Towards a better battery model for INET

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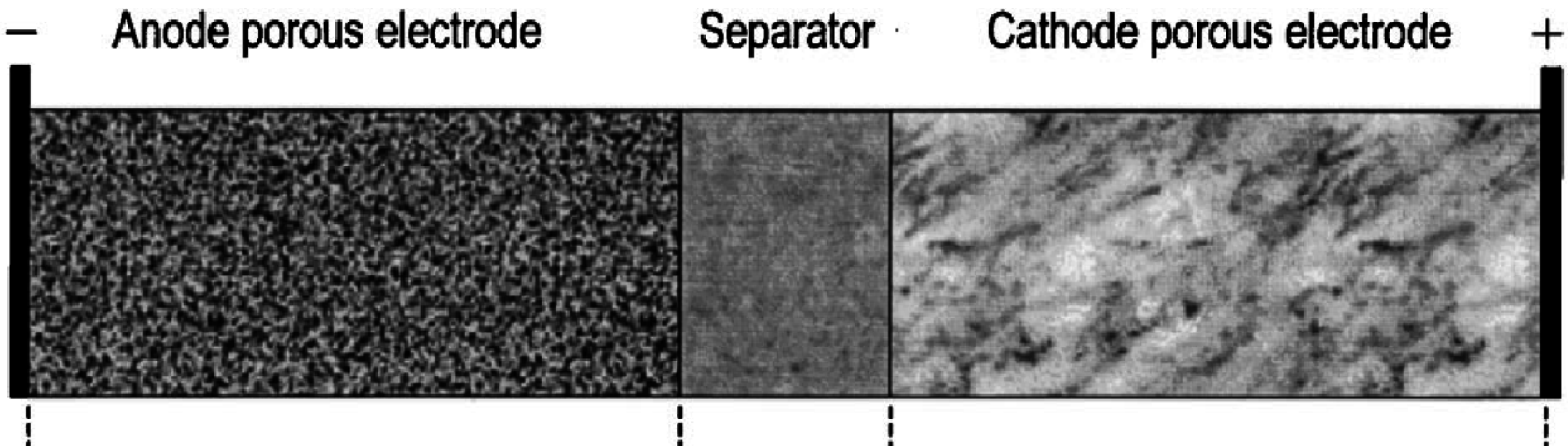
Outline

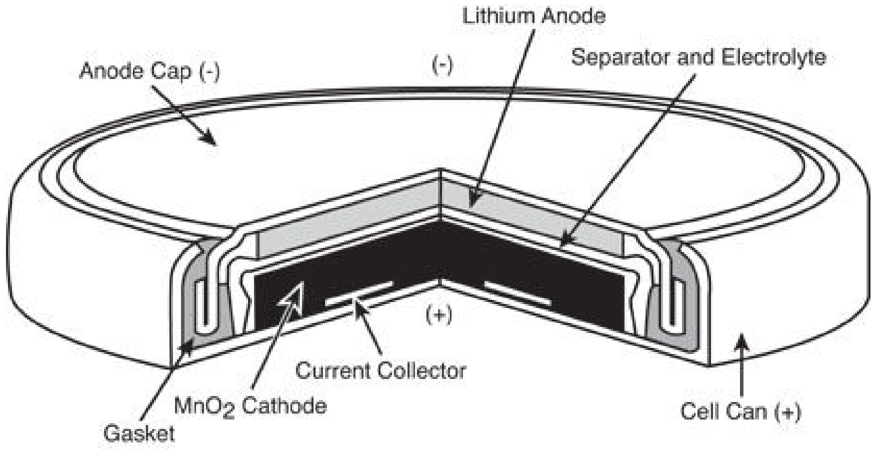
- batteries are complex electro-chemical systems
- simulating power consumption
- simulating batteries in INET using the KiBaM model
- validating KiBaM in a testbed
- why do we care about batteries?
- caveats and to-do's

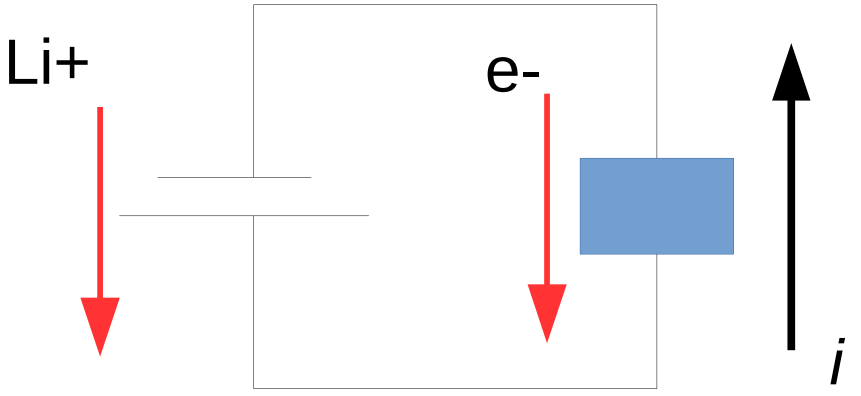
batteries are complicated



- complex electro-chemical system
- depends heavily on battery chemisty and structure
  - even manufacturer specific

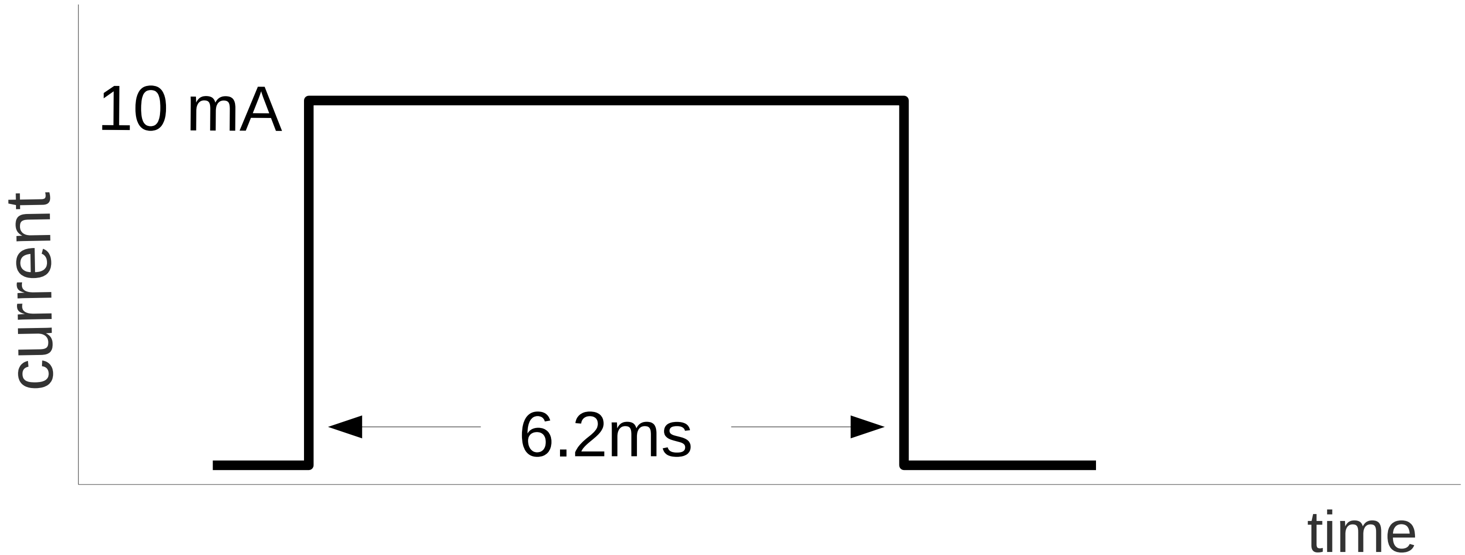
Li-coin cell





- primary (non-rechargeable) Li-coin cell
  - Li anode oxidized: Li → Li+ + e-
  - MnO2 cathode reduced: MnO2 + Li+ + e- → Li Mn(III)O2

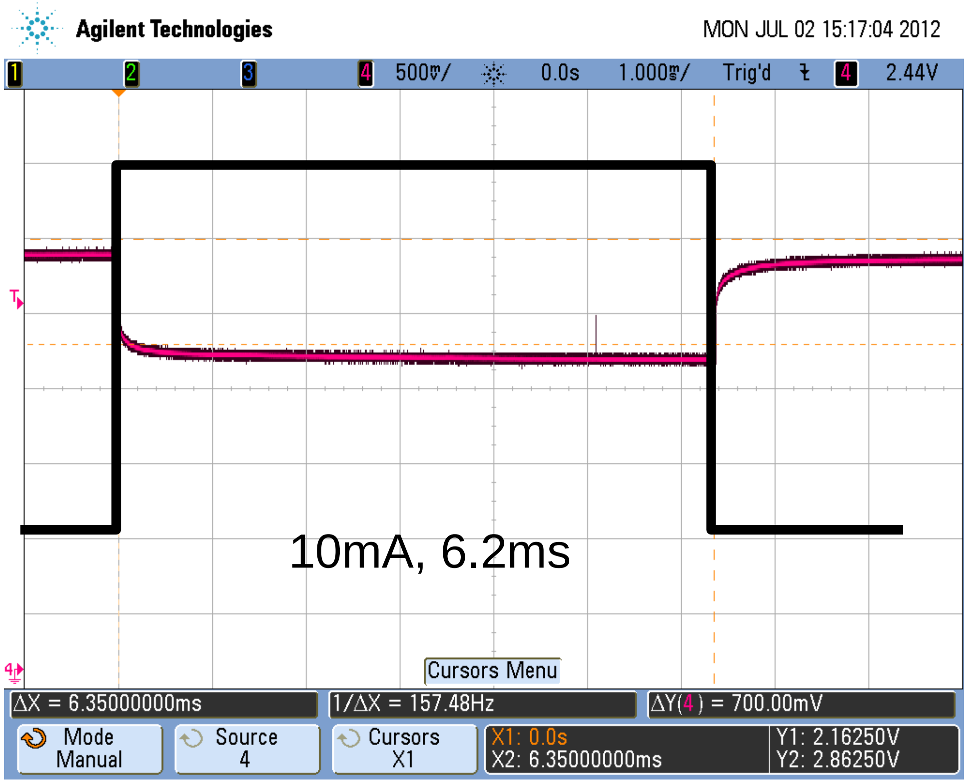
output voltage under load



- load = I(t)

output voltage under load

voltage

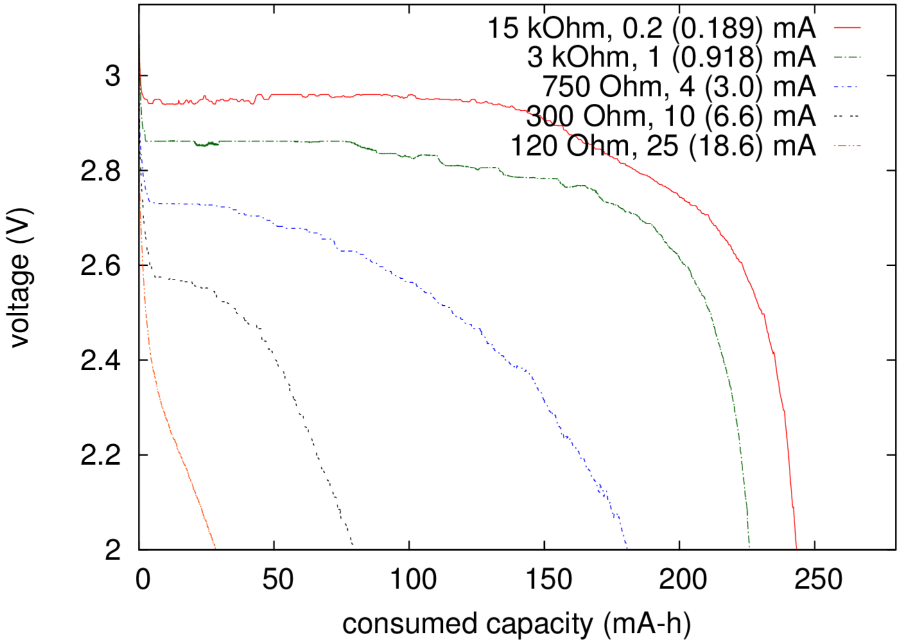


time

- output = V(t)

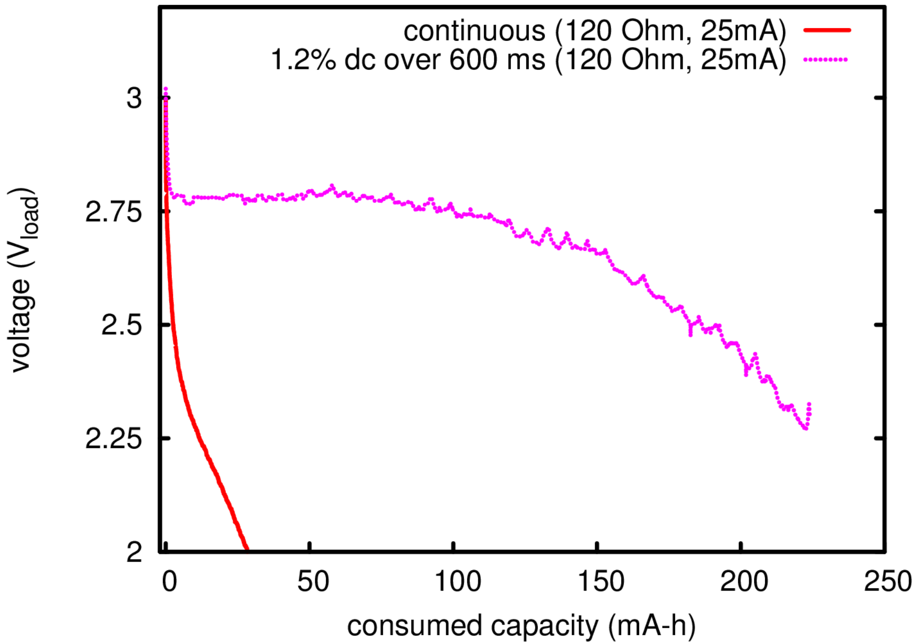
non-linear characteristics

- rate-capacity effect
  - lower current discharges the battery more efficiently
  - doubling the current decreases the lifetime by more than half



non-linear characteristics

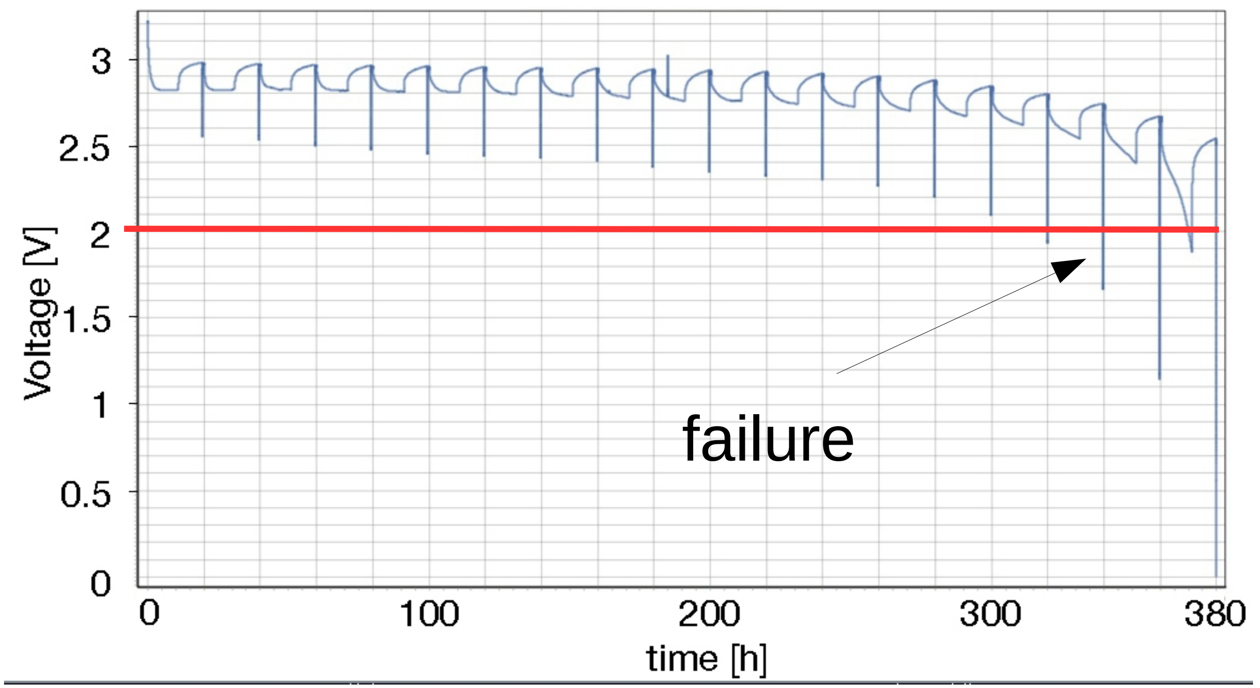
- charge recovery
  - intermittent loads discharge the battery more efficiently
  - 50% duty cycle more than doubles the lifetime



non-linear characteristics

- manufacturing variation
  - batteries vary
  - hardware varies
- temperature
  - colder temperatures decrease the battery lifetime

non-linear characteristics



- device failure
  - battery cannot maintain output voltage under load
  - depends on cut-off voltage for device electronics

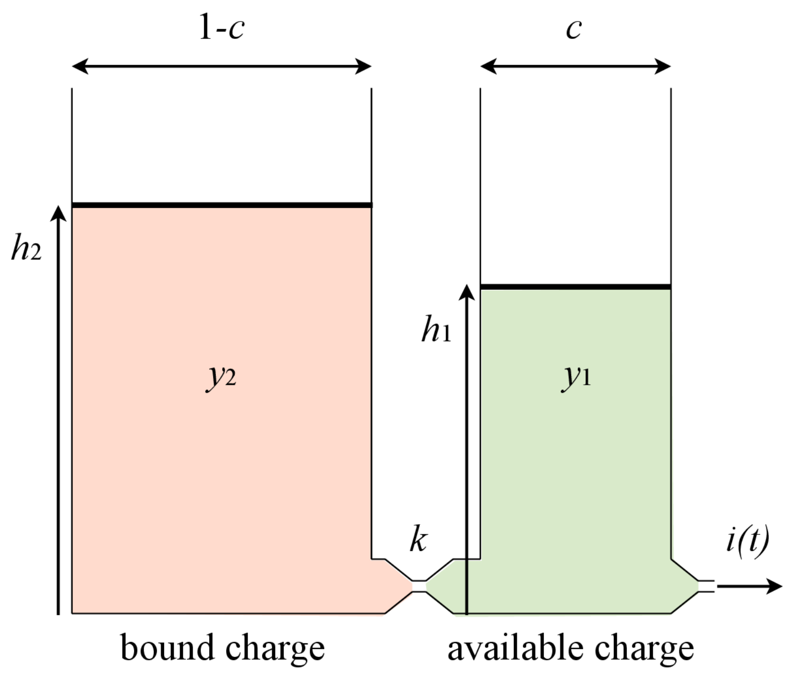
non-linearities

- experimental results suggest that non-linearities matter
- mA-h model
  - relative lifetimes vary ~15-20% among loads with the same time-average current, but different load patterns
  - absolute estimates lifetimes vary 2-3x from linear models

modeling batteries

- empirical models
- electro-chemical models
  - battery as chemical system (very slow, very complex)
  - existing models may not be well suited for fine-grain loads
- analytic models
  - V(t) = F (I(t))
- equivalent circuit models
  - battery as electical system (RC or RLC circuit)

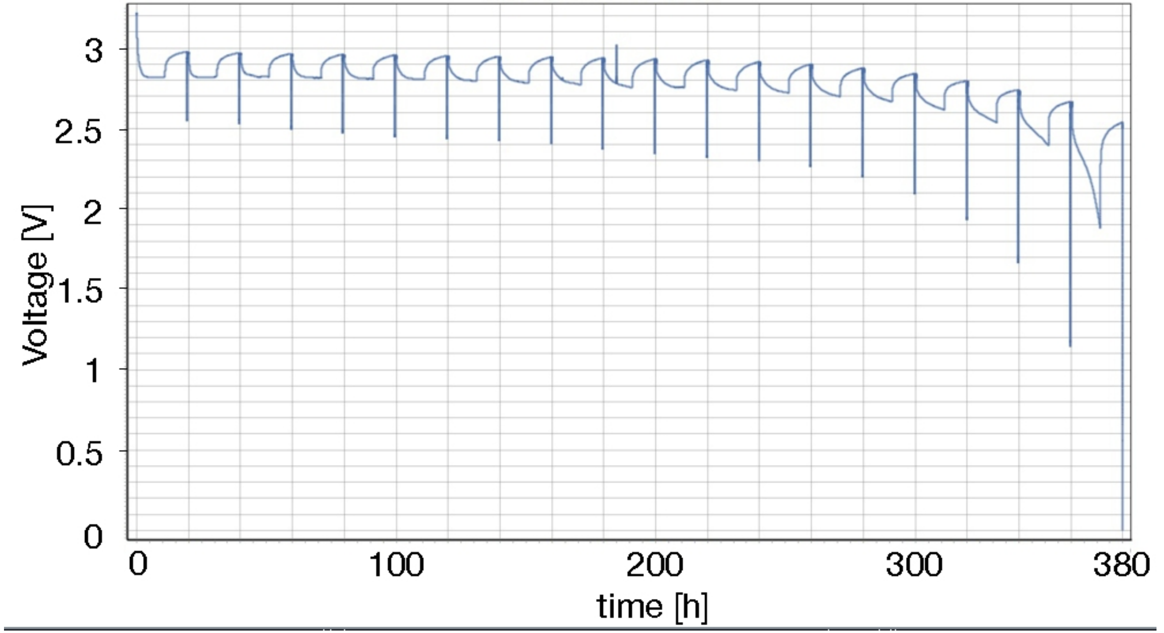
KiBaM: kinetic battery model



- analytic model for state-of-charge
  - battery fails when available charge is empty
  - system of differential equations

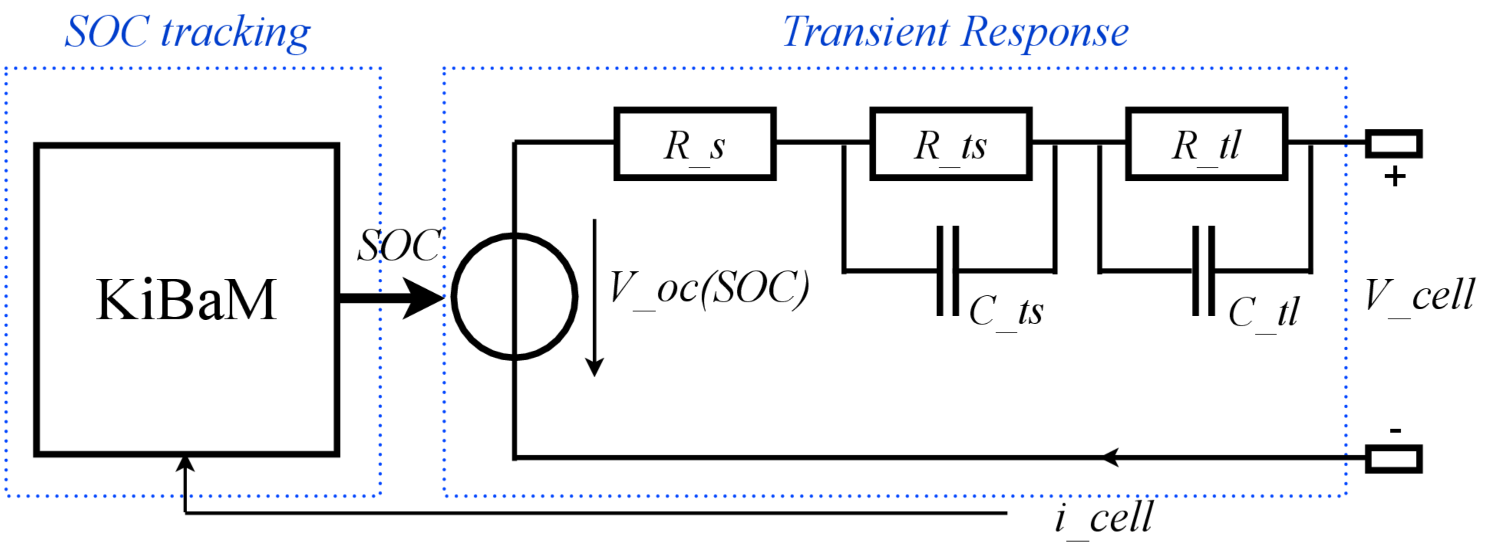
hybrid-KiBaM: kinetic battery model

- <math deleted >
- simple closed forms (fast to compute)



- parameterization is complex
  - measurements under highly controlled loads
  - battery specific

hybrid-KiBaM: kinetic battery model



- equivalent circuit model for output voltage
  - KiBaM state-of-charge input voltage
  - equivalent circuit model for output voltage

hybrid-KiBaM: kinetic battery model

- <math deleted >
- simple closed forms (fast to compute)
- parameterization is complex
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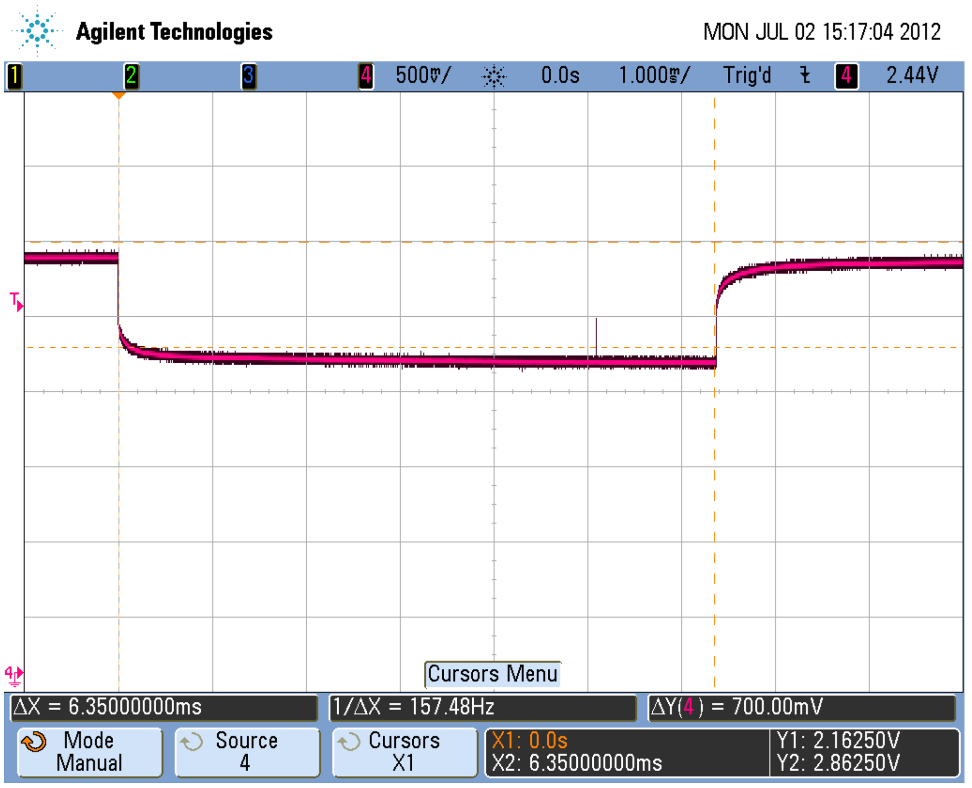
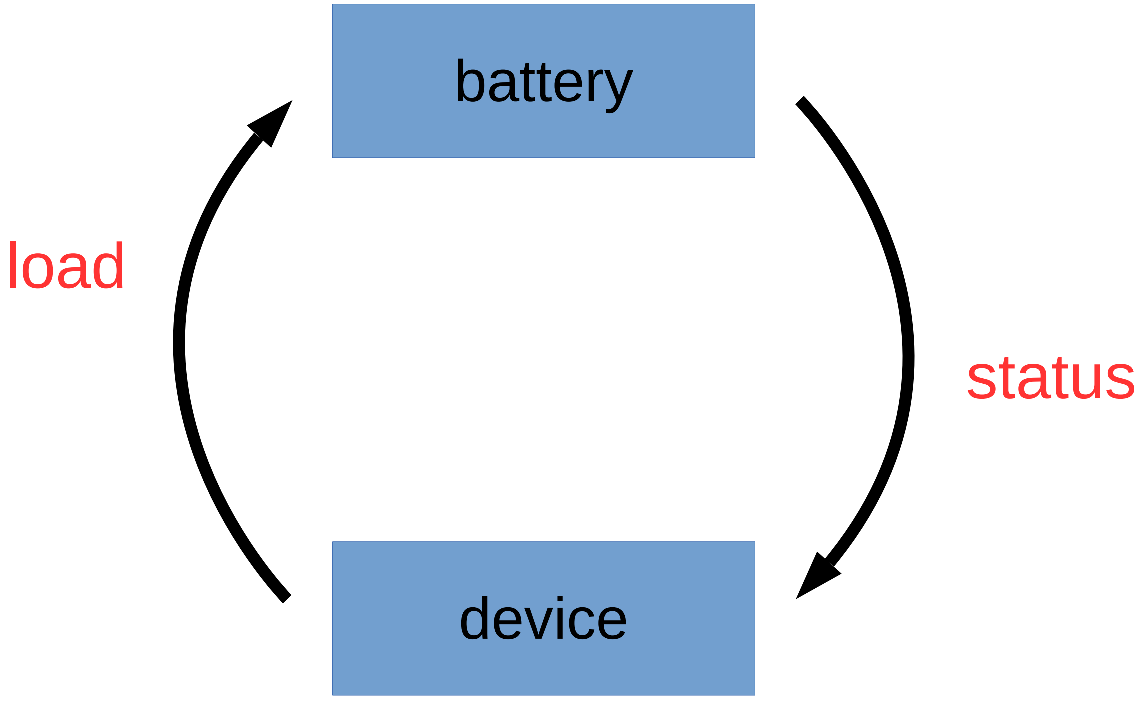
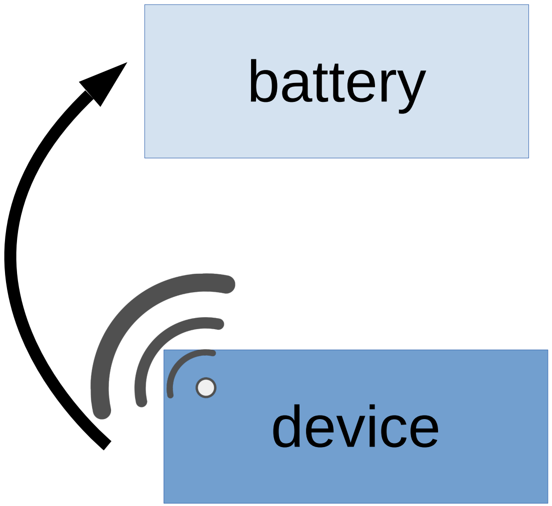


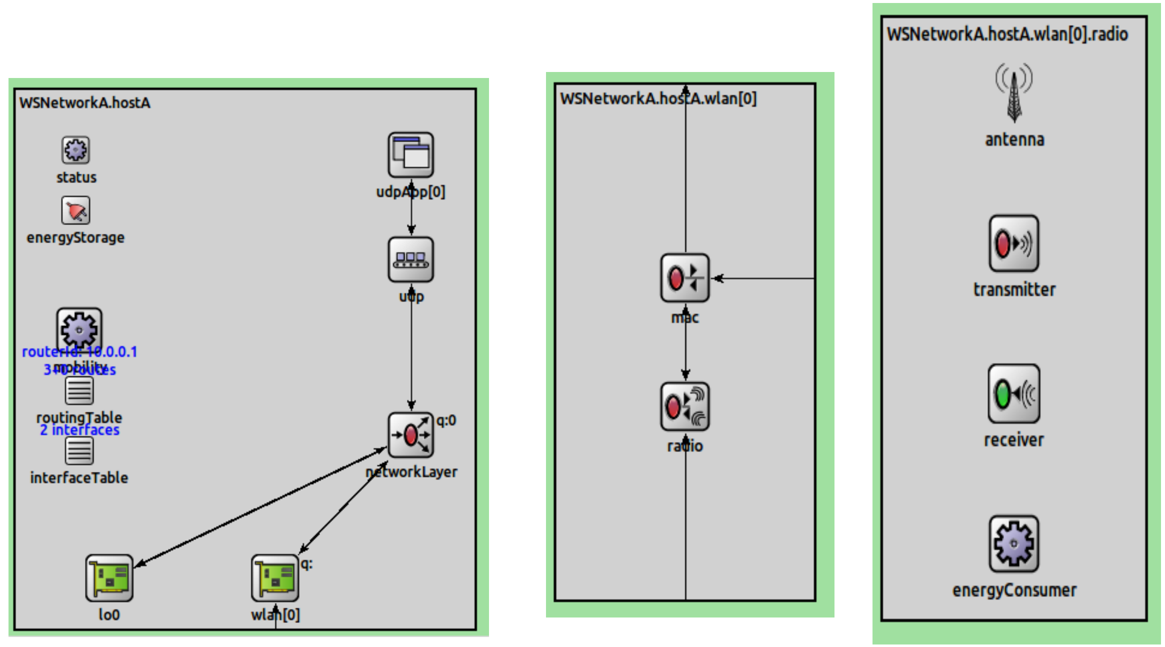
simulating battery powered devices

- device activity
- load on battery
- battery state-of-charge
- battery status affects device



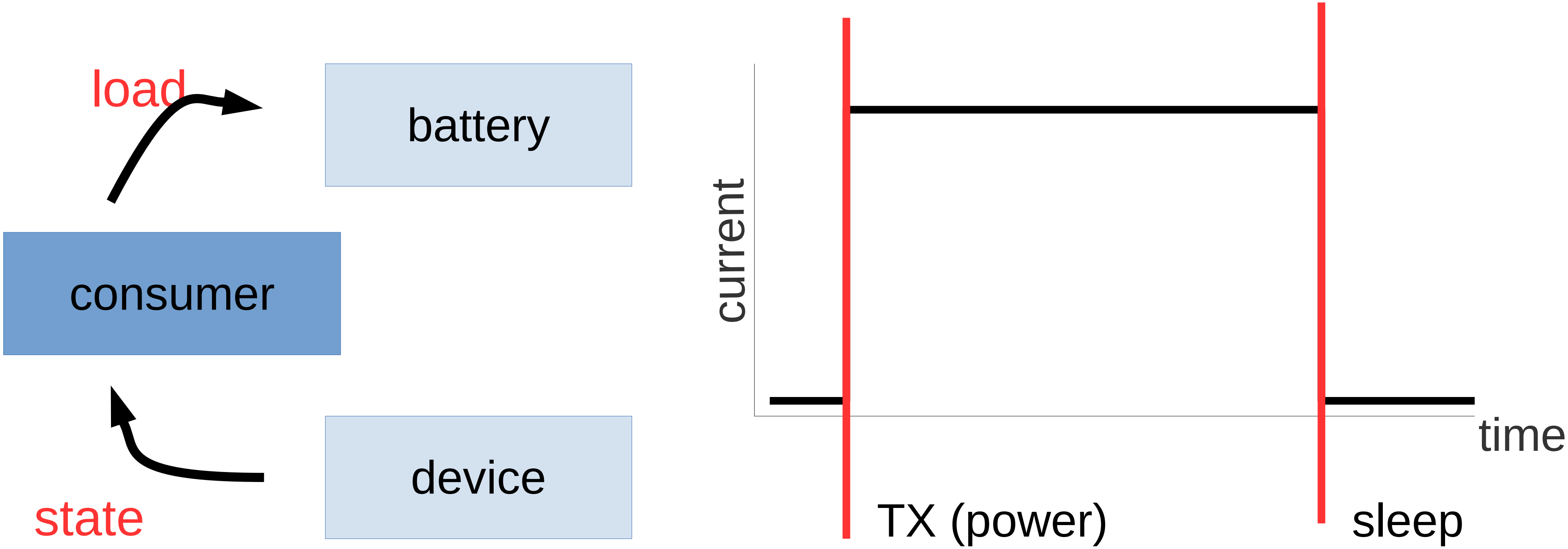
device activity





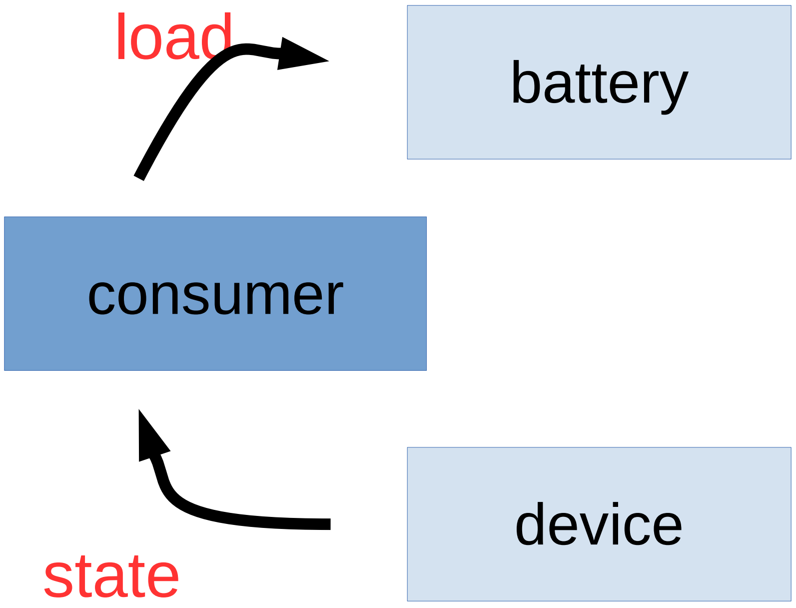
- model protocol or application
- *lowest level* element that models device operation
  - host can have multiple devices

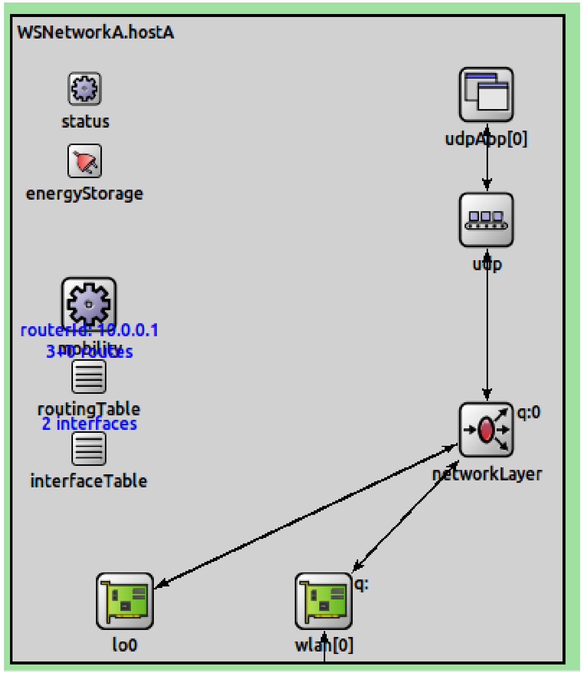
load



- translate device activity into load on battery
  - values based on datasheets or measurement

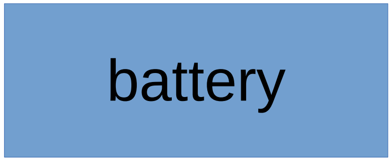
load

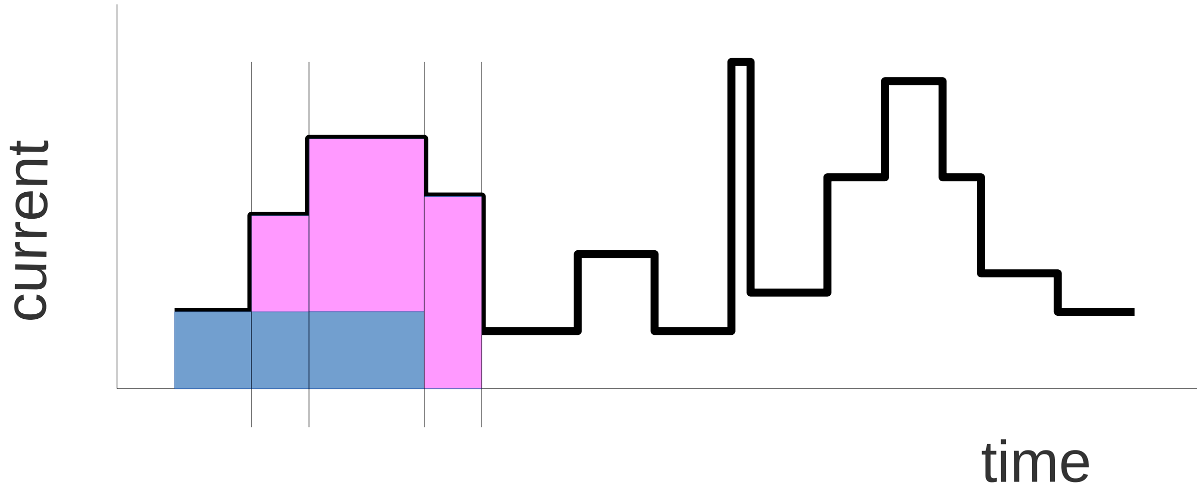




- support diverse representations of loads
- combine loads from mulitple devices/activities

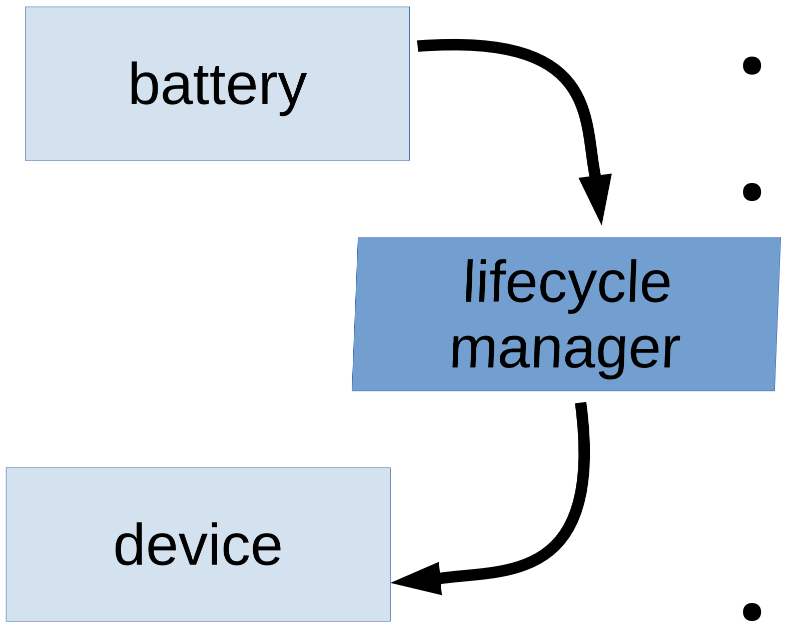
battery state: mA-h battery model





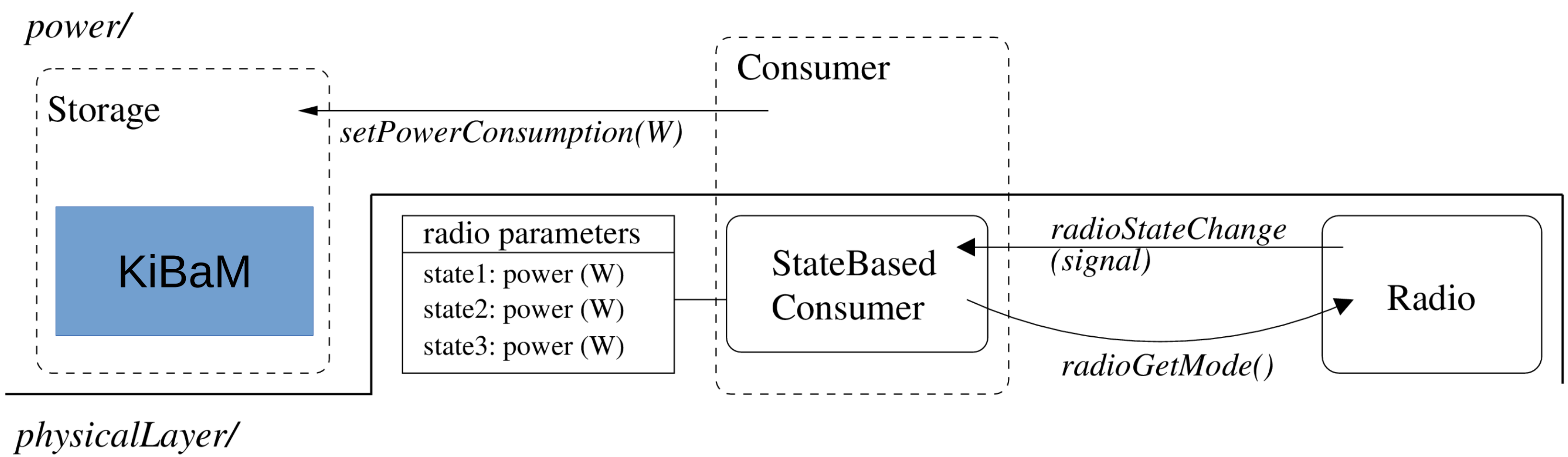
- charge = integral of current over time
  - piecewise sum
- nominal battery capacity = C mA-h
- state: C = C – i*t

battery status



- battery is depleted when C == 0
- shut down the device
  - all modules need to know (e.g. stop generating statistics)
  - INET lifeCycleManager
- on-device battery state-of-charge estimation
  - residual capacity

INET power consumption model



- radio signals all state changes
- consumer reports relevant changes to the source
  - values from lookup table

INET implementation issue

- contract

```
virtual void setPowerConsumption(int energyConsumerId, consumedPower) = 0
virtual W getPowerConsumption(int energyConsumerId) const = 0;
```

```
virtual J getNominalCapacity() = 0;
virtual J getResidualCapacity() = 0;
```

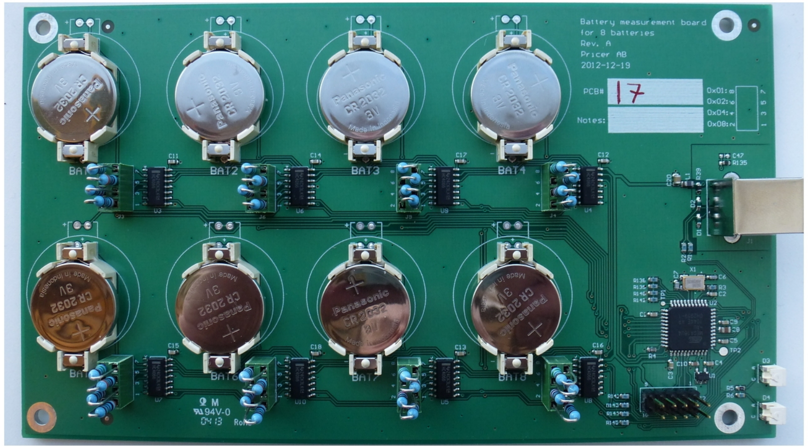
- energyStorageBase (bookeeping interface)

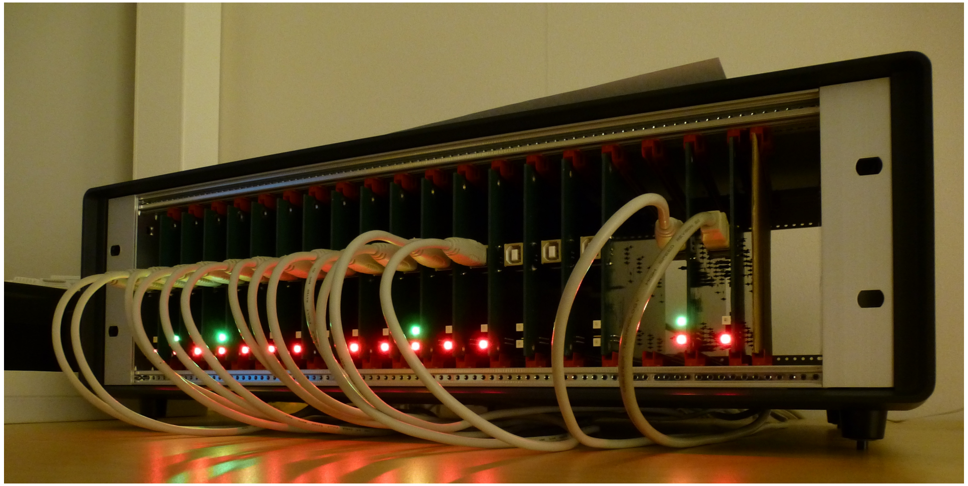
```
EnergyConsumerEntry(const IEnergyConsumer *energyConsumer, W consumedPower) :
    energyConsumer(energyConsumer), consumedPower(consumedPower) {}
```

INET implementation issue

- Watts (consumption) + Joules (capacity)
  - P = I * V
  - constant voltage sources (mains power, simple battery models)
  - lifetime depends on capacity
- Amps (consumption) + Amp-h (capacity)
  - I = dQ/dt
  - output voltage varies
  - lifetime depends on output voltage

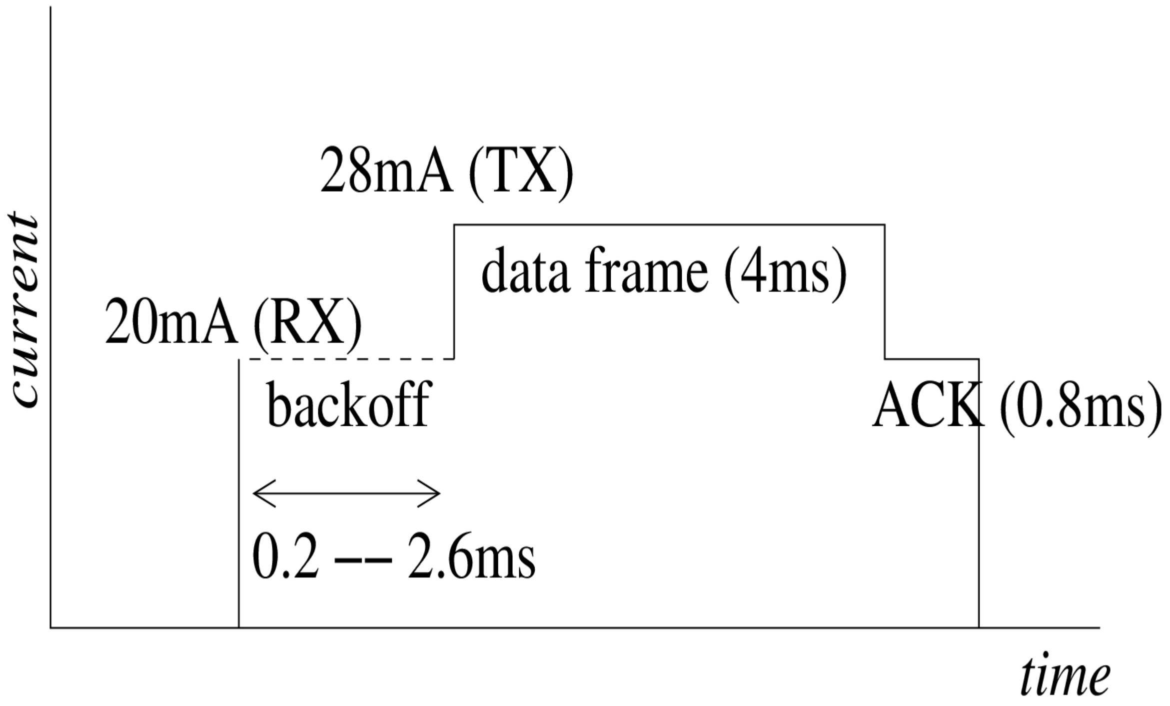
testbed





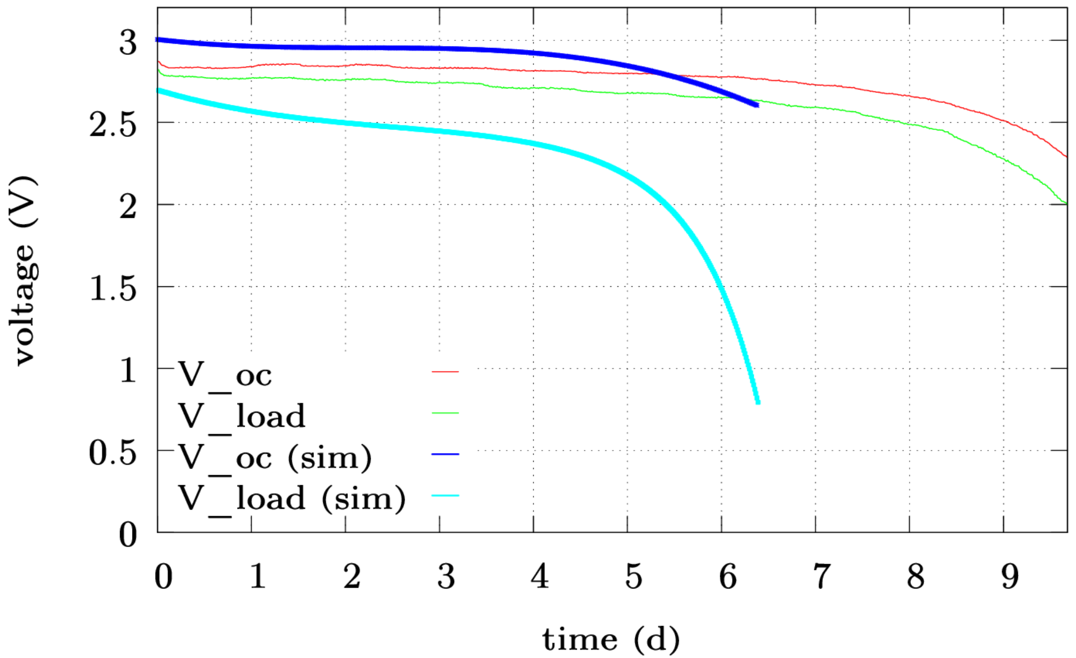
- custon harware – large-scale low-cost testbed
- measure controlled discharge of CR 2032 batteries
- simple resistive loads and timing patterns

testbed



- INET IEEE 802.15.4 MAC layer + hybrid KiBaM battery model
- mimic same load in testbed

testbed



- INET IEEE 802.15.4 MAC layer + hybrid KiBaM battery model
- mimic same load in testbed

why do we care about simulating batteries?

- performance evaluation and dimensioning
  - load has to be simulated with comparable accuracy!
- modeling on-device state-of-charge estimation
  - load/lifetime balancing
  - how accurate is the estimate?
- voltage modeling
  - voltage regulation – interface between the battery and the device

thanks!

- Christian Rohner, Uppsala University
- UU Computer Networking Project Course
  - Felix Farjsjo, Andreas Gawerth, Jonas Nilson, Eric Stenberg
- OMNeT++ team, especially Levente
- the audience :-)

power consumption in networks

- ICT infrastructure
  - data centers, ISPs, etc.
  - energy efficiency, reduce cost

- battery-powered wireless devices
  - mobiles, sensor networks, IoT
  - maximize device or network lifetime