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

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Outline

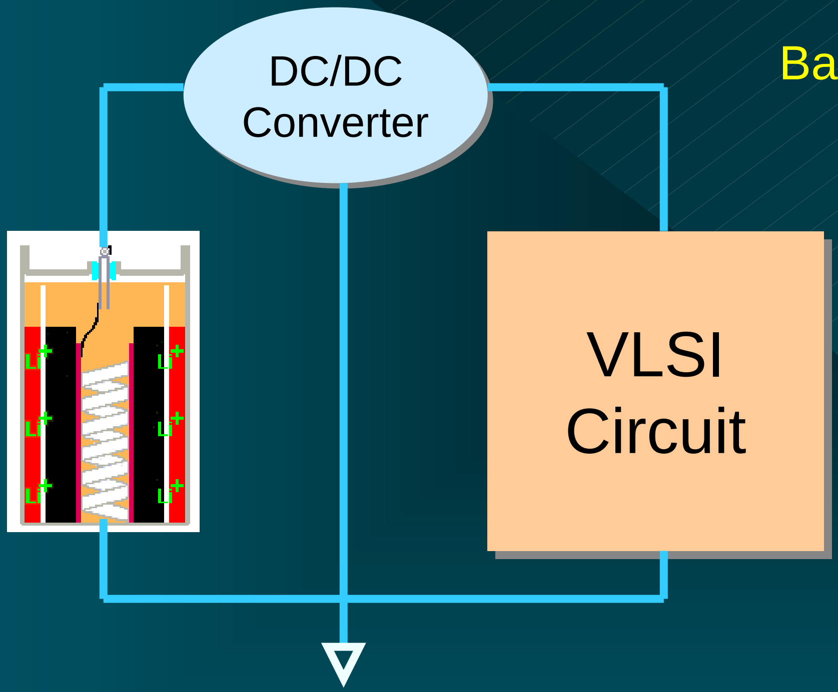
- Introduction
- Background
- Analysis of Optimal Supply Voltage
- Design of Interleaved Dual-Battery Power Supply
- Conclusions

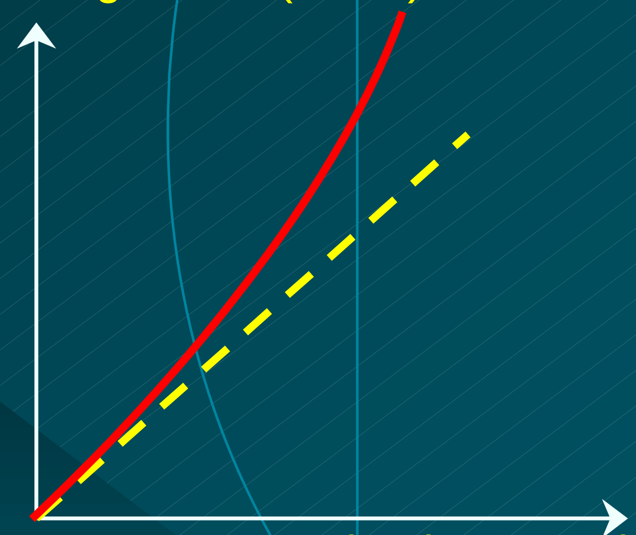
Batteries in Mobile/Portable Electronics

Extending the battery service life for mobile electronics is a major motivation for low power design

Battery Power Supply System

In reality, the battery discharge rate is super-linearly related to the average power consumption in the VLSI circuit





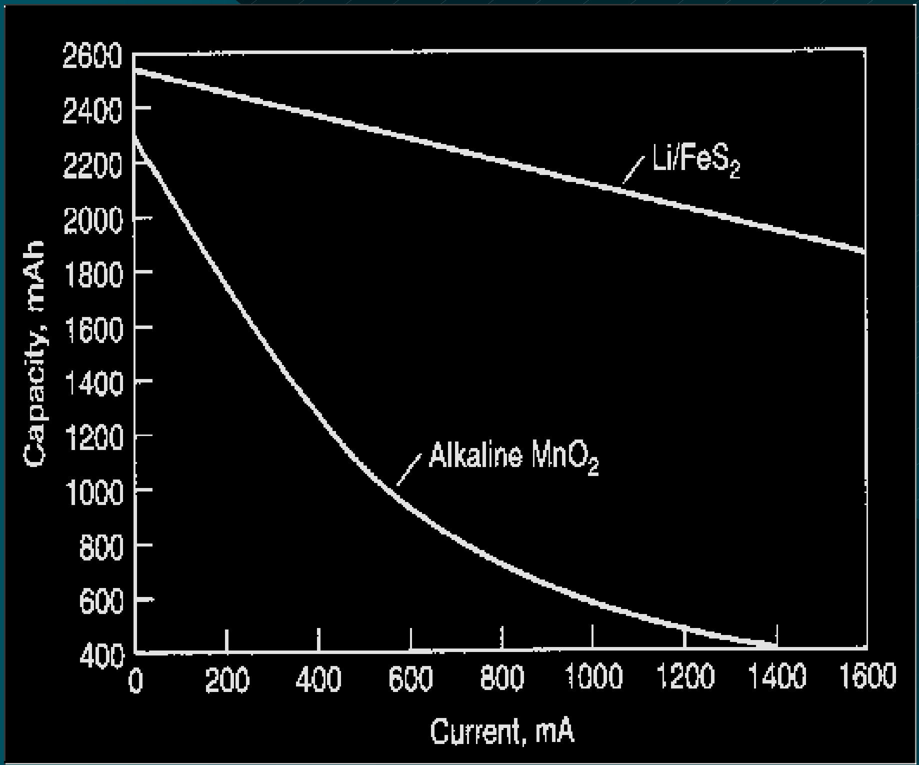
Low Power Design Metrics

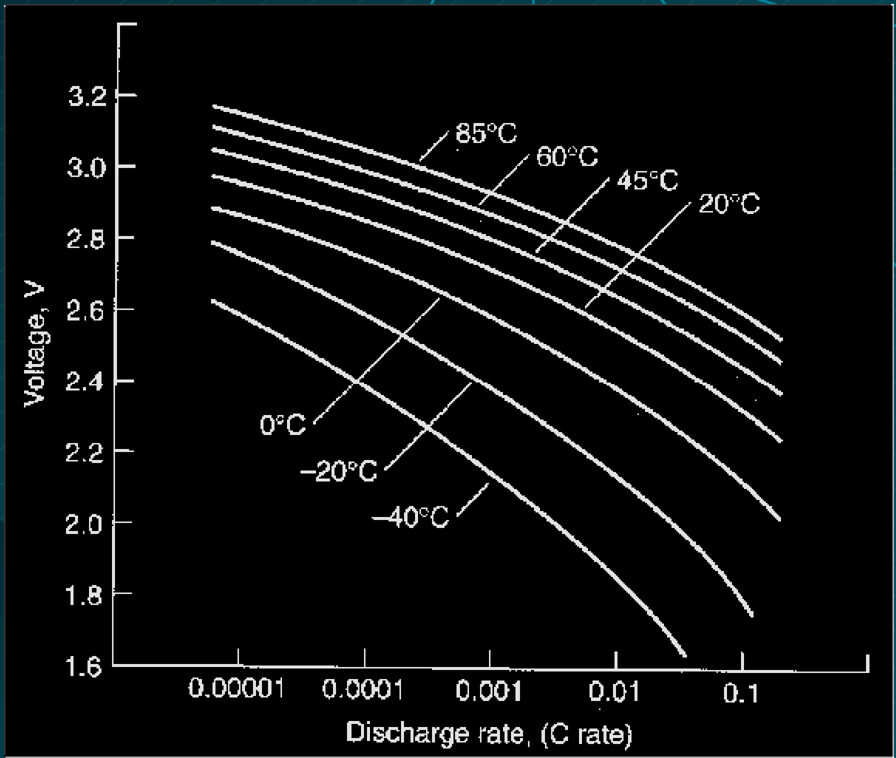
- Energy-delay (E-D) product [M. Horowitz, et al, 1994]
  - Measures circuit speed for energy dissipation per operation
  - Does not consider the characteristics of the battery power supply system
- Battery discharge-delay (BD-D) product [M. Pedram, et al, 1999]
  - Measures circuit speed for battery discharge per operation
  - Only considers the current-capacity characteristics of the battery

In This Paper

- Further analysis of the BD-D product
  - Considers the current-voltage characteristics of the battery, in addition to its current-capacity characteristics
- Design of an Interleaved Dual-Battery (IDB) power supply system
  - Uses two batteries of different current-capacity characteristics
  - Calculates the optimal combination of the two battery types
  - Increases the battery life time

Battery Characteristics





Current-capacity

Current-voltage

An Analytical Model

Actual battery energy discharge

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

Efficiency factor (current-capacity relation)

$$\mu = 1 - \beta \cdot I_0$$

Output voltage function (current-voltage relation)

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

Conversion efficiency equation (DC/DC converter)

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

Battery Discharge (BD)

Definition

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

Energy dissipation of the VLSI circuit

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

BD as a function of V_{dd} and I_0

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

Calculating the Battery Discharge Current

Relation between V_{dd} and I_0

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

I_0 as a function of V_{dd}

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

BD-Delay (BD-D) Product

Delay of CMOS circuits

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

BD-D product

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

Determining the Cycle Time

Assuming clock cycle time is proportional to circuit delay

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

Complete expression for battery discharge current

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

By substituting I_0 in the expression for BD-D , we can obtain a complicated expression for BD-D in which V_{dd} is the only variable.

An Example

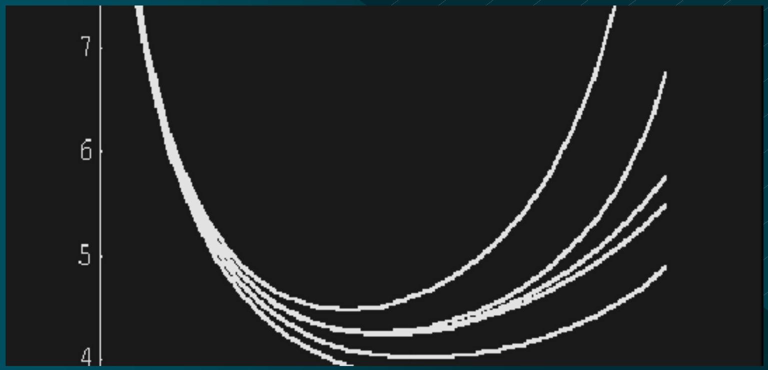
Assume a VLSI circuit consumes 13.5W power at supply voltage of 1.5V

Parameter	Value	Comment
V_0	4V	Typical lithium battery
η	0.9	Typical DC/DC converter
C_{sw}/m'	21	Calculated
α	1.5	Typical CMOS technology
V_{th}	0.6	Typical CMOS technology
$\frac{m \cdot C_{sw}}{2 \cdot \eta \cdot CAP_0}$	1	Normalized

$\beta = \{0, 0.05, 0.1, 0.15\}$ $\gamma = \{0, 0.15, 0.3\}$

BD-D Curves

***BD-D* product**



β=0.15, γ=0.3

β=0.1, γ=0.3

β=0.1, γ=0.15

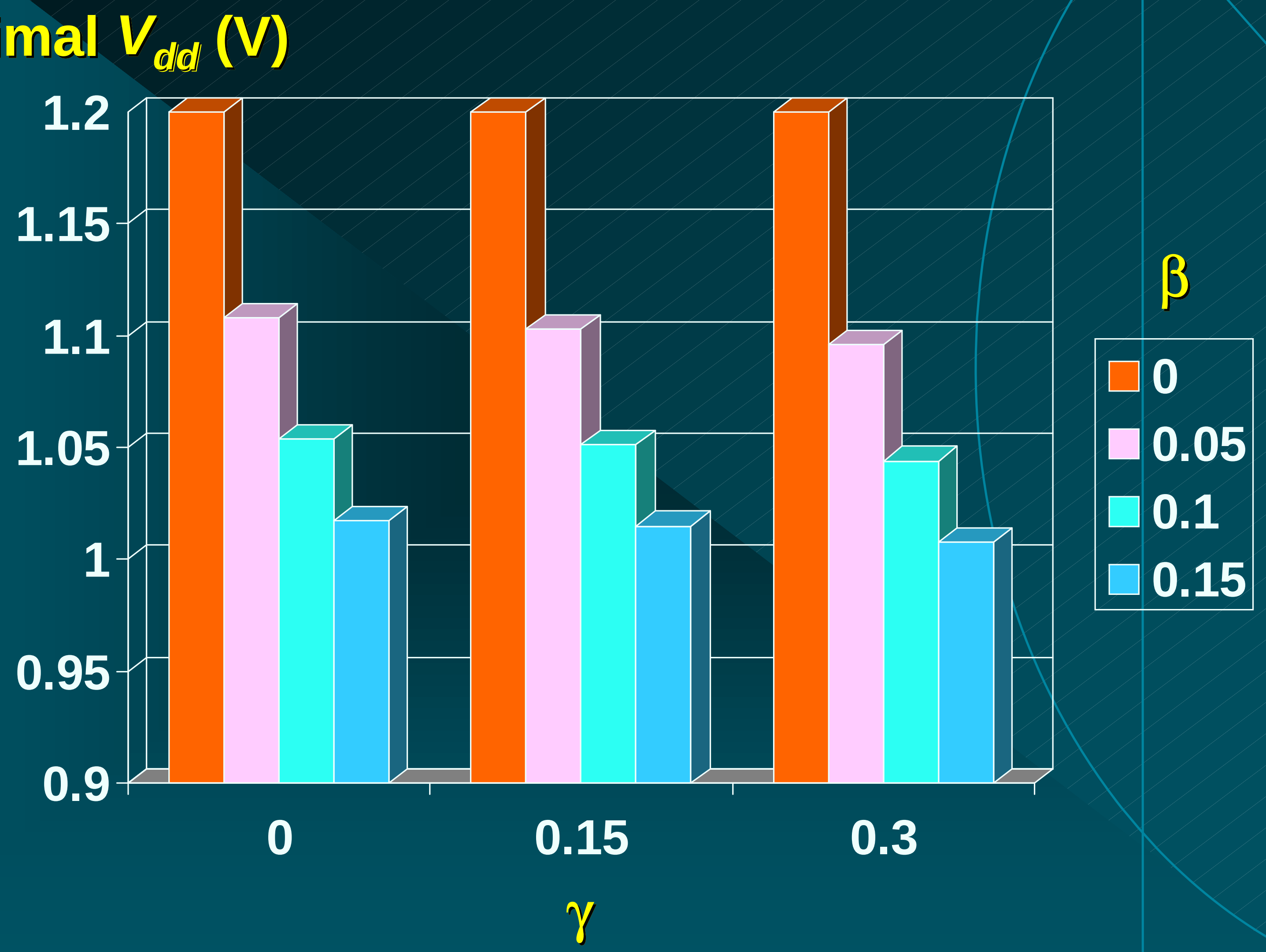
β=0.1, γ=0

β=0.05, γ=0.3

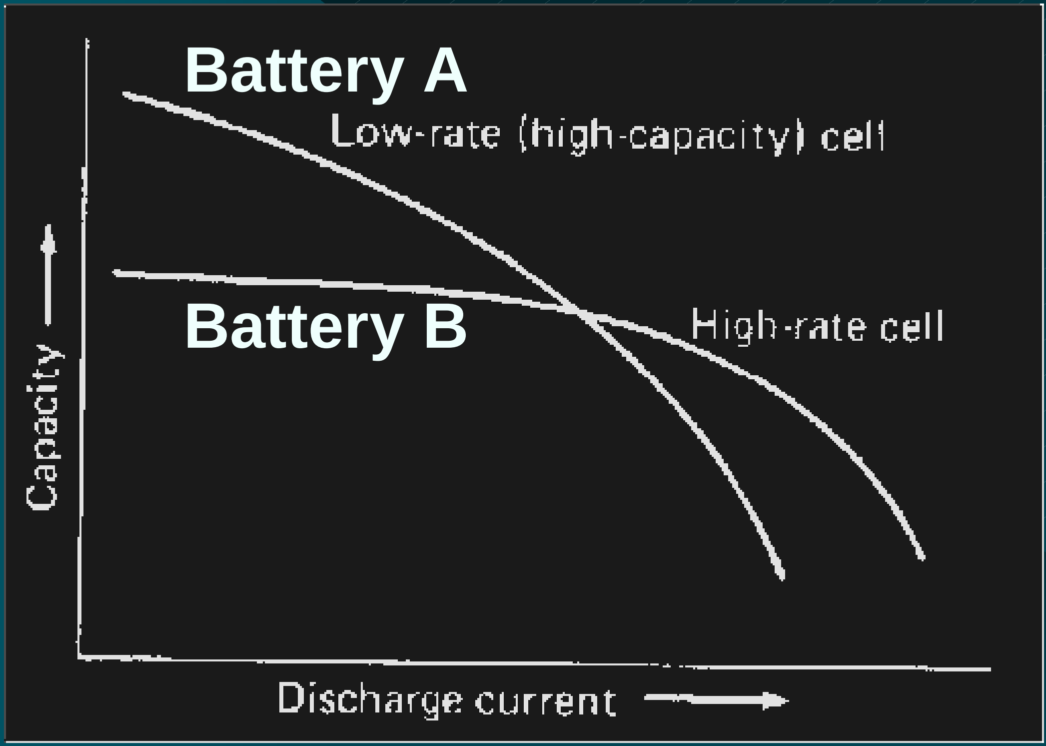
β=0, γ=0 (ideal case)

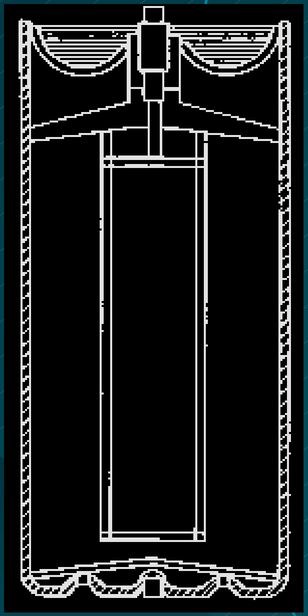
V_{dd}(V)

Optimal V_{dd} Values

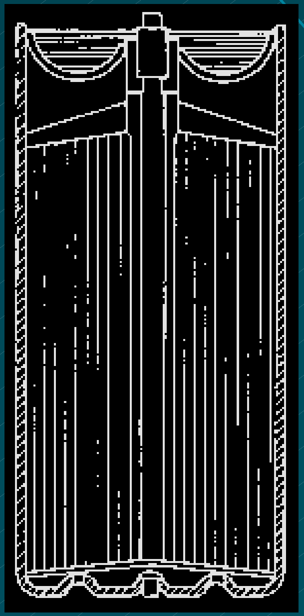


Batteries with Different Characteristics



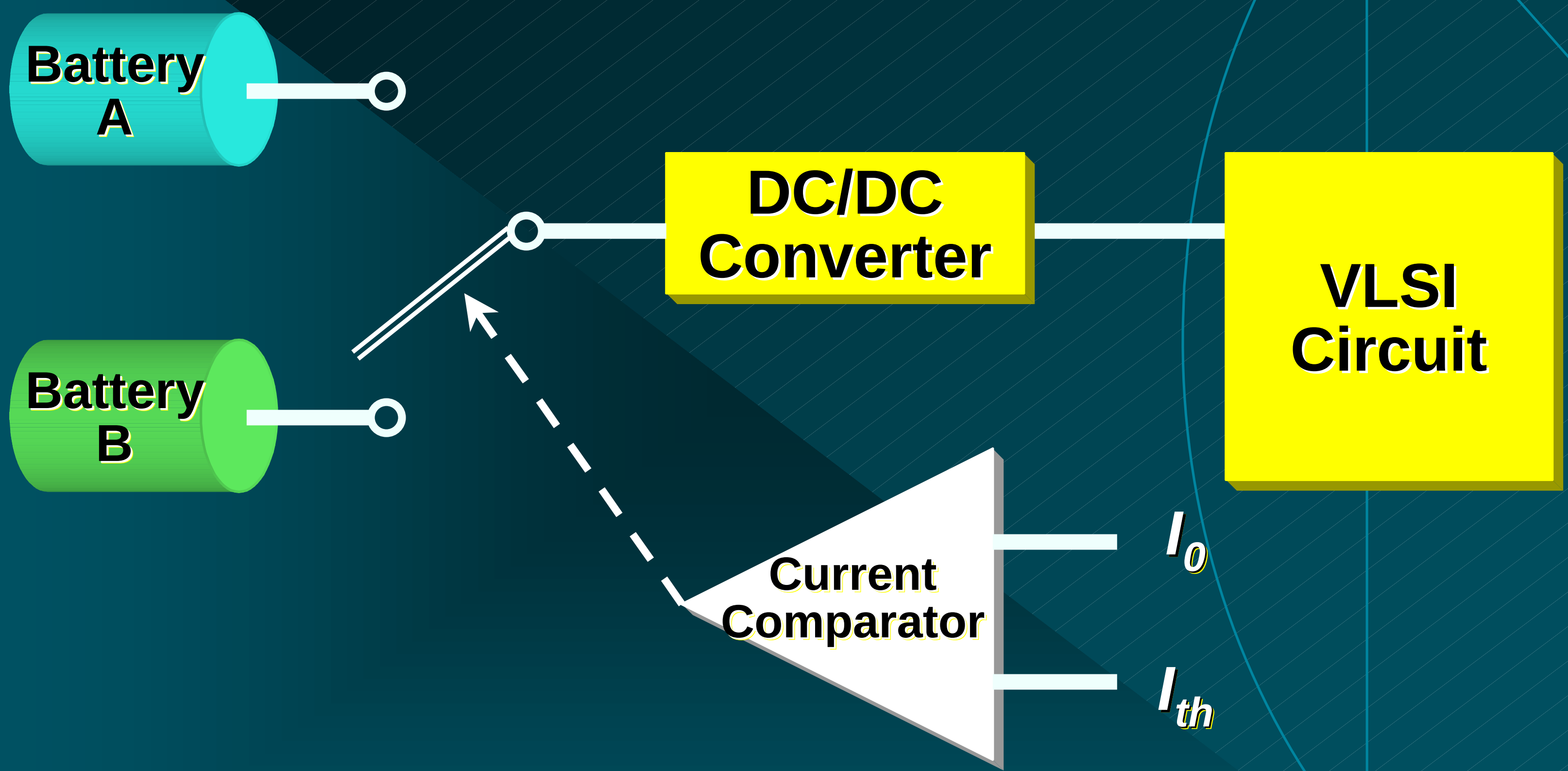


bobbin cell



spiral cell

Block Diagram for the IDB Power Supply System

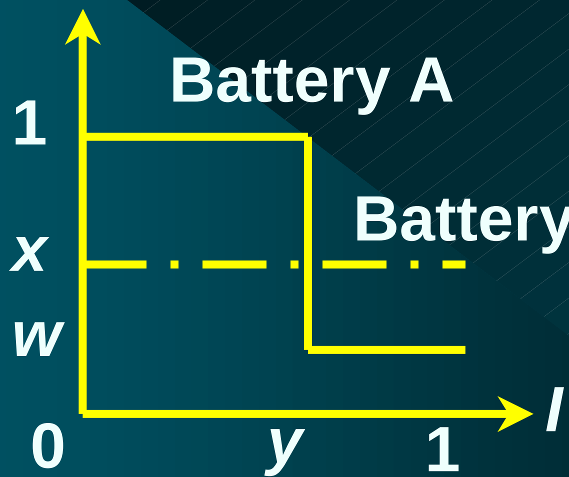


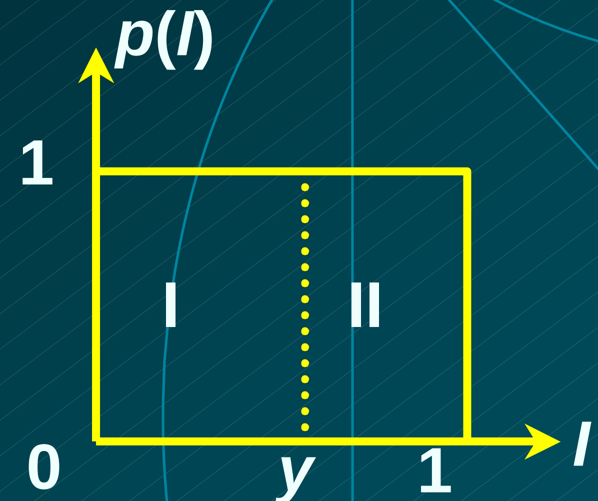
Design Problem Statement

- **Given:**
  - **Two batteries with different current-capacity characteristics**
  - **Current dissipation profile of the VLSI circuit**
  - **A volume (or weight) limit (normalized to 1) for the 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**

Analysis Setup

Capacity (Battery efficiency μ)





Battery Service Life (BSL)

$$BSL = 1 / I_{ave}^{act}$$

Single Battery Power Supply

Using Battery A only

$$BSL = 2w \big/ (1-(1-w)y^2)$$

Using Battery B only

$$BSL = 2x$$

IDB Power Supply

Optimal threshold current

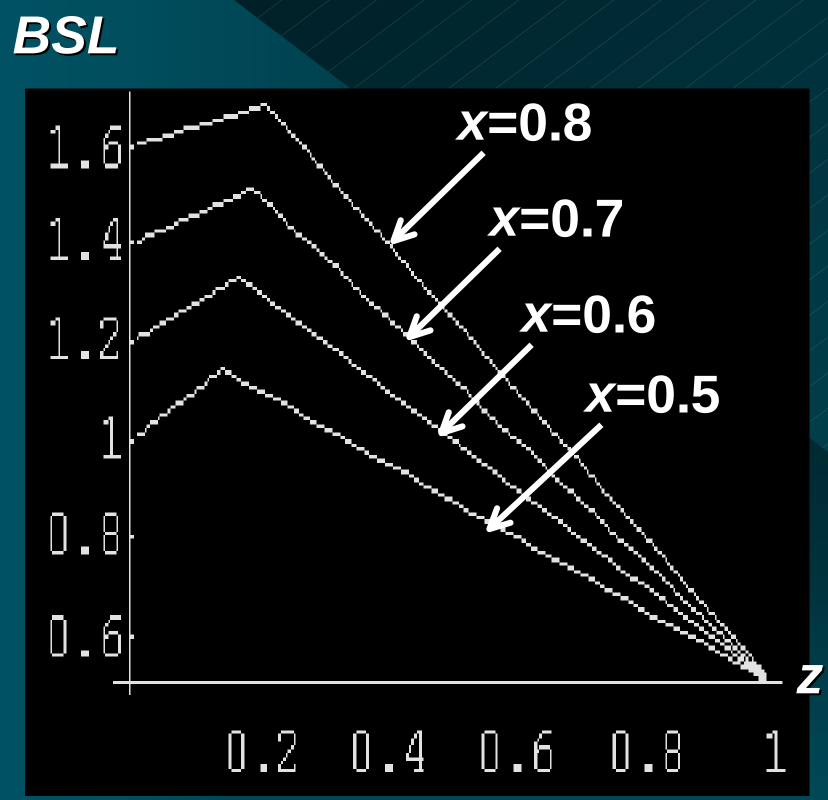
$$I_{th} = y \quad \Rightarrow \quad \begin{cases} \text{use Battery A} & \text{if } I_0 < \text{y} \\ \text{use Battery B} & \text{if } I_0 \geq \text{y} \end{cases}$$

Optimal weight/volume distribution of the power supply

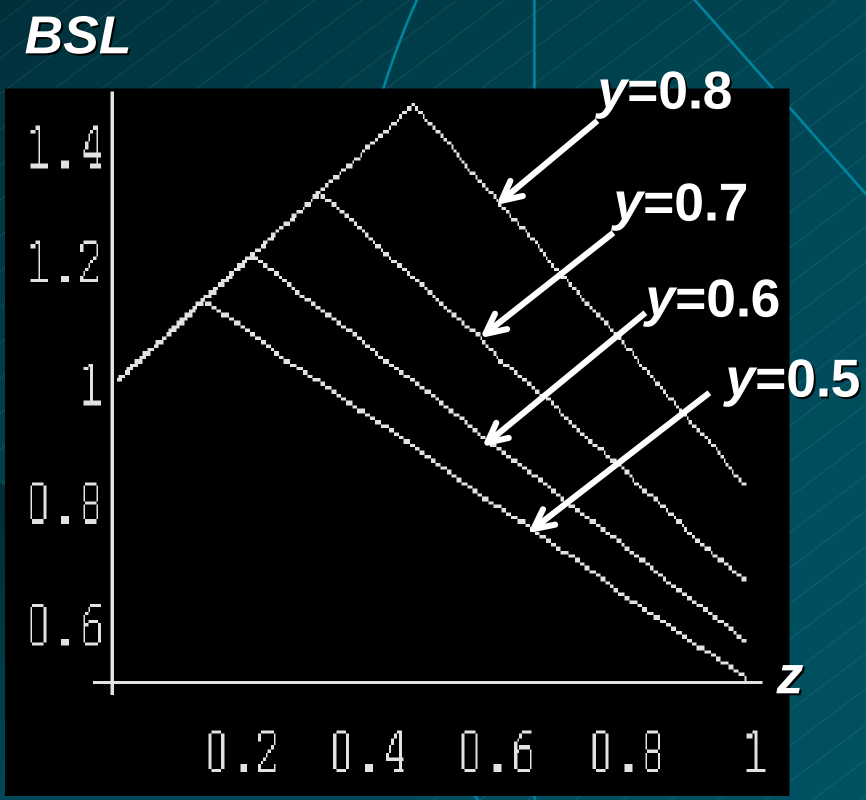
$$z^* = (xy^2)\big/(1 - y^2 + xy^2), \quad 0 \leq z^* \leq 1$$

$\Rightarrow$ Battery A occupies a portion of *z**
Battery B occupies a portion of (1-*z**)

BSL as a Function of *x, y* and *z*

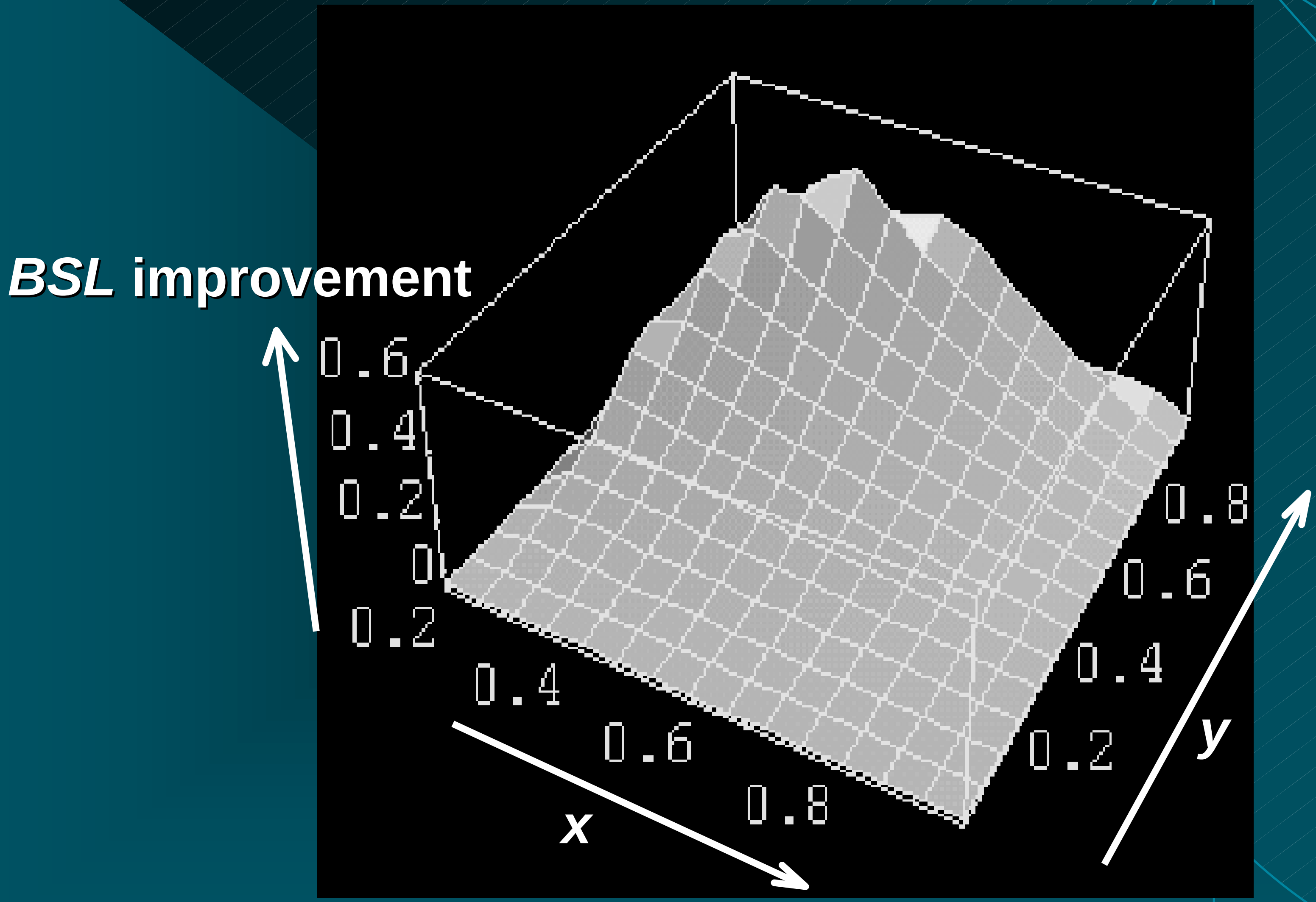


(a) *y* is fixed at 0.5



(b) *x* is fixed at 0.5

BSL Improvement Plot



Conclusions

- It is important to consider the current-voltage characteristic of the battery in addition to its current-capacity characteristic.
- By appropriately combining batteries with different current-capacity characteristics (w.r.t. optimal portion of each battery type), the IDB power supply can significantly extend the battery service life.