An Interleaved Dual-Battery Power Supply for Battery-Operated Electronics

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Abstract — *After a detailed analysis and discussion of two important characteristics of today's battery cells (i.e., their current-capacity and current-voltage curves), this paper describes the design principles and architecture of a dual-battery power supply system for portable electronics. The key idea is to integrate two battery types with different energy capacity and current rate curves into the power supply system, and then use them in an interleaved manner in response to varying current requirement of the VLSI circuit that is powered by this dual-battery system. Analytical and empirical results demonstrate the effectiveness of the new battery architecture in maximizing the service life of a battery system with fixed volume (or weight).*

I. INTRODUCTION

With the Moore's law still in effect, integrated circuit densities and operating speeds continue to rise. Chips however cannot get larger and faster without a sharp increase in power consumption beyond the current levels. Minimization of power consumption in VLSI chips has thus become an important design objective. In fact, with exponential growth in demand for portable, battery-powered electronics and the usual push toward more complex and higher performance, power consumption has in many cases become the limiting factor in satisfying the market demand.

This challenge has been met by an active research and development community both in industry and academia. Rapid advances are taking place in low-power process technologies, architecture and circuit optimization techniques, power-aware simple and complex cell design, use of variable and/or multiple supply voltages and dynamic power management schemes, and low power computer aided design (CAD) tools from system and software levels to layout and transistor levels.

A battery-powered digital system consists of the VLSI circuit, the battery, and the DC/DC converter. In spite of the fact that the goal of low-power design for battery-powered electronics is to extend the battery service time, most research works on low-power design metrics and methodologies have focused on the VLSI circuit itself. People usually assume that the battery sub-system (battery and the DC/DC converter) is an ideal source that outputs a constant voltage and stores/delivers a fixed amount of energy [4].

However, in reality, the battery sub-system has complicated characteristics rather than ideal. Research has been done [7][8] to study the influence of the current-capacity characteristics of the battery on CMOS digital design. It has been found that, by selecting the optimal supply voltage that minimizes the *Battery Discharge-Delay product*, we can achieve the best trade-off between battery service life and circuit delay. It is also shown in [8] that, even with the same mean value, different current discharge (energy dissipation) profiles will lead to different battery service life. However, these research works have not considered other important characteristics of the battery sub-system.

In this paper, we extend the work of [8] by doing analysis of optimal supply voltage for a VLSI circuit by considering not only the current-capacity characteristics, but also the current-voltage characteristics of the battery. In a significant departure from the work reported in [7][8], in this paper, we also present design principles and a design procedure for constructing a dual-battery power supply system which would interleave two different batter types (i.e., with different energy capacity and current rate) in order to match the current requirements of the VLSI circuit which is powered by this dual-battery power supply. The goal is to maximize the total battery service life for given battery volume (or weight). Analytical and empirical results demonstrate that battery life increases of up to 60% can be achieved if the dual-battery power supply is designed and used properly.

This paper is organized as follows. Section II provides some background on battery characteristics. Section III considers the problem of optimal supply voltage selection. Section 0 gives the design and analysis of dual-battery interleaving power supply system. Sections V presents conclusions.

II. BACKGROUND

A. Notation

We first give some useful notations:
T: Clock cycle time for one operation
V_0: Output voltage of the battery
I_0: Average output current of the battery over time $N \cdot T$
V_{dd}: Supply voltage of the circuit
I_{dd}: Average supply current of the circuit over time $N \cdot T$
μ: Efficiency factor of the battery
η: Efficiency of the DC/DC converter
E^{ide}: Ideal energy needed to complete an operation
E^{act}: Actual battery energy needed to complete an operation
CAP_0: Total energy stored in a new battery
BD: Battery discharge

B. Battery Overview and Characteristics

Many different types of batteries are being used in a wide range of applications [10]-[12]. Among these, the Nickel-Metal Hydride battery and the Lithium-Ion battery are currently the most popular secondary batteries for portable electronic devices, ranging from cellular phones to notebook computers.

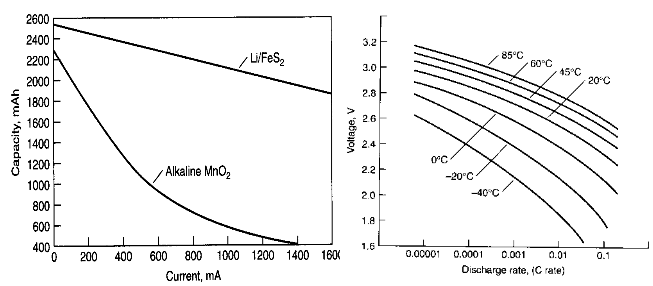


Figure 1 The relations between battery capacity, output voltage and discharge current.

A typical lithium rechargeable battery consists of the lithium foil anode, the composite cathode, and the electrolyte that serves as an ionic path between electrodes and separates the two materials. During discharge, the electrochemical process involves the dissolution of lithium ions at the anode, their migration across the electrolyte and their insertion within the crystal structure of the cathode. Positive current flows in the opposite direction in the external circuitry. Applying electrical recharging can reverse the reaction; hence the battery can be used for multiple times (normally several hundred times).

The principles of electrochemical reaction make the battery not an ideal energy source. Many factors define the complicated relations between battery capacity, output voltage, and discharge current. Some major relations for typical lithium batteries [10][11] are shown in Figure 1. We can conclude from Figure 1 that:

1. The *deliverable capacity* (in brief, capacity) of the battery decreases when the discharge current increases.
2. The output voltage of the battery decreases when the discharge current increases.

For our analysis, we need to model and approximate these relations using analytical equations. To simplify the analysis and presentation, in this paper, we use linear functions for approximation; high-order approximations can be used to obtain higher accuracy.

A decrease of actual battery capacity is equivalent to an increase of the actual energy drawn from the battery [8]. Therefore the actual energy that is taken out of the battery is:

$$E^{act} = \frac{V_0 \cdot I_0 \cdot T}{\mu}, \quad 0 \le \mu \le 1 \tag{2.1}$$

where μ is called the battery efficiency (or utilization) factor. The efficiency factor μ is a function of discharge current I_0, we approximate it as:

$$\mu = 1 - \beta \cdot I_0 \tag{2.2}$$

where β is a positive constant number.

Similarly we approximate the relationship between the battery output voltage and the discharge current as a linear function:

$$V_0 = V^{OC} - \gamma \cdot I_0 \tag{2.3}$$

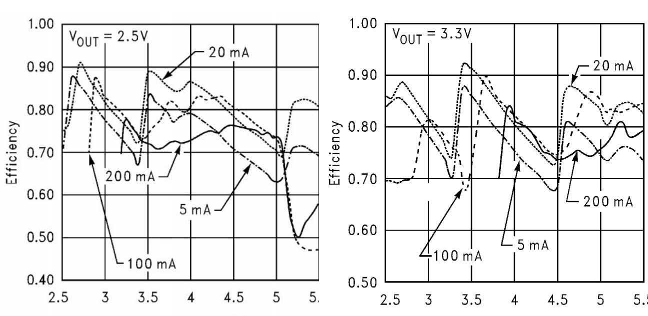
where V^{OC} is the open-circuit output voltage of the battery.

C. *DC/DC Converters*

The role of a DC/DC converter is to convert the battery output voltage to and stabilize at the operation voltage of the CMOS circuit. If we define η as the conversion efficiency of the DC/DC converter, we have:

$$\eta \cdot V_0 \cdot I_0 = V_{dd} \cdot I_{dd} \tag{2.4}$$

where I_0 and I_{dd} are average input and output current of the DC/DC converter over some period of time. V_0 and V_{dd} are similarly defined. Notice that V_0 and I_0 are also the output voltage and current of the battery, V_{dd} and I_{dd} are also the supply voltage and current for the VLSI circuit.



(a) V_{OUT}=2.5V (b) V_{OUT}=3.3V

Figure 2 DC/DC converter efficiency versus input/output voltage and output current

In real circuit design, the conversion efficiency η varies in large region due to different input voltage V_{IN} (V_0), output voltage V_{OUT} (V_{dd}) and output current I_{OUT} (I_{dd}). Figure 2 [6] shows an example for a commercial product. Obviously it is difficult to model the behavior shown in Figure 2. However, we also know from [5] that, given the specific input/output voltages and output current, a DC/DC converter circuit can be optimized for high efficiency (90% to 95%). Since in our analysis, V_0, V_{dd} and I_{dd} are all fixed for each calculation (of the optimal supply voltage), we can assume that the DC/DC converter is always optimized and has nearly constant conversion efficiency for each calculation.

III. NEW ANALYSIS OF OPTIMAL V_{DD} FOR MINIMUM BD-D PRODUCT

Ref. [8] proposed a new metric for low power design in an integrated battery-hardware model, the *battery discharge-delay product*. This metric is similar to the energy-delay product while accounting for the battery characteristics and the DC/DC conversion efficiency. The *BD*-delay product states that the design goal should be to minimize delay and maximize battery lifetime at the same time.

In this section, we will extend the work of [8] in that, we consider the current-voltage characteristics as well as the current-capacity characteristics of the battery.

A. *New Analysis*

The Battery Discharge (*BD*) is defined as:

$$BD = \frac{E^{act}}{CAP_0} = \frac{V_0(I_0) \cdot I_0 \cdot T}{CAP_0 \cdot \mu(I_0)} \tag{3.1}$$

The ideal energy needed for circuit to complete an operation is [2]:

$$E^{ide} = V_{dd} \cdot I_{dd} \cdot T = \tfrac{1}{2} C_{sw} \cdot V_{dd}^2 \tag{3.2}$$

where C_{sw} is the total switched capacitance during the operation.

From Equations (2.4), (3.1) and (3.2), we can write *BD* as:

$$BD = \frac{C_{sw}}{2 \cdot \eta \cdot CAP_0} \cdot \frac{V_{dd}^2}{1 - \beta \cdot I_0} \tag{3.3}$$

To write I_0 as a function of V_{dd}, we have to solve the following equation:

$$\eta \cdot (V^{OC} - \gamma \cdot I_0) \cdot I_0 \cdot T = \tfrac{1}{2} C_{sw} \cdot V_{dd}^2 \tag{3.4}$$

We have two solutions of I_0 to (3.4), however the one that is reasonable in reality (i.e., the solution should be meaningful when γ is 0) is:

$$I_0 = \frac{\eta \cdot V^{OC} - \sqrt{\eta^2 \cdot (V^{OC})^2 - 2 \cdot \eta \cdot \gamma \cdot C_{sw} \cdot V_{dd}^2 / T}}{2 \cdot \eta \cdot \gamma} \tag{3.5}$$

We can write *BD* as function of V_{dd} by substituting (3.5) into (3.3).

For today's deep sub-micron CMOS technology, the delay of a circuit can be modeled as:

$$t_d = m \frac{V_{dd}}{(V_{dd} - V_{th})^{\alpha}}, \qquad 1 < \alpha \le 2 \tag{3.6}$$

where m is some constant and V_{th} is the threshold voltage of the transistor.

We can thus write the *BD*-delay (*BD-D*) product as:

$$BD\text{-}D = \frac{m \cdot C_{sw}}{2 \cdot \eta \cdot CAP_0} \cdot \frac{V_{dd}^3}{(1 - \beta \cdot I_0) \cdot (V_{dd} - V_{th})^{\alpha}} \tag{3.7}$$

where I_0 is given in Eqn(3.5).

We consider only the case of variable operation latency where:

$$T \propto t_d \Rightarrow T = m' \frac{V_{dd}}{(V_{dd} - V_{th})^{\alpha}}, \qquad 1 < \alpha \le 2$$

Therefore, Eqn. (3.5) need to be re-written as:

$$I_0 = \frac{\eta \cdot V^{OC} - \sqrt{\eta^2 \cdot (V^{OC})^2 - 2 \cdot \eta \cdot \gamma \cdot C_{sw} \cdot V_{dd} \cdot (V_{dd} - V_{th})^{\alpha} / m'}}{2 \cdot \eta \cdot \gamma} \tag{3.8}$$

B. *Quantitative examples*

Assume a VLSI circuit consumes 13.5W power at supply voltage of V_{dd}=1.5V. Let V_0=4V and η=0.9. We have C_{sw}/m'=21. Let α=1.5, and V_{th}=0.6V. We normalized $(m \cdot C_{sw})/(2 \cdot \eta \cdot CAP_0)$=1 since their values will not influence the optimal V_{dd} and the shape of *BD-D* product. To show the influence of the battery characteristics on the optimal V_{dd}, we use β values of (0, 0.05, 0.1, 0.15) and γ values of (0, 0.15, 0.3) to generate a group of *BD-D* product curves and compare the optimal V_{dd} values. Notice that if β=0, we are not considering the current-capacity characteristics, if γ=0, we are not considering the current-voltage characteristics (as in [8]). When they are all 0, it is the ideal case where the battery is a constant-voltage and constant capacity energy source. Figure 3 shows the plot of *BD-D* product curves with different β and γ values. Table 1 shows the corresponding optimal V_{dd} values. Notice that the effect of current-voltage characteristics of the battery on the optimal V_{dd} assignment for the circuit is relatively small.

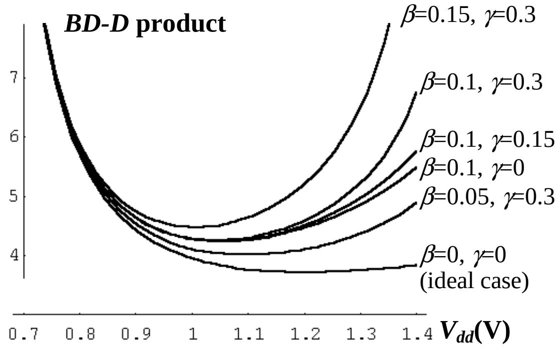


Figure 3 *BD-D* product curves.

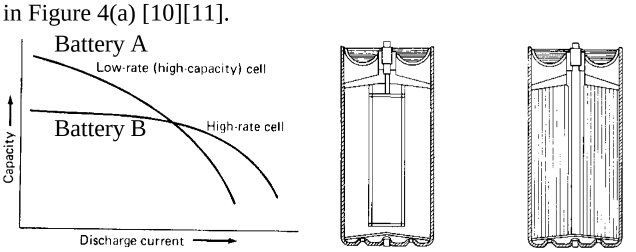
Table 1 Optimal V_{dd} for minimum *BD-D product*.

Optimal V_{dd} (V)		β			
		0	0.05	0.1	0.15
γ	0	1.2*	1.108	1.054	1.017
	0.15	1.2*	1.103	1.051	1.015
	0.3	1.2*	1.096	1.044	1.008

* Ideal case without considering the characteristics of the battery.

IV. DESIGN OF AN INTERLEAVED DUAL-BATTERY POWER SUPPLY

Consider two batteries with the same volume (or weight) which have different current-capacity (characteristic) functions as shown in Figure 4(a) [10][11].



(a) (b) bobbin cell (c) Spiral cell

Figure 4 Batteries of different current-capacity relations.

Note that battery A has higher capacity per unit volume (weight) than battery B at low discharge current; battery B has higher capacity per unit volume (weight) than battery A at high discharge current. This phenomenon is commonly encountered in today's batteries. For example, using different materials for the anode and cathode or using different battery structures could cause such an effect. For the latter case, Figure 4(b) and (c) [10] show two typical structures of D-size lithium batteries. The battery in Figure 4(b) produces the behavior of battery A while the battery in Figure 4(c) produces the behavior of battery B [11]. We assume that although the capacity of a battery changes as we change its volume (or weight), its current-capacity function remains unchanged.

The question of which battery (A or B) provides a longer service life can only be answered when the current requirement of the circuit is known. Indeed, battery A has longer service life at low discharge current, whereas battery B has longer service life at high discharge current. Therefore, obtaining the circuit current profile is very helpful for selecting an appropriate battery for the circuit.

Obviously, the battery service life is maximized if we include both batteries in the power supply system and use them alternately according to the current requirement from the circuit. We will give the design and analysis of this battery interleaving technique.

The schematic of the proposed interleaved *dual-battery* (IDB) power supply system is shown in Figure 5. Its working principle is simple: when the discharge current is lower than some threshold I_{th}, system uses battery A as the power supply, otherwise system uses battery B.

Figure 6(a) shows simplified current-capacity characteristics (per unit volume or weight) for batteries A and B. The highest current and highest capacity have been normalized to 1. We assume that batteries A and B have the same output voltage and normalize it to 1. Without loss of generality, we also assume that the discharge current is uniformly distributed and its profile is shown in Figure 6(b), where $p(I)$ is the density function of the discharge current. Notice that it is straight forward to repeat the analysis for other discharge current distributions (e.g. normal, bimodal).

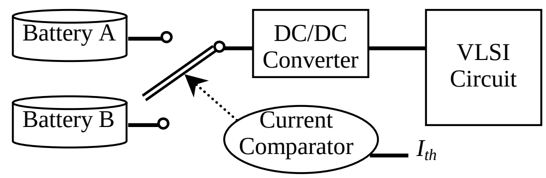
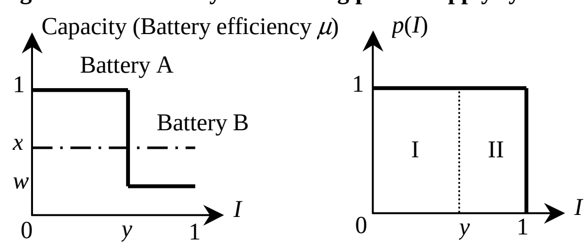


Figure 5 Dual-battery interleaving power supply system.



(a) current-capacity characteristics (b) discharge current profile

Figure 6 Analysis basis.

When the battery discharge current is not constant (δ-function distribution), the current-capacity curves cannot be used directly for our analysis of *BSL* [8]. We have to transform the current-capacity curves into current-efficiency curves using the concept of battery efficiency μ, which was mentioned in Section II. Since we have normalized the highest capacity to 1, Figure 6(a) is then both the current-capacity curve and current-efficiency curve. In Figure 6(a), battery B has a constant efficiency of x for all value of discharge current. Battery A has a constant efficiency of 1 if the discharge current is lower than y, and a constant efficiency of w is the discharge current is higher than y.

The problem of optimal design of the IDB power supply system is defined as follows. Given two batteries with current-capacity characteristics shown in Figure 6(a) and discharge current profile shown in Figure 6(b), and a volume (or weight) limit (normalized to 1) for the whole power supply, divide the total battery volume (or weight) between these two battery types such that the service life of the IDB power supply system is maximized. Assume battery A occupies a portion z and battery B occupies a portion (1-z) of the total power supply volume (or weight).

We normalize the total energy stored in the power supply system to 1. The service life of the power supply system can be calculated as:

$$BSL = 1\Big/ I_{ave}^{act} \tag{4.1}$$

where I_{ave}^{act} is the average of actual current I^{act} drawn from the battery. I^{act} is calculated as: $I^{act} = I/\mu(I)$, where I is the discharge current and $\mu(I)$ is defined by Figure 6(a).

We have 4 variables in our analysis: w, x, y and z. Some constraints on them are: $0<w<x<1$, $0<y<1$ and $0\leq z\leq 1$. Let us first study two extreme cases: z=1 (only use battery A) and z=0 (only use battery B).

A. *Only use battery A (z=1)*

In this case, we divide the current domain into two regions I and II, as shown in Figure 6(b). In region I, the average discharge current is $I_{ave,I}=y/2$. The actual average discharge current is:

$$I_{ave,I}^{act} = I_{ave,I} / \mu = y/2$$

In region II, the average discharge current is $I_{ave,II}=(1+y)/2$. The actual average discharge current is:

$$I_{ave,II}^{act} = I_{ave,II} / \mu = (1+y)/2w$$

The overall actual average discharge current is calculated as:

$$I_{ave}^{act} = y \cdot I_{ave,I}^{act} + (1-y) \cdot I_{ave,II}^{act} = (1-(1-w)y^2)/2w$$

Therefore, we obtain the *BSL* as:

$$BSL = 1/I_{ave}^{act} = 2w/(1-(1-w)y^2) \qquad (4.2)$$

B. *Only use battery B (z=0)*

In this case, the *BSL* can be easily got by: $BSL=1/(1/2x)=2x$

C. *Use batteries A and B with interleaving (0<z<1)*

In this case, we use battery A when discharge current is in region I and use battery B when discharge current is in region II. We have:

$$I_{ave,I}^{act} = y/2 \text{ and } I_{ave,II}^{act} = (1+y)/(2x)$$

Let us first find the optimal *z* value for maximum battery service life. It is obvious that when *z* is chosen optimally, batteries A and B will deplete at the same time. Therefore, we have the following equation: $BSL_A/BSL_B=y/(1-y)$, which is:

$$\frac{2z/y}{(1-z)2x/(1+y)} = \frac{y}{1-y} \qquad (4.3)$$

By solving (4.3) we get the optimal value for *z* as:

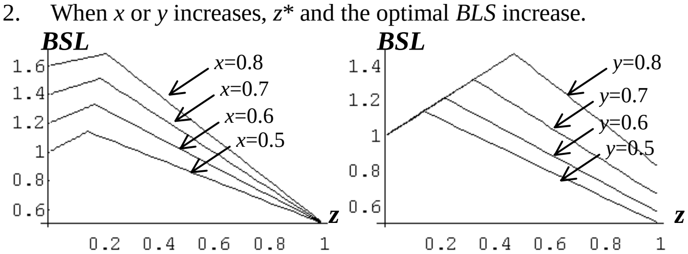
$$z^* = (xy^2)/(1-y^2+xy^2) \qquad (4.4)$$

Notice that z^* is not dependent on *w*. In the remainder of this section, we fix *w* at 0.2.

If *z* is not chosen as the optimal value, one of the batteries will be depleted earlier than the other, which means the remaining one will have to provide the required discharge current until it is depleted.

Figure 7 shows some plots of *BSL* as a function of *x*, *y* and *z*. From it we can see that:

1. For *z* values smaller than z^*, the *BSL* monotonically decreases when *z* decreases; For *z* values larger than z^*, the *BSL* monotonically decreases when *z* increases.
2. When *x* or *y* increases, z^* and the optimal *BLS* increase.



(a) *y* is fixed at 0.5 (b) *x* is fixed at 0.5

Figure 7 *BSL* plots versus *x*, *y* and *z*.

Figure 8 shows the *BSL* improvement by using our dual-battery interleaving method. The data is obtained by compare out method using optimal *z* value with the best *BSL* of single-battery power supply using only battery A or B. We can see that out dual-battery interleaving power supply system design can extend the battery service life by as much as 60%.

D. *Validation*

To validate our analysis of IDB power supply using, we have simulated our design using HSPICE. The circuit consists of two batteries (described using macro-models in [13]) with current-capacity characteristics shown in Figure 4(a), a current comparator (macro-modeled), and a current source where the discharge current is randomly generated to follow a uniform distribution.

Firstly we need to approximate the current-capacity curves in Figure 4(a) using the curves in Figure 6(a). The parameters we use are: $w=0.2$, $x=0.55$ and $y=0.75$. We calculate z^* to be 0.41. z^* is then used to define the allocation of total battery volume (or weight) to batteryies A and B. The comparison of analysis and experimental results are shown in Table 2. We can see that the use of IDB provides 25% improement over the use of a sinble best battery type.

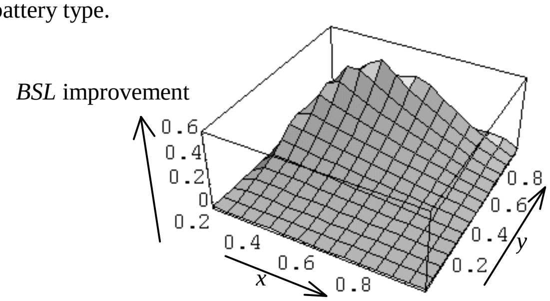


Figure 8 *BSL* improvement as function of *x* and *y*.

Table 2 Comparison of analysis and experimental results.

BSL	Only battery A	Only battery B	IDB power supply	Improvement
Analysis	0.73	1.1	1.46	33%
Simulation	0.65	0.99	1.25	25%

V. CONCLUSIONS

In this paper, we showed that it is essential to consider the current-voltage characteristic of the battery as well as the current-capacity characteristic. We have proposed a new design of dual-battery interleaving power supply. The new design combines different batteries to supply power for electronic devices and utilizes different advantages of them to extend the service life of the power supply significantly.

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