How do the dynamics of battery discharge affects sensor lifetime?

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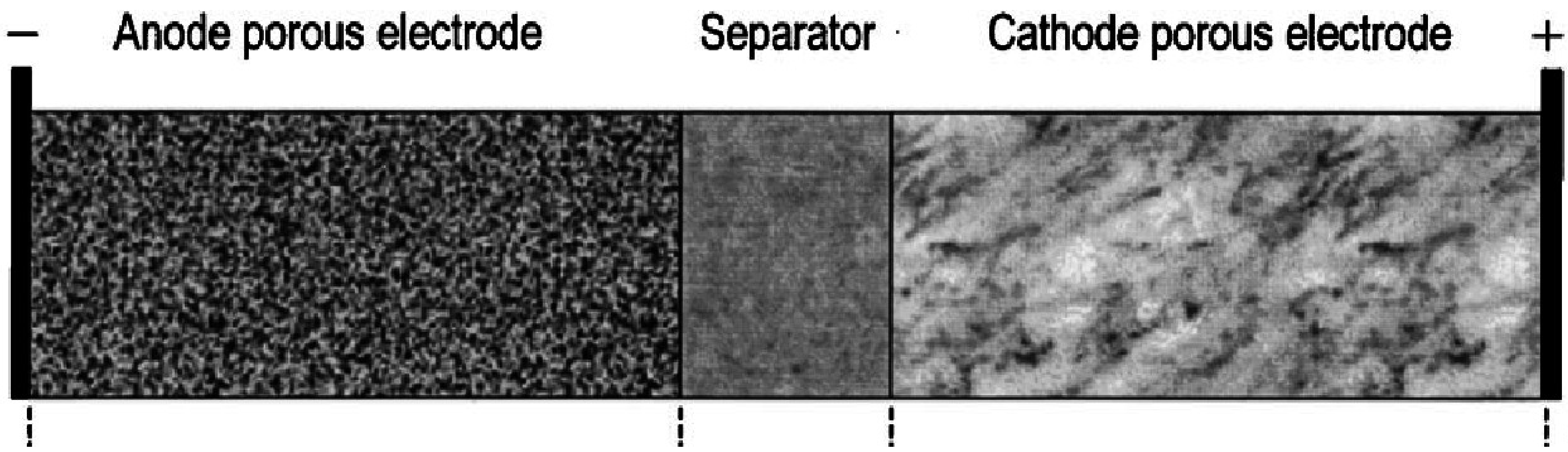
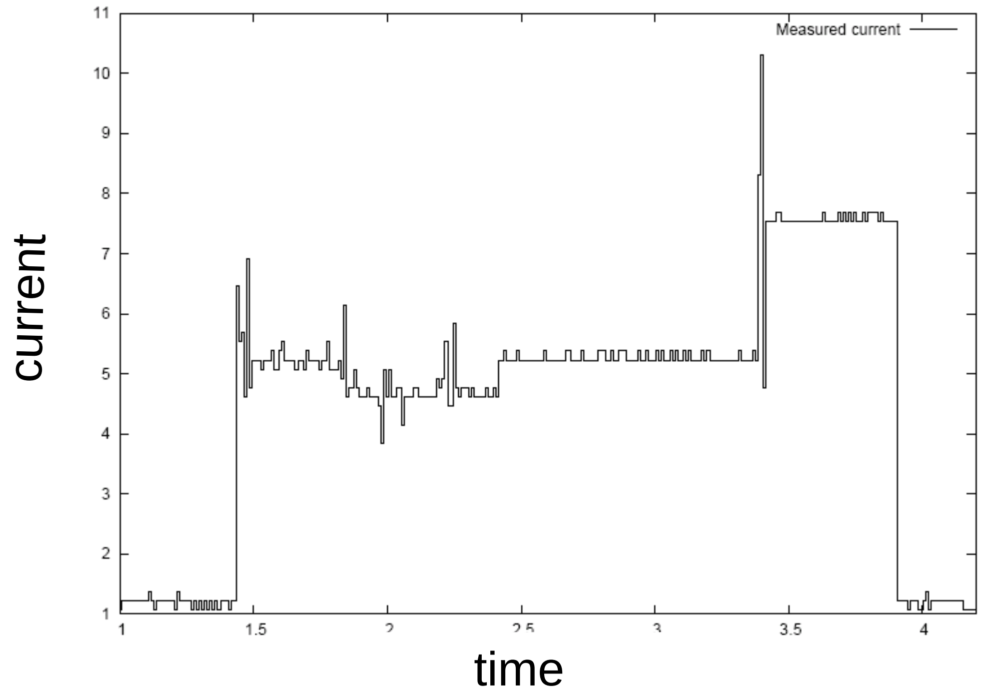
Battery discharge behavior



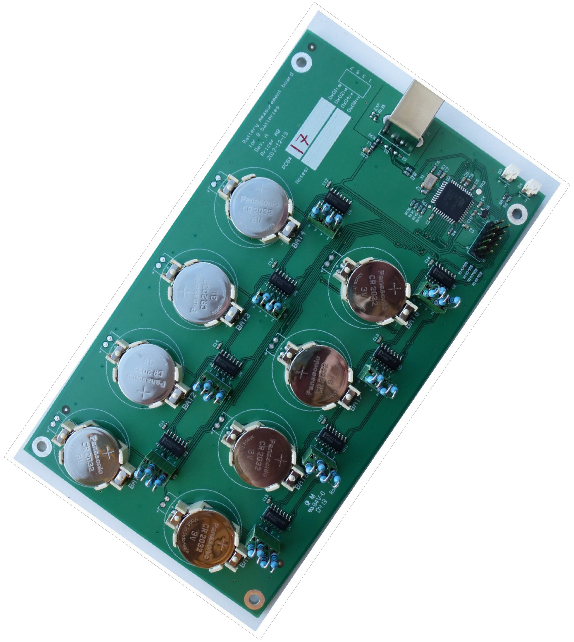
- complex electro-chemical system
- modeled as a simple “bucket of mA-h”
- contribution: characterize discharge behavior
  - protocol design and evaluation; state of charge estimation

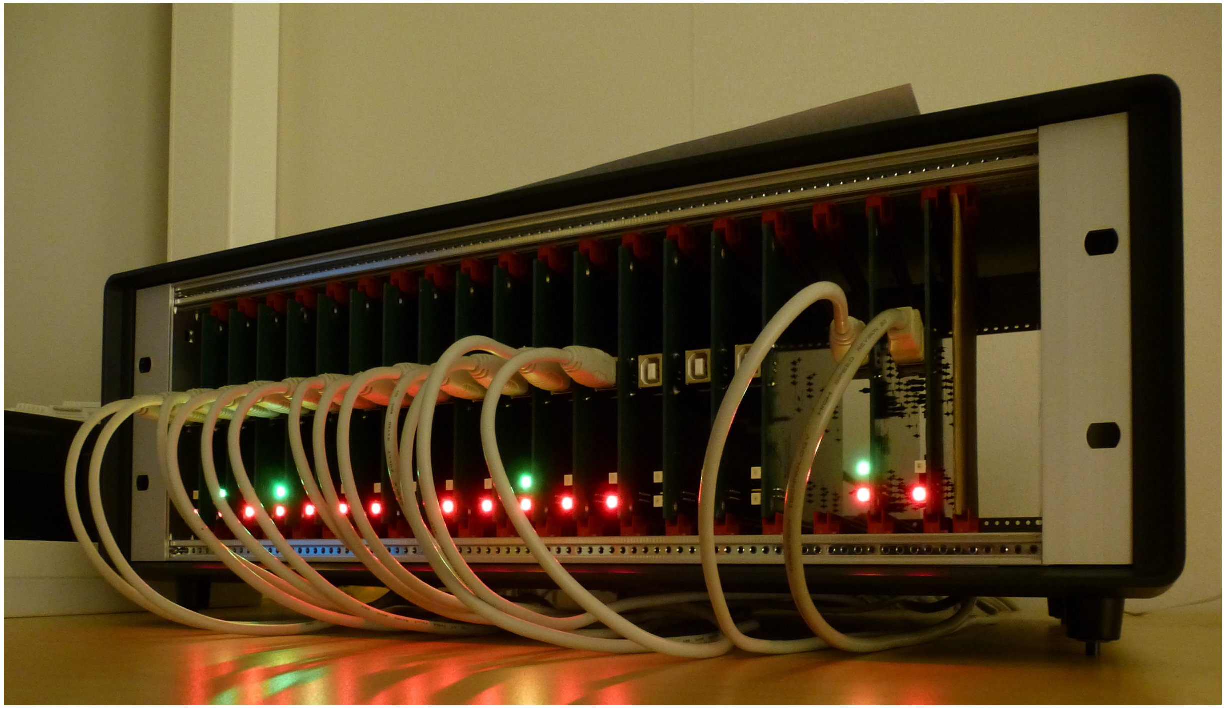
Wireless sensor networks



- WSN power consumption profile is complex
- quantify key macroscopic behaviors
  - synthetic loads, systematically defined load patterns
  - intensity and duration parameters based on typical WSN

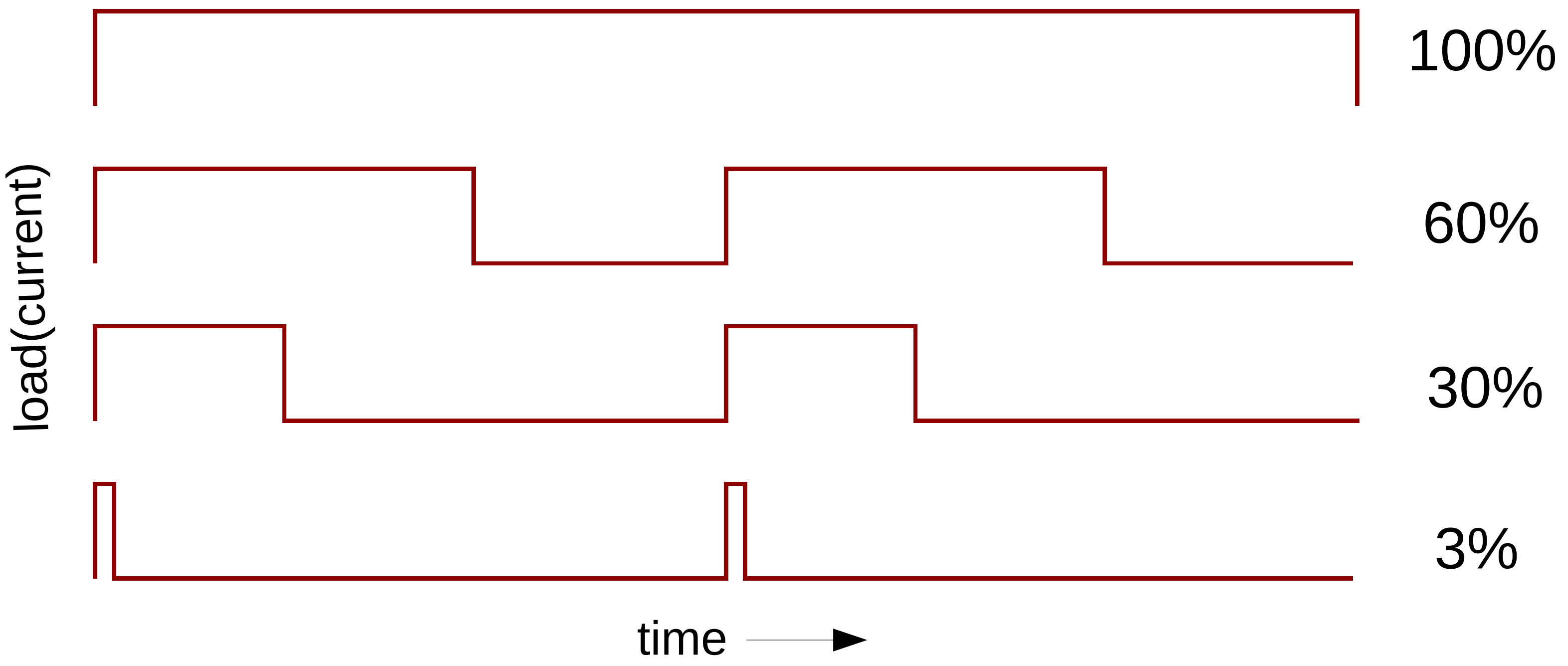
Testbed





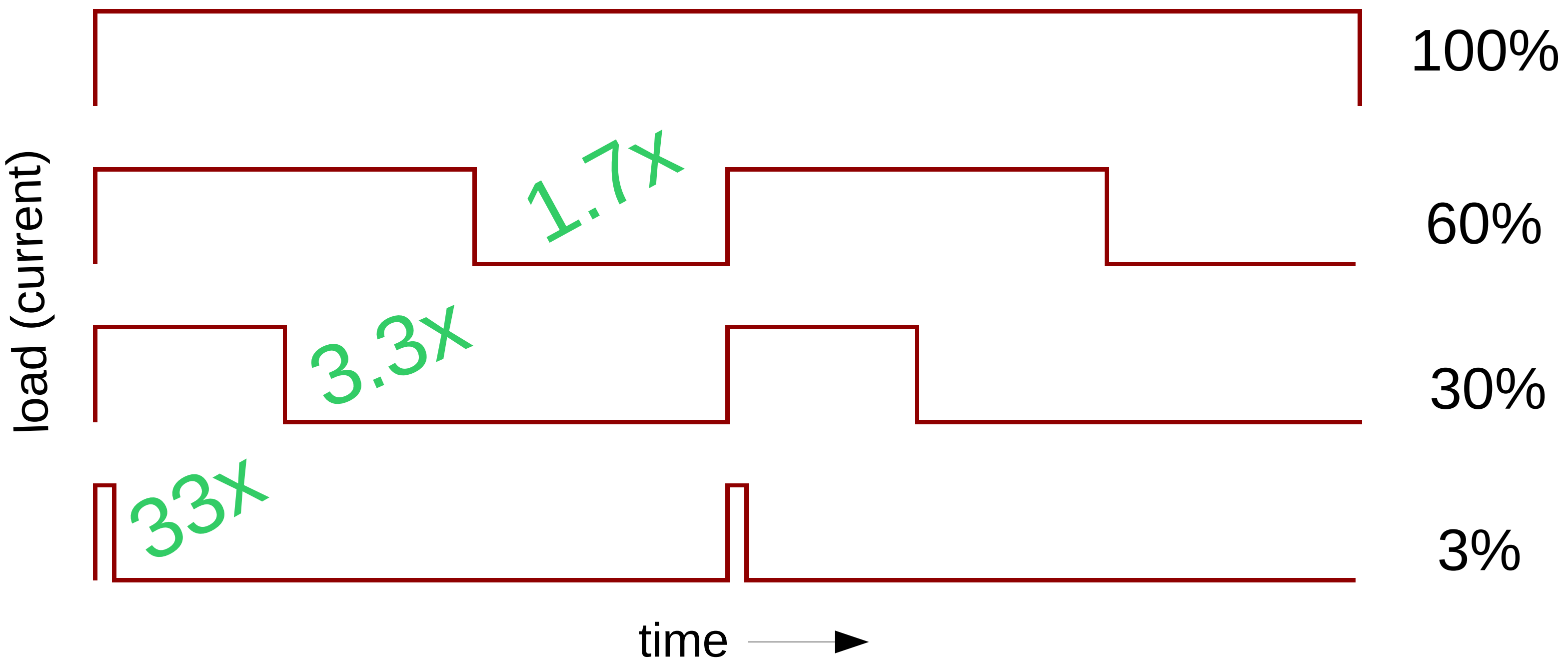
- apply load and measure battery output voltage
- Li coin cell (CR2032)
  - personal/body area networks, wildlife

Duty cycle



- lifetime estimation
  - based on lifetime at 100% duty cycle

Duty cycle



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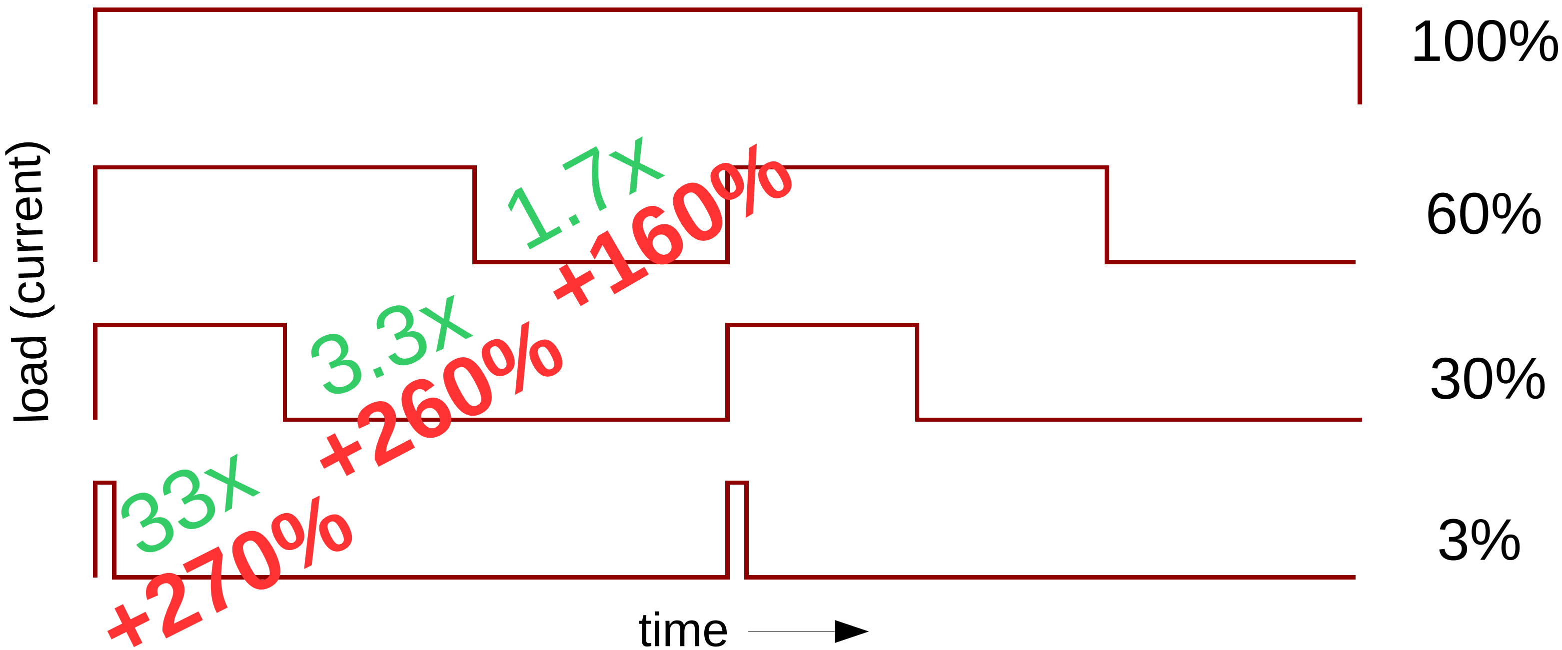
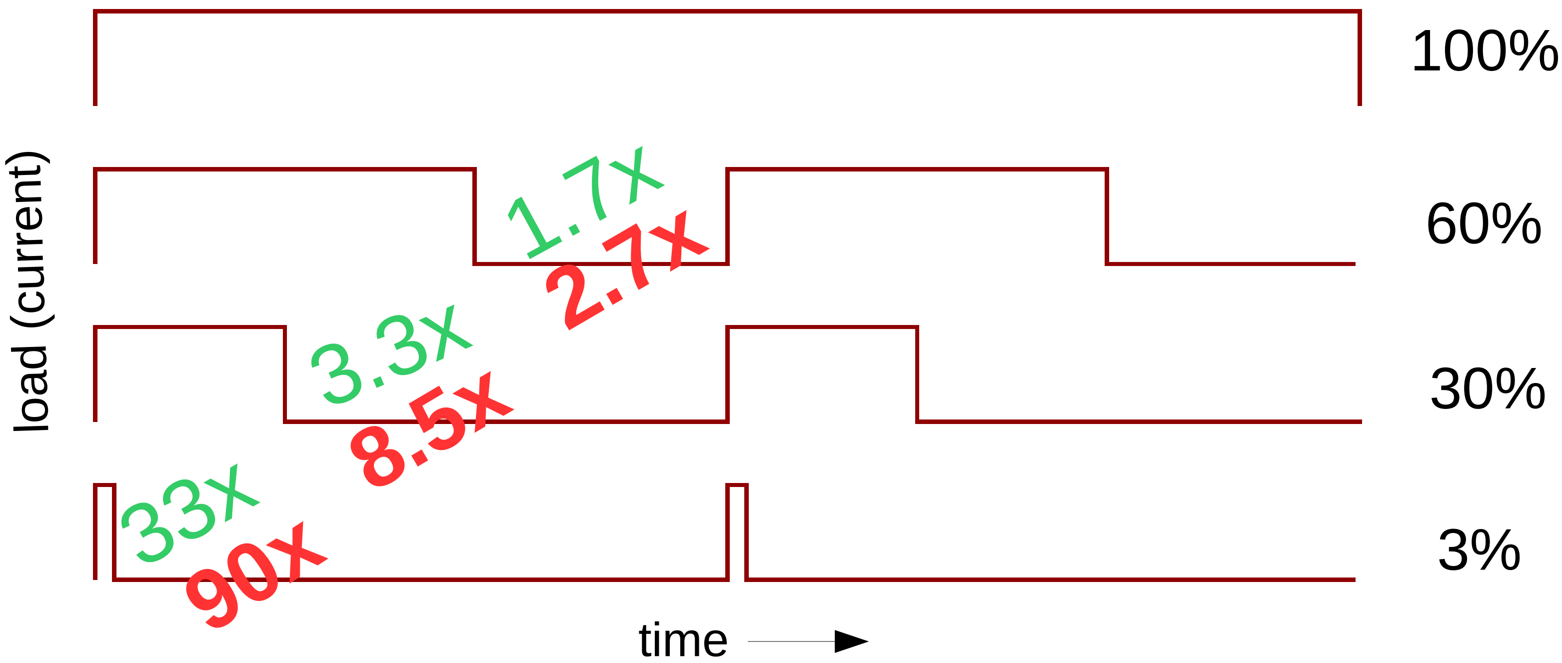
Lifetime estimation



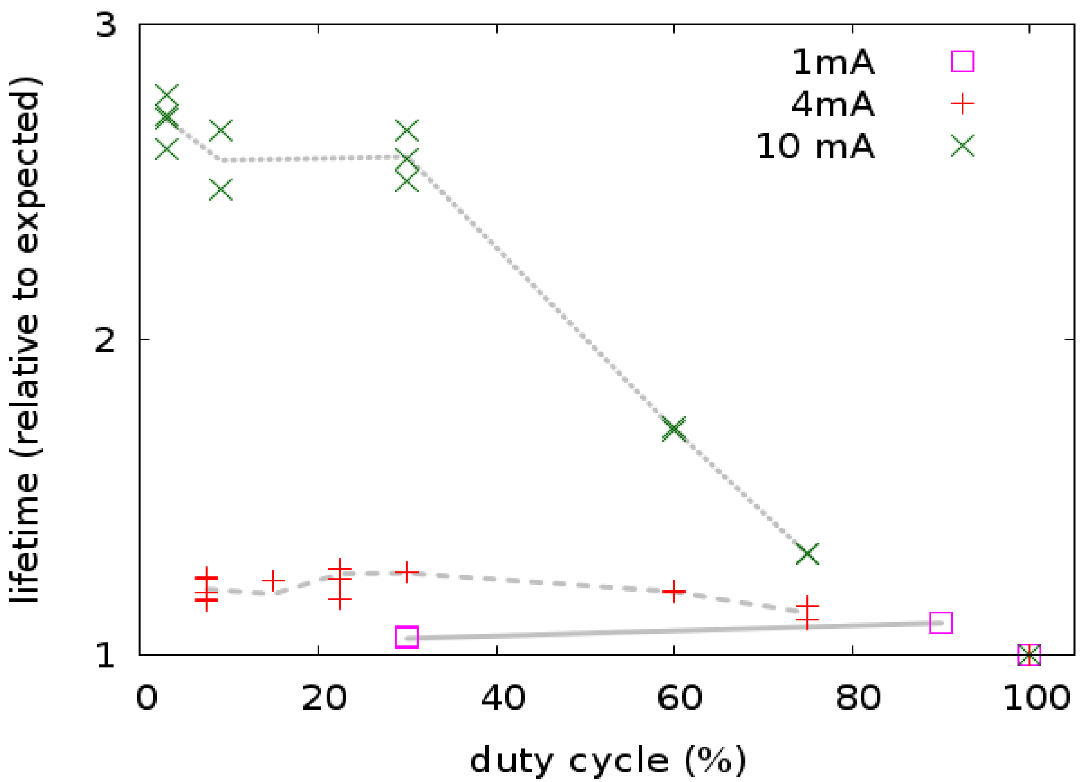
- for a 10 mA load
  - under-estimates observed lifetime by as much as a ***factor of 3*!**

Lifetime estimation



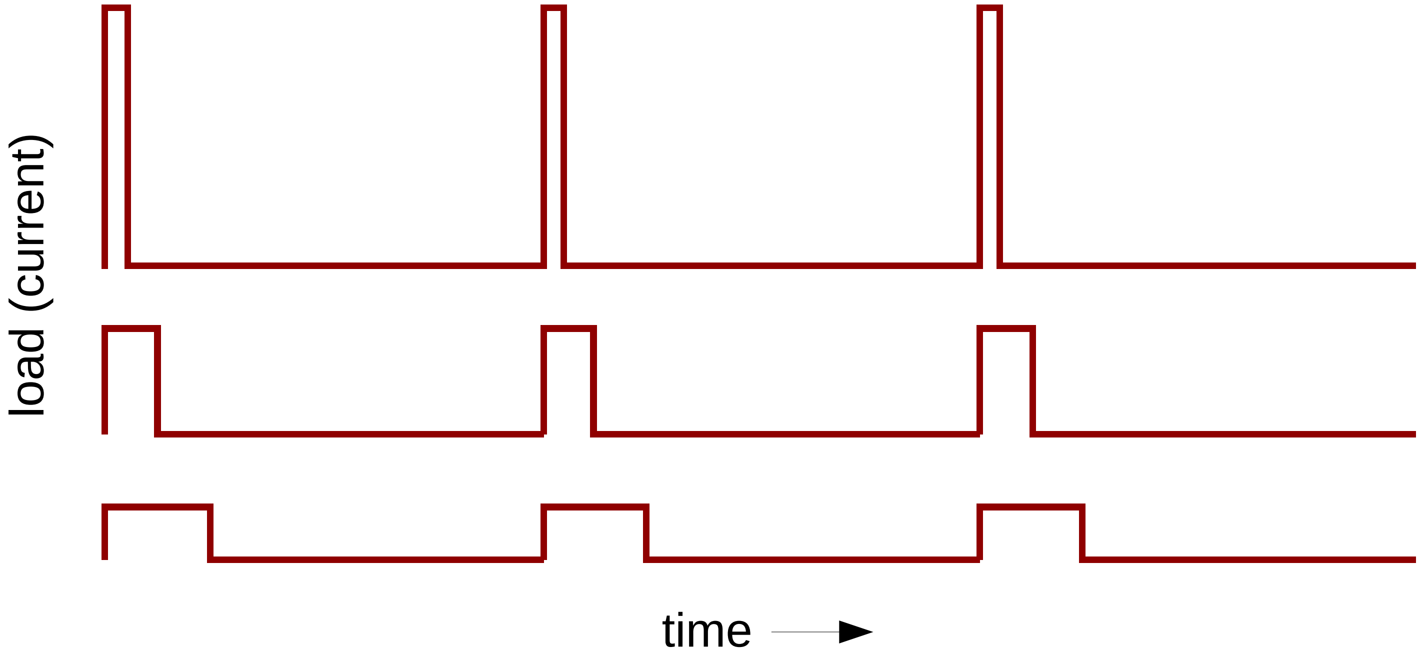
- for a 10 mA load
  - under-estimates observed lifetime by as much as a ***factor of 3*!**
- for a 4 mA load
  - only slight under-estimate (~10-15%)

Why?



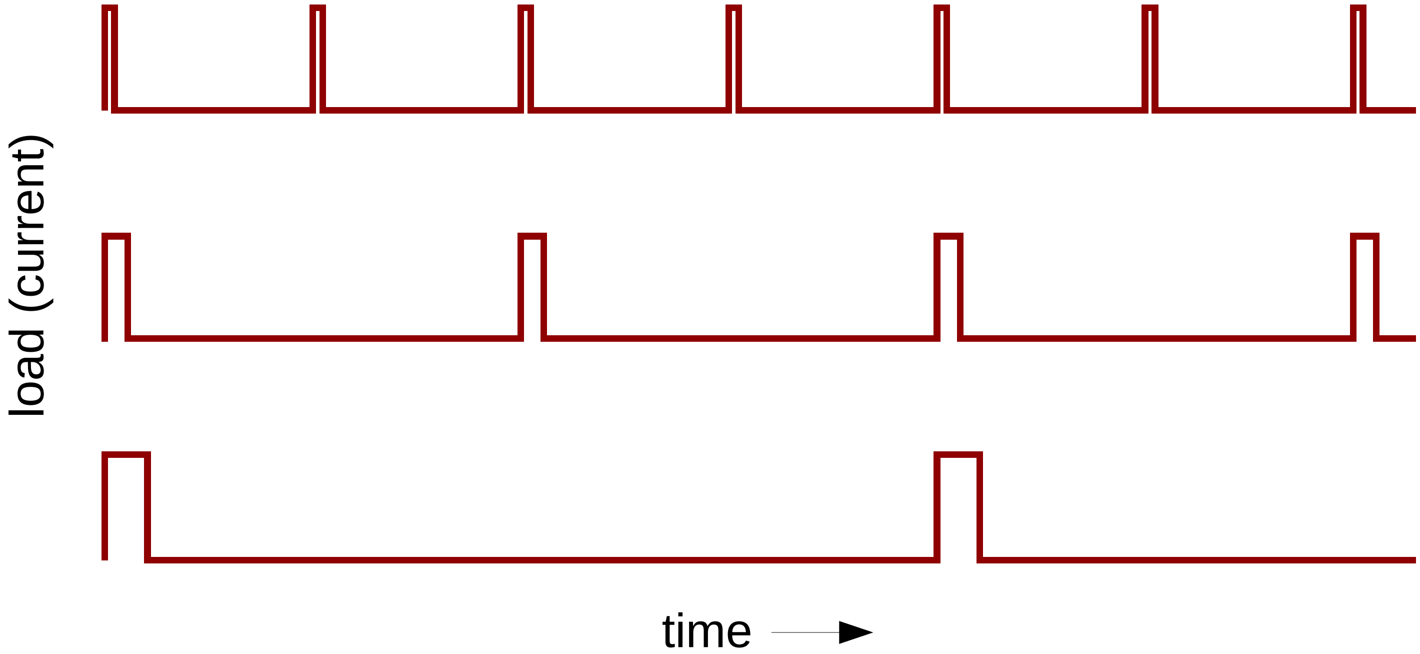
- charge recovery
  - intermittent load utilizes more capacity than continuous load
- rate dependent capacity
  - low current utilizes more capacity than a higher one

Load Intensity



- model consumed capacity = $\sum i \times t$ or $\int i(t)\,dt$
- compare load patterns with *same* time-average current

Load Timing



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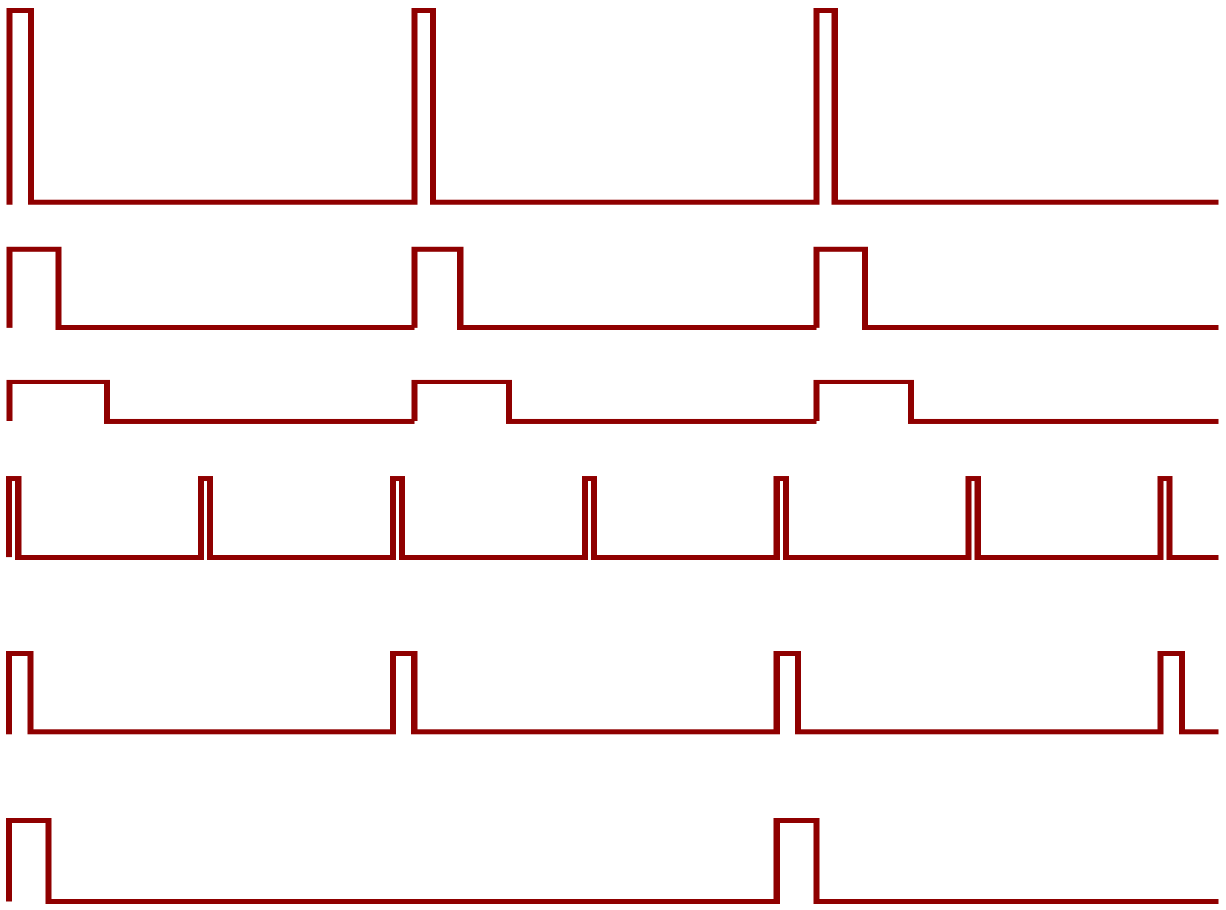
Consumed capacity



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- expect them to consume same total capacity

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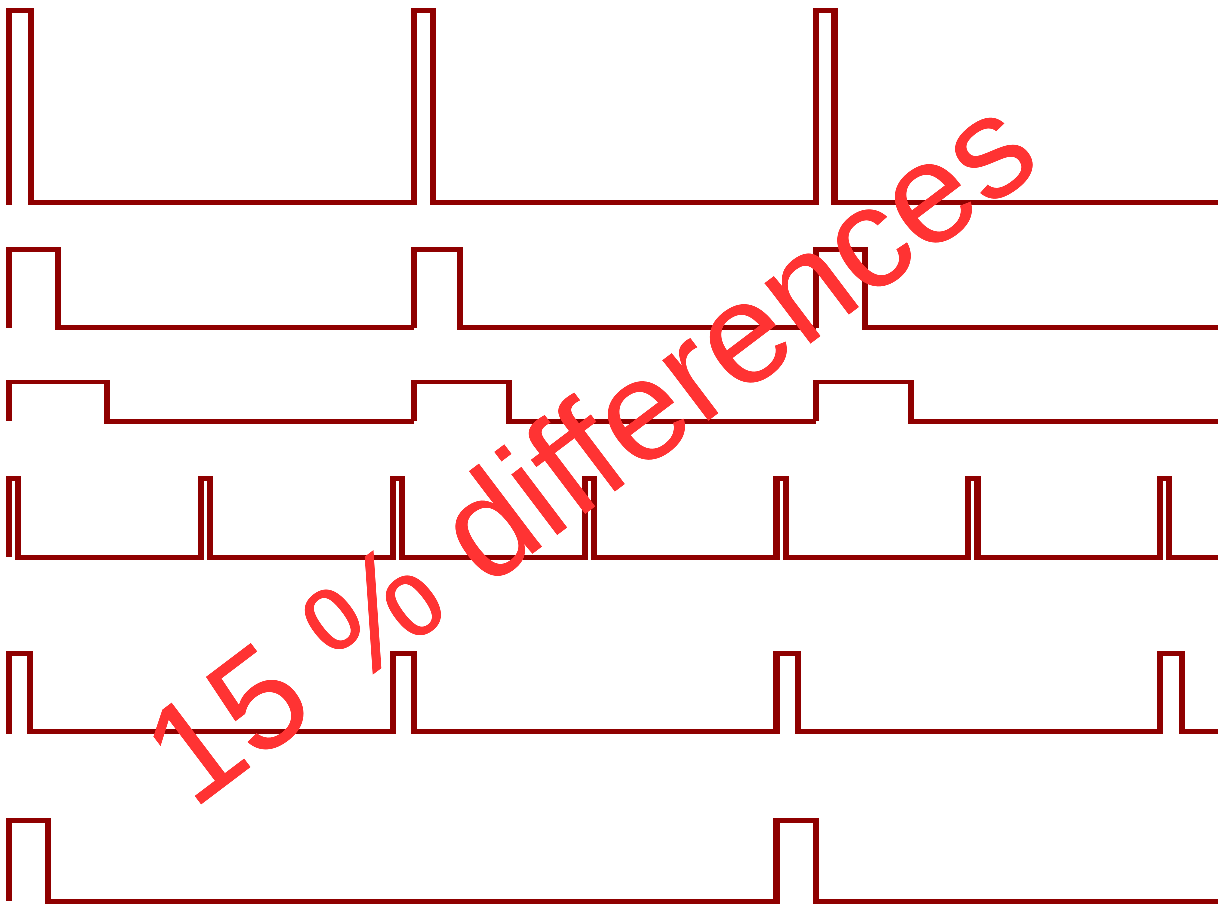

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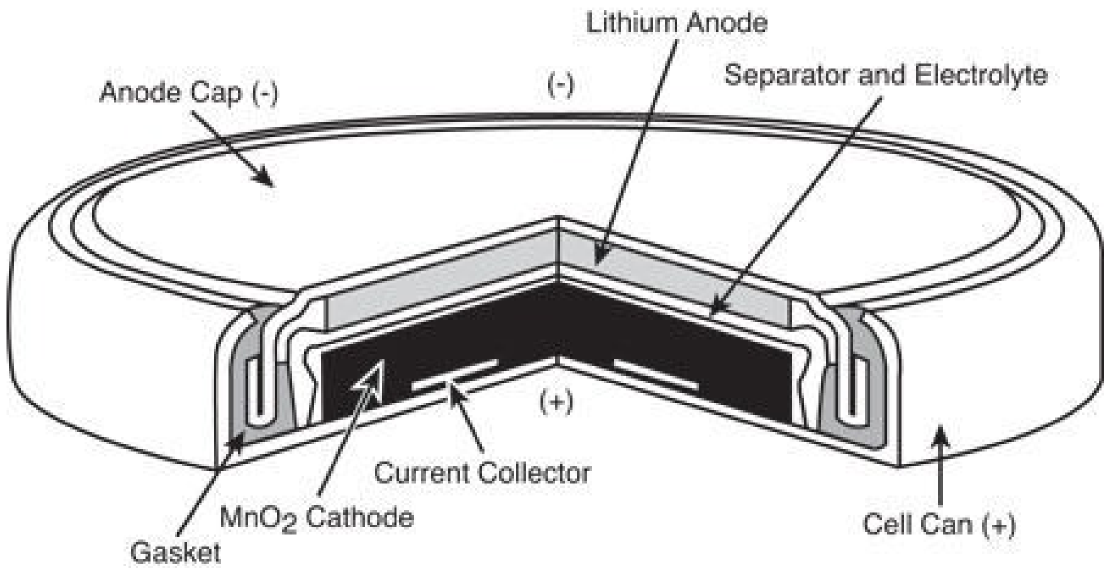
What is a battery? It's complicated.



- primary (non-rechargeable) Li-coin cell
  - Li anode oxidized: $Li \rightarrow Li^{+} + e^{-}$
  - $Mn0_2$ cathode reduced: $Mn0_2 + Li^{+} + e^{-} \rightarrow LiMn^{(III)}0_2$
- discharge behavior depends on chemistry and structure
  - even manufacturer specific

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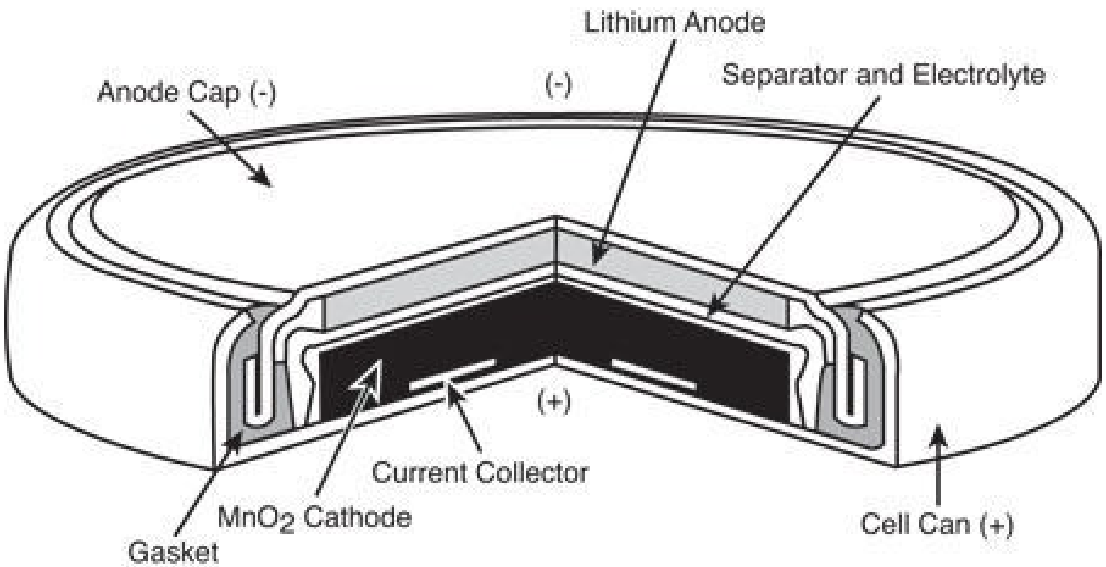

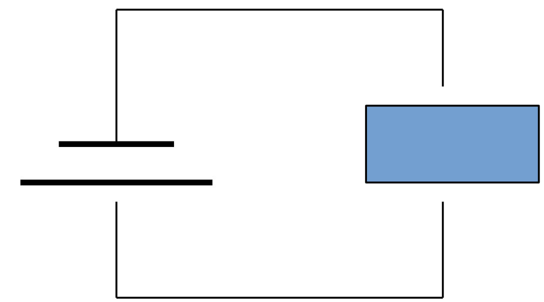

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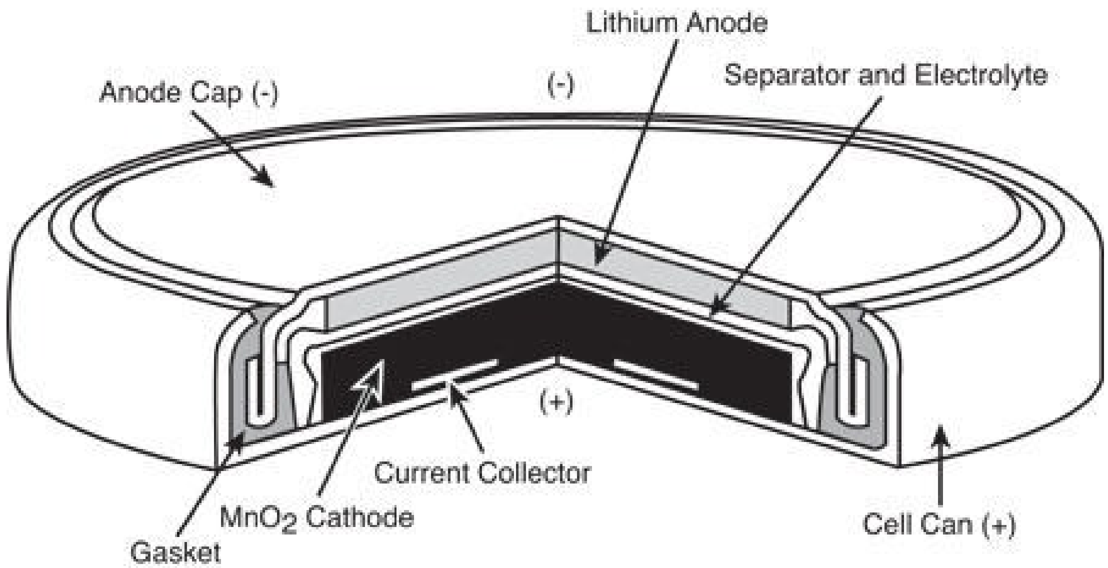

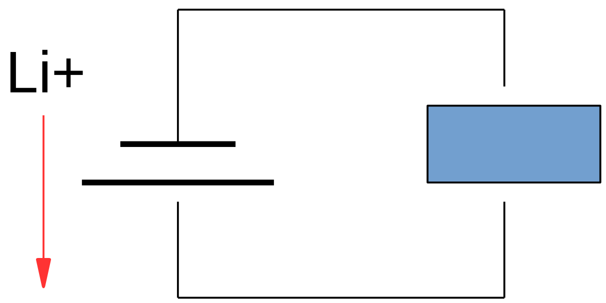

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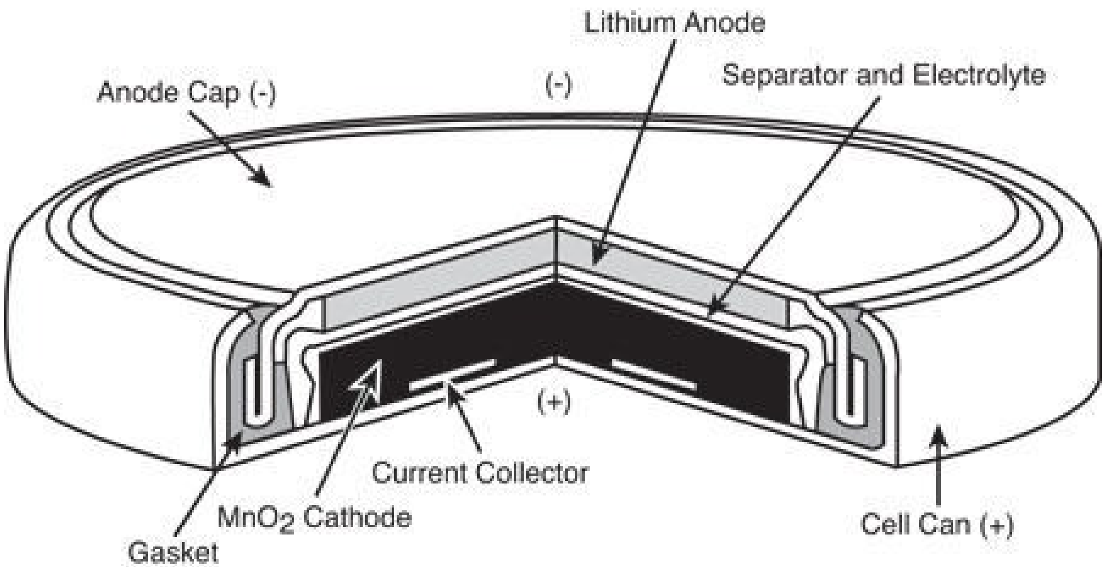

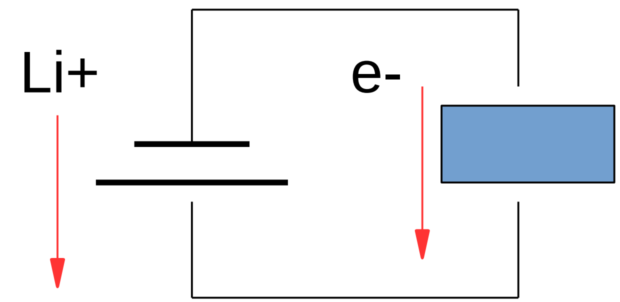

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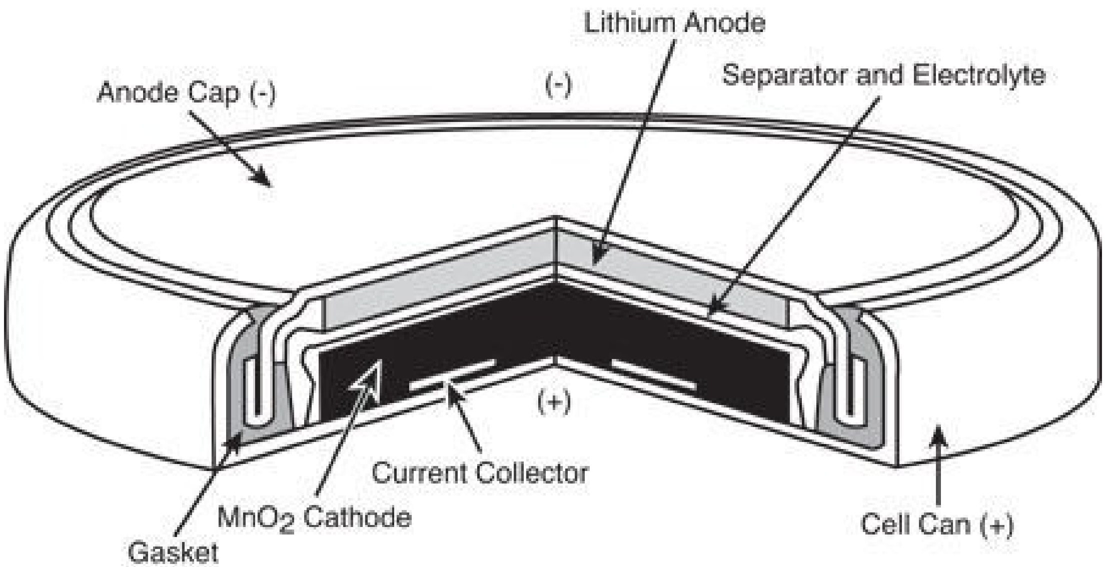

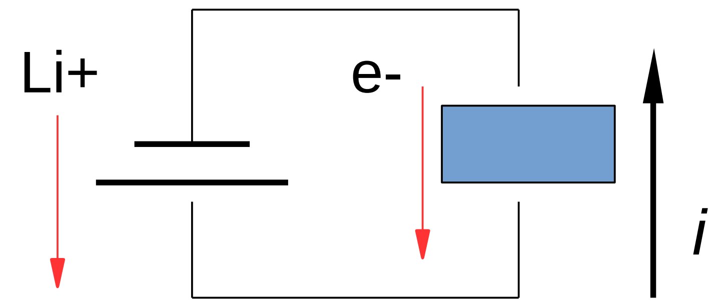

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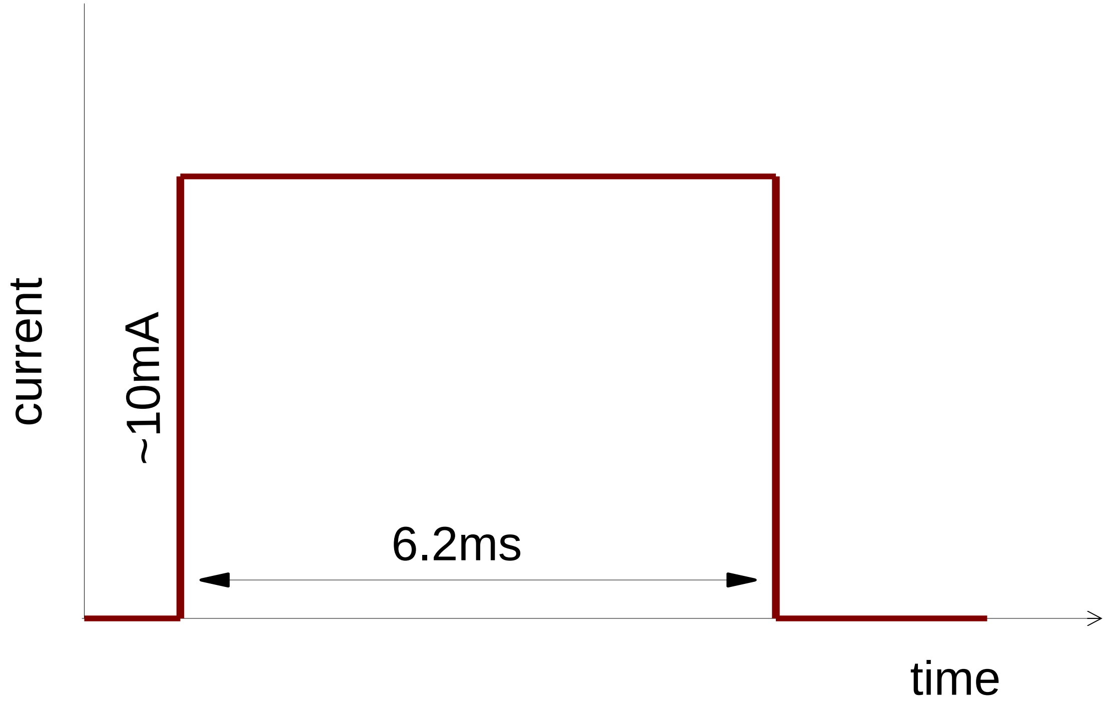
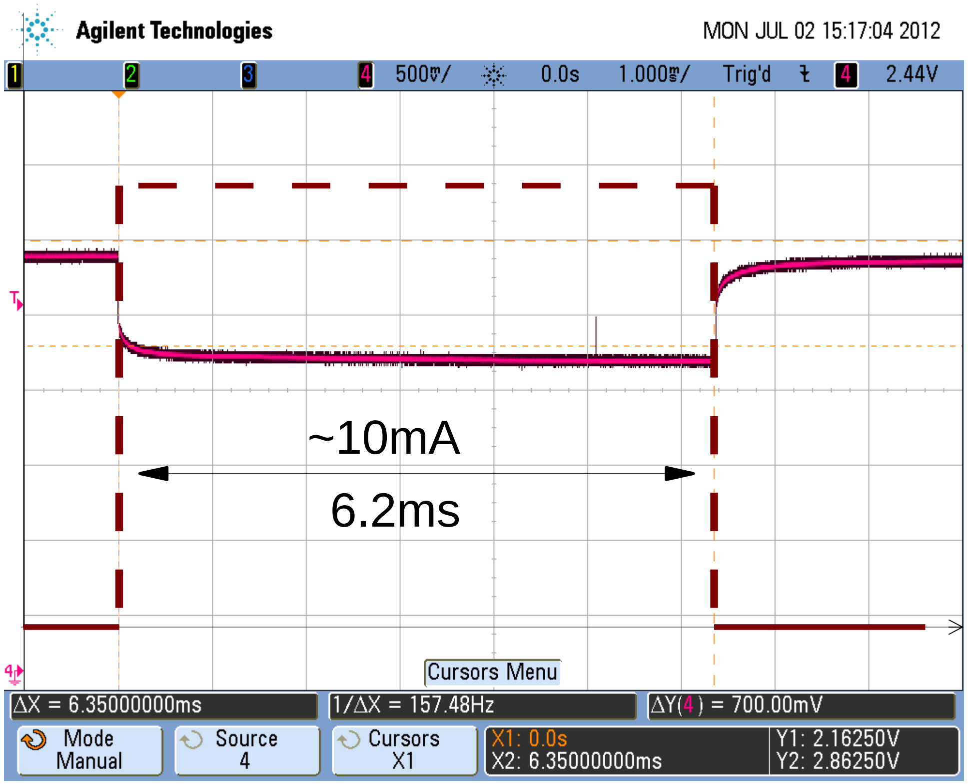
Output voltage under load



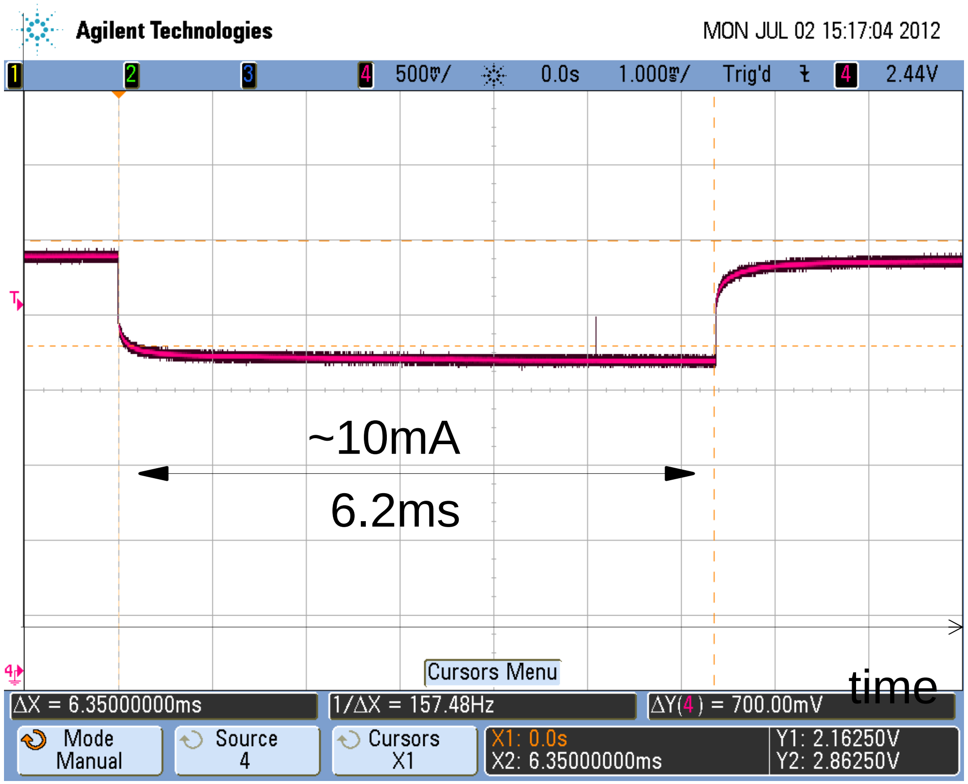
- apply a load to a battery
- e.g. lower bit-rate, sub-GHz transceiver

Output voltage under load



- battery output voltage drops
  - internal resistance
  - efficiency of electro-chemical reactions

Output voltage under load



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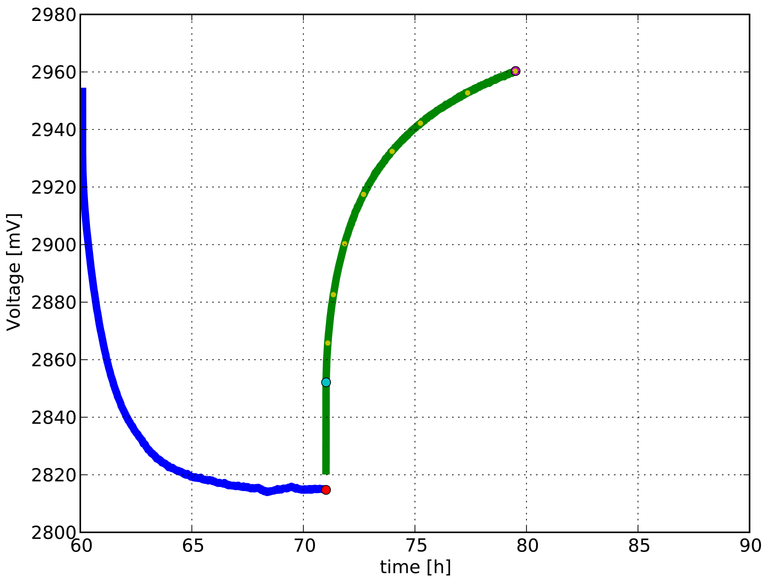
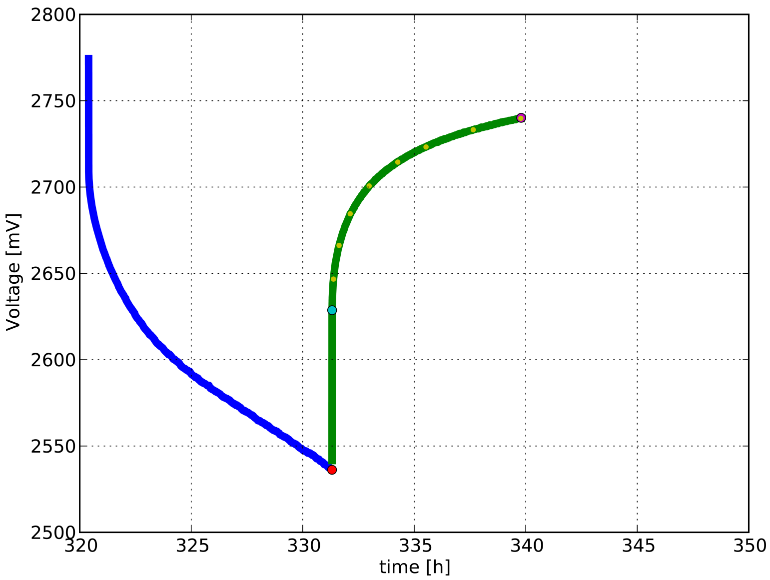
Battery output voltage under load



85% soc

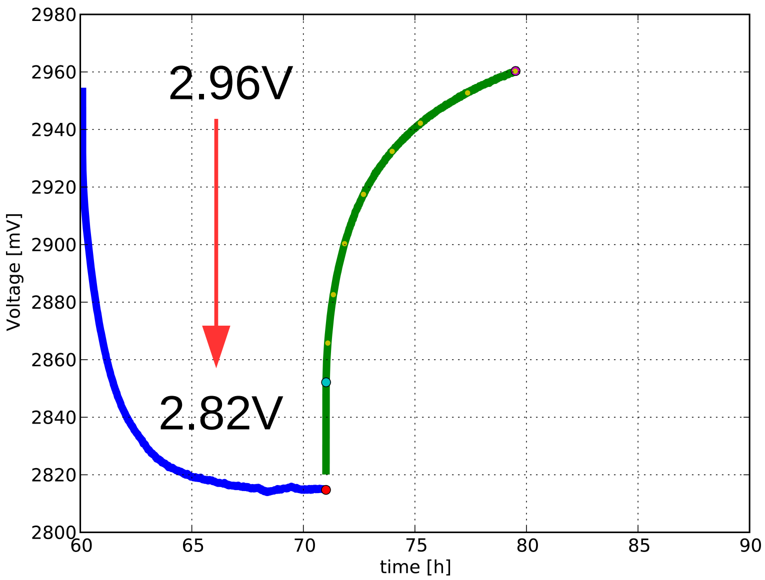


20% soc

1mA load, 11h

- load response also depends on state-of-charge

Battery output voltage under load



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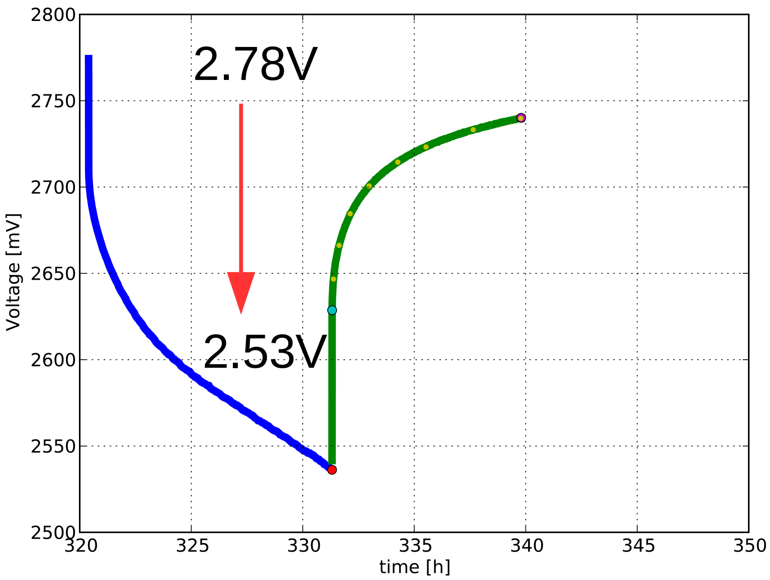

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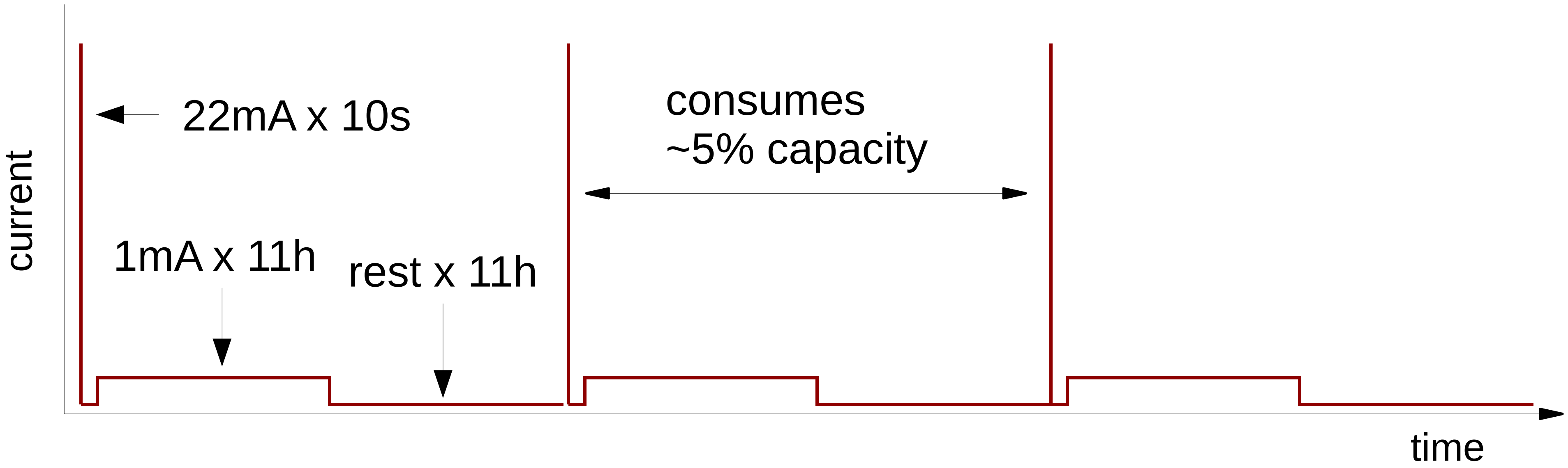
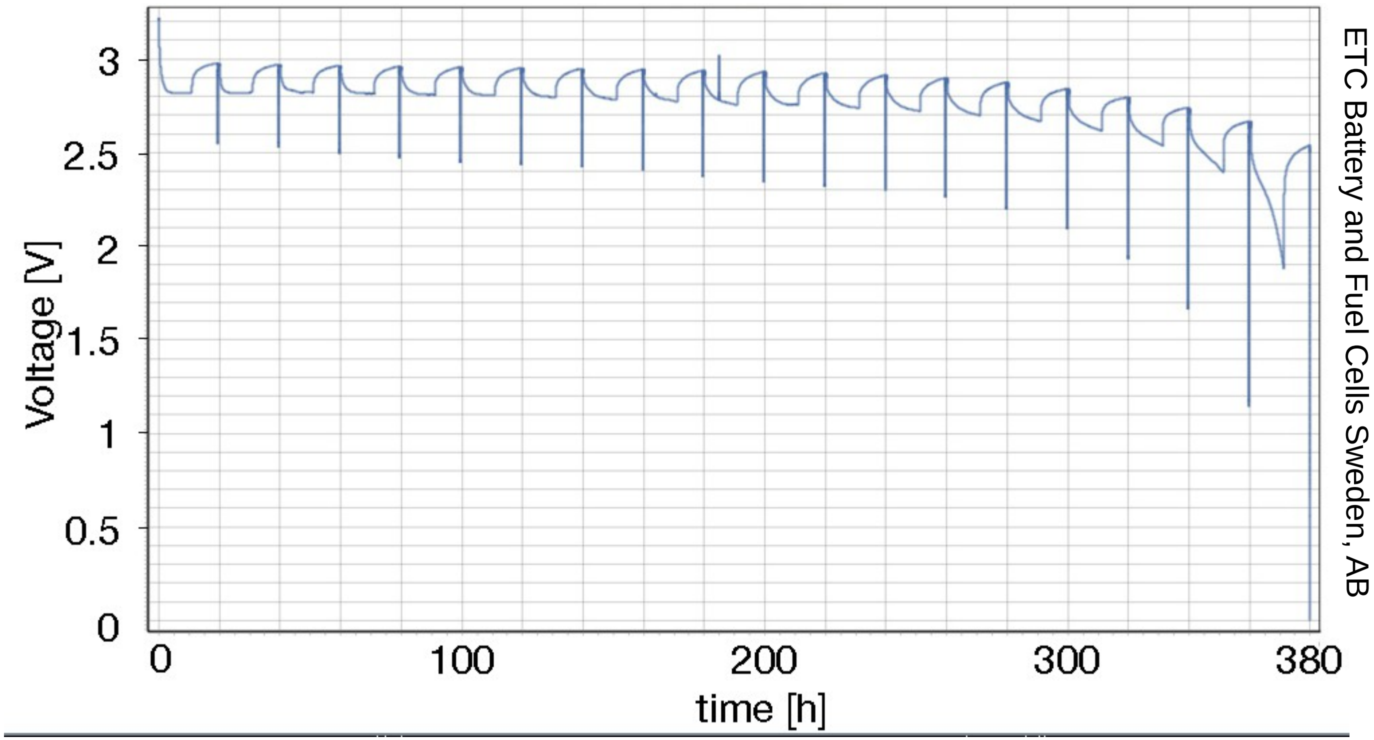
Load



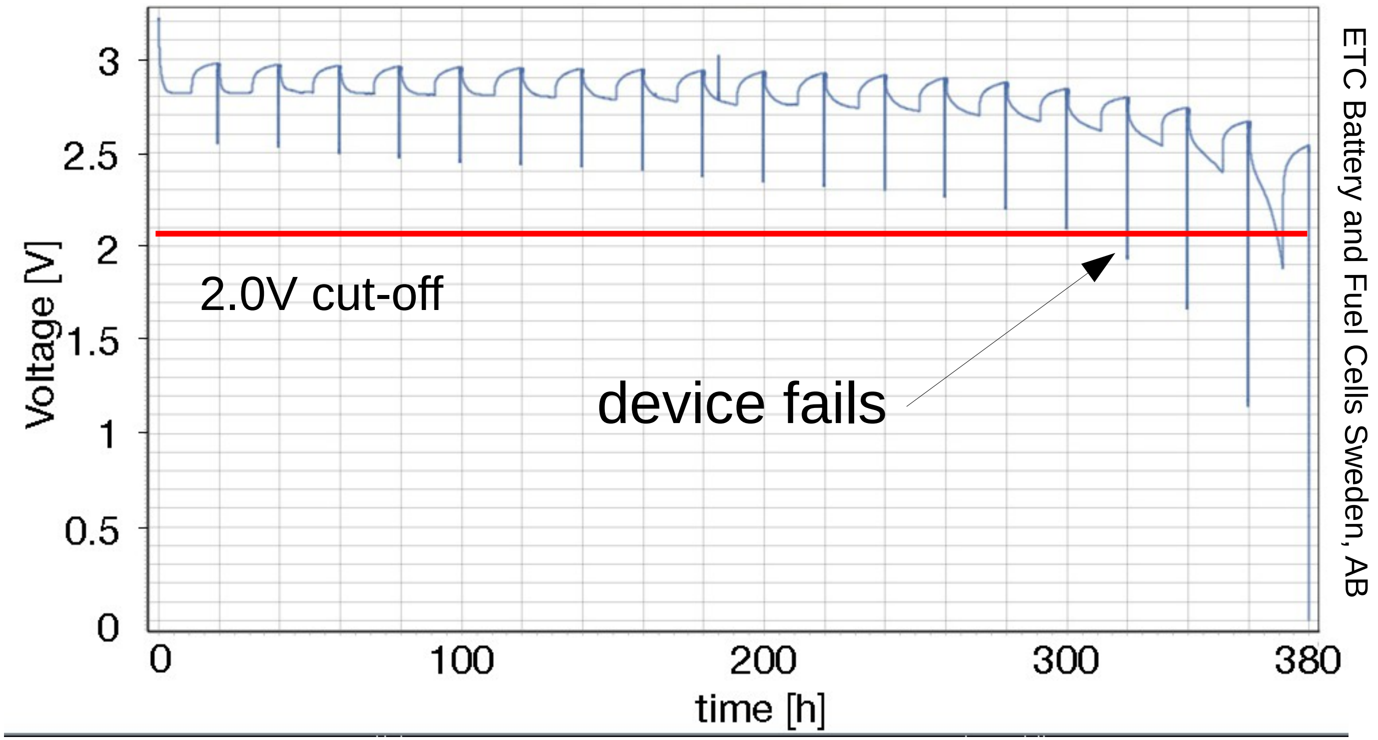
- alternate short intense loads and low current loads
- drain ~5% capacity each period
  - based on standard battery test sequence

Device lifetime



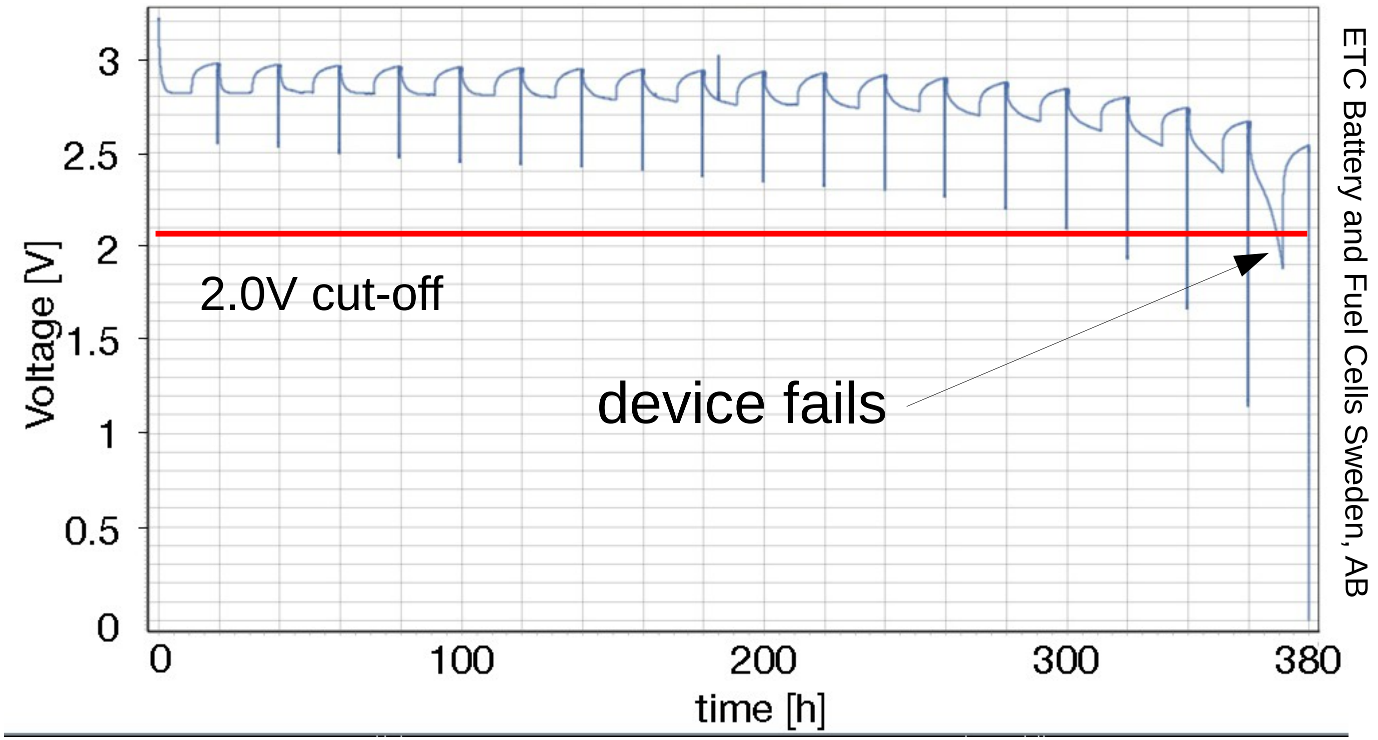
- rate dependent capacity
- charge recovery
- state of charge dependence

Device lifetime



- device failure
  - battery cannot maintain output voltage under load
  - depends on cut-off voltage for device electronics
- ***not*** determined by the charge consumed

Device lifetime



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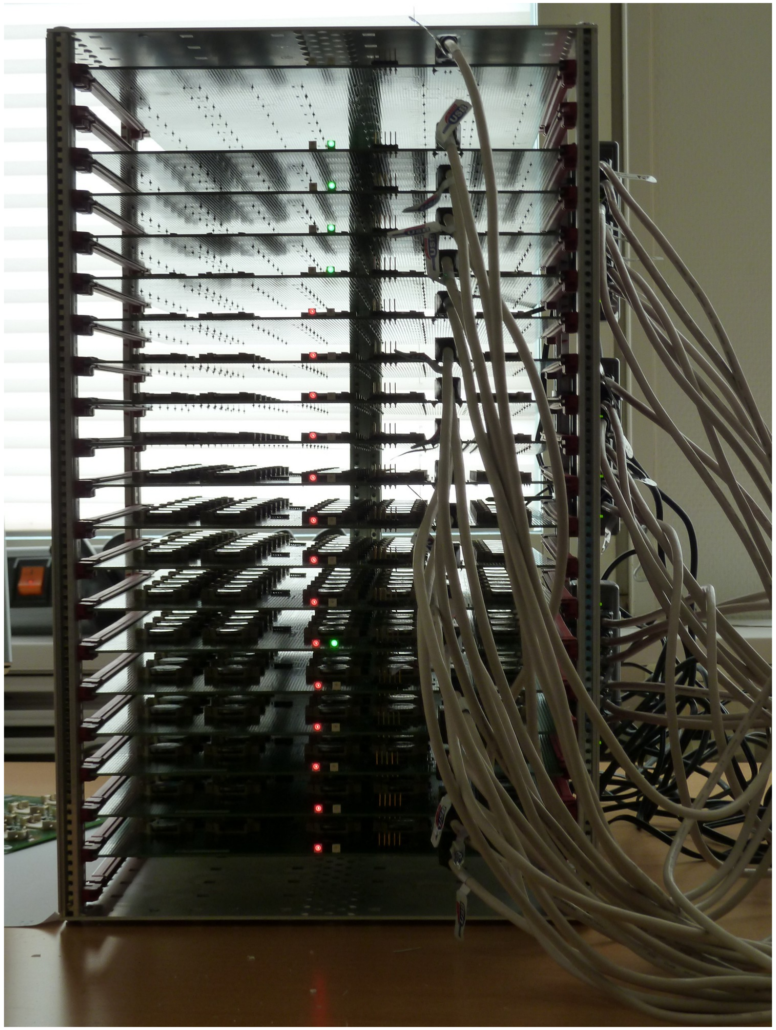
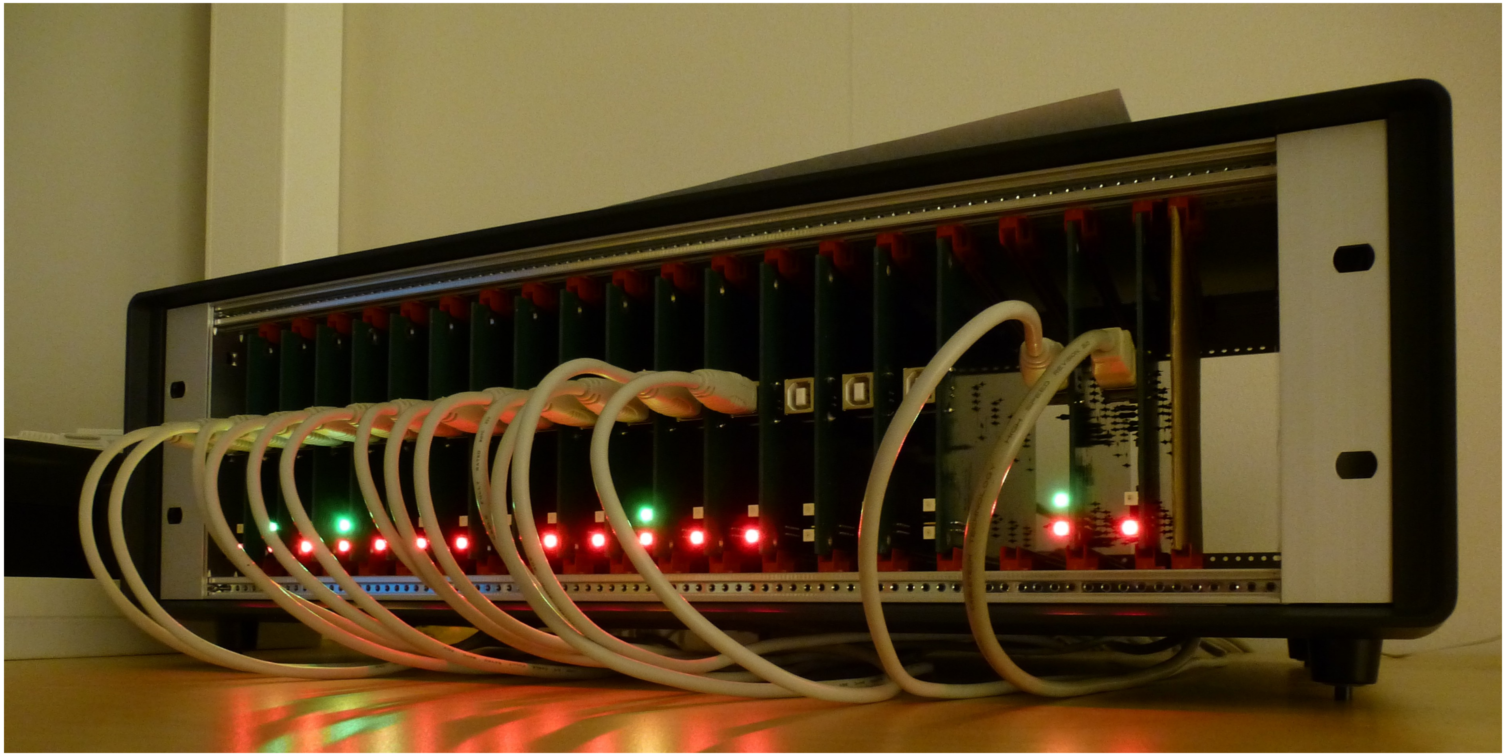
Testbed



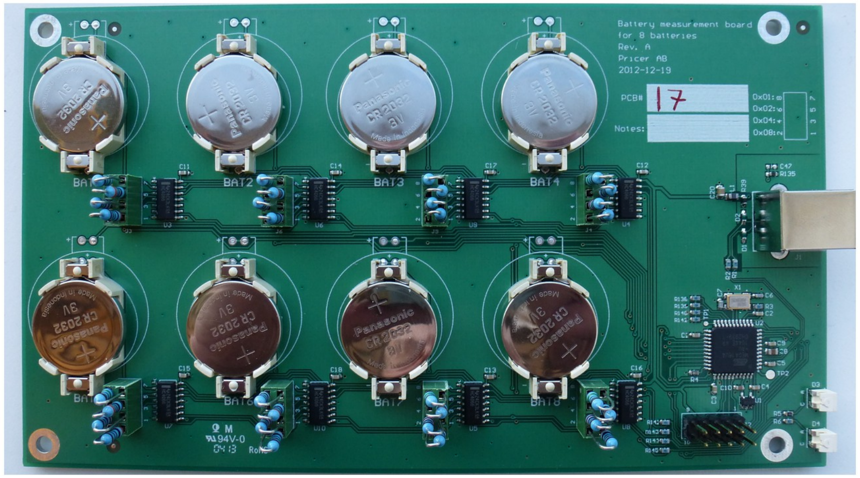
- macroscopic behaviors are well understood
  - rate-dependent capacity
  - charge recovery
  - soc dependence
  - temperature (future)

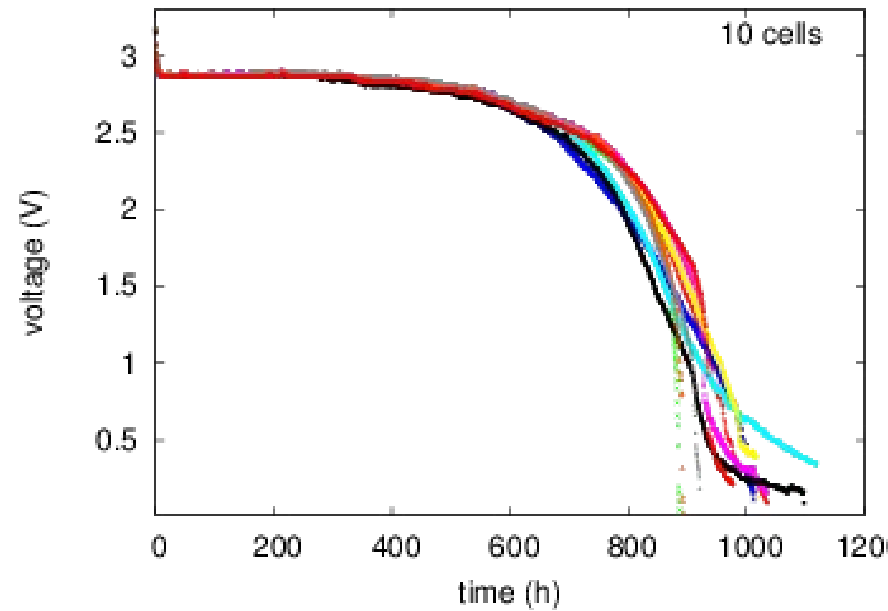
Testbed



- very little data for cheap, non-rechargeable batteries
  - Panasonic Li-coin cell (CR2032), ~225mA-h

Testbed





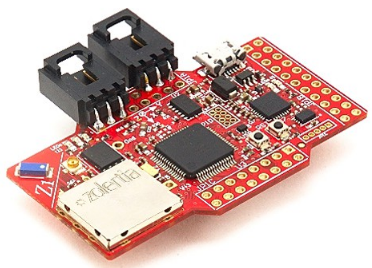
- large-scale measurement program – cost efficient
- simple, ***controlled*** resistive loads
  - sensor behavior is messy, simplified loads with realistic parameters
  - variation between batteries (cheap manufacture)

WSN-typical parameters

- **Experiments**
  - **1 - 25 mA**
  - **2 – 150 ms load**
  - **50 ms - 2.0s rest**
  - **300 µA mean**
  - **20-22ºC (ambient)**

WSN-typical parameters

- CC2420 (250kb/s)
  - tx: 17mA
  - rx: 18mA



- cpu (active)
  - 1.2-2.4mA (tmote-sky)
  - 4.3-5.7mA (cc2480)
- adc
  - 1.2mA

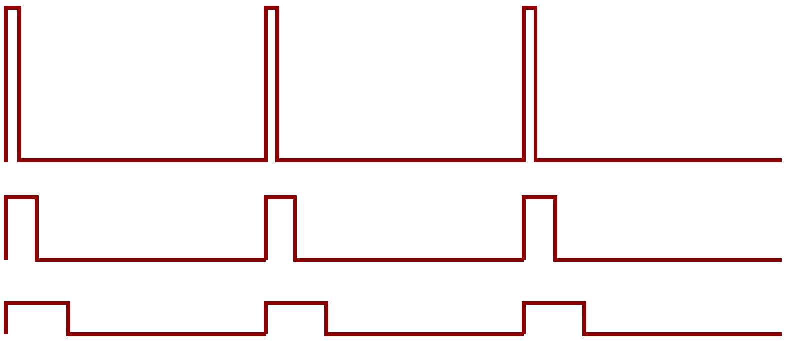
- **Experiments**
  - **1 - 25 mA**
  - **2 – 150 ms load**
  - **50 ms - 2.0s rest**
  - **300 µA mean**
  - **20-22C (ambient)**
- TR1001 (2-115kb/s)
  - tx: 12mA
  - rx: 1.3-3.8 mA
- SX1212 (25kb/s)
  - rx: 3mA
  - tx: 16mA

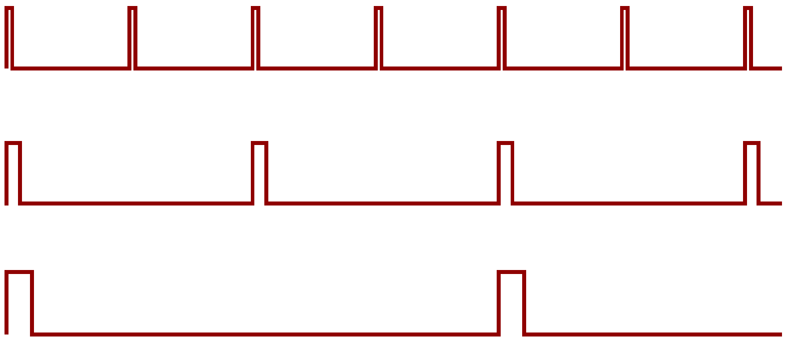
- contikiMAC
  - 125ms (2-16Hz)
- pTunes
  - 6/100ms
  - 11/350ms

q

- ANT+
  - search: 2.8mA
  - tx: 11-15mA
  - rx: 17mA
  - avg: 20-200µA

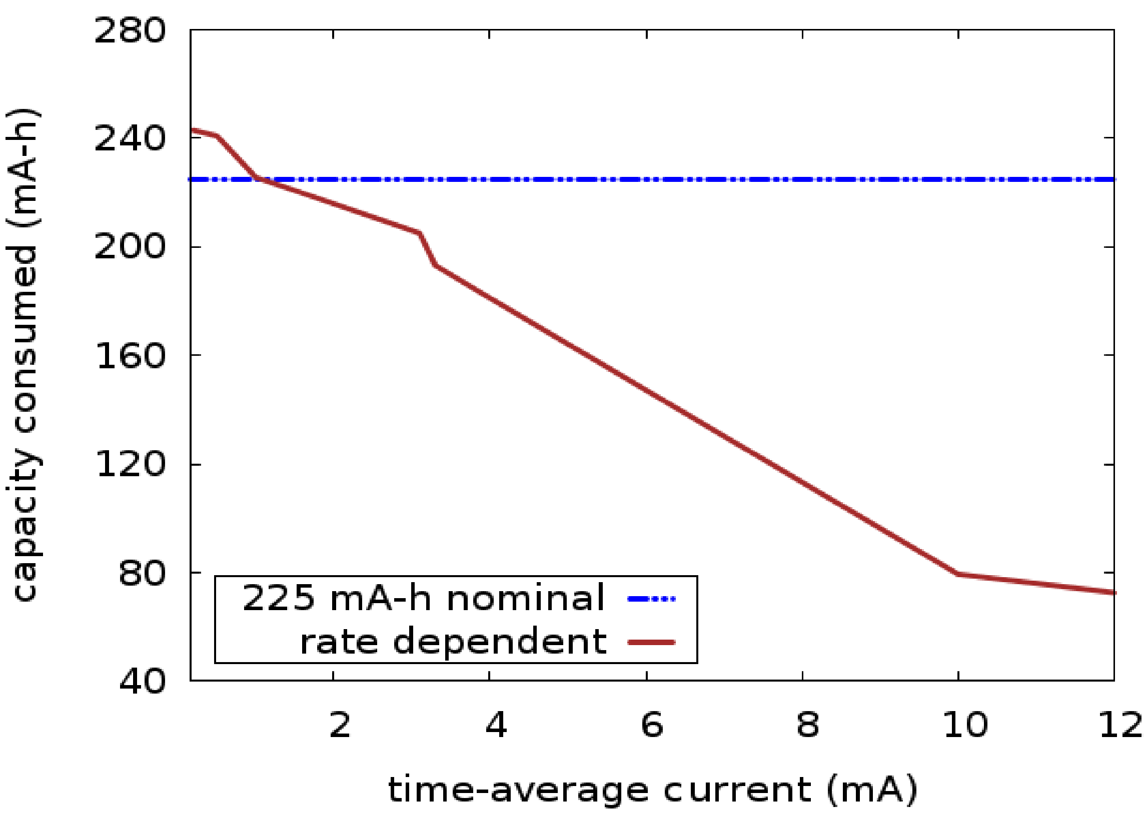
Experiments





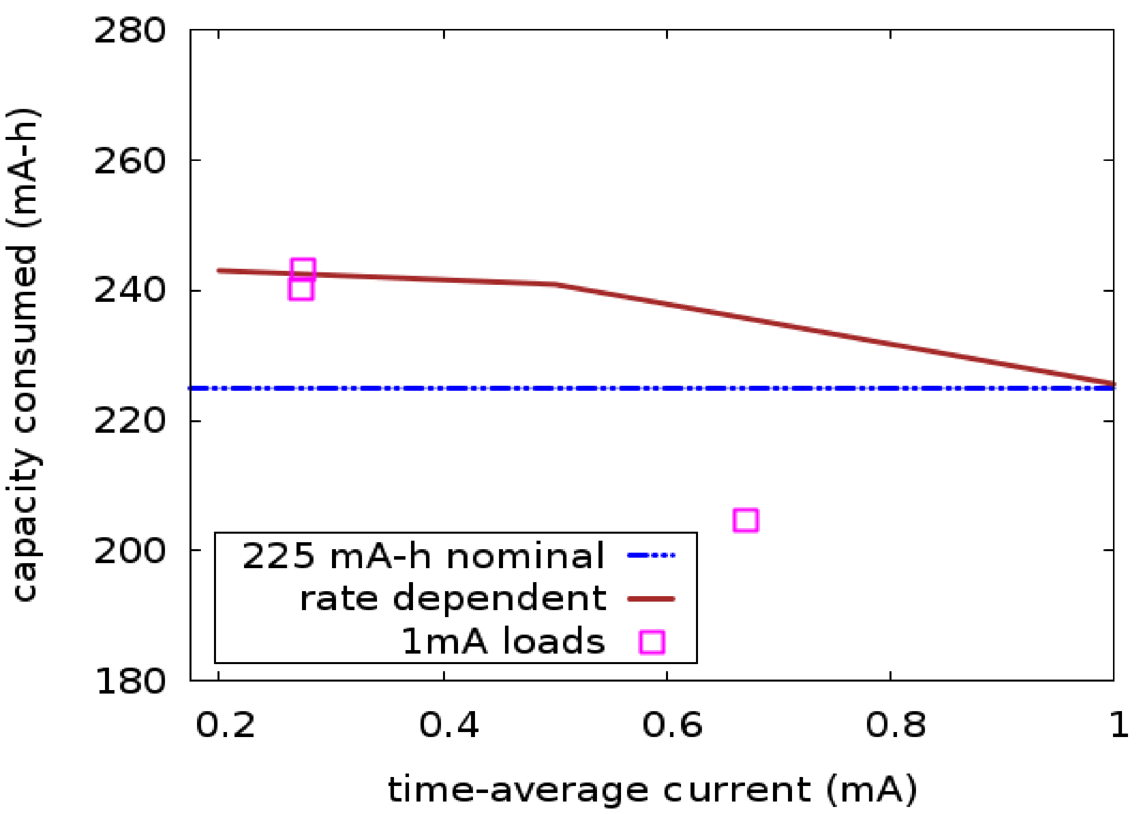
- simple, synthetic loads, systematic investigation
  - over 50 experiment configurations
- loads with *same time-average current*
  - focus on intensity (load current) and timing
  - reduce rate dependent capacity effects
- metric: capacity consumed (until 2.0V cut-off)

Results



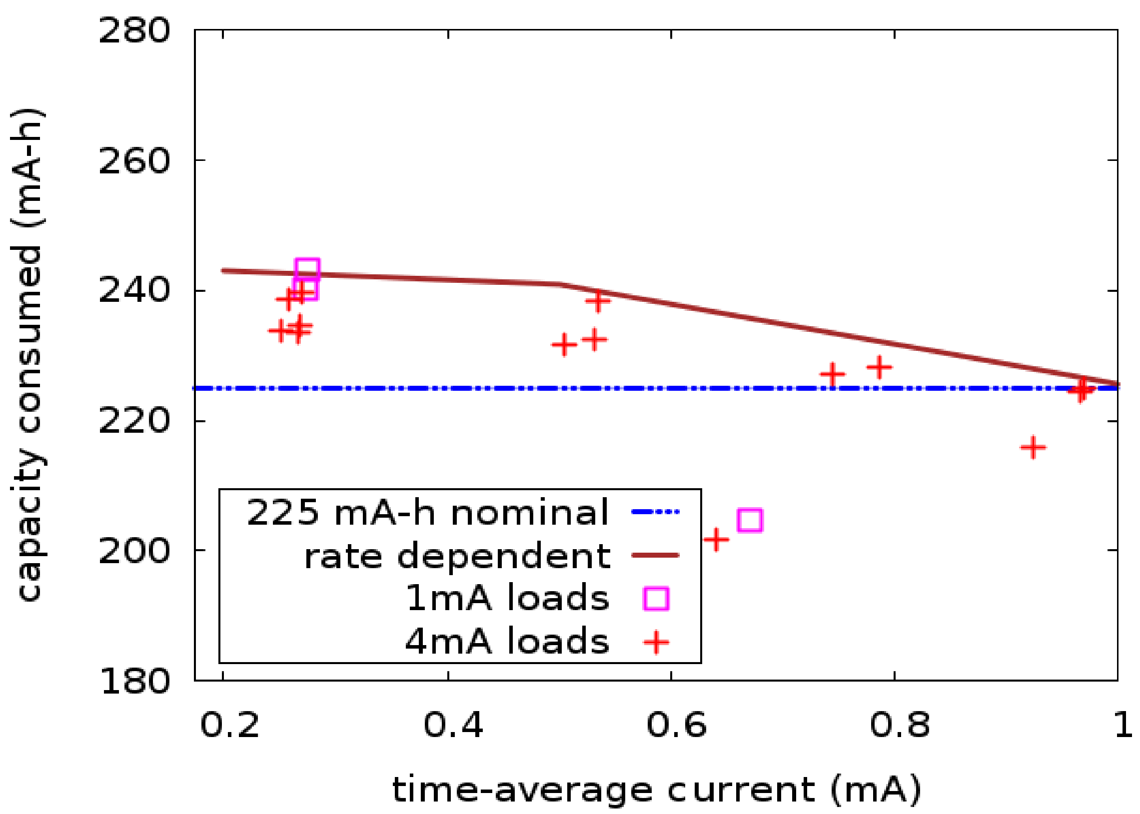
- rate-dependent capacity
  - as current decreases, utilizable capacity increases

Results



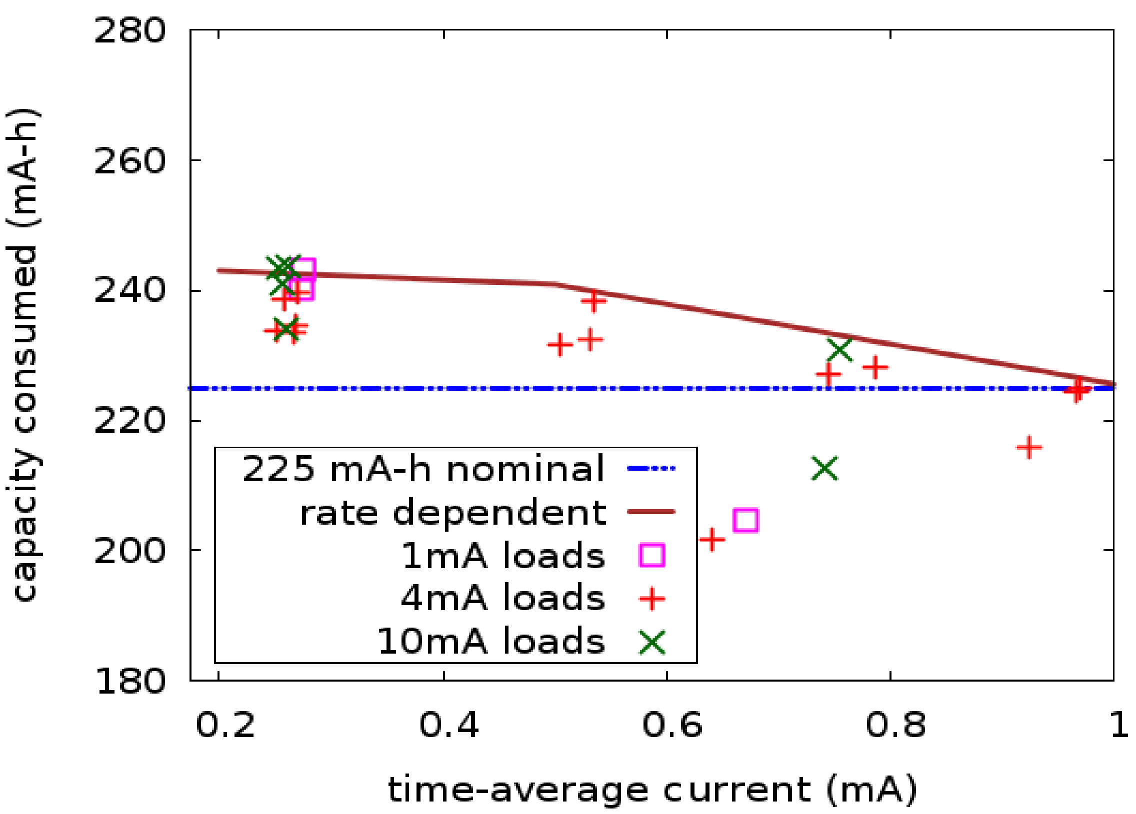
- load patterns with 1mA load current

Results



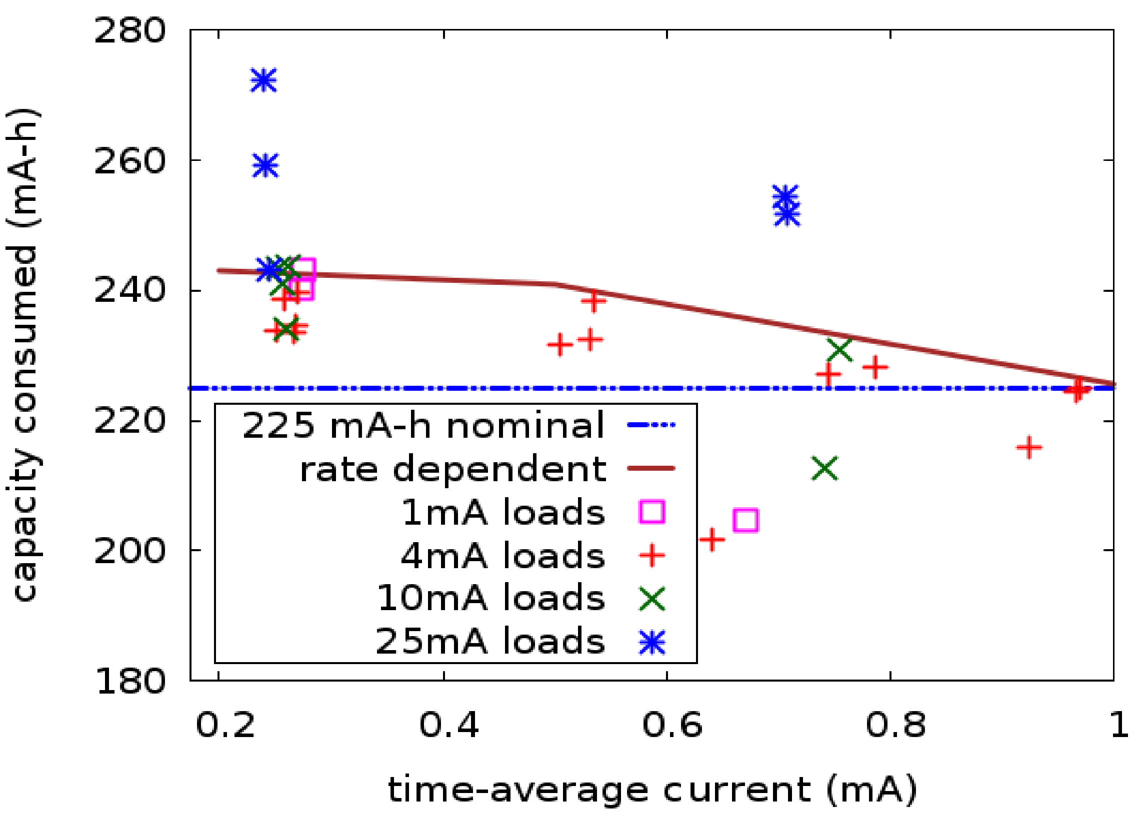
- load patterns with 4mA peak current

Results



- load patterns with 10mA load current

Results



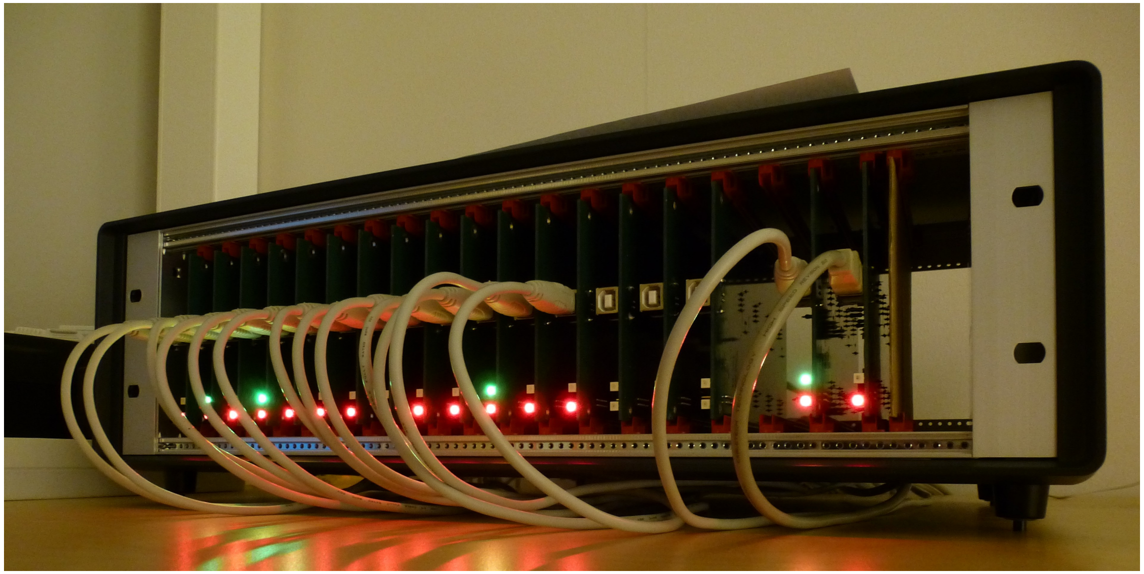
- load patterns with 25mA load current

Applications

- design
  - data suggests high currents with low duty cycle is OK
- evaluation
  - parameterization and validation of analytic battery models for use in e.g. simulation

- real time state of charge estimation
  - state of charge on deployed device
  - needed for management, also *lifetime* balancing
  - lack of on-device resources
  - off-line modeling? on-device voltage tracking?

Conclusions



- in-depth characterization of Li-coin cell (CR2032)
  - large scale testbed for systematic measurement
  - ***not*** a bucket of mA-h
- applications
  - design, evaluation, state of charge estimation