Battery-Aware Power Management Based on Markovian Decision Processes

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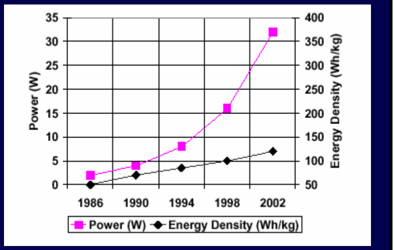
Outline

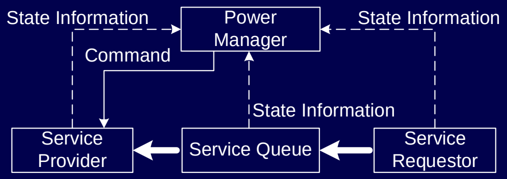
- Introduction
- Battery Characteristics, Models and Management Policies
- Modeling a Battery-powered Electronic System
- The Proposed Battery-aware Power Management Solution (BAPM)
- Experimental Results
- Conclusions

Dynamic Power Management 101

- Motivation and principle of operation
  - Rationale: Power-constrained systems, A widening "battery gap" [Lahiri-02]
  - Method: Selectively shut-down the idle components or slow the underutilized components



- A simple power management system
  - It consists of three components: a service requestor (SR), a service provider (SP), a service queue (SQ)
  - A power manager (PM) monitors the system state and issues commands
  - The SP has multiple states which are different in terms of their power dissipation and service speeds, e.g., Power-Off, Standby, and Busy



State Information

Power Manager

State Information

Command

State Information

Service Provider

Service Queue

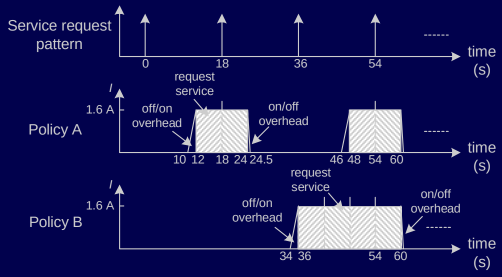
Service Requestor

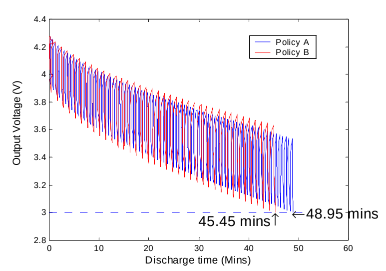
Review of DPM Approaches

- Heuristic policies
  - "Time out" and "Predictive" techniques [Karlin-94], [Srivastava-96]
- Competitive analysis-based policies
  - Adversary games [Ramanathan-00]
- Economics-based policies
  - Game-theoretic techniques [Shang-02]
- Stochastic policies
  - Discrete-time Markov decision process (DTMDP) [Benini-99]
  - Continuous-time Markov decision process (CTMDP) [Qiu-00]
  - Time-indexed semi-Markov decision process (TISMDP) [Simunic-01]
  - Petri net-based models [Wu-00]

What Is Missing from Existing DPM Models

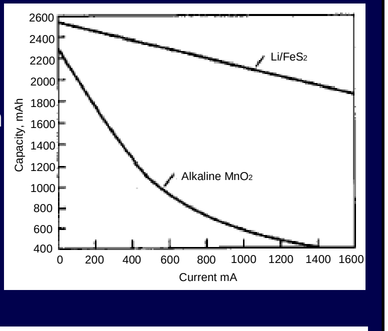
- Does "minimum power consumption" always imply the "longest battery lifetime"?
  - **No**, consider the example shown below
  - Policy B is "minimum power" policy, but Policy A is superior to Policy B in terms of the battery lifetime by 7.7%
  - The battery characteristics strongly influence the choice of an "optimal" policy
  - DPM models must account for the battery characteristics

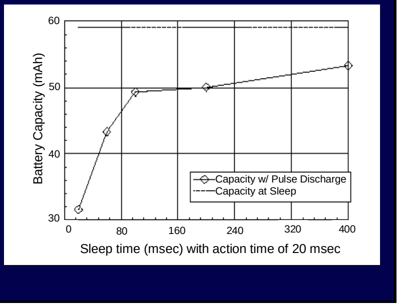


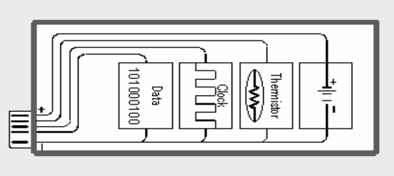


Battery Characteristics and Smart Batteries

- Nonlinear characteristics of batteries
  - Rate capacity effect
    - ➢ The total energy capacity that a battery can deliver during its lifetime depends on its current discharge rate
  - Recovery effect
    - ➢ Battery capacity can be recovered during pauses in the current discharge
- Smart battery standard (SMBus)
  - Provide battery internal state and data, such as battery chemistry, SOC, temperature, etc., to the Operating System

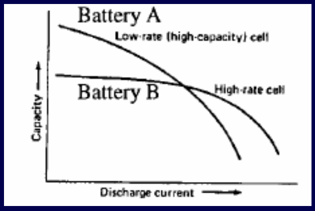


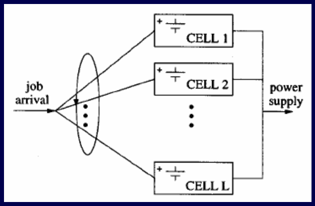




Battery Models and Management

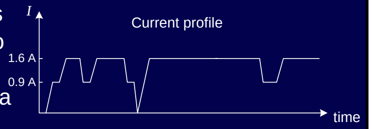
- Battery Models
  - Stochastic model: A discrete-time Markovian-based model [Chiasserini-99]
  - Electrical circuit model: A spice model of the lithium-ion batteries [Gold-97]
  - Electro-chemical model: Generic dual-foil lithium-ion battery model [Doyle-94]
- Battery Management
  - Discharge rate-based policy [Wu-00]
    - Two heterogeneous batteries
    - Switch to battery that is most suitable for the current discharge rate
    - Exploit the rate capacity effect
  - Periodic switching policy [Benini-01]
    - Two identical batteries
    - Alternately switch from one battery to next with a predetermined period
    - Exploit the recovery effect
  - Round-robin policy [Chiasserini-01]
    - Assign batteries to different jobs in a round-robin fashion
    - Exploit the recovery effect

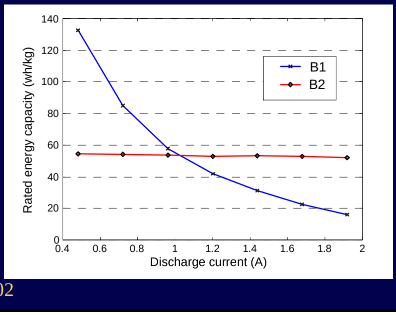


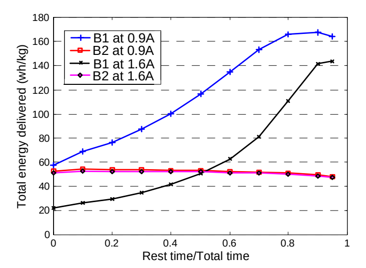


Shortcomings of Previous Battery Management Policies

- They are not based on a unified mathematical model that incorporates characteristics of both the electronic system and the batteries
  - Existing policies do not utilize the properties of the service requestor and the service provider to maximize the battery lifetime
- They do not exploit the rate-capacity and recovery effects together
  - Because of the rate-capacity effect, a power supply system consisting of two different batteries may provide a longer system lifetime compared to one with two identical batteries
  - The recovery effect implies it may be better to let a battery have some rest time

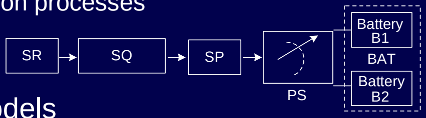




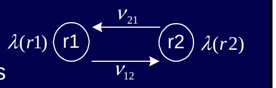


Model of a Battery-powered System

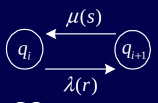
- System model
  - Contains five components: a service requestor (SR), a service queue (SQ), a service provider (SP), a power switch (PS), and a battery subsystem (BAT)
  - All system components are modeled as stationary, continuous-time Markov decision processes



- Component models
  - Service requestor (SR)
    - State set ***R*** and a generator matrix $\boldsymbol{G}_{SR}$
    - Different states mean different request generation rates

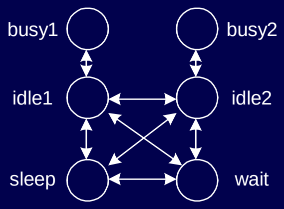


  - Service queue (SQ)
    - State set ***Q*** and a parameterized generator matrix $\boldsymbol{G}_{SQ}$
    - State q_i denotes that there currently are *i* requests waiting in the SQ
    - The number of waiting requests is incremented by one each time a new request comes in, and is decremented by one each time the SP completes servicing the earliest request in the SQ

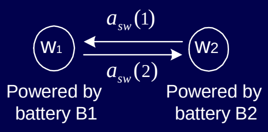


Modeling (Cont'd)

- Service provider (SP)
  - State set ***S***, action set ***A***, and a parameterized generator matrix $\boldsymbol{G}_{SP}$
  - Each state represents a different set of power dissipation and service speed transition energy
  - Each state transition is annotated with a transition time and energy cost
  - Some transitions are autonomous while others are action-activated transition



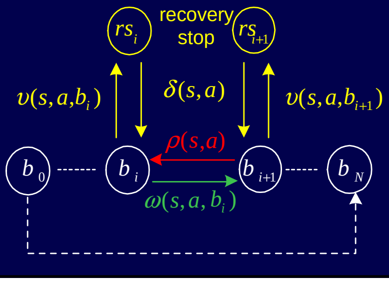
- Power switch (PS)
  - State set ***W***, action set $\boldsymbol{A}_{SW}$, and a generator matrix $\boldsymbol{G}_{SW}$
  - Actions determine which battery unit should be used next to power the system

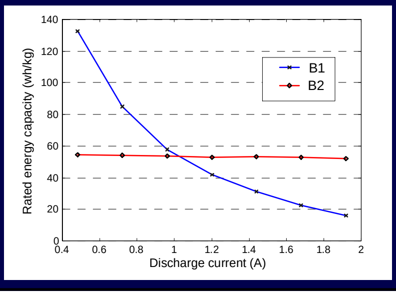


Battery Model

- Model of the battery (BAT)
  - State set ***B*** and a parameterized generator matrix ***G***$_B$
  - Each state corresponds to a particular state-of-charge (SOC) of the battery
  - Transitions represent different electrochemical processes as described below
- Capturing the battery discharge process
  - The red edges marked with $\rho(s,a)$ denote the normal battery discharge process
  - $1-\beta(s, a)$ captures the rate-capacity phenomena
    - The battery discharge rate scales inverse linearly with $1-\beta(s, a)$
  - The dashed edge represents the case when an exhausted (used-up) battery is replaced with a fresh (fully-charged) battery of the same type

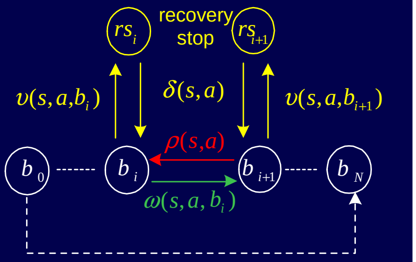
$$\rho(s,a) = \frac{pow(s,a)}{(1-\beta(s,a))\cdot C/N}$$





Battery Model (Cont'd)

- Capturing the recovery effect
  - The green edges, marked with $\omega(s,a,b_i)$, represent capacity recovery during the rest time
  - The yellow portion of the Markov process model, including "recovery stop" states rs_i and transitions $\upsilon(s,a,b_i)$ capture the phenomenon that the energy recovery rate of a battery diminishes (and eventually goes to zero) as the rest time increases
  - When the battery is used again, it changes state from rs_i to b_i through edges marked with $\delta(s,a)$



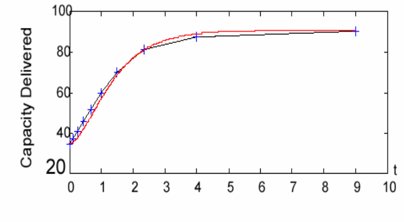
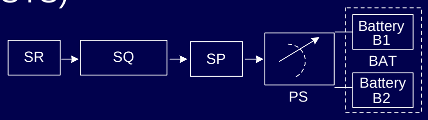


Figure 5. Relationship between the capacity recovery effect and ratio of the rest time to the discharge time for a Li-ion battery.

Building Generator Matrix of the Complete System

- System model (SYS)



  - The system state set ***X*** is given by

$$X = R \times Q \times S \times W \times B - \{invalid \quad states\}$$

where

$$B = B_1 \times B_2 \qquad x = (r, q, s, w, b)$$

  - The system generator matrix ***G***$_{SYS}$
    - SR is independent of the other components

$$G_{SYS}(a) = G_{SR}(a) \otimes G_{SQ-SP-PS-BAT}(a)$$

    - SQ, SP-PS, and BAT are correlated. Each entry of ***G***$_{SQ\text{-}SP\text{-}PS\text{-}BAT}$(***a***) must be calculated separately. The basic method is that at each time, we only allow one state variable to change while fixing all of the others

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Mathematical Program Formulation (BAPM)

- Objective function:

$$Minimize_{\{x^{a_x}\}} \left(\sum_x \sum_{a_x} f_x^{a_x} \gamma_x^{a_x} \right)$$

where

$f_x^{a_x}$: the frequency that system SYS will be in state *x* and an action *a$_x$* is chosen

$\gamma_x^{a_x}$: the expected cost , which represents the expected energy delivered from the battery when the system is in state *x* and action *a$_x$* is chosen. It is calculated as:

$$\gamma_x^{a_x} = \sum_{x'} p_{x,x'}^{a_x} \cdot ene(b, b')$$

Subject to:

$$\sum_{a_x} f_x^{a_x} - \sum_{x' \neq x} \sum_{a_{x'}} f_{x'}^{a_{x'}} p_{x',x}^{a_{x'}} = 0 \qquad \forall x \in X$$

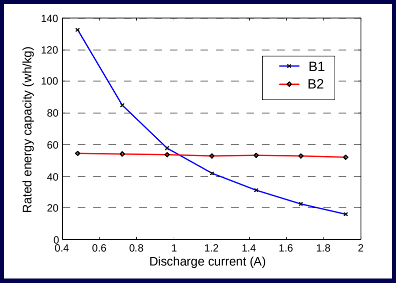
$$\sum_x \sum_{a_x} f_x^{a_x} \tau_x^{a_x} = 1 \quad , \qquad \sum_x \sum_{a_x} f_x^{a_x} lq_x^{a_x} < D$$

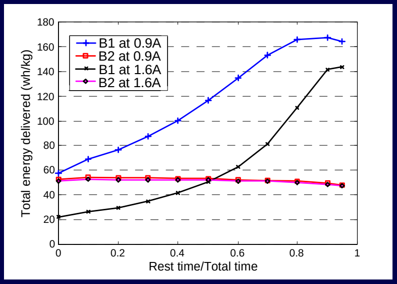
$$\sum_x \sum_{a_x} f_x^{a_x} \tau_x^{a_x} \delta(q_x^{a_x}, Q) < P_{req\_block} \quad \text{where} \quad \delta(x,y) = \begin{cases} 1, & if \ x = y; \\ 0, & otherwise. \end{cases}$$

$$f_x^{a_x} \geq 0$$

Experimental Setup

- Used two batteries exhibiting different Rate capacity and Recovery effects





- Service requestor (SR)
  - Use an input trace file to capture the statistical behavior of the SR
  - Distribution of the input requests is a combination of the exponential and Pareto distributions

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Experimental Setup (Cont'd)

- Service Provider (SP)
  - Power dissipation values: $pow = [0.9 \quad 1.6 \quad 0.9 \quad 1.6 \quad 0.3 \quad 0] \quad (unit : A)$
  - Transition rates:

$$\chi = \begin{bmatrix} \infty & 0 & 0.2 & 0 & 0 & 0 \\ 0 & \infty & 0 & 0.33 & 0 & 9 \\ \infty & 0 & \infty & 1.68 & 1 & 0.5 \\ 0 & \infty & 1.68 & \infty & 1 & 0.5 \\ 0 & 0 & 0.454 & 0.454 & \infty & 1.5 \\ 0 & 0 & 0.166 & 0.166 & 1.5 & \infty \end{bmatrix}$$

  - Transition energies:

$$ene = \begin{bmatrix} 0 & \infty & 0 & \infty & \infty & \infty \\ \infty & 0 & \infty & 0 & \infty & \infty \\ 0 & \infty & 0 & 0.017 & 0.056 & 0.11 \\ \infty & 0 & 0.017 & 0 & 0.056 & 0.11 \\ \infty & \infty & 0.25 & 0.25 & 0 & 5.3 \\ \infty & \infty & 1.69 & 1.69 & 0.51 & 0 \end{bmatrix}$$

$(unit : A \cdot s)$

Battery Scheduling and Replacement Policies

- Scheduling policies
  - M1: Similar to the “discharge rate-based policy”, we use a pre-assigned battery (B1 or B2) when the SP is in a particular state (busy1 or busy2
  - M2: Similar to the “periodic switching policy”, i.e., we switch between the two batteries of type B1 and B2 with a fixed frequency of 0.1 Hz
  - M3: Similar to M2 except that we use two batteries of type B1, switching between them at a fixed frequency (0.1 Hz)
  - M4: Similar to M3 except that we use two batteries of type B2
- Replacement policies
  - P1: As soon as a battery is completely consumed, it is immediately replaced with a new battery of the same type
  - P2: The both batteries are replaced together and only after both of them have been completely used up. If only one battery is used up early on, the other battery will be used in all situations until it is also exhausted

Experimental results (Cont’d)

- Experimental results

		M1	M2	M3	M4	BAPM
P1	Average graviometric energy delivered (wh/kg)	54.35	53.24	53.32	53.20	61.25
	BAPM Capacity Gain	12.7%	15.0%	14.9%	15.1%	--
P2	Average graviometric energy delivered (wh/kg)	51.64	52.66	53.05	53.19	60.37
	BAPM Capacity Gain	16.9%	14.6%	13.8%	13.5%	--

Conclusions

- A new stochastic model for the battery-powered portable electronic system is proposed based on continuous time Markovian decision processes.
- Two important battery characteristics, i.e., the current-capacity rate and the recovery effects were taken into account
- The battery-aware power management policy was formulated as a Linear Programming problem and solved accordingly
- Experimental results demonstrate the effectiveness of the proposed method
- Future work will focus on battery lifetime prediction and its influence on DPM strategies