Modelling Hybrid Battery-Supercapacitors for Successive and Simultaneous Workloads in Embedded Systems

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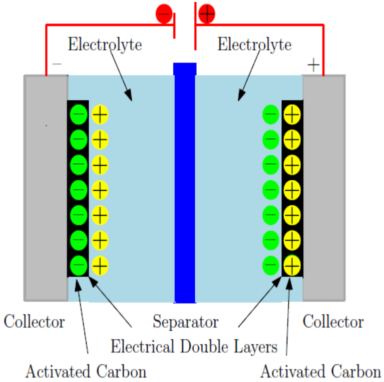
Need for Battery Aware Design

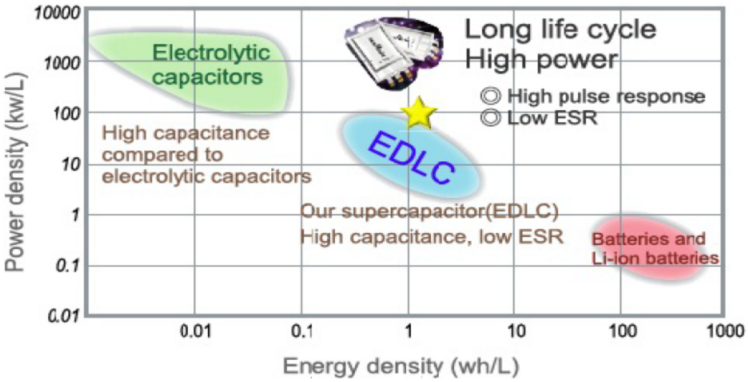
- Increase in functionality of devices - larger power consumption
- For battery operated devices, battery life is of primary concern
- Slow improvement of battery technology meet energy requirements
- Earliest battery models - discharging and charge recovery effect
- Charge recovery effect limited to lead acid batteries
- Recovery effect is negligible in Li-ion, NiMH and Li-Po batteries

Battery characteristics and lifetime enhancement

- Rate capacity effect (C-rate)
    - C-rate a function of time
    - Charging/discharging rates effect C-rate
    - C-rate is 1C $\implies$ battery is fully discharged in 1 hour
    - Higher C-rate - lower concentration of cations near cathode
    - Lower the discharge current longer is the life
    - Other factors – C-rate $\propto$ temperature
- Recovery effect
    - Battery capacity improves if kept idle for some time
    - Increases concentration of cations near the cathode
    - Utilized by multi-battery systems
    - Applicable to lead acid batteries
    - Not very effective for NiCd, NiMH, Li-ion, Li polymer

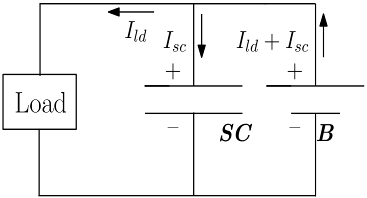
Supercapacitors (*SCs*)



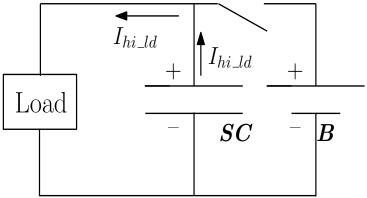


- Electrochemical double layered capacitors (EDLCs), ultracapacitors
- Higher energy density than conventional capacitors
- Rapid charging and discharging, systems requiring high peak currents
- Suitable for large amount energy storage and delivery in bursts

Hybrid Battery-Supercapacitors (*B-SC*)



(a) Normal load, discharge B and charge SC



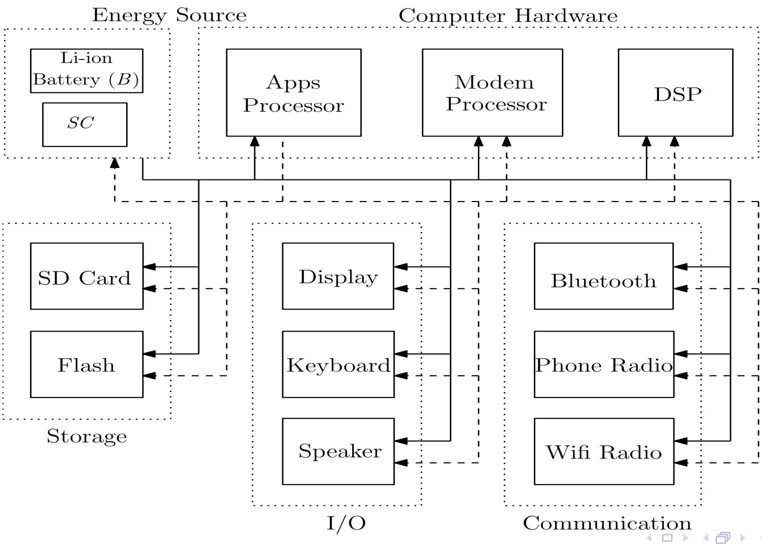
(b) Discharging SC for higher load

- System powered by *B-SC*, high peak current drawn from the *SC*
- Current for normal operation and charging of *SC* drawn from *B*
- Reduction of *C-rate*, longer battery lifetime

Motivation

- Sudden rise in battery workload very common in modern smartphones
- Example - simultaneous file download, playing video, app installing
- Several components of smartphone activated
- Increase battery workload
- *SC* can be discharged to meet the demand in such situations
- *SC* should have enough charge to meet the required demand
- Prevent peak load current to be drawn from battery
- For successive or simultaneous workloads
- Nature of workloads from behviour of embedded system programs
- Cardiac pacemaker - successive workloads periodically
- Smartphone and UAV - aperiodic simultaneous workloads

B-SC powered smartphone



Human Heart and Cardiac Pacemaker

- Human heart has four chambers – right atrial, right ventricle, left atrial and left ventricle
- To contract and relax periodically heart requires electric impulses from sinus node
- Sinus node located in right atrium
- Electric signal travels through conduction pathways to contract and pump out blood
- Each contraction of ventricles represents one heartbeat
- Atrials contract for a fraction of a before the ventricles contract
- Atrial blood empties into ventricles before the ventricles contract
- Malfunction of heart's electrical system leads to abnormal heart rhythms – arrhythmia
- Heartbeat rate may fall below expected level leading to bradycardia
- Tachycardia occurs when the heartbeat rate goes above expected level
- Artificial pacemaker treats bradycardia by restoring synchrony between atria and ventricles

How do Cardiac Pacemakers work ?

- Pacemaker monitors rate of heart and rhythm
- If heart does not beat or beats too slowly, pacemaker provides electrical stimulation
- Pacemakers classified depending on number of heart chambers monitored and stimulated
- Single-chamber and dual-chamber pacemakers
- Dual-chamber pacemaker performs better than single-chamber
- In terms of atria fibrillation, pacemaker syndrome and heart failure
- At the cost of higher energy consumption
- Dual-chamber pacemakers require frequent battery change
- Surgeries which is neither easy nor safe as well as expensive

Components of a Dual-chamber Pacemaker

- A pair of heartbeat sensors and pulse generators for each of atrial and ventricle
- A rate modulation sensor to detect body activity
- A pair of countdown timers to keep track of VAI and AVI
- VAI - Ventriculoatrial Interval, AVI - Atrioventricular Interval
- Components are controlled by a program running on a micro-controller
- Powered by a lithium iodine-polyvinylpyride (PVP) battery

Dual-chamber Pacemaker in DDDR mode

- Pacing in both (**D**ual) chambers
- Sensing in both (**D**ual) chambers
- Responding by triggering and inhibition (**D**ual)
- Modulates its activity according to physical activity of patient (**R**ate)

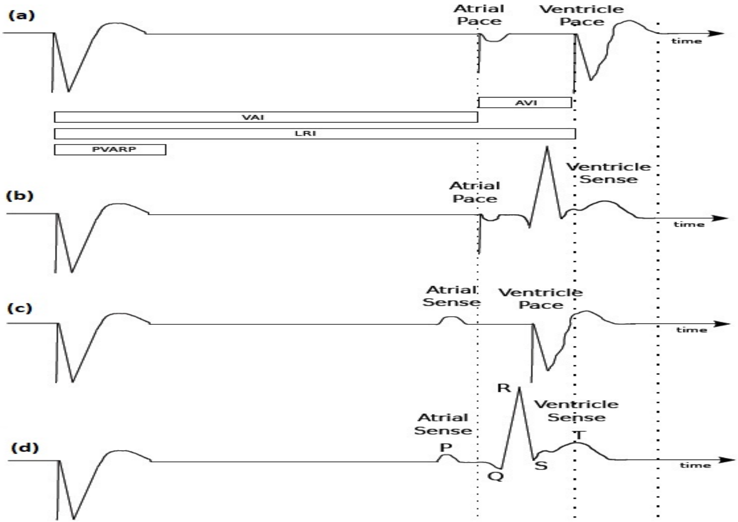
Time Intervals for a Single Heartbeat Pacing Cycle

Time Interval	Purpose	Time (msec)
P wave length	Time for sensing atrium activity	110
Duration of pulse	Time for which pacing signals should be maintained	1
QRS complex (combination of Q, R and S waves)	Time for sensing ventricle activity	100
AVI length	Time for ventricle fill after atrial contraction	150
VAI length	Time between ventricle activity followed by atrial sense	850
Postventricular atrial refractory (PVARP) length	Ignoring false atrium activity	350
Mode Switching Interval (MSI)	Time between atrial events to switch mode	500
Lower rate interval (LRI)	Longest interval between two ventricular events	1000

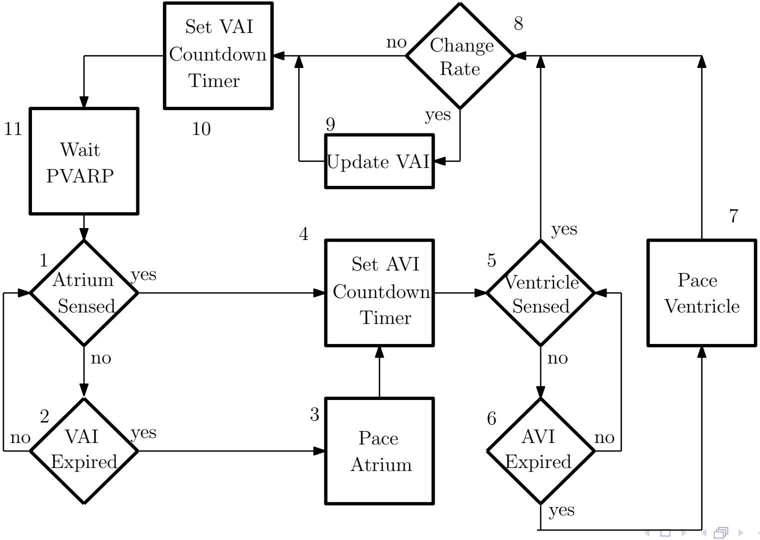
DDDR Pacing Scenario

- A - pacemaker paces after a standard time interval in both chambers
  - this reaction when no intrinsic heart activity is detected
- B - pacemaker paces in atrial chamber after a standard interval,
  - while ventricular pacing is inhibited due to a sensing of intrinsic activity from ventricle
- C - intrinsic atria activity is sensed
  - pacing inhibited in atrial chamber,
  - but occurs in the ventricular chamber after AVI (due to a lack of intrinsic ventricular activity)
- D - both pacing activities are inhibited due to sensing intrinsic activities in both chambers
  - situation when heart activity is normal

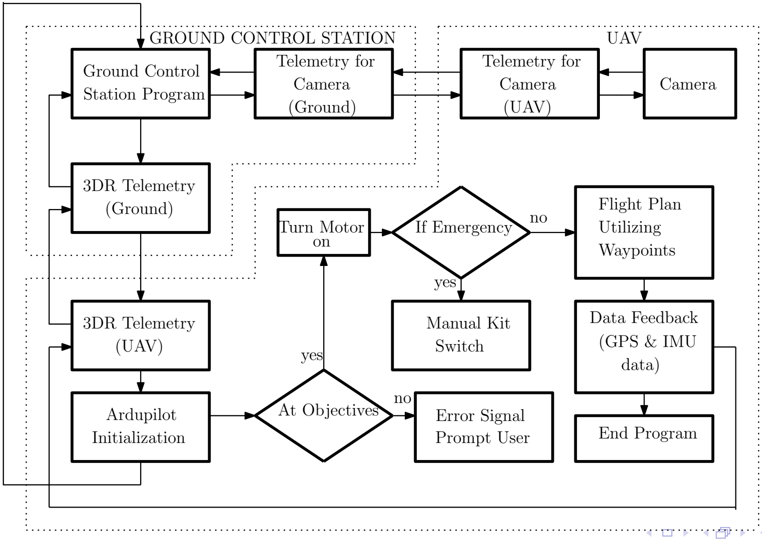
DDDR Pacing Scenario



B-SC powered Cardiac Pacemaker



B-SC powered Unmanned Aerial Vehicle (UAV)



Goal

- Unpredictable workloads - discharge *SC* or keep it recharged for future
- Single *SC* replaced by multiple *SC*s with equivalent capacitance
- Multiple *SC*s beneficial where some *SC*s discharged, others recharged
- Problem of multiple *SC*s - find a subset of *SC*s to meet demand
- Precharge a subset of *SC*s for future requirements
- Minimize peak load current drawn from battery
- Need to design a suitable mathematical model for *B-SC*
- Find required capacity of *SC* for an embedded system with battery *B*
- Find number of *SC*s to meet successive and simultaneous workloads
- Design fast scheduling algorithms for multiple *SC*s

Problem Statement 1 - Design a stochastic *B-SC* model

- Extend Chiasserini-Rao and modified KiBaM models
- Excluding charge recovery effect
- *B-SC* is defined by a discrete time Markov chain
- State $(i,j) \in \{0,1,\ldots,Q\_B\} \times \{0,1,\ldots,Q\_sc\}$
- i and j - charge units available in *B* and *SC*
- Q_B and Q_sc - maximum charge units in *B* and *SC*
- State transition $(i,j) \rightarrow (i\text{-}k,j)$
  - k charge units discharged from *B* with probability p(k,0)
- State transition $(i,j) \rightarrow (i,j\text{-}k)$
  - k charge units discharged from *SC* with probability p(0,k)
- State transition $(i,j) \rightarrow (i\text{-}k,j+l)$
  - k charge units discharged from *B*, and
  - l charge units stored in *SC* with probability p(k,l)
- p(k,0), p(0,k) and p(k,l) from workloads of an embedded system

Problem Statement 2 - Find charge storage capacity of *SC*

- Worst case successive and simultaneous loads obtained
- For smartphone, cardiac pacemaker and UAV systems
- Charge storage capacity of *SC* is total charge for higher load
- Beyond a threshold load, drawn in shorter spans

Disadvantage of *B-SC* with single *B-SC*

disadvantage_single_bsc.png

B-*SC* with multiple *SC*s

dual_bsc.png

Problem Statement 3 - Find number of *SC*s required

- Successive and simultaneous workloads
- Partioning total charge storing capacity of *SC*
- Simultaneous discharging and charging of *SC*s
- Probability distribution - all possible load currents for given workloads
- Mean - estimate average storage capacity of each *SC*
- Enable to find number of *SC*s required by system

Problem Statement 4 - Schedule multiple *SC*s

- The subset-sum problem reduces to this problem - NP-Complete
- An optimal schedule requires exponential time
- Approximation algorithms for faster sub-optimal solutions