Karlsruhe Institute of Technology

Low Power Design

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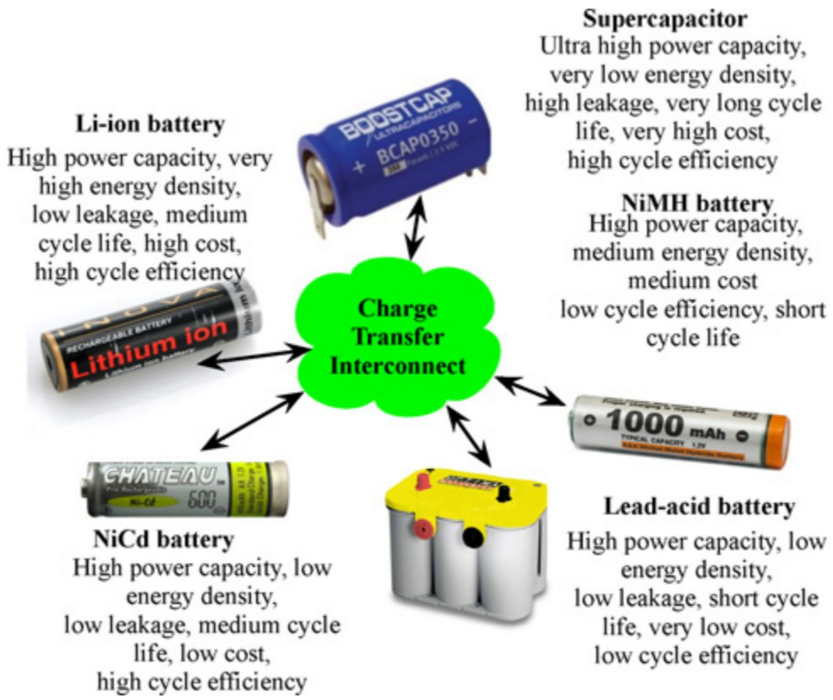
Summer Term 2016

CES – Chair for Embedded Systems

Lecture Slides Download

Homework



Concept diagram of the HEES systems (src.:[Xie])

(src.:www.warnerbros.com)

Side Remark: Spiroergometrie

- Messung von Atemgasen während sportlicher Belastung
- Bestimmung von Kalorimetrie bzw. Fettverbrennung
- Alternative: Activity Tracker
  - deutlich weniger genau

(src.: http://www.suedeutsche.de/)

Oxycon Mobile 5.0

(src.: http://www.carefusion.de/)

Overview Low Power Design Lecture

- Introduction and Energy/Power Sources (1)
- Energy/Power Sources(2): Solar Energy Harvesting
- Battery Modeling – Part 1
- Battery Modeling – Part 2
- Hardware power optimization and estimation – Part 1
- Hardware power optimization and estimation – Part 2
- Hardware power optimization and estimation – Part 3
- Low Power Software and Compiler
- Thermal Management – Part 1
- Thermal Management – Part 2
- Aging Mechanisms in integrated circuits
- Lab Meeting

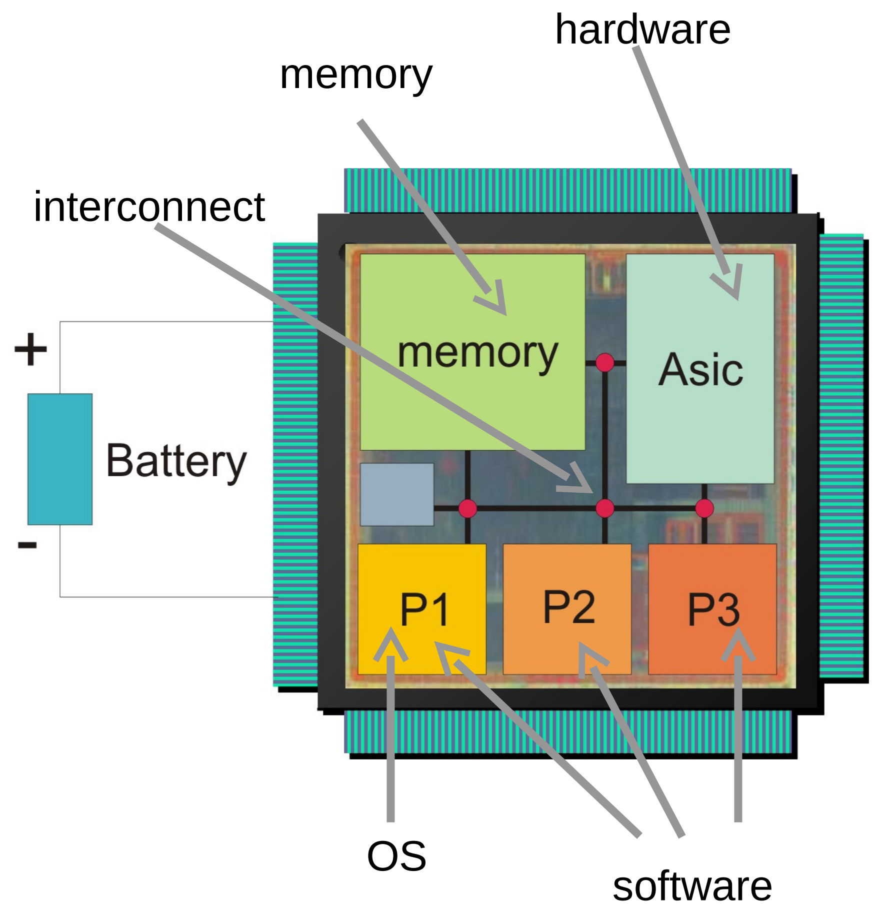
Overview for today

- Motivation and battery characteristics
  - definition of battery capacity
  - rate dependent capacity
  - temperature dependent capacity
  - fading of capacity through charge-/discharge cycles
- Need for battery modeling
- Battery models
- Applying battery models

Course overview: topics

- Levels of abstraction
  - system
  - RTL
  - gate
  - transistor
- Tasks
  - optimize (ie. minimize for low power)
  - design / co-design (synthesize, compile, …)
  - estimate and simulate

Compenents consuming power:



Battery capacity: some terms

Summary:

- reduction-oxidation process makes electrons migrate from anode to cathode
- chemical energy is converted into electrical energy
- when discharged, the voltage drops

- Various definitions of capacity [Wh] (since capacity is NOT constant)
  - Full charge capacity: remaining capacity of a fully charged battery at the beginning of a discharge cycle
  - Full design capacity: capacity of a newly manufactured battery
  - Theoretical capacity: max amount of charge that can be extracted from a battery based on the amount of active material (chemical) it contains
  - Standard capacity: amount of charge that can be extracted from battery when discharged under standard load and temp. conditions
  - Actual capacity: amount of charge the battery delivers under applied load and given temperature

Rate dependent battery capacity

Rate: defines how fast the battery is discharged

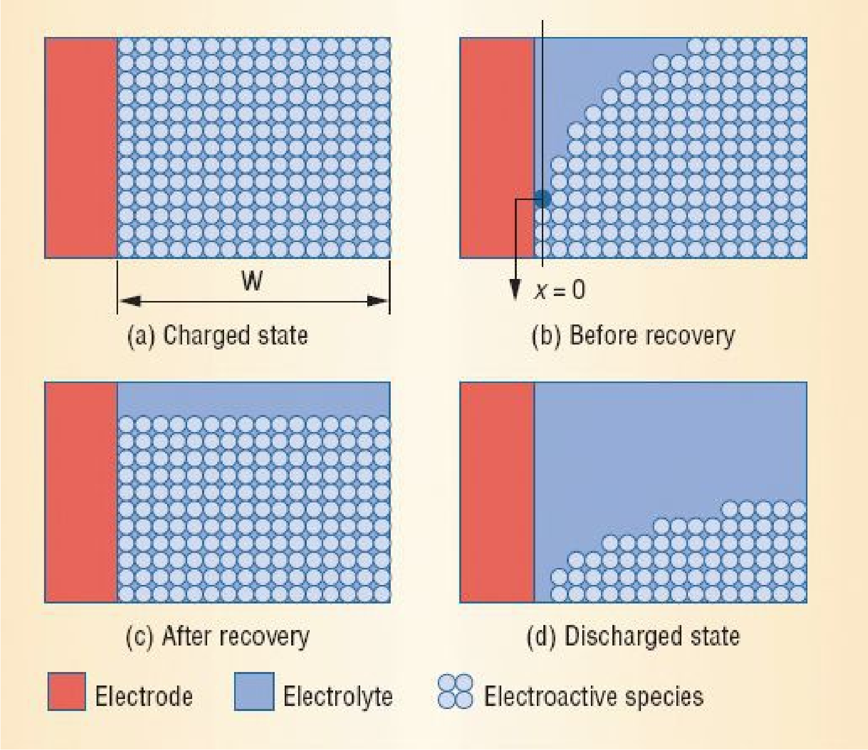
Shown is the mechanism that defines rate-dependent capacity

a) charged state

b) before recovery

c) after recovery

d) discharged state



(Src: [Rao03])

Rate dependent capacity (cont'd)

Why does battery capacity depend on the (discharge) rate?

State A: electrode surface contains max. # of active species;

State B: when connected to a load,

- current flows through external circuit
- active species are consumed at electrode surface and replenished by diffusion from the bulk of the electrolyte
- however, diffusion cannot keep pace
- → a concentration gradient builds up over the width of the electrolyte

Note: a higher load current results in a higher gradient
→ less active species available at electrode surface

Rate dependent capacity (cont'd)

State B/C/D: if concentration is below a certain threshold (voltage cutoff), chemical reaction cannot be sustained at electrode surface; the charge that was unavailable (but kind of present through gradient) cannot be used → capacity of battery is reduced

State D: non-used charge is physically not lost but unavailable due to lag between reaction and diffusion rates
(load was probably too large current-wise)

Note: reducing discharge rate reduces the effect

The lower the discharge rate the faster the battery can recover and make formerly unavailable charge available again (recovery)

Note: if system designers are aware of the effect they can maximize the energy drawn from a battery and prevent early discharged state

If discharge rate is very small → maximum amount of energy can be drawn from battery

Dependency on **Temperature**

Discharging a battery involves a chemical reaction.
→ Depends on the temperature (some chemical reactions increase activity by 2x when temperature rises by 10K)

Below room temp (~25°C): chemical activity in battery decreases notably and internal resistance (migration through electrolyte etc.) increases

→ full-charge capacity is decreased

→ increases slope of discharge curve

Higher temperatures:

→ increase of chemical activity, full charge capacity, voltage

→ but leads also to higher rate of self-discharge -> might actually decrease actual capacity

Fading of battery capacity

Problem: every charge/discharge cycle reduces full charge capacity

Reason: side effects occurring in battery during chemical reaction

- electrolyte decomposition
- Active material dissolution
- Passive film formation

→ all these effects are irreversible

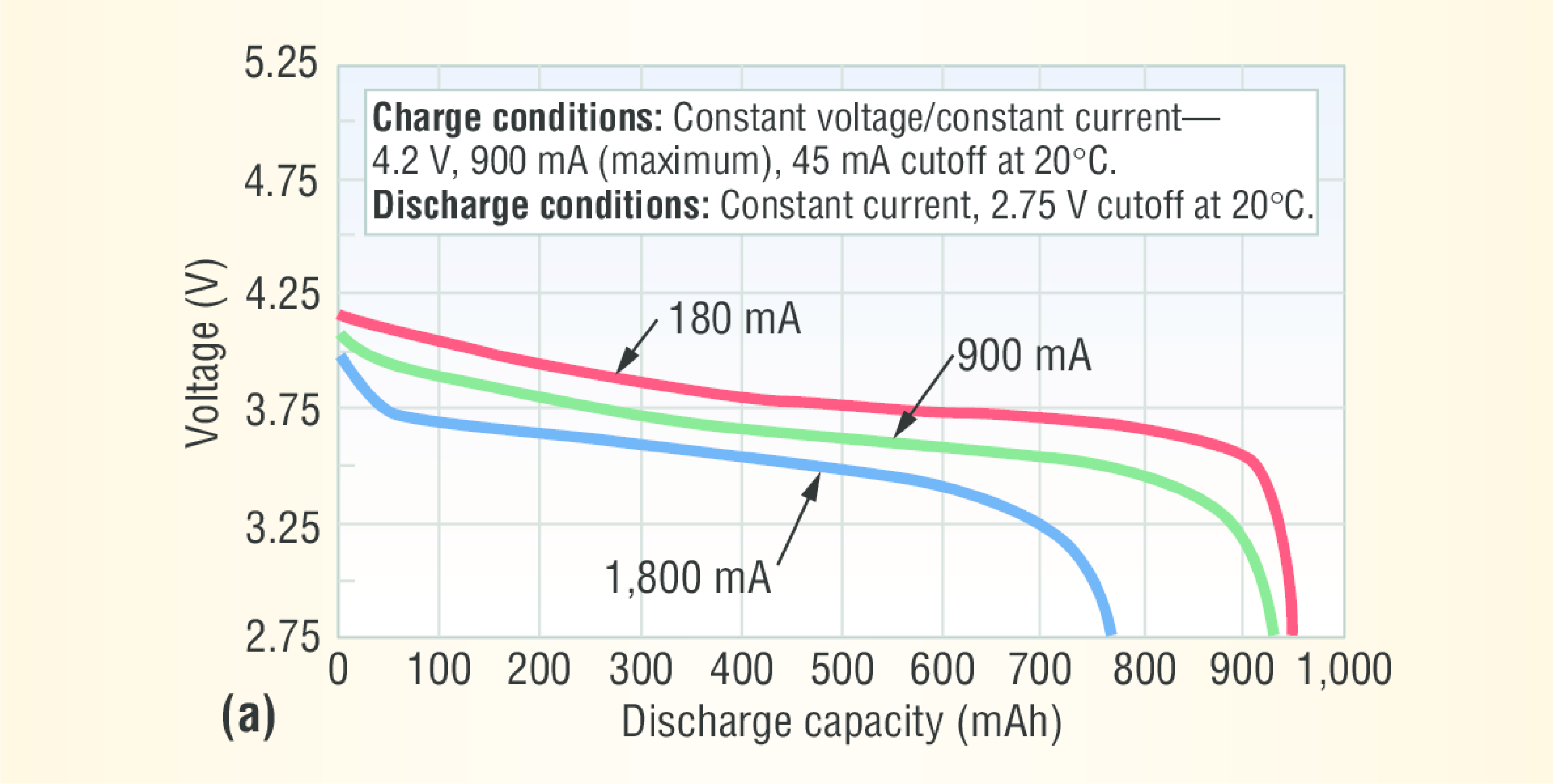
→ reduces capacity in the short/mid term

→ leads to failure of battery in long term

How to reduce these effects:

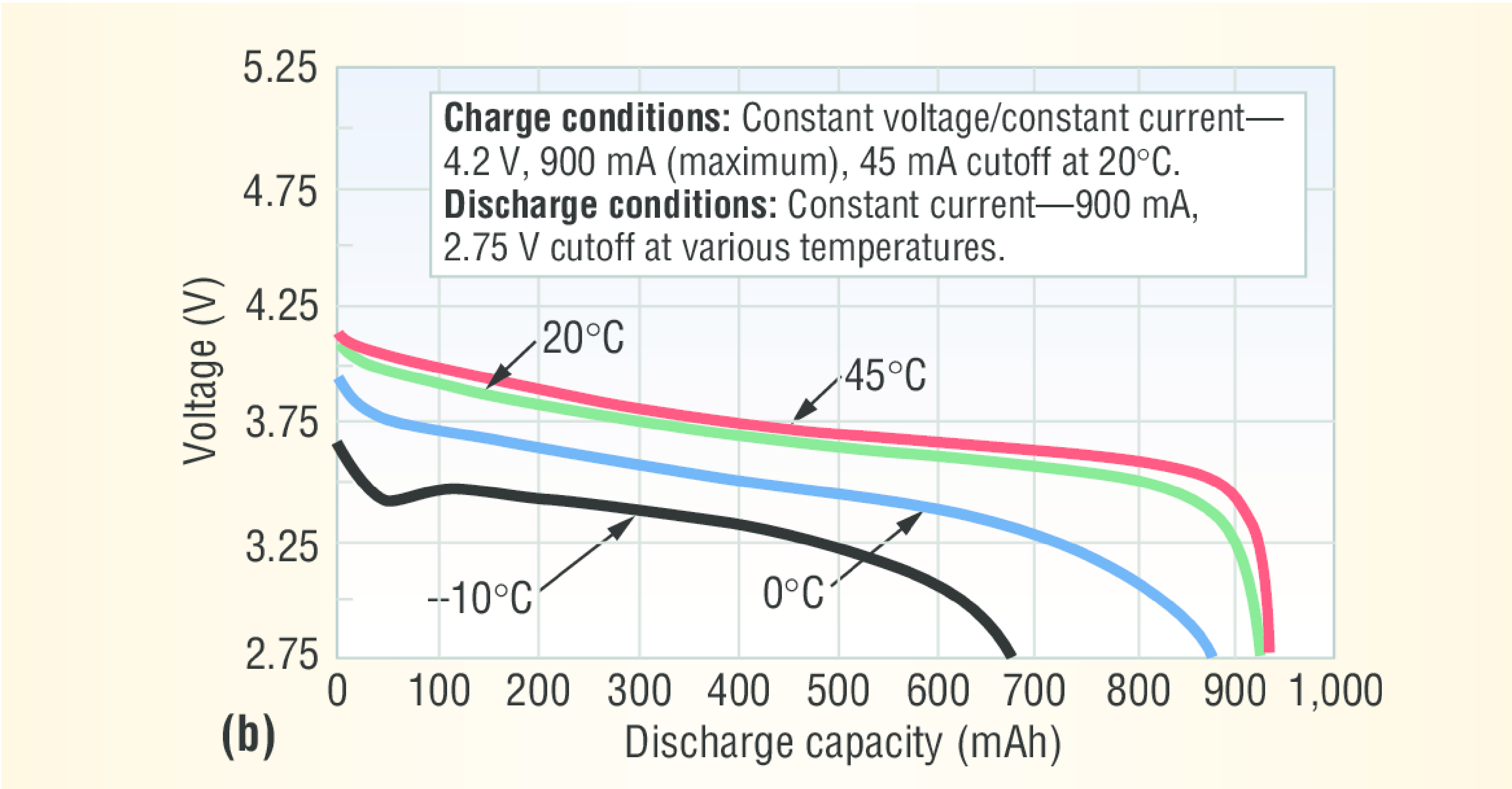
- electronic system needs to control the discharge level (i.e. switch off when battery is almost empty)
- Deep discharge will reduce life (i.e. # of charge/discharge cycles of battery). This holds even for Lithium-Ion batteries!

Battery capacity: rate-dependent capacity



src.: [Rao03]

Battery capacity: temperature dependency



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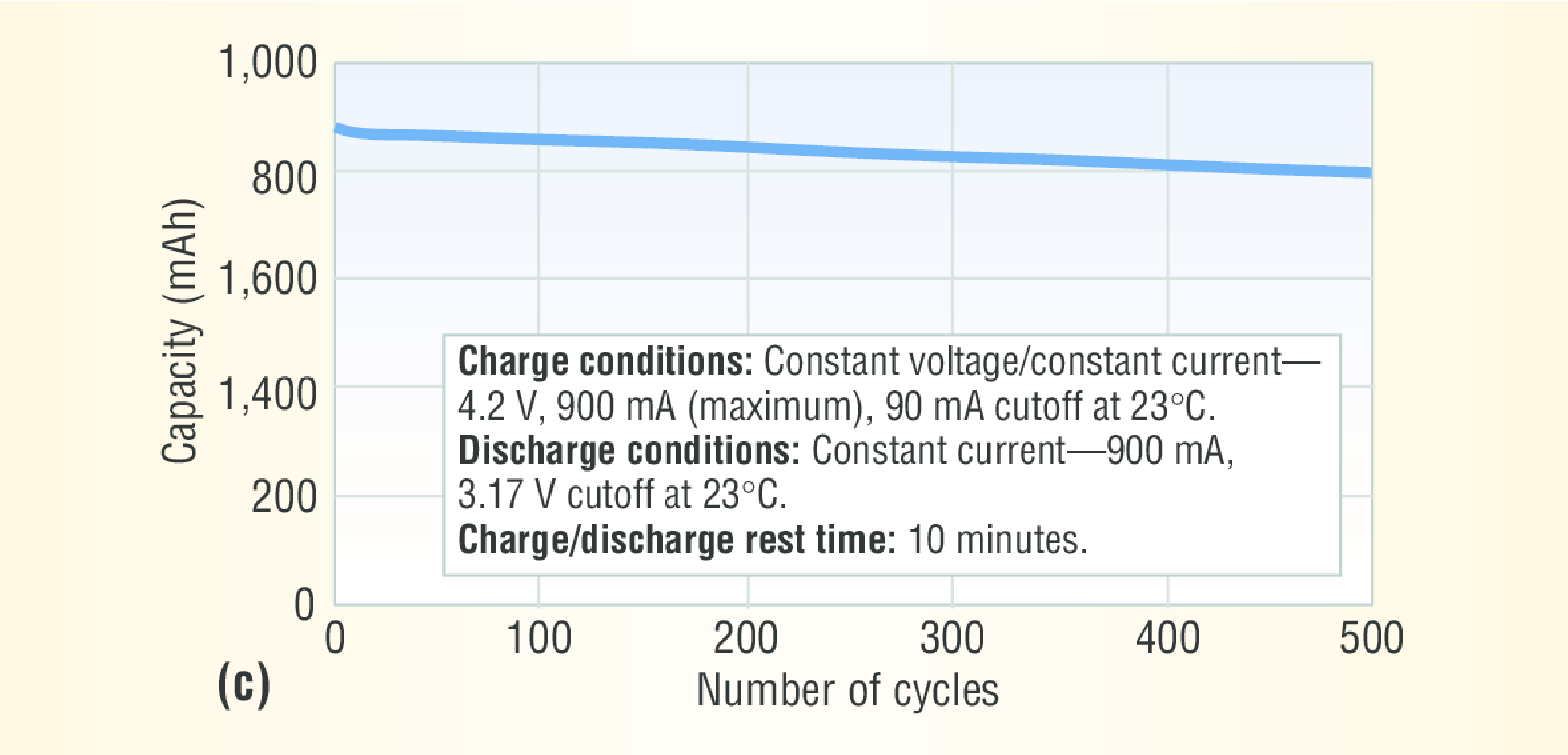
Battery capacity: fading of capacity with number of charge/discharge cycles



src.: [Rao03]

Battery Modeling: Why and how?

- Why:
  - If designer of portable knows about the effects the system can be designed such that
    - Amount of energy drawn from battery can be maximized => leads to longer run-time of system before re-charge is necessary
    - Optimize trade-off between energy drawn and life time of the battery
    - Life time of battery can be maximized -> reduces costs for maintaining a system
    - Need to predict battery capacity in order to choose right battery for a given electronic system
- How? -> Issues:
  - Accuracy: what accuracy is necessary?
  - Computational complexity
  - Optimize trade-off between
    - Configuration effort (# of parameters; is chemical knowledge of battery necessary?)
    - Analytical insight: qualitative understanding of battery behavior. Useful in exploring ways to trade off lifetime and performance

Battery Models – Comparison –

Shown are approaches at various levels of abstraction capturing more or less diverse battery characteristics

Model	Temperature effect	Capacity fading	Accuracy	Computational complexity	Configuration effort	Analytical insight	Applications
Physical							
Lithium-polymer-insertion cell (Doyle et al.)	Yes	Yes; support for Arrhenius temperature dependence and cycle aging added by Rong and Pedram	Very high	High	Very high (> 50 parameters)	Low	
Empirical							
Peukert's law	Yes; needs recalibration for each temperature	No	Medium (14% average error for constant load, 8% average error for interrupted and variable loads)	Low	Low (2 parameters)	Low	
Battery efficiency (Pedram and Wu)	Yes; needs recalibration for each temperature	No	Medium	Low	Low (2 parameters)	Low	Design of interleaved dual-battery power supply; load splitting for maximum lifetime of multibattery systems
Weibull fit (Syracuse and Clark)	Yes	No	Medium	Low	Low (3 parameters)	Low	

Battery Models – Comparison – (cont'd)

Abstract							
Electrical-circuit (Gold)	Yes	Yes	Medium (12% error predicting cell voltage and thermal characteristics, 5% error predicting cycle aging)	Medium	Medium (> 15 parameters)	Medium	
Electrical-circuit (Bergveld et al.)	Yes	No	Medium	Medium	High (> 30 parameters)	Medium	Thermostatic charge method: high charging efficiency
Discrete-time (Benini et al.)	Yes	No	Medium (1% compared to Hspice continuous-time model)	Medium	Medium (>15 parameters)	Medium	Dynamic Power Management; multibattery discharge
Stochastic (Chiasserini and Rao)	No	No	High (1%)	Low	Low (2 parameters)	Medium (stochastic model of load pattern assumed)	Shaping load pattern to exploit charge recovery
Mixed							
Analytical high-level (Rakhmatov et al.)	No	No	High (5%)	Medium	Low (2 parameters)	High	Task scheduling by sequencing and *V*/*f* scaling; analysis of discharge methods for multibattery systems
Analytical high-level (Rong and Pedram)	Yes	Yes	High (3.5%)	Medium	Medium (> 15 parameters)	High	

An empirical model: Peukert's law

Ideal battery: *capacity*$_N$ = t_{run} * I, *(for constant* I*)*
(note: capacity may be given in Wh or Ah)

Peukert Law: *capacity*$_N$ = t_{run} * I^{α}

Alpha: exponent accounts for discharge rate

capacity$_N$*:* normalized capacity for 1 Ampere (standard capacity)

+ simple way to model *capacity(discharge_rate)*

- α is different for different temperatures → needs to be obtained empirically

- α also depends on battery type etc. (e.g. Li-ion: α=1.05)

Actual capacity: $I \cdot t_{run} = \frac{capacity_N}{I^{\alpha-1}}$

Abstract battery models

Idea: Rather than describing the behavior of a battery how it has been observed, the idea of abstract techniques is to model the individual effects of the battery in a constructive way

Models differ at level of abstraction and amount of details that are included

Some approaches to battery modeling/emulation

- Battery emulation (more details later)
- Stochastic model (more details later)
- Discrete-time model using VHDL (more details later)
- Others: eg. PSPICE model (electrical circuit)

Battery emulation

Problem: want to design electronic system to adapt to battery characteristics. System exists already in form of hardware and is analyzed by measuring the current/voltage of diverse components

Obvious ways

1. Use non-rechargeable batteries

 - under circumstance large costs since many runs need to be performed until all characteristics are explored

2. Use re-chargeable batteries:

 - problem: after recharge, battery might have different characteristics (fading of capacity) and as such results may not be reproducible

Additional problem: temperature dependency might prevent reproducibility

Goal: full reproducibility

Battery emulation

V_{oc}: initial potential of a fully charged cell under no-load condition (i.e. no current)

Solution: hardware that emulates battery

Fig. a)

- a regular battery with internal resistance R_i
- Observed voltage:

$$V_b = V_{oc} – I\, R_l$$

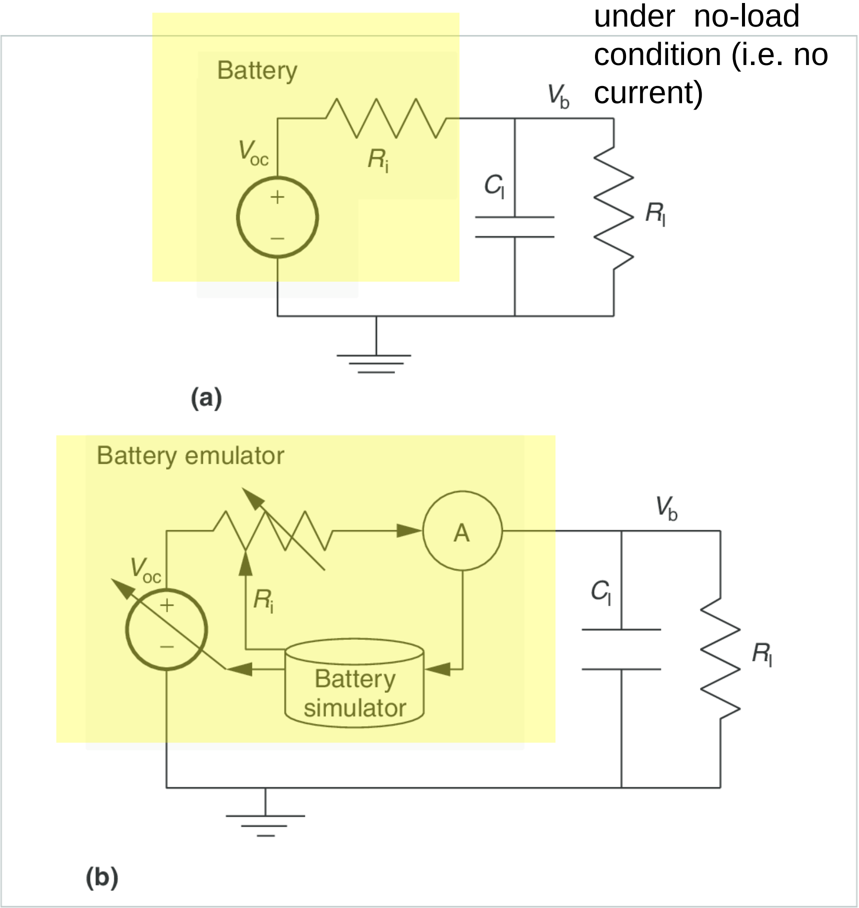
When battery discharges, V_{oc} decreases while R_i increases (dep. on batteries state and internal temperature)

Fig. b)

The simulation model can maintain battery's state; ambient temp. and current can be measured

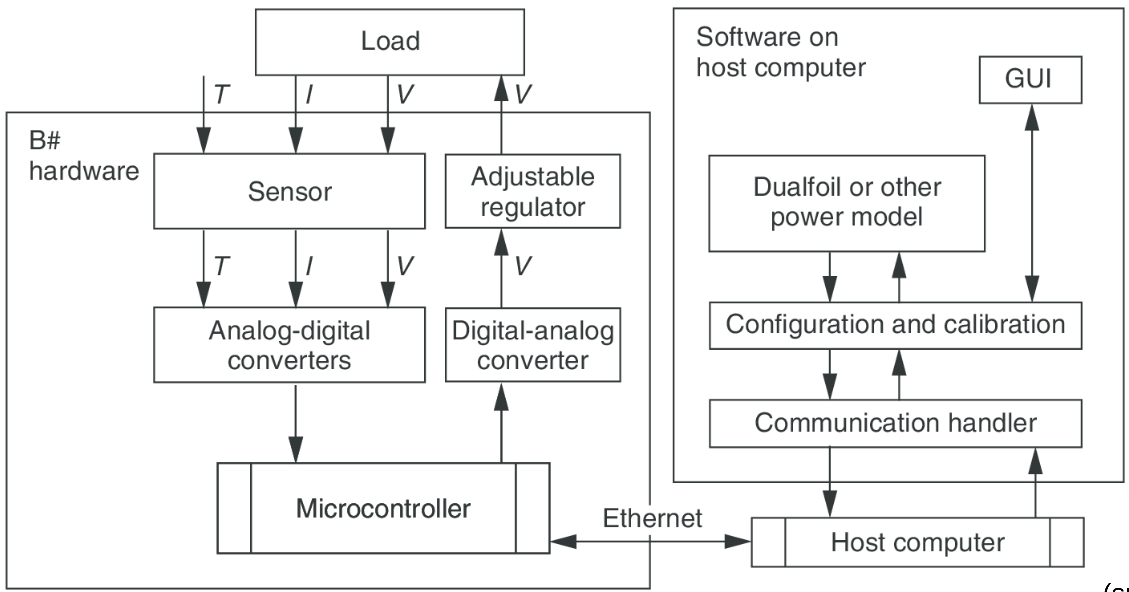
Emulator performs repeatedly:

- measure I and T
- Call simulator to compute V_{oc} and R_i in response to I and T
- Set V_{oc} and R_i



(src.: [Park05])

B# system block diagram

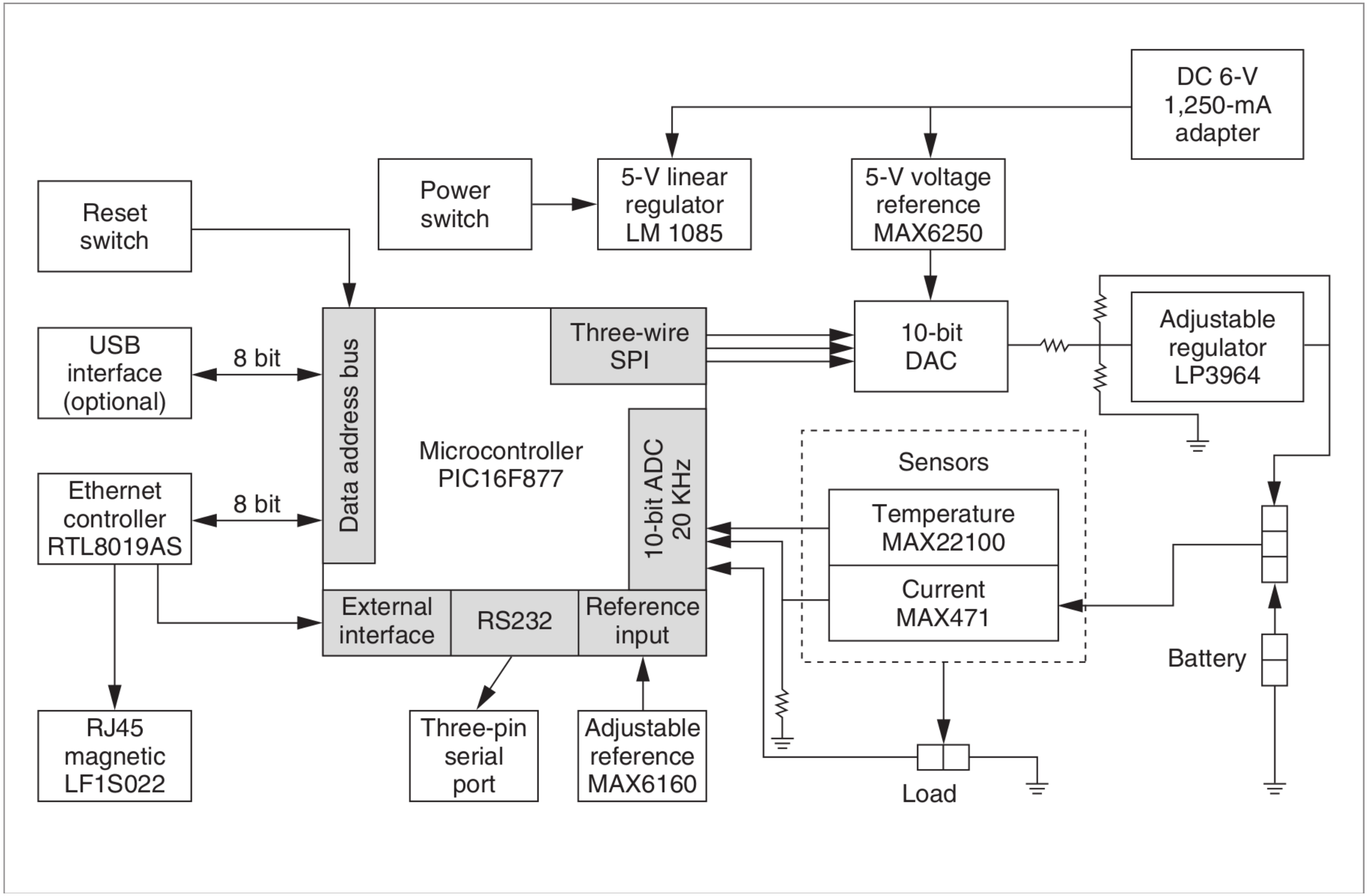


(src.: [Park05])

Basic idea: combine speed and accuracy of a measurement-based approach with flexibility and reproducibility of simulation-based approach

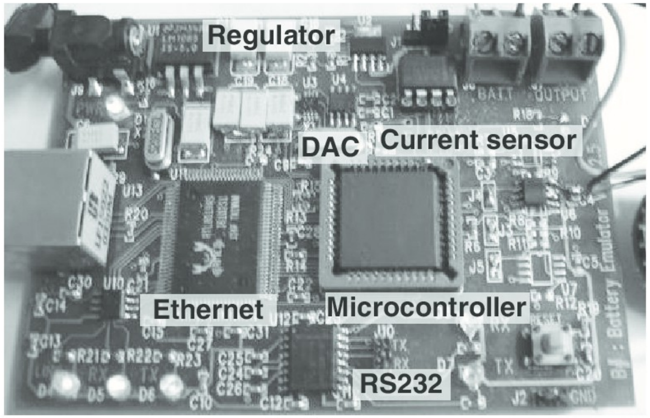
Can implement many battery models eg. “Dualfoil” (Dualfoil”: one of the most accurate simulators for Lithium-Ion batteries; has 58 paramters: geometrical dimension of anode, cathode etc. plus chemistry parameters etc.)

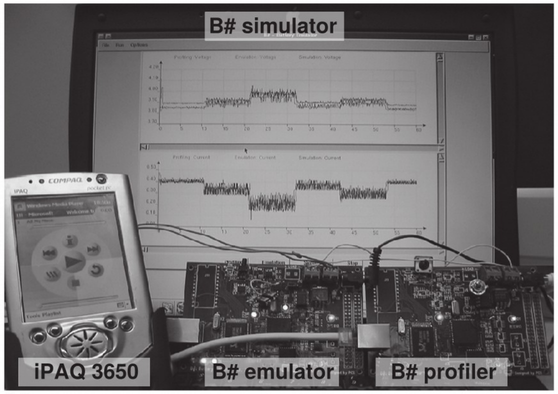
B# hardware block diagram



(src.: [Park05])

B# hardware





(a)

(b)

(src.: [Park05])

Discrete-Time battery models

Idea: Need to overcome the gap between electrical level and high-level simulation.

[Benini01] describes first-order effects and second order effects and implements them as a VHDL model

First-Order Effects:

- Battery voltage depends non-linearly on its state of charge
- The actual usable capacity of a battery cell depends on the discharge rate
- The “frequency” of the discharge current affects the amount of charge the battery can deliver

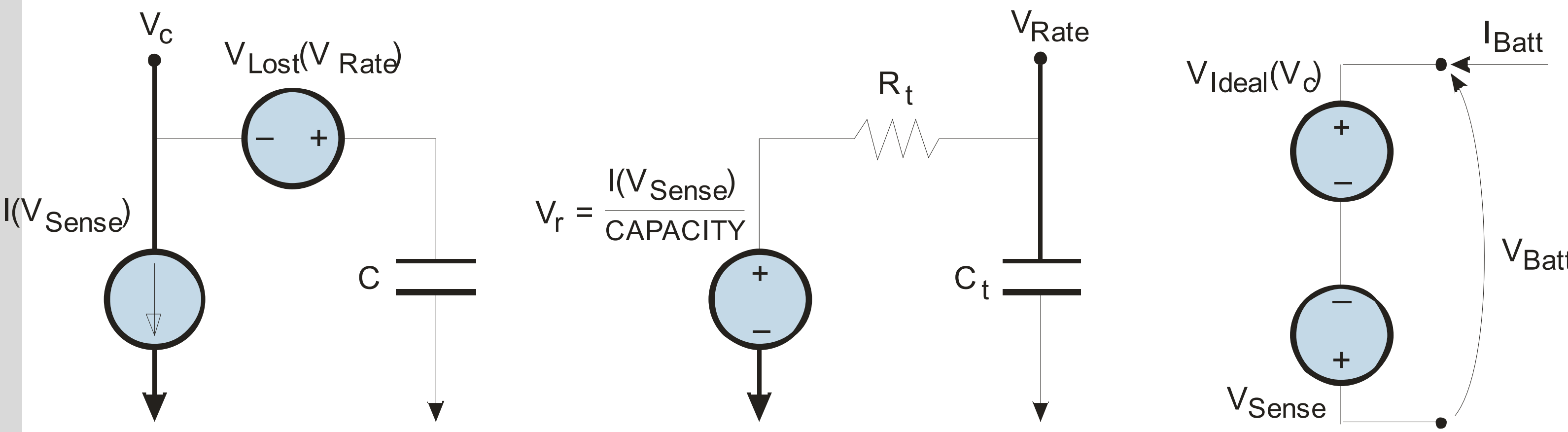
Second-Order Effects:

- external temperature
- battery internal resistance
- ...

(src.: [Benini01])

First order continuous-time battery model

(src: [Benini01])



V_sense is a zero-valued voltage source added in series as the discharge-current (I_Batt) sensor

Dependency on **discharge rate** is modeled with a voltage source V_lost in series with the charge storage capacitor. Voltage V_lost reduces the apparent charge of the battery [which controls battery voltage (V_Batt)]. The value of V_lost is a nonlinear function of the discharge rate (which can be modeled by another LUT).

Dependency on the **discharge frequency**, and the time-domain transient behavior of the battery are modeled by averaging the instantaneous discharge rate used to control V_lost through a low-pass filter (R_f, C_f). The low-pass filter models the relative insensitivity of batteries to high-frequency changes in discharge current.

Dependency on the SOC (state-of-charge) (V_ideal(V_C)) is realized by storing several points of the curve into a lookup table (LUT) addressed by the value of the state of charge (V_C). The model is accurate up to a minimum cutoff voltage, after which the battery is considered fully discharged.

Discrete-time power supply model

VHDL program is based on circuit-level model and consists of two concurrent, communicating processes. The **first** one (Compute_V_C) computes the value of node V_C in the instantaneous state of charge of the battery (accounting for **losses due to high discharge rate).** The **second** process (Compute)V_lost) computes the value of V_lost (**low-pass filter**).
The output voltage of the battery V_Batt is a function of V_C. It is implemented as a continuous assignment: V_Batt=F(V_C) where F is realized by a LUT with linear interpolation (PWL). The main challenge: discretization is required to simulate values in an event-driven setting. Therefore, implemented are an autonomous source of events (signal update) that generates events at a fixed frequency. The state of charge V_C and the value of V_Rate are updated when the autonomous source generates an event. The change in SOC is obtained by integrating the differential equations of the continuous-time model over the update period.

```
entity battery is
  port( I_Batt : in amps; update : in std_logic;   V_batt : out real);
end battery;

architecture behavior of battery is
begin
  V_Batt <= PWL( V_C) + V_Cell_Temp – R_Int * I_Batt;
  -- V_Cell_Temp is 0.0 if no second order effects are considered
  Compute_V_C : process ( I_Batt, update, V_Lost)
  begin
    cap_act := ( cap_act – I_BattOld * (NOW – chgt));
(*) V_C <= ( cap_act/cap_i – V_Lost);
    I_BattOld = I_Batt;
    chgt = NOW;
  end process;
  Compute_V_Lost : process ( I_Batt, update, Compute)
  begin
    V_τ := I_BattOld /CAPACITY;
(**) V_Rate := ( V_RateOld -V_τ) * exp(–(NOW – chgt)/(R_f * C_f)) + V_τ;
    V_Lost := PWL( V_Rate);
    if I_Batt'event) then
      V_RateOld := V_Rate;
      Compute <= '1' after ( τ/ 5.0),
                 '0' after ( τ/ 5.0  * 2.0),
                 '1' after ( τ/ 5.0 * 3.0),
                 '0' after ( τ/ 5.0 * 4.0),
                 '1' after ( τ/ 5.0 * 5.0),
                 '0' after ( τ/ 5.0 * 6.0);
    end if;
  end process;
end behavior;
```

(src: [Benini01])

Side Remark: A mixed model

An analytical model that characterizes a battery using two constants, α and β, derived from the lifetime values for a series of constant load tests.

β - models the rate at which the active charge carriers are replenished at the electrode surface (recovery)

α - a measure of the battery's theoretical capacity,

- starting with Faraday's law for electrochemical reaction and Fick's law for concentration behavior during one-dimensional diffusion in an electrochemical cell, the relation between load i, battery lifetime L, and other battery parameters is:

$$\alpha = \int_0^L \frac{i(\tau)}{\sqrt{L-\tau}} d\tau + 2\sum_{m=1}^{\infty} \int_0^L \frac{i(\tau)}{\sqrt{L-\tau}} e^{-\frac{\beta^2 m^2}{L-\tau}} d\tau$$

(src: [Rakh01])

The charge the load consumed over the period [0, L)

The charge that was "unavailable" at the electrode surface at the time of failure L. The unavailable charge models the effect of the **concentration gradient** that builds up as the flow of active species through the electrolyte falls behind the rate at which they discharge at the electrode surface.

Applications for battery modeling

- Battery-aware scheduling (next lecture)
- Battery-aware power supply design
- Load-profile shaping for multi-battery systems (Benini)
  - Sequentially discharging each battery until empty
  - Static switching: discharge each battery for fixed duration in round-robin schedule (allows batteries to recover)
  - Dynamic switching of batteries: schedule the healthiest battery for discharge at any time
- Battery-aware dynamic power management (DPM)
  - DPM: typically only try to minimize power consumption of whole system
  - Idea: include non-ideal battery characteristics into the strategy (e.g. “sleep” adapted to battery recovery cycle, etc.)

Summary Battery Modeling

- (rechargeable) batteries have non-ideal effects like:
  - recovery effect
  - capacity depending on temperature
  - capacity depending on discharge rate
  - ...
- When these effects are known, they can be modeled at different levels of abstraction (transistor, or higher levels) depending on what accuracy is needed and how much time is available for simulation
- The battery models can eventually be deployed in order to estimate or optimize the system's power/energy consumption and increase the system's run-time before a recharging is necessary

Sources

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