Karlsruhe Institute of Technology

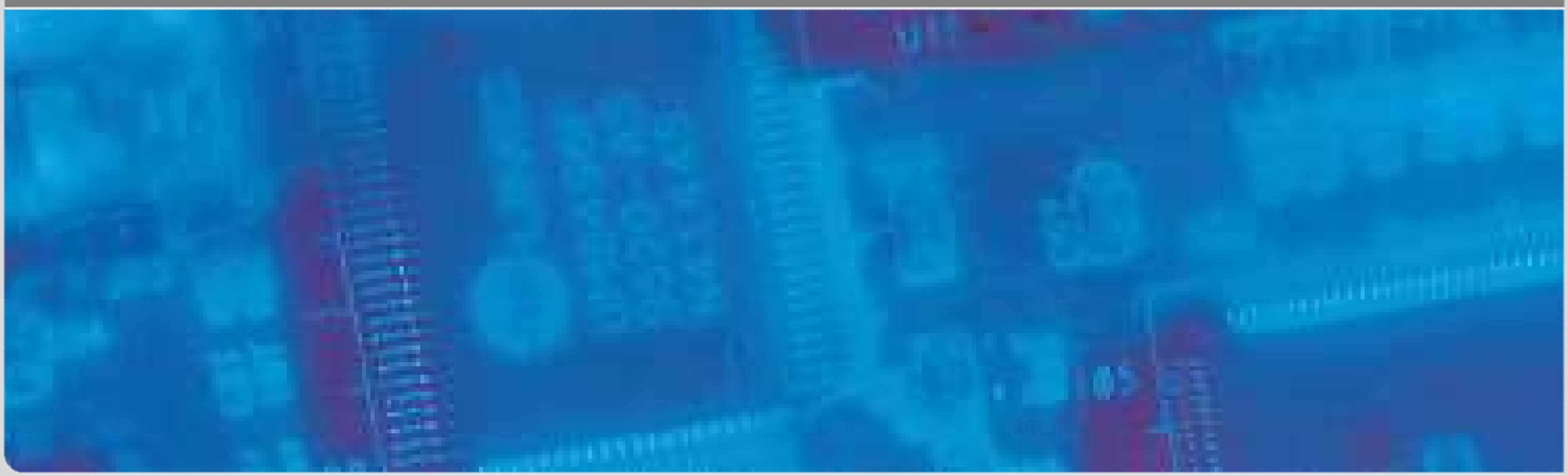
Lower Power Design

Lecture 3: Battery Modeling 2

Anuj Pathania on behalf of Prof. Dr. Jörg Henkel

Summer Semester 2017

CES – Chair for Embedded Systems



Organizational Issues

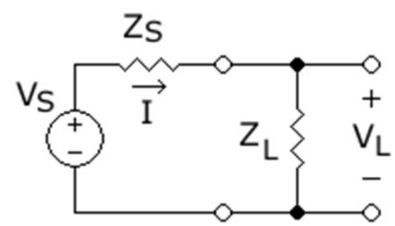
- Slides available for download -
  - http://cesweb.itec.kit.edu/teaching/LPD/s17/slides/
  - Username: student
  - Password: CES-Student
- Homework
  - Read a relevant scientific paper.
  - Discussion next class.
- Oral Exam
  - Make appointment with KIT CES secretary 6-8 weeks in advance.
  - Exam will be in English (or German if told in advance).
  - More information: http://ces.itec.kit.edu/972.php

Lectures

- 27.04.2017 – ~~Lecture 0: Introduction~~
- 04.05.2017 – ~~Lecture 1: Energy Sources~~
- 11.05.2017 – ~~Lecture 2: Battery Modelling Part 1~~
- 18.05.2017 – Lecture 3: Battery Modelling Part 2
- 25.05.2017 – Ascension Day (Holiday)
- 01.06.2017 – Hardware Power Optimization and Estimation 1
- 08.06.2017 – Hardware Power Optimization and Estimation 2
- 15.06.2017 – Corpus Christi (Holiday)
- 22.06.2017 – Hardware Power Optimization and Estimation 3
- 29.06.2017 – TBA
- 06.07.2017 – TBA
- 13.07.2017 – TBA
- 20.07.2017 – TBA
- 27.07.2017 – TBA

Internal Resistance

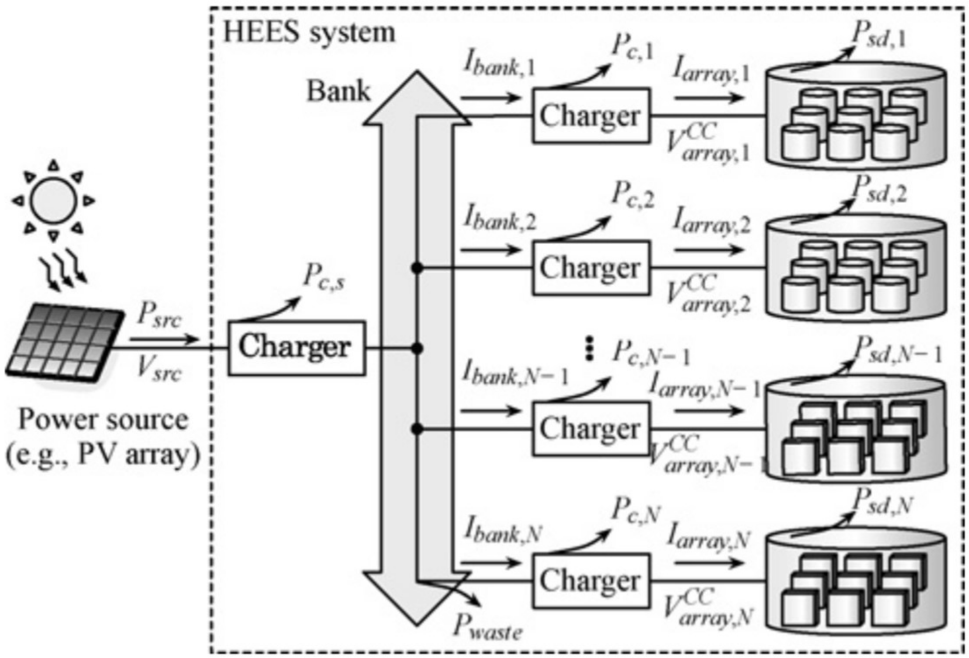
- Battery may be modeled as a voltage source in series with a resistance; internal resistance of the battery.
- Internal resistance of a battery dependent on -
    - Size
    - Chemical properties
    - Age
    - Temperature
    - Discharge Current
    - …



- Measure of the internal resistance of a battery is guide to its condition, but may not apply at other than the test conditions.
- Internal resistance increase on depletion of battery.

Connecting Non-Identical Batteries in Parallel

- Non-Identical charged batteries have different voltage.
  - Batteries will mutually charge and discharge.



Source: Xie [2013]

Self-discharge of Batteries

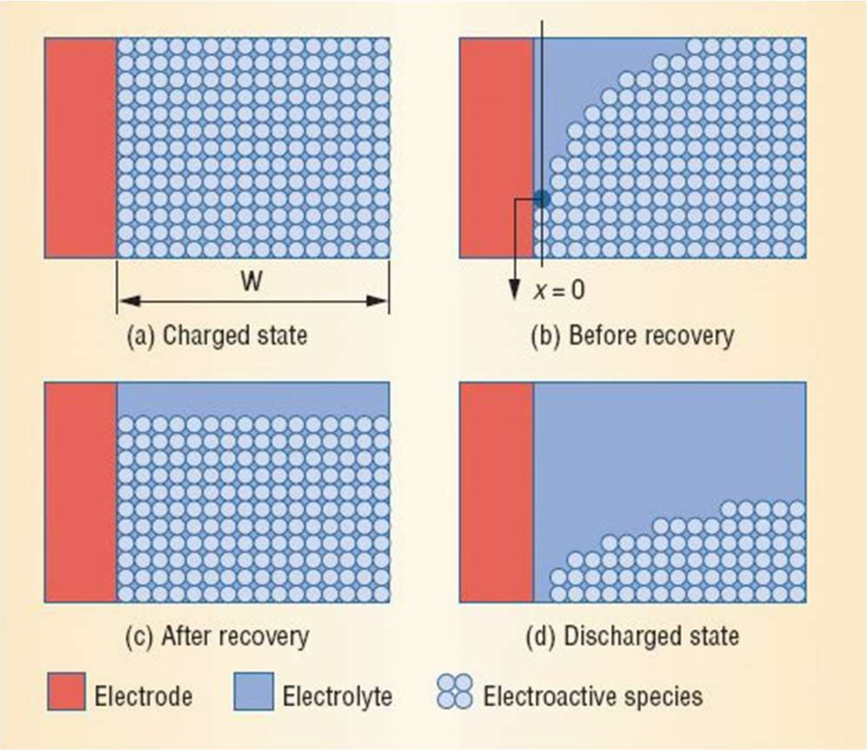
- Self-discharge present in all batteries due to internal chemical side reactions, internal short circuits.
  - Chemical reaction depend on battery technology.
  - Increases with charge.
  - Increases with temperature.
- Self-discharge in Li Ion is around 1.5% - 2% per month.
- Self-discharge in NiMH is around 15% – 100% per month.

Overview for Today

- Stochastic battery modeling.
- Battery-aware scheduling.

Revision: Rate Dependent Battery Capacity

- Rate
  - Speed at which battery is discharge.



Source: [Rao 2003]

Stochastic Battery Model

- Idea:
  - Battery-life estimation of HW/SW embedded systems.
  - Exploration of alternative fast implementations without losing accuracy.
- Definitions:
  - Charge unit: Smallest amount of charge that can be discharged from battery.
  - T: Number of maximum available charge units.
  - N: Nominal capacity of charge units (nominal: for very small currents).
    - In practice: N<<T.
  - N,T vary dependent upon battery technology, discharge current, etc.
  - State of charge is tracked via **discrete** time transient stochastic process.
    - Using a probabilistic Finite State Machine (FSM).

Source: Pani [2001]

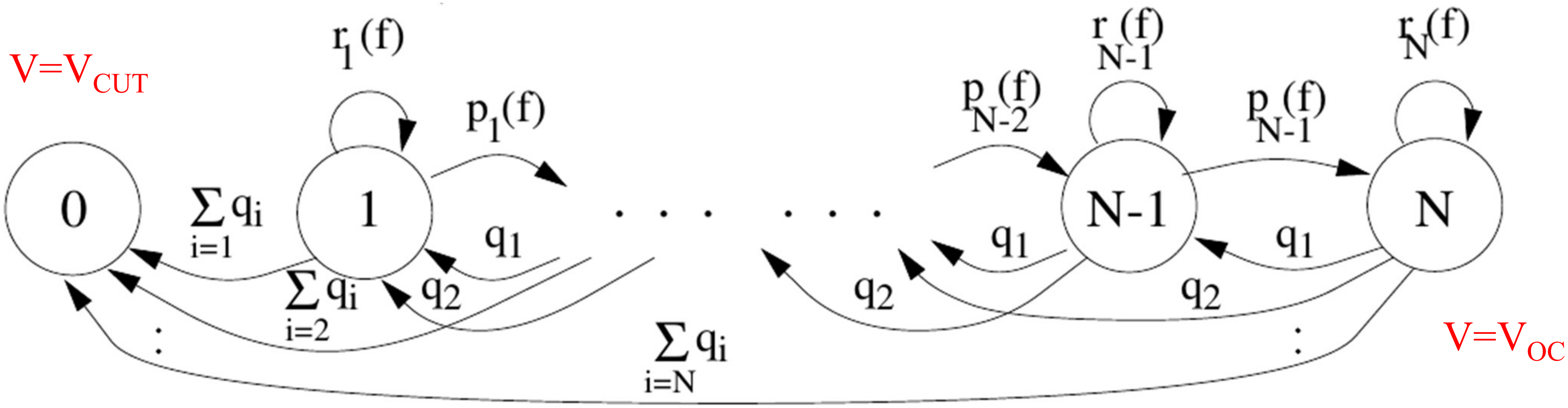
Fundamental Electricity Terms

- Voltage: 1 Volt.
- Current: 1 Ampere
- Charge: 1 Coulomb = 1 Ampere * 1 Second
- Capacity: 1 Farad = 1 Coulomb / 1 Volt
- Energy: 1 Joule = 1 Volt * 1 Coulomb

Notations and Definitions

Symbol	Term	Meaning
V_{OC}	Open-Circuit Potential	Initial potential of a fully charged cell without load.
V_{CUT}	Cut-Off Potential	Potential at which the cell is considered discharged.
T	Theoretical Capacity	Charge that can be extracted theoretically.
N	Nominal Capacity	Charge that can be extracted at rated current.
C_{rated}	Rated Current	Used to determine nominal capacity.
	Battery Lifetime	Time until fully charged cell reaches $V_{CUT.}$
	Delivered Specific energy	Delivered energy over weight of battery.
q_i	Demand Probability	Probability of demanding *i* charge units in a time slot.

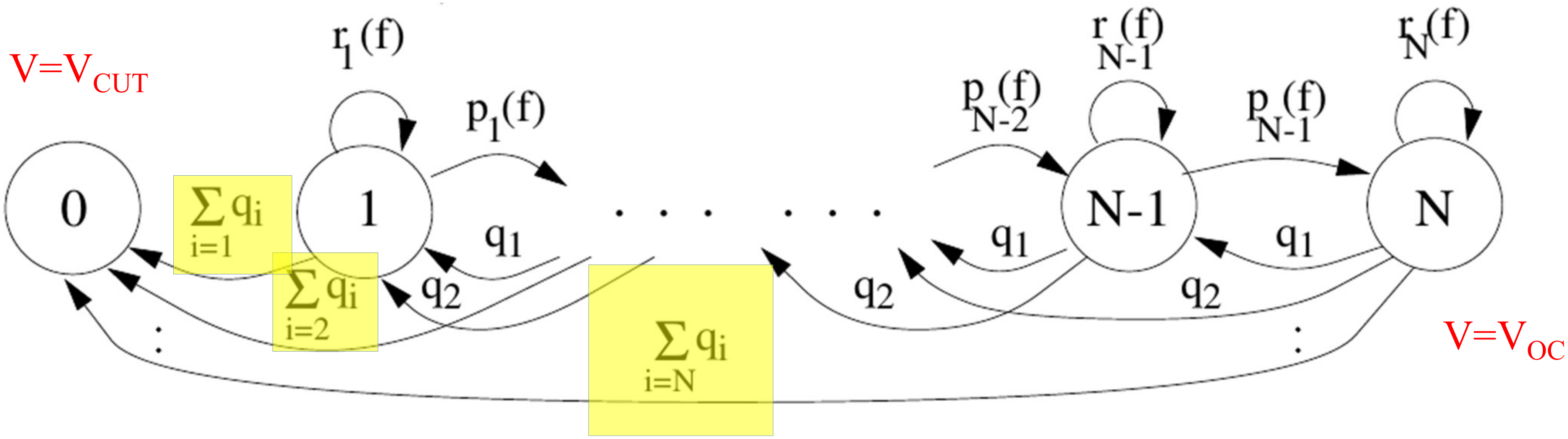
Stochastic Battery Model



- Stochastic process starts from state of full charge (V = Voc), denoted by N.
- At each time unit, the state of charge decreases from state *z* to *z-n* with *n* being the charge units demanded from the battery.
- On the other side: if no charge units are demanded, battery may recover → state of charge z may increase.
- Stochastic process stops at absorbing state (V = V_{cut}) or the max available capacity *T* is reached.
- Allowing idling periods between discharges → battery recovers and # of charge units drained before reaching state 0 is greater than N.

Source: Pani [2001]

Stochastic Battery Model 2



- Let us define q_i to be the probability that in one time unit, called slot, *i* charge units are demanded.

Source: Pani [2001]

Stochastic Battery Model 3

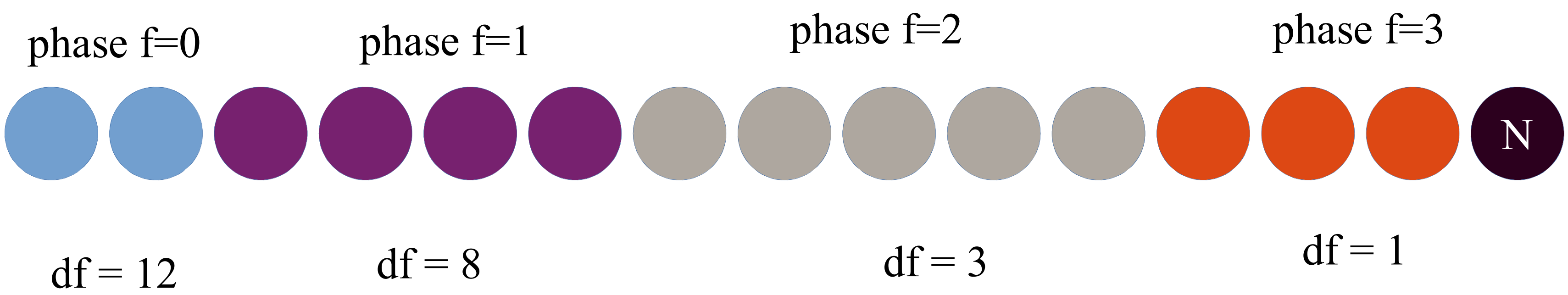
- Recovery Process
  - Is represented as a decreasing exponential function of the state of the battery (i.e. the smaller the remaining charge of the battery is, smaller is recovery potential).
  - During discharge, different phases can be identified.
  - Each phase *f, (f=0, … ,* f_{max}*)* starts right after d_f charge units have been drained from battery and ends when the amount of discharged capacity reaches d_{f+1} charge units.
  - Probability of recovering 1 charge unit in a time slot dependent upon state *j (j=1, …, N-1)* and phase *f* is

$$p_j(f) = \begin{cases} q_0 e^{-g_N(N-j)-g_C(f)} & f = 0 \\ q_0 e^{-g_N(N-j)-g_C(f)d_f} & f = 1, \dots, f_{max} \end{cases}$$

g_N, g_C - parameters that depend upon the capability of recovery of the battery; a small g_N represents high cell conductivity (high recovery capability) and a large g_N represents high internal resistance. Value of g_C is related to cell potential drop during discharging.

Source: Pani [2001]

Stochastic Battery Model 4



Source: Pani [2001]

Stochastic Battery Model 6

g_C - is related to the voltage drop of the battery cell during discharge.

q_0 - is probability of an idle slot.

There is a **probability to remain in the same state** when discharged (due to the recovery effect):

$$
\begin{aligned}
r_j(f) &= q_0 - p_j(f) \qquad j=1,\ldots,N-1 \\
r_N(f) &= q_0 \,.
\end{aligned}
$$

Assumption: g_N is constant;

g_C is a piecewise constant function of the number of charge units already drawn off the cell; it changes value in correspondence with d_f (f = 1, … , f_max). It is d_0=0 and d_(f-max+1)=T. Proper values are chosen according to the battery.

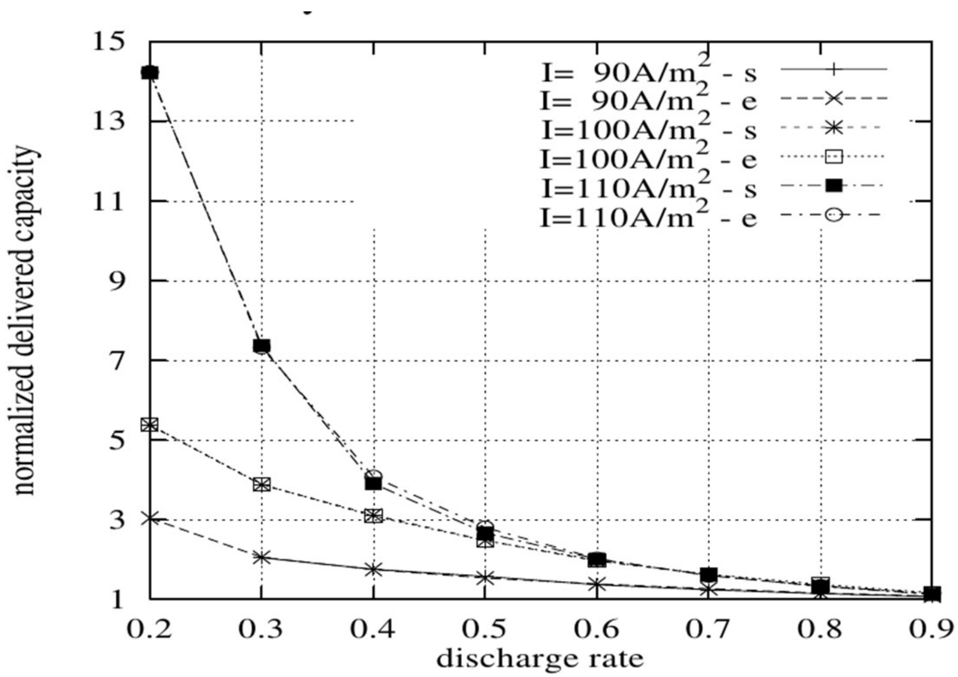
Source: Pani [2001]

Stochastic Battery Model 7

```
Simulation_Step
inputs:        Current_State,Recovery_Probability[],
Discharge_Rate
outputs: Next_State
begin
    Generate a random number R between 0 and 1;
    If (R < Discharge_Rate) then
        Next_State := Current_State - 1;
    else if ( R < Recovery_Probability[Current_State]) then
        Next_State := Current_State + 1;
    end if
end
```

Source: Pani [2001]

Stochastic Battery Model 8

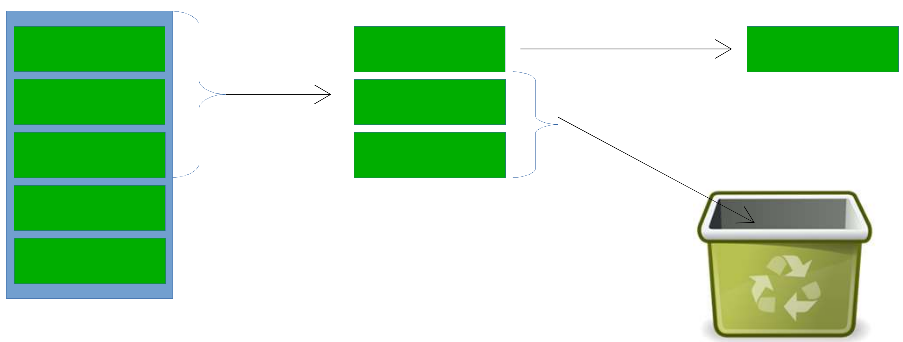


It can be seen that curves obtained from the PDE model and the stochastic models match closely.

Source: Pani [2001]

Stochastic Battery Model 9

- Next step: Make battery model deterministic.
- Introduce battery efficiency to account for:
  - Rate capacity effect.
  - Build efficient LUT using PDE model.



Source: Pani [2001]

Stochastic Battery Model 10

```
Simulation_Step
inputs: Current_State, Current_Demand, Recovery_Probability[], Efficiency_Table[]
outputs: Next_State
variables: Actual_Demand
begin
    Generate a random number R between 0 and 1;
    Actual_Demand := Efficiency_Table[Current_Demand];
    If (Current_Demand > 0) then
        Next_State := Current_State - Actual_Demand;
    else if ( R < Recovery_Probability[Current_State]) then
        Next_State := Current_State + 1;
    end if
end
```

Source: Pani [2001]

Stochastic Battery Model 10

Table 3: Estimation of Battery Life and Delivered Energy Using Stochastic Model

System	Rate Capacity Effect		Recovery Effect		Rate Capacity & Recovery Effect		
	Delivered Spec.Energy (Wh/Kg)	Life Time (ms)	Delivered Spec. Energy (Wh/Kg)	Life Time (ms)	Delivered Spec. Energy (Wh/Kg)	Life Time (ms)	Packets Processed
SYS1	1.369	16875	13.357	163650	1.369	16875	20250
SYS2	3.754	67717	15.553	280543	3.754	67717	81260
SYS3	2.858	88383	32.924	1115616	4.974	153817	92290

Table 4: Comparison with PDE model : Speed and Accuracy

System	Delivered Spec. Energy (Wh/Kg)			Life Time (ms)			Computation Time	
	STOC	PDE	% Err	STOC	PDE	%Err	STOC	PDE
SYS1	1.36	1.33	2.25	16785	17264	2.85	18.62 sec	>1 Day
SYS2	3.75	3.79	1.06	67717	65723	2.94	19.52 sec	>1 Day
SYS3	4.97	5.07	2.01	153817	154956	1.00	40.35 sec	>2 Days

Source: Pani [2001]

Battery Aware Scheduling

- Idea:
  - Adjust task schedule such that battery's capacity as a function of current distribution is taken into consideration.
  - Based on the following Equation -

$$p^{act} = \int dI \, \frac{V \cdot I}{c(I)} \cdot \hat{P}(I)$$

V : voltage (assumed constant)

I : actual current drawn (piece-wise constant)

c(I) : utilization factor (i.e. ratio of battery capacity at discharge current I to standard capacity.)

May be expressed through Peukert's law:

$c(I) = k / I^b$ (normalized)

$\hat{P}(I)$ is the Probability Density Function (PDF) of I (a measure of how evenly the value of the current is distributed). Probability Mass Function (PMF) is discrete equivalent.

Source: Luo [2001]

Battery Aware Scheduling 2

- Goal: Extend battery lifespan.
- Means: Schedule transformations.
- Terms:
  - Task Graph
  - Schedule (Real-Time)
  - PE
- Assumptions:
  - 2 Pes are connected via 1 bus.
  - Intra-task communication costs are 0.
  - Power drawn during each task execution is constant.
  - Notation: tx (y) means task x has power consumption of y units.

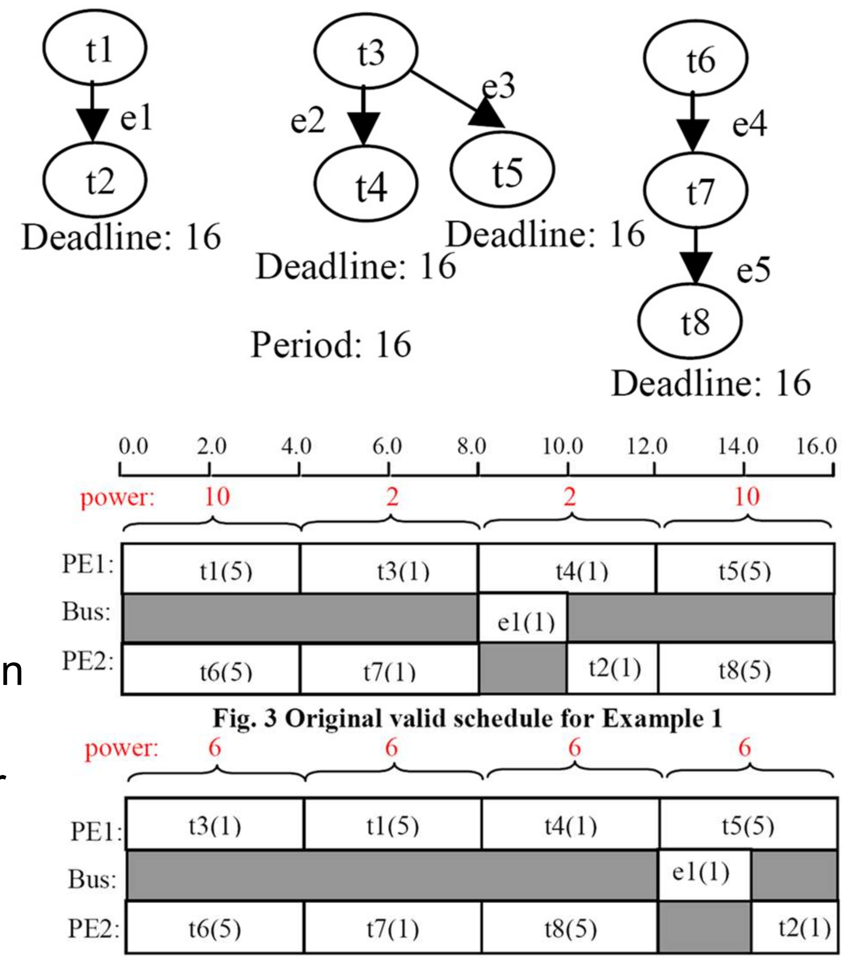


Fig. 3 Original valid schedule for Example 1

Source: Luo [2001]

Battery Aware Scheduling 3

Example 1: (cont'd)

Two different valid schedules are shown.

Using equations 1 and 2 (and appropriate parameters) it turns out that the lower schedule is 15% more power efficient.

=> obviously equations 1 and 2 can be used in a cost function of a schedule to minimize the power consumption through considerations of battery effects.

Example 2:

Same assumptions as before except for

t1, t3, t4, t5, t7 -> 0.2 sec Worst-Case Execution Time (WCET)

t2, t6 -> 0.3sec

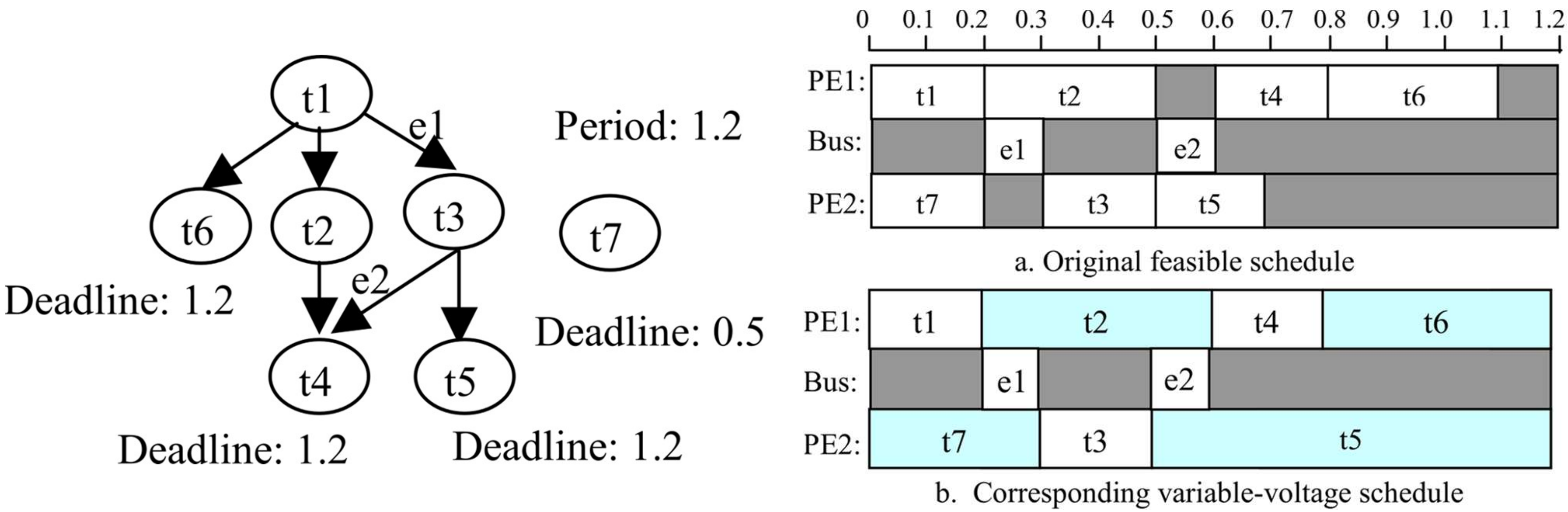
Edges (communication) e1, e2 -> 0.1sec

Task graph as shown on next slide.

P (average) of each task is 1 unit; … of each edge is 0.2units.

Source: Luo [2001]

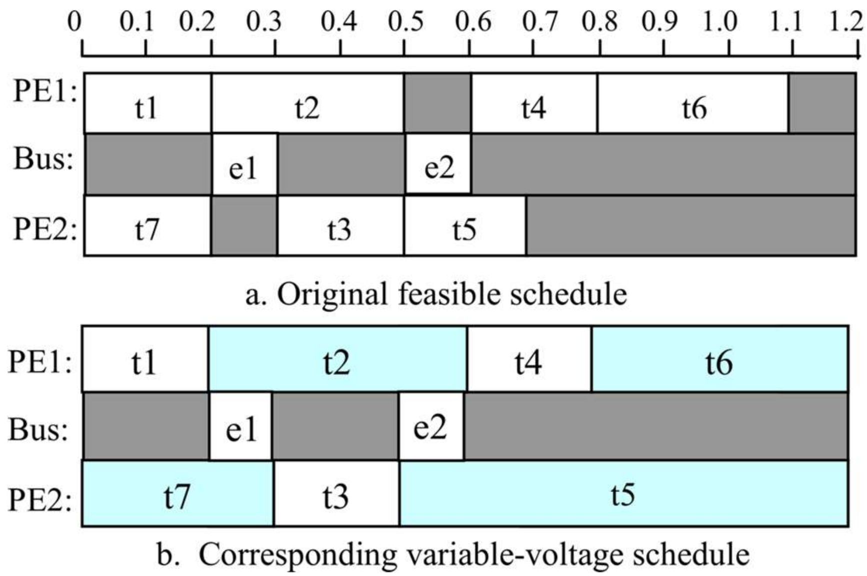
Battery Aware Scheduling 5

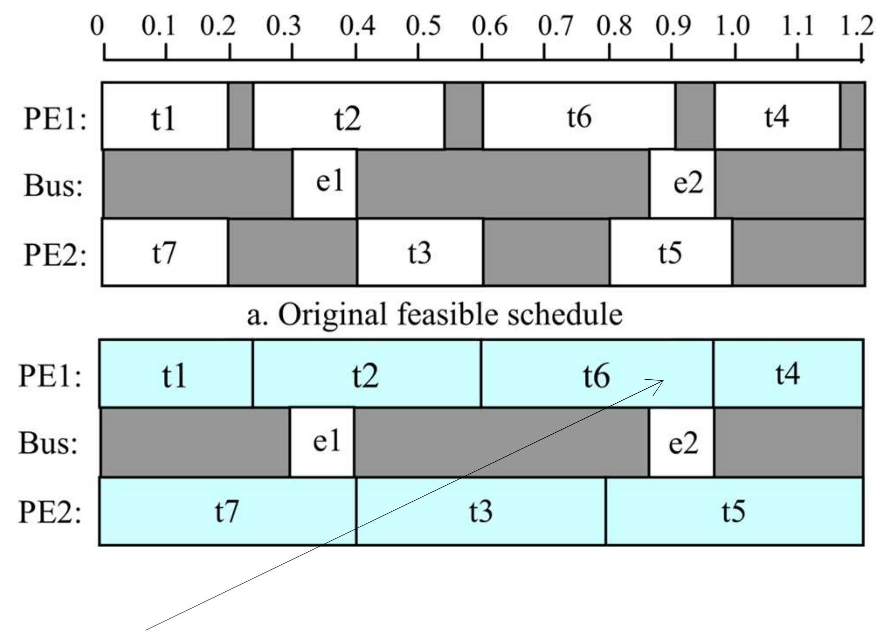


First schedule: ASAP. Voltage scaling extends execution time to latest finish time.

Source: Luo [2001]

Battery Aware Scheduling 6





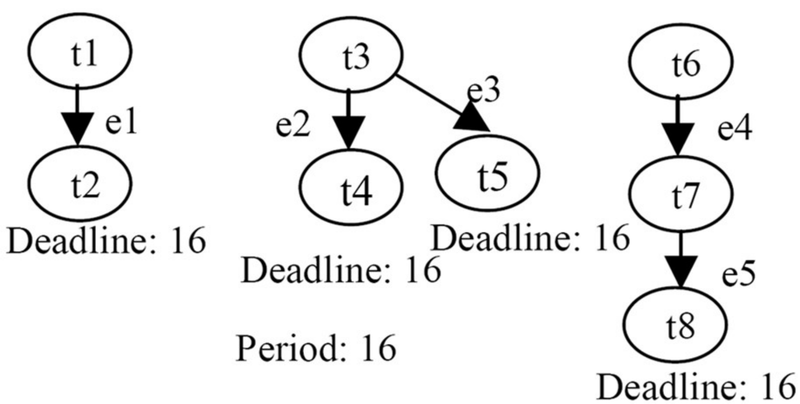
Even more improvement possible with slot shifting and swapping.

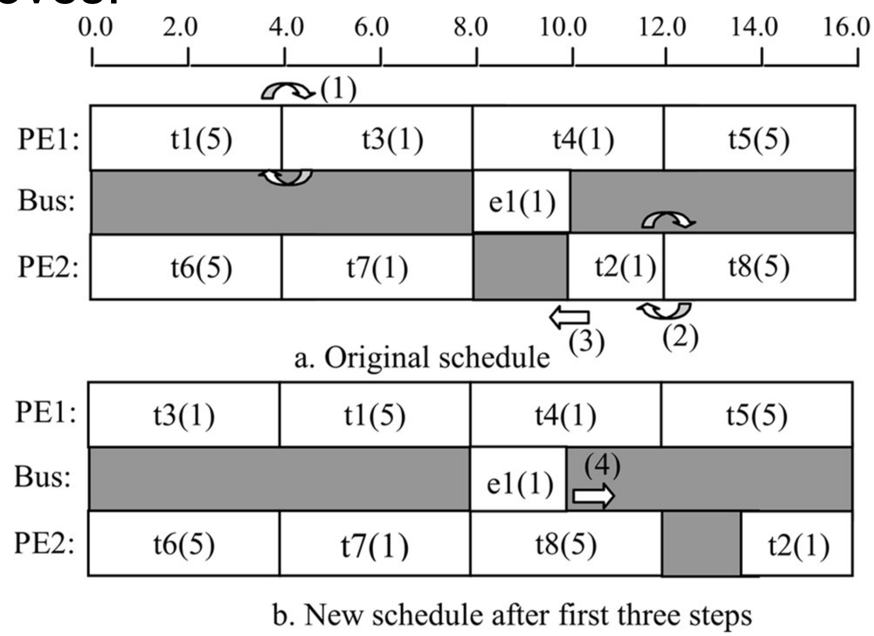
Source: Luo [2001]

Battery Aware Scheduling 7

- Battery-aware improvements of slack-based list scheduling (heuristic).
  - Slack is time left after a task, if task starts now.
- Hyperperiod: Lease common multiple of all deadlines.
  - Proving feasibility in the hyperperiod is enough.
- Reduce actual power using local moves.

$$p^{act} = \frac{1}{hyperperiod} \int_0^{hyperperiod} dt \, \frac{p(t)}{c_p(t)}$$

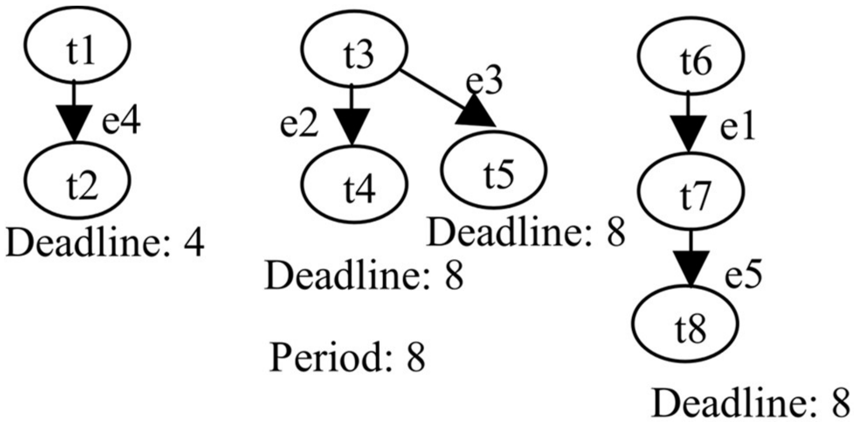


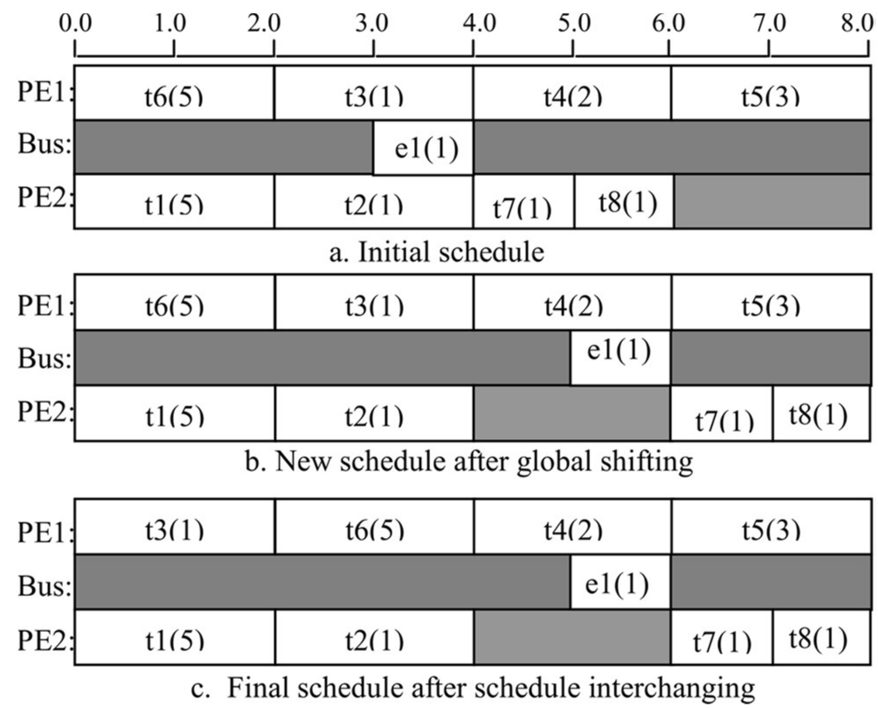


Source: Luo [2001]

Battery Aware Scheduling 8

- Breaking local optima using global moves.





Source: Luo [2001]

Source

- Xie, Qing, et al. "Charge allocation in hybrid electrical energy storage systems." *IEEE Transactions on Computer-Aided Design of Integrated Circuits and Systems* 32.7 (2013): 1003-1016.
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- Rao, Ravishankar, Sarma Vrudhula, and Daler N. Rakhmatov. "Battery modeling for energy aware system design." *Computer* 36.12 (2003): 77-87.