Lower Power Design

Lecture 2: Battery Modeling 1

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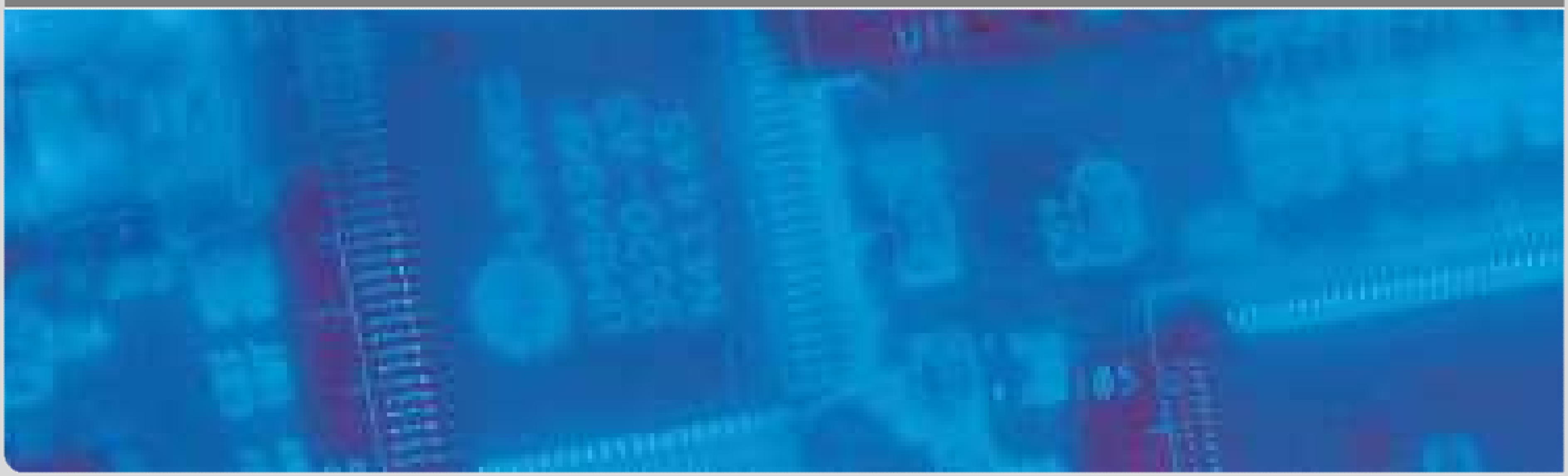
Summer Semester 2017

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 – TBA
- 08.06.2017 – TBA
- 15.06.2017 – Corpus Christi (Holiday)
- 22.06.2017 – TBA
- 29.06.2017 – TBA
- 06.07.2017 – TBA
- 13.07.2017 – TBA
- 20.07.2017 – TBA
- 27.07.2017 – TBA

Overview for Today

- 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.

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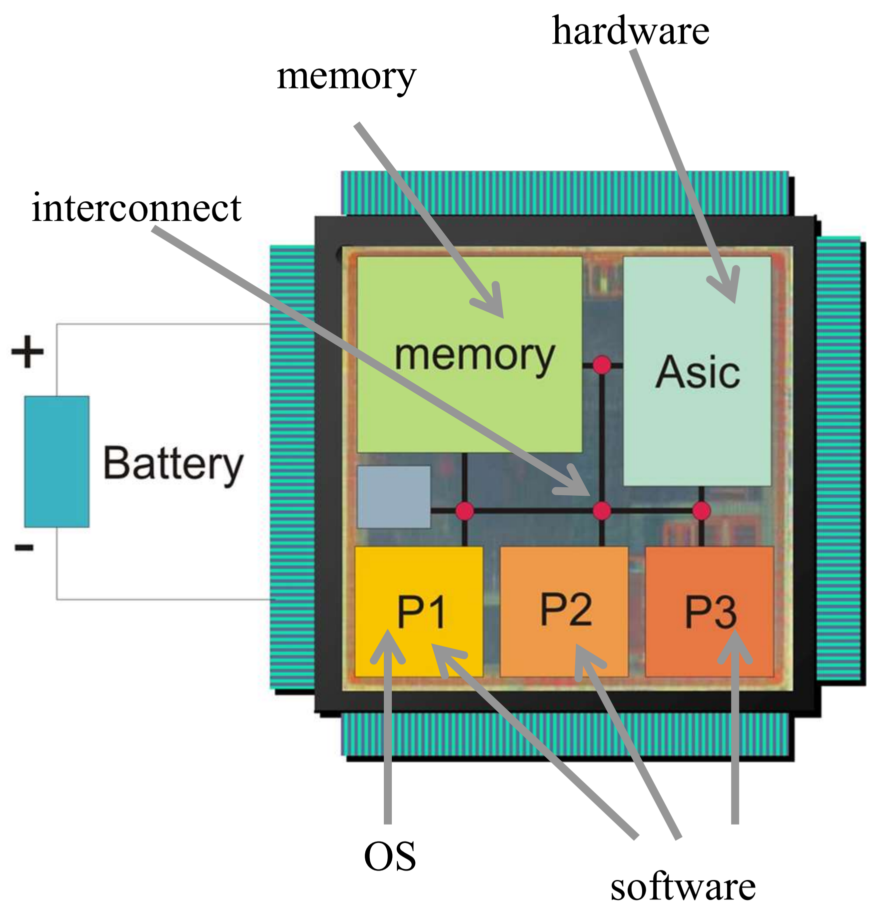
Power Consuming Components

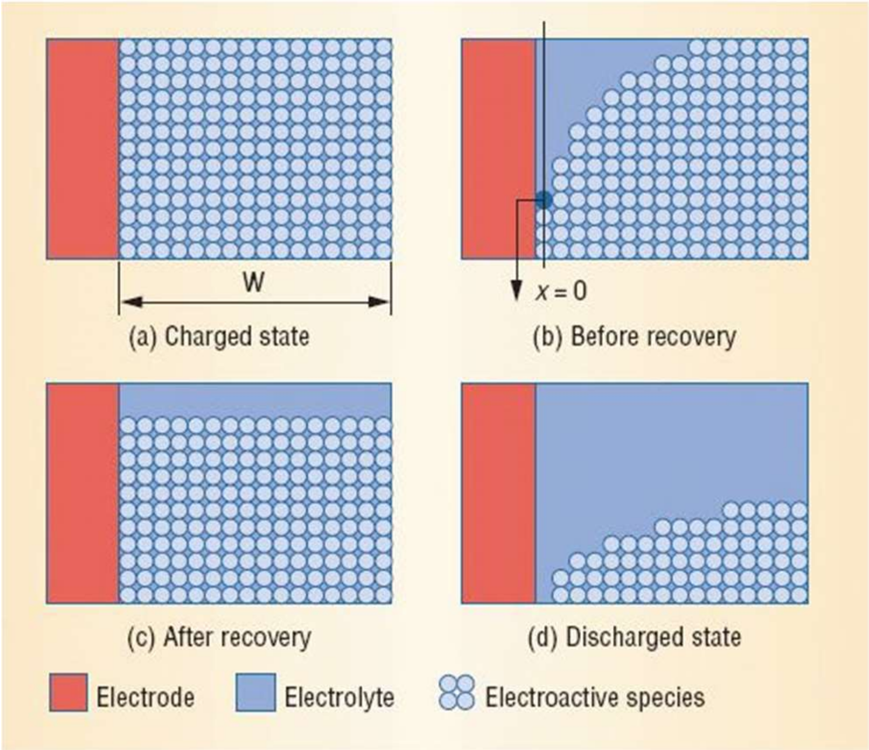


Terminology for Capacity [Wh]

- Full Charge Capacity.
  - Remaining capacity of a fully charged battery at beginning of a discharge cycle.
- Full Design Capacity.
  - Capacity of a newly manufactured battery.
- Theoretical Capacity.
  - Maximum amount of charge that can be extracted from a battery based on the amount of active materials (chemicals) contained.
- Standard Capacity.
  - Amount of charge that can be extracted from battery when discharged under standard load and temperature conditions.
- Actual Capacity.
  - Amount of charge the battery delivers under applied load and given temperature.

Rate Dependent Battery Capacity

- Rate
  - Speed at which battery is discharge.



Source: [Rao 2003]

Rate Dependent Battery Capacity 2

- Why does battery capacity depend on the discharge rate?
- State A: Electrode surface contains max. number of active species.
- State B:
  - Active species are consumed at electrode surface and replenished by diffusion from the bulk of the electrolyte.
  - Diffusion cannon keep pace.
    - A concentration gradient builds up over the width of the electrolyte.
  - A higher load current results in a higher gradient.
    - Less active species available at electrode surface.
- State B/C/D: Voltage cutoff
  - If concentration is below a certain threshold, chemical reaction cannot be sustained at electrode surface; the charge that was unavailable (but kind of present through gradient) cannot be used as a result 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).

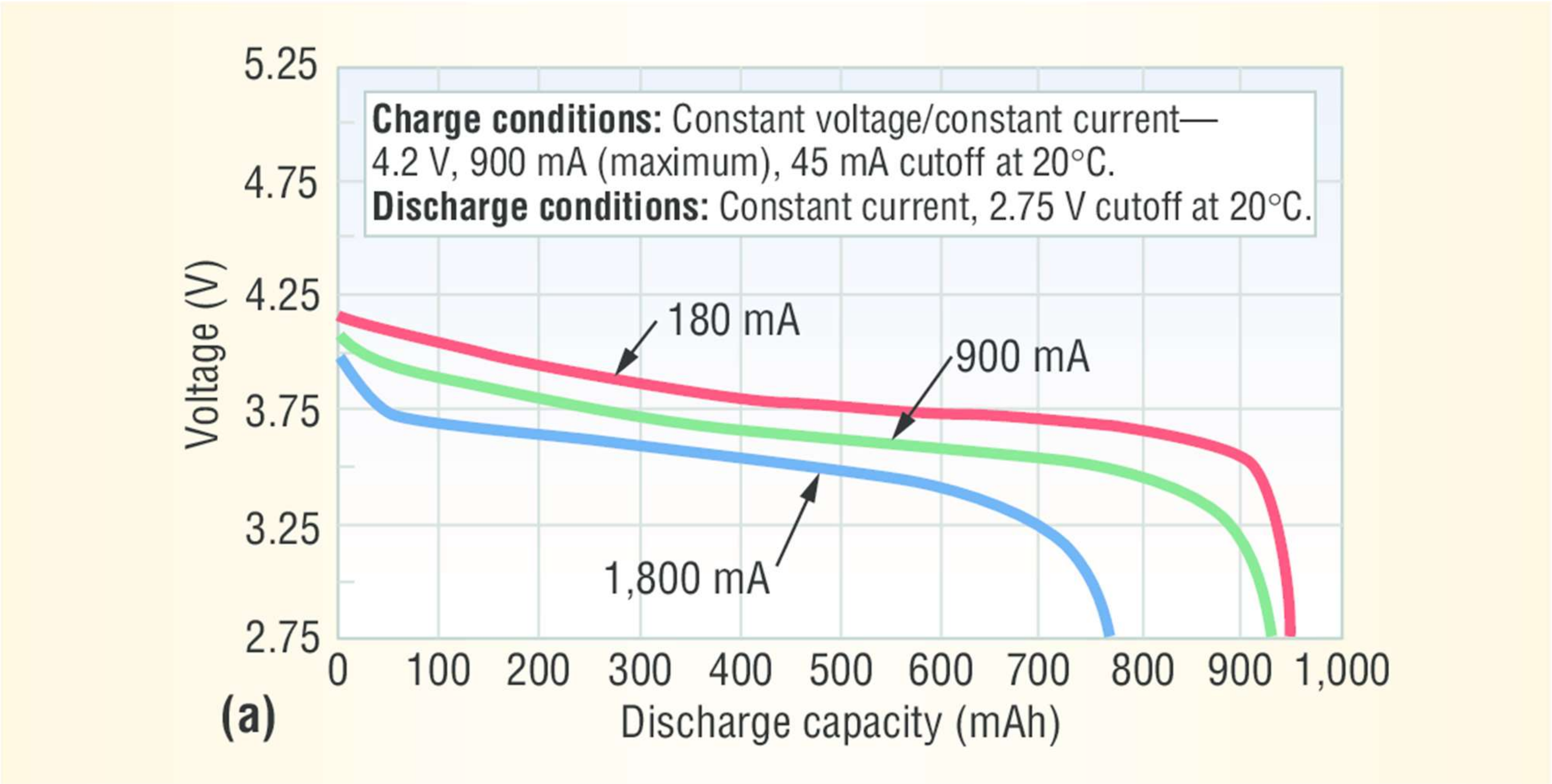
Source: [Rao 2003]

Rate Dependent Battery Capacity 3

- 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.

Source: [Rao 2003]

Battery Capacity: Rate Dependent Capacity 4



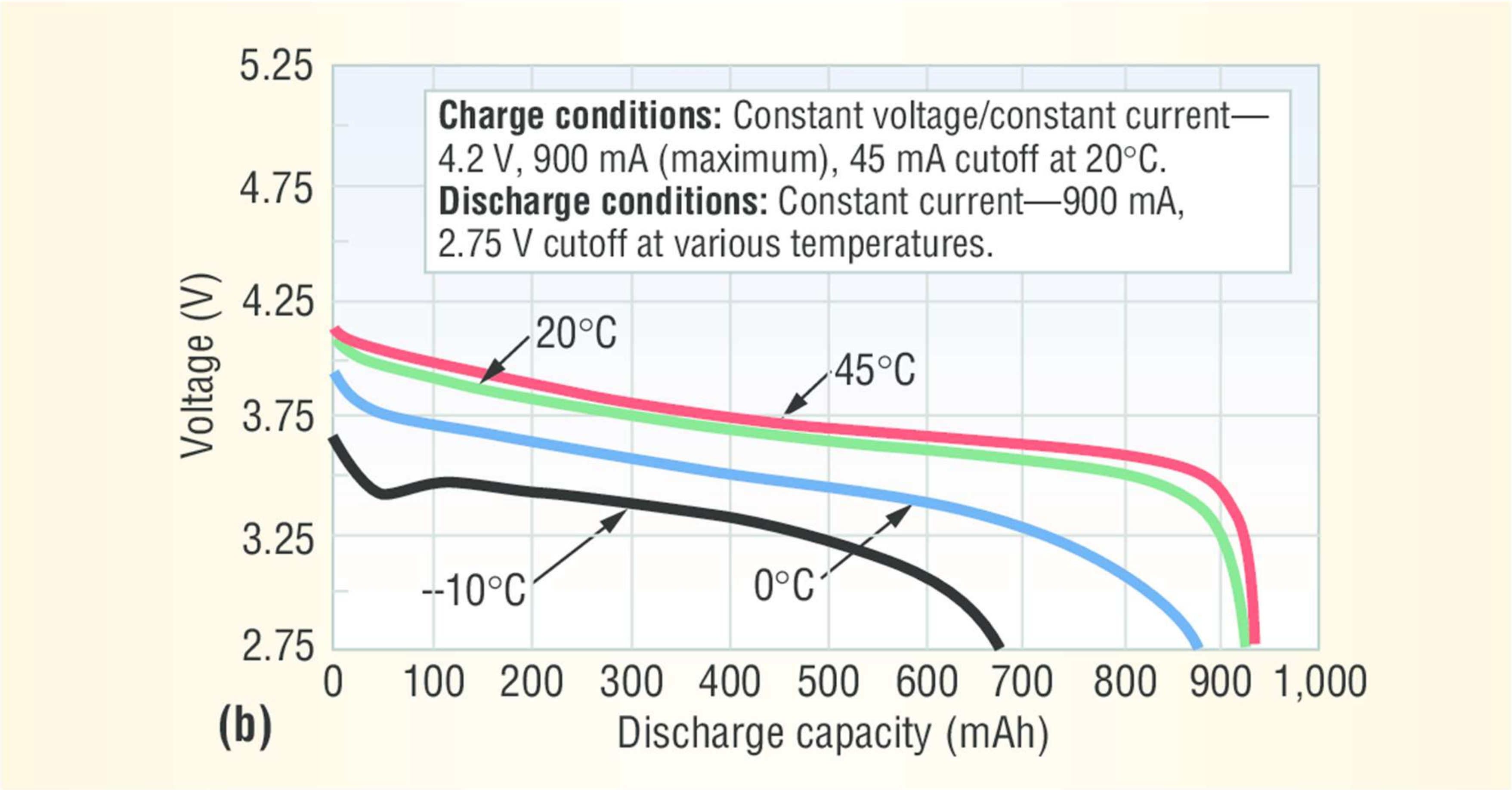
Source: [Rao 2003]

Temperature Dependency

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

Source: [Rao 2003]

Battery Capacity: Temperature Dependency 2

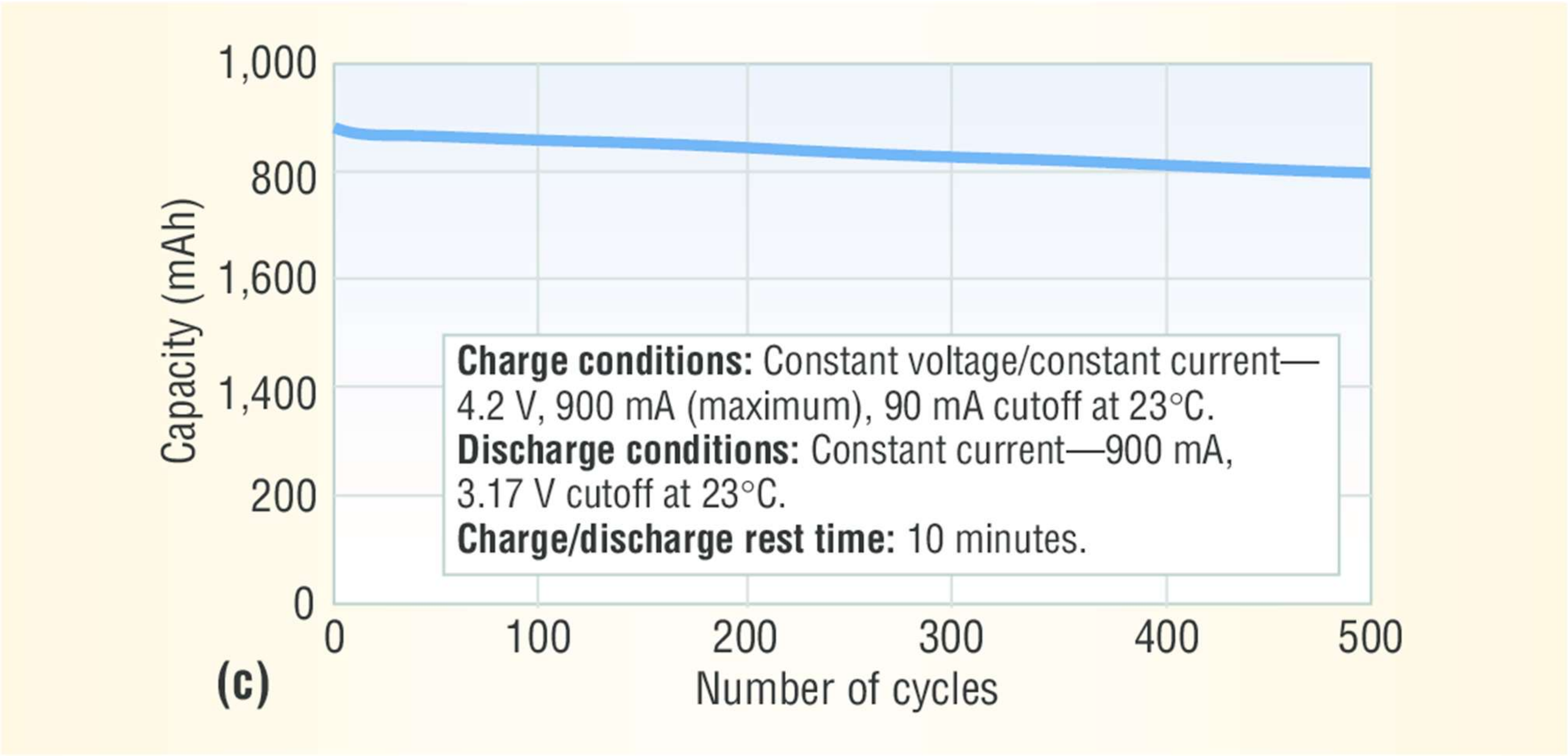


Source: [Rao 2003]

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.
- Irreversible.
- Reduce capacity in the short/mid term.
- Leads to failure of battery in long term.
- How to reduce battery fading:
  - 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: Fading Capacity



Source: [Rao 2003]

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? By modeling battery behavior.
  - 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 1

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	

Source: [Rao 2003]

Battery Models Comparison 2

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	

Source: [Rao 2003]

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)

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).
  - 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.

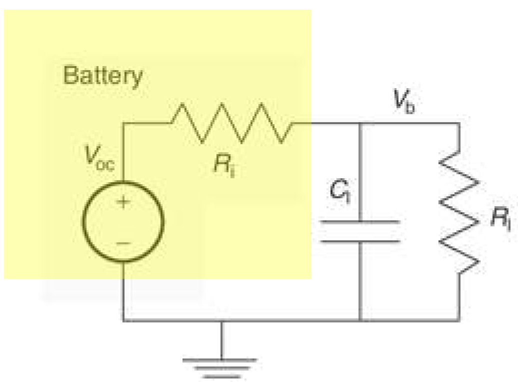
Source: [Park 2005]

Battery Emulation 2

Solution: hardware that emulates battery.

- 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)

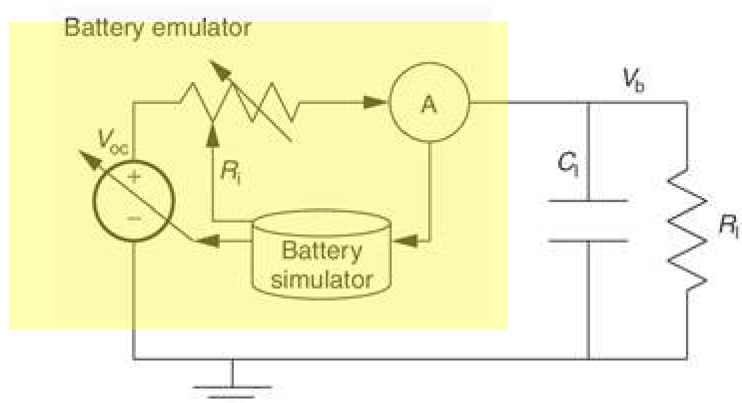


V_{oc} : initial potential of a fully charged cell under no-load condition (i.e. no current)

Source: [Park 2005]

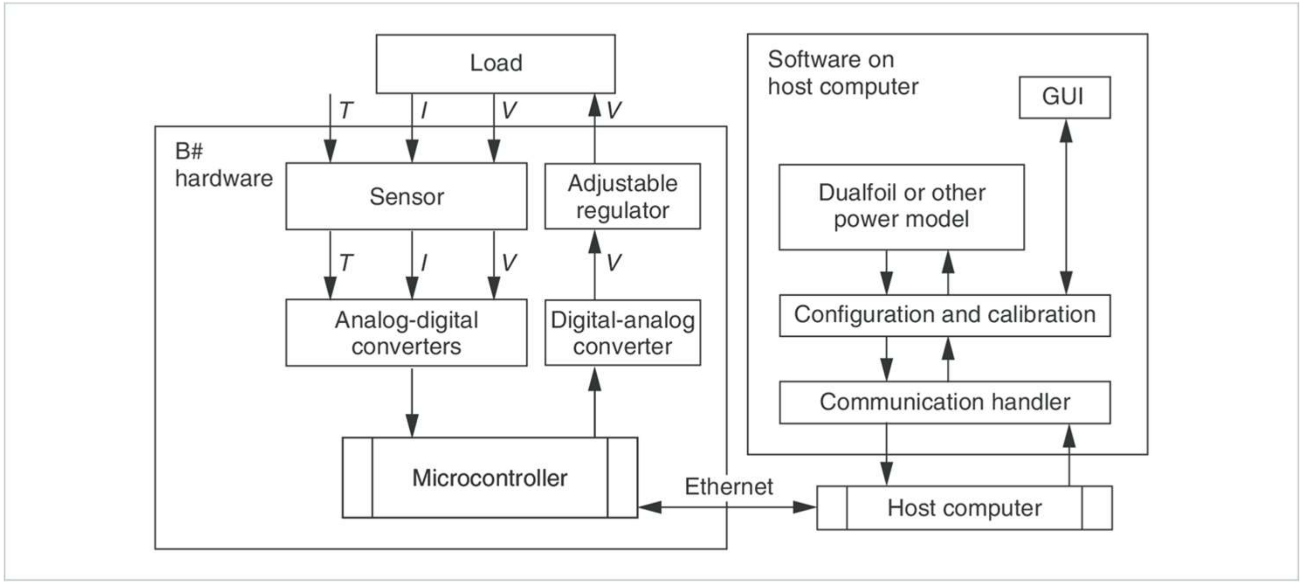
Battery Emulation 2

- 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 $R_{i.}$



Source: [Park 2005]

B# System Block Diagram

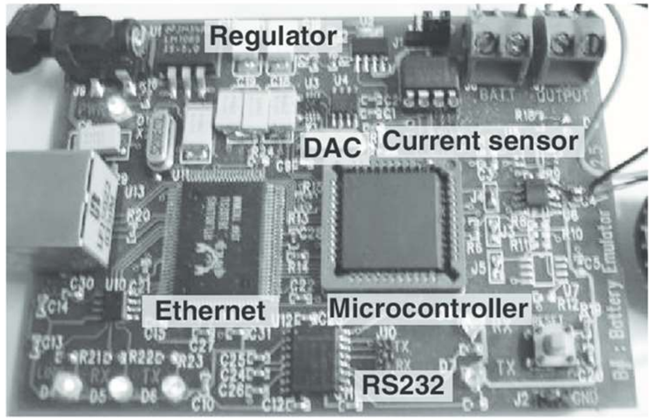


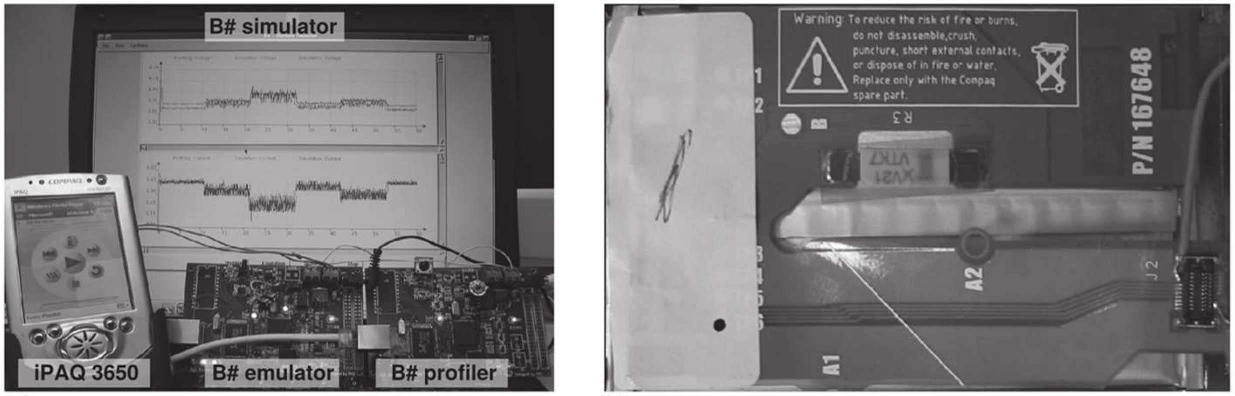
Basic idea: combine speed and accuracy of a measurement-based approach with flexibility and reproducibility of simulation-based approach

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.)

Source: [Park 2005]

B# Hardware





(a) (b)

Source: [Park 2005]

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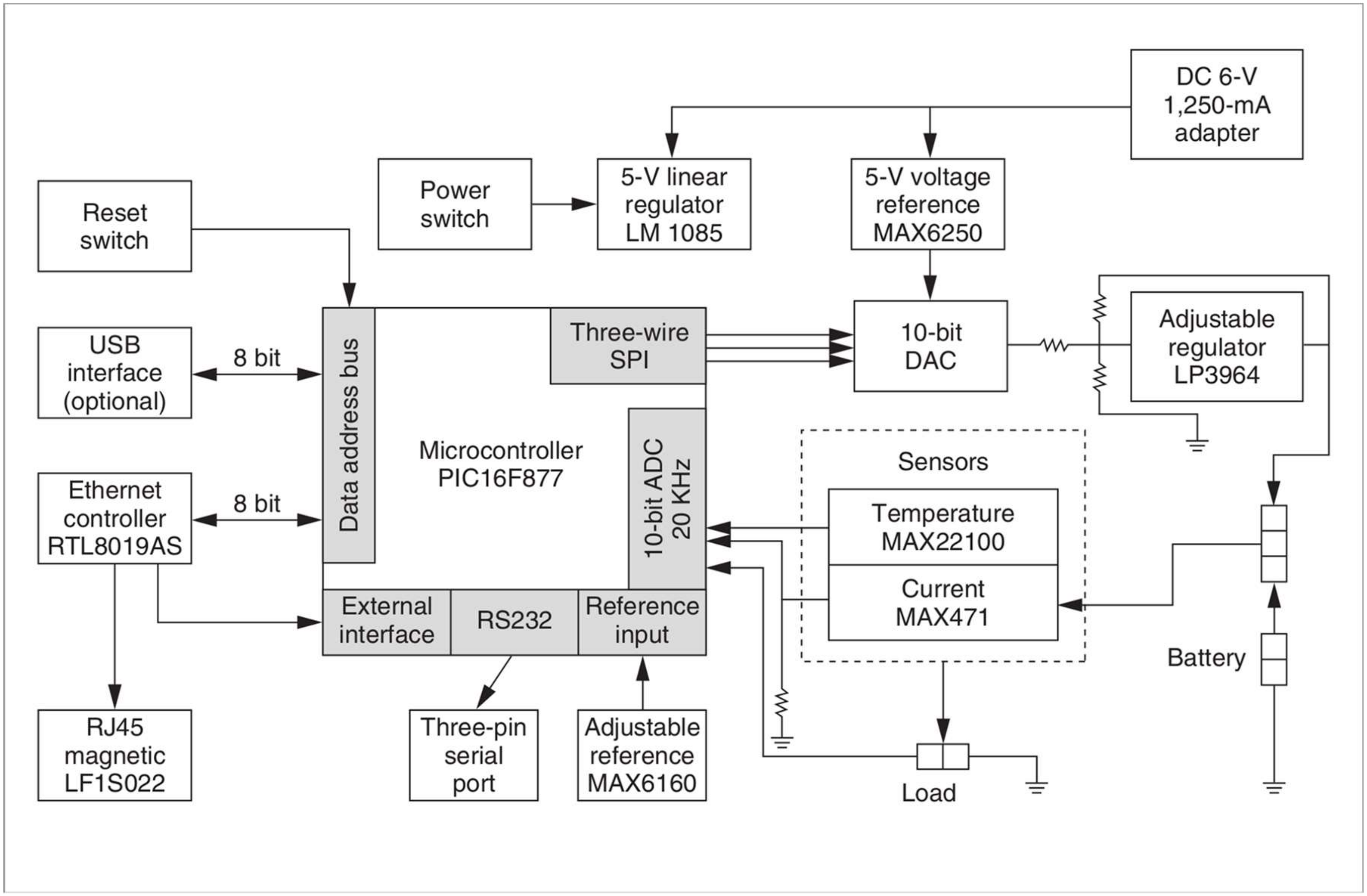


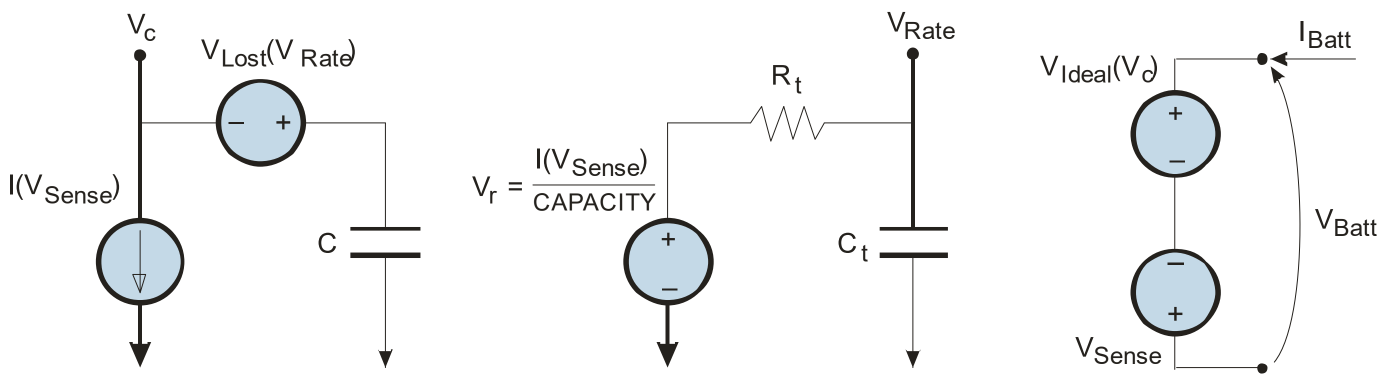
Source: [Park 2005]

Discrete-Time Battery Models

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

Source: [Benini01]

First Order Continuous-Time Battery Model



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.

Source: [Benini01]

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;
```

Source: [Benini01]

Applications for Battery Modeling

- Battery-aware scheduling (next lecture).
- Battery-aware power supply design.
- Load-profile shaping for multi-battery systems.
  - Sequentially discharging each battery until empty.
  - Static switching: discharge each battery for a fixed duration in round-robin schedule (allows batteries to recover).
  - Dynamic switching of batteries: schedule healthies 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.)

Source: [Benini01]

Summary of 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 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

Source: [Benini01]

Source

- Homework >> Rao, Ravishankar, Sarma Vrudhula, and Daler N. Rakhmatov. "Battery modeling for energy aware system design." *Computer* 36.12 (2003): 77-87.
- Park, Chulsung, Jinfeng Liu, and Pai H. Chou. "B#: A battery emulator and power-profiling instrument." *IEEE design & test of computers* 22.2 (2005): 150-159.
- Benini, Luca, et al. "Discrete-time battery models for system-level low-power design." *IEEE Transactions on Very Large Scale Integration (VLSI) Systems* 9.5 (2001): 630-640.