + 0.04669 \quad (6)$$

$$C_{Transient\_S}(SOC) = -752.9e^{-13.51\times SOC} + 703.6 \quad (7)$$

$$R_{Transient\_L}(SOC) = 6.6038e^{-155.2\times SOC} + 0.04984 \quad (8)$$

$$C_{Transient\_L}(SOC) = -6056e^{-27.12\times SOC} + 4475 \quad (9)$$

To the original model [4] in Figure 2 we have added a zero-voltage source, V_{Sense}. This is done to facilitate Hspice simulation in which we must specify the value I_{Batt} of the current source of the battery lifetime portion as equal to the current through this voltage source V_{Sense}. The current is sensed as positive if it flows into the positive terminal of V_{Sense}.

4. Finding the Right Battery

The analysis to find a matching battery for an electronic system contains several steps:

- Step 1 (Determine circuit characteristics). The circuit is simulated for several supply voltages (VDD) to find its critical path delay. This gives the clock frequency for each VDD. Using the corresponding clock frequency, the average current consumption is determined for each VDD.
- Step 2 (Determine smallest battery size). The model of the selected battery type is simulated for various current loads obtained in the previous step. Every battery type has its terminal voltages corresponding to fully charged state and fully discharge state. Using the load current, scaled for the ratio of battery voltage to circuit VDD, the battery model is simulated to determine the terminal voltage as a function of time. In practice this scaling is achieved by a DC-to-DC converter that is known to have high conversion efficiency (greater than 90%) [1, 6]. Alternatively, the circuit of DC-to-DC converter

can be attached to the battery model. The time between the fully charged state to the fully discharged state gives the battery lifetime in time units (seconds). This is repeated for increasing battery sizes, normalized with respect to the smallest unit. A lower bound on battery size is determined for a minimum of 85% efficiency. While the selected battery should not be smaller, its actual size is determined by the recharge interval requirement of the system.

- Step 3 (Determine minimum energy modes). The previous step determines two battery sizes, namely, the smallest usable battery that meets the performance requirement and another size that can meet both performance and recharge interval requirements. We now determine maximum lifetime modes for each battery. In this mode the performance requirement is completely relaxed and the supply voltage (VDD) is determined for maximum lifetime in clock cycles. For some nanometer technologies, this VDD can be below the sub-threshold voltage [8].

In the next section, we illustrate these three steps with an example.

5. Example

Our example consists of a 70 million gate hypothetical system. We assume that the critical path consists of a 32-bit ripple-carry adder consisting of 352 NAND gates. The technology assumed is 45 nanometer bulk CMOS. For simulation, the predictive technology model (PTM) is used [3, 9]. The 32-bit adder was simulated using the Hspice simulator [7]. The description of this circuit follows:

- Function: 32-bit ripple-carry adder.
- Inputs: Operand A (32-bit), Operand B (32-bits), Carry-in (1-bit).
- Outputs: Sum (32-bits), Carry-out (1-bit).
- Transistors: 1,472 (352 two and three input NAND gates).
- Technology: 45nm bulk CMOS.
- Critical path: B(0) to Carry-out. Sensitizing vectors (3): A = 8h'FFFF FFFF, B = 8h'0000 000x, where x changes 0-1-0, Carry-in = 0.

5.1 Step 1: Circuit characteristics

Using the Hspice simulator [7] and the 45nm PTM [3, 9], we determined the critical path delay of the 32-bit adder for VDD ranging from 1.0V to

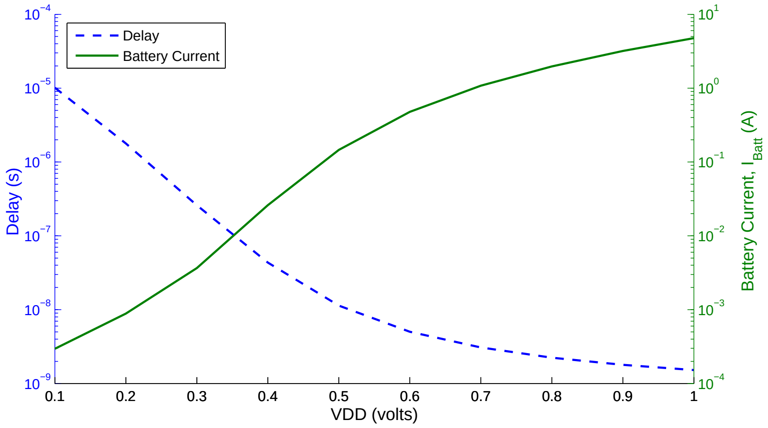

Figure 3. Circuit delay and current versus VDD obtained from Hspice [7] simulation.

0.1V at interval of 0.1V. This is shown in Figure 3. We found that the although the circuit slows down by more than three orders of magnitude, it works correctly up to $VDD = 0.1V$, which is below the threshold voltage of 0.292V for the 45nm PTM devices [9].

Next, to determine the average current we simulated the circuit using 100 random vectors. The simulation was repeated for all the same values of VDD as before. In each case, vectors were applied at an interval equal to the corresponding critical path delay. Assuming a similar activity for the entire 700 million gate system, the average current measured for the 352-gate adder from Hspice simulation was multiplied by 200,000. Considering a 100% efficiency DC-to-DC converter that translates VDD to the 4.2V rated terminal voltage of Lithium-ion battery, we determine the battery load current I_{Batt} by multiplying the circuit current by $VDD/4.2$. That I_{Batt} as a function of VDD is shown in Figure 3.

5.2 Step 2: Battery size

We assumed the use of Lithium-ion batteries with a unit battery ($N = 1$) of 400mAHr rating. As an example, consider the battery load current $I_{Batt} = 3.6A$ for $VDD = 0.9V$ in Figure 3. Figure 4 shows the battery terminal voltage V_{Batt} obtained from Hspice [7] simulation of the battery model of Figure 2. In this figure the battery size is $N = 3$, i.e., $Capacity = 1.2AHr$. The leakage resistance, usually very large, was takes a 1 giga-ohms. All other parameters were as described in Section 3.

From Figure 4, the terminal voltage drops to 3.0V, i.e., battery needs

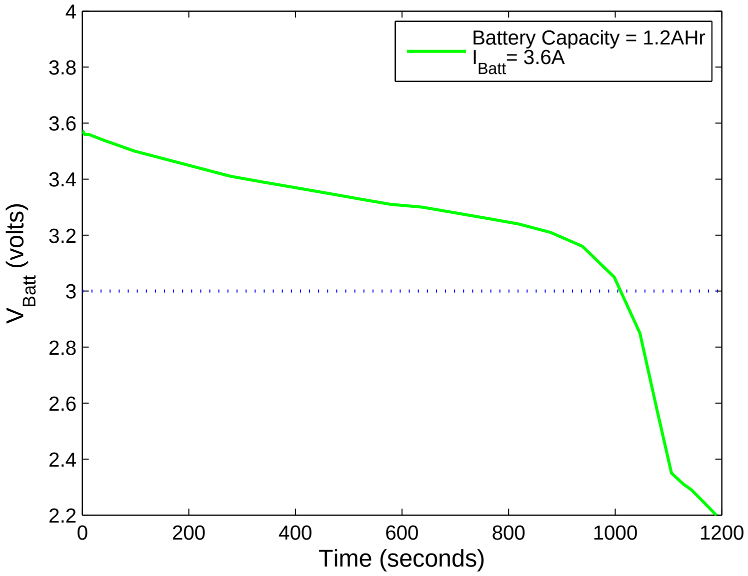

Figure 4. Hspice [7] simulation of battery model, terminal voltage V_{Batt} vs. time for load $I_{Batt} = 3.6A$ and Capacity = 1.2AHr $(N = 3)$.

recharge, after it supplies current for 1008 seconds. This is the actual lifetime for this battery. From equation 1 the ideal lifetime is $3600 \times 1.2/3.6 = 1200$ seconds. This, according to equation 2, gives an 84% efficiency. Figure 5 shows the battery efficiencies obtained in this way for various battery sizes and for varying load currents. We observe,

1. When the load current is small compared to the AHr rating, the efficiency is 100% or higher. For example, for a battery of size $N = 5$ (2AHr) the efficiency for $I_{Batt} = 0.6A$ is 107%.

2. When the load current is large compared to the AHr rating, the efficiency can be significantly lower. The 85% line is shown to indicate that a power source with lower efficiency may be considered unacceptable. For any given load current this 85% line allows us to determine the smallest battery that can be used.

While the smallest size battery has advantages of weight and cost, it can provide a lifetime (time between recharges) of about 1,000 seconds. This is not often sufficient. Figure 3 is used to determine the battery current I_{Batt} for given performance requirement. Suppose, the system under consideration has a peak performance requirement of 500MHz clock.

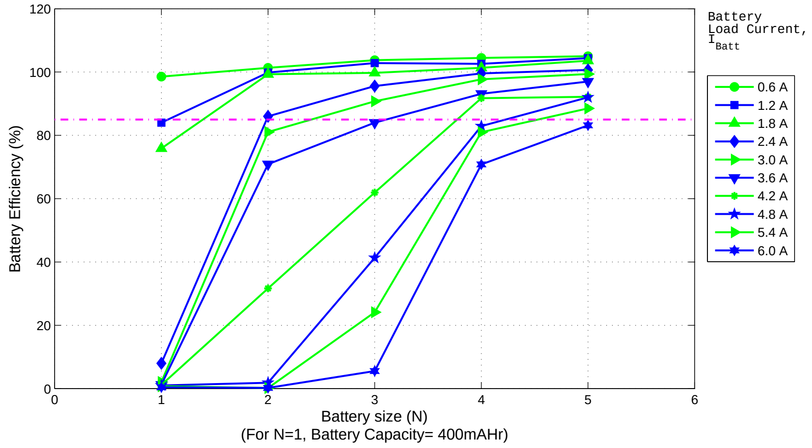

Figure 5. Battery efficiency versus battery size for various load currents.

Table 1. High performance and minimum energy modes of operation.

Battery size		500MHz, $VDD = 0.9V$			5MHz, $VDD = 0.3V$		
		Effici.	Lifetime		Effici.	Lifetime	
N	AHr	%	sec.	cycles	%	sec.	cycles
3	1.2	93	1263	7.03×10^{11}	> 100	1233781	4.86×10^{12}
9	3.6	103	4198	2.28×10^{12}	> 100	3894000	15.03×10^{12}

This corresponds to a critical path delay of 2ns. From Figure 3, we select $VDD = 0.9V$ and $I_{Batt} = 3.18A$. From Figure 5, we get $N = 3$ or 1.2AHr as the smallest battery. The efficiency is about 93%, giving a lifetime $= 3600 \times 0.93 \times 1.2/3.18 = 1263$ seconds.

Consider the case where the system has a battery lifetime requirement of over one hour. We, therefore, triple the battery size to $N = 9$ or 3.6AHr. From Figure 5, the efficiency for $I_{Batt} = 3.18A$ is 103%. The lifetime is computed as $3600 \times 1.03 \times 3.6/3.18 = 4198$ seconds.

These two battery options are shown in Table 1 as 500MHz, $VDD = 0.9V$ operation.

5.3 Step 3: Minimum energy mode

Most electronic systems have performance and uninterrupted operation requirements that determines the battery size as discussed above. But, a system does not always operate in the maximum performance environment.

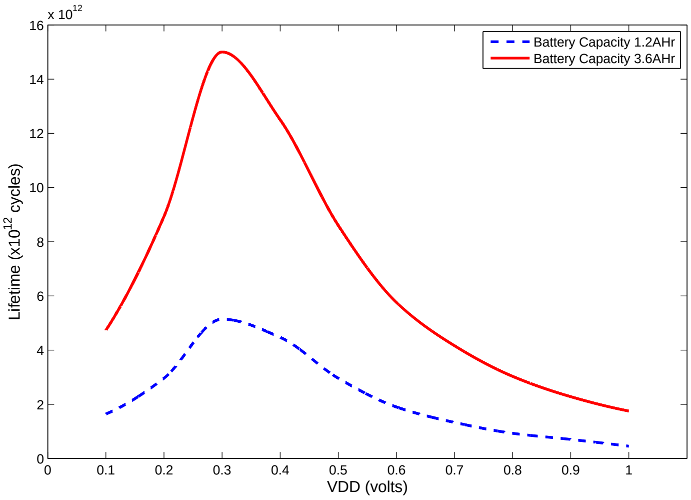

Figure 6. Battery lifetimes in clock cycles as a function of chip voltage for 1.2AHr and 3.6AHr batteries.

Lowering VDD that can be easily done by the DC-to-DC converter reduces I_{Batt} and hence extends the battery lifetime. Critical path delay, however, increases and clock frequency must be reduced. A relevant measure of lifetime, therefore, is the lifetime in clock cycles. Thus, instead of expressing the lifetime in raw seconds, we express it in terms of *computational work units*.

Figure 6 shows the lifetime in clock cycles as a function of VDD for the two batteries of Table 1. For each VDD the current I_{Batt} is given by Figure 3. The lifetime in seconds is obtained as $3600 \times \mathit{efficiency} \times (battery\ AHr)/I_{Batt}$, where *efficiency* is obtained from Figure 5. This lifetime is divided by the critical path delay (clock cycle time), which is also given by Figure 3, to obtain the lifetime in cycles. Figure 6 indicates the optimum lifetime at $VDD = 0.3V$ for both batteries. According to Figure 3, the critical path delay for $VDD = 0.3V$ is 0.2μs, giving a clock frequency of 5MHz.

The high performance mode and the minimum energy modes are summarized in Table 1. The minimum energy mode increases the time between recharges by thousand fold. That is misleading because the clock frequency is reduced 100 times. However, it does provide a seven fold increase in the number of clock cycles per battery recharge.

6 Conclusion

This paper shows how a power source is selected to economically satisfy the operational requirements of a sytem. An electrical model of a battery allows the determination of its lifetime and efficiency. Lifetime measured in terms of clock cycles is shown to be a useful measure. Simulation of the battery as well as that of the circuit being powered allows determination of high performance and minimum energy operational modes.

Other applications of battery analysis may be in assessing and optimizing the power management techniques. Given the size of the battery, its efficiency reduces for higher currents. While power reduction is necessary from temperature and other environmental requirements of semiconductor chips, the influence of power reduction on battery lifetime is important for portable devices.

References

[1] L. Benini, G. Castelli, A. Macci, E. Macci, M. Poncino, and R. Scarsi, "Discrete-time battery models for system-level low-power design," *IEEE Trans. VLSI Systems*, vol. 9, no. 5, pp. 630–640, Oct. 2001.

[2] L. Benini, G. Castelli, A. Macii, E. Macii, M. Poncino, and R. Scarsi, "A Discrete-Time Battery Model for High-Level Power Estimation," in *Proceedings Conference on Design, Automation and Test in Europe*, Mar. 2000, pp. 35–41.

[3] Y. Cao, "Predictive Technology Model." http://ptm.asu.edu/.

[4] M. Chen and G. A. Rincón-Mora, "Accurate Electrical Battery Model Capable of Predicting Runtime and I-V Performance," *IEEE Transactions on Energy Conversion*, vol. 21, no. 2, pp. 504–511, June 2006.

[5] D. Linden and T. B. Reddy, *Handbook of Batteries.* New York: McGraw-Hill, 2002.

[6] M. Pedram and Q. Wu, "Design Considerations for Battery-Powered Electronics," in *Proc. 36th Design Automation Conference*, June 1999, pp. 861–866.

[7] Synopsys, Inc., "HSPICE The Gold Standard for Accurate Circuit Simulation." www.synopsys.com/Tools/Verification/AMSVerification/ CircuitSimulation/HSPICE/Documents/hspice_ds.pdf.

[8] A. Wang, B. H. Calhoun, and A. P. Chandrakasan, *Sub-Threshold Design for Ultra Low-Power Systems.* Springer, 2006.

[9] W. Zhao and Y. Cao, "New Generation of Predictive Technology Model for Sub-45nm Early Design Exploration," *IEEE Transactions on Electron Devices*, vol. 53, no. 11, pp. 2816–2823, Nov. 2006.