Using a Supercapacitor to Power Wireless Nodes from a Low Power Source such as a 3V Button Battery

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Key words: Supercapacitor

Abstract

Portable and remote data gathering systems often need to be powered from small long life batteries and are required to transmit data sporadically. GPRS RF transmitters typically operate at a minimum voltage of 3.2 Volts and draw pulsed currents in the order of 1 to 2 Amps. Zigbee typically requires 10 - 100mA transmit current from a 3V battery. These peak load powers are too great to be supplied by small long life batteries such as a CR2032, even though the battery can supply the average system power. This paper offers a solution using a single cell supercapacitor to supply the peak loads with low cost circuitry. A single cell supercapacitor cannot operate at 3V, but does not require a balancing circuit and is lower cost and half the size of a dual cell supercapacitor required for 3V operation.

1. The Problem

Portable and remote data gathering systems are often powered from small long life batteries and required to transmit data daily or even less frequently to a central monitoring point. GPRS RF transmitters typically operate at a minimum voltage of 3.2 Volts and draw pulsed currents in the order of 1 to 2 Amps. Portable or remote control applications may operate with supply voltages as low as 2 Volts and require a short burst of power to drive an actuator or similar output. Such short high peak demands on power are not available from a 3 volt lithium battery or any low voltage high impedance source, such as a small energy scavenging transducer: vibration, heat, solar.

2. Solutions

A solution is to use a supercapacitor to provide the peak power when needed. The supercapacitor is trickle charged with a low current from the power source between load events. The energy stored in the supercapacitor over time is then used to provide a high current burst during a load event. Supercapacitors have:

- Physical rather than chemical charge storage, so they are not limited by the number of times they are cycled in the same way as a rechargeable battery
- very large C which enables them to supply the peak power for the duration required,
- extremely low ESR which enables delivery of high power
- very low leakage current so it does not waste significant battery energy

These attributes make supercapacitors ideal for this type of application.

3. Supercapacitor Types

Supercapacitors are an electrical double layer capacitor. Their electrodes are nano porous carbon coated on a current collector, typically aluminium. The porous structure of the electrode can achieve surface areas > 2000m^2/gm, which gives a massive charge storage area. They are filled with electrolyte and the electrodes are separated by a porous separator which prevents the electrodes short circuiting, but allows ions dissolved in the electrolyte through the separator for charge transport. The ions in the electrolyte are adjacent to ions at the surface of the activated carbon, so charge separation distance is in the order of the diameter of the ions. This massive charge storage/minute charge separation distance gives supercapacitors their “super” capacitance. However, the maximum voltage/cell is limited by the breakdown voltage of the electrolyte. There are two types of electrolyte:

– aqueous electrolyte with a breakdown voltage of ~1V/cell
– organic electrolyte, with a breakdown voltage of ~2.7V/cell

Both types of supercapacitor have capacitance constrained by their volume and specific capacitance of carbon electrode. Three aqueous cells are needed in series to reach the same voltage rating as a single organic cell. If the three aqueous cells together have the same volume as the one organic cell and their carbon electrodes have similar specific capacitance, than they will each contain ~1/3 the volume of carbon, so each aqueous cell is ~1/3 the capacitance of the organic supercapacitor cell. Given that the 3 aqueous cells are in series, their combined capacitance is 1/9 of the organic cell of the same volume. This is illustrated in Fig 1.

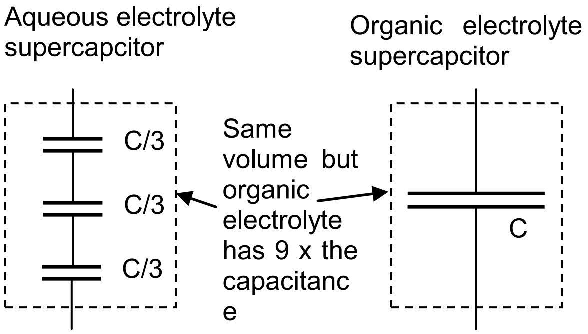

Figure 1. Comparison of energy density for aqueous and organic electrolyte supercapacitors rated at 2.7V

For this reason, this paper considers the use of a single organic supercapacitor cell in conjunction with a 3V source such as a CR2032 battery.

4. Solution using a single cell organic supercapacitor

As discussed above, the maximum voltage for a single cell supercapacitor is 2.7V but the source voltage, in this case a CR2032 battery is 3V. Hence simply connecting the super capacitor directly across a 3V battery, whilst attractive is not possible. A single cell supercapacitor does not require a balancing circuit which may be a significant drain on battery energy and is lower cost and half the size of a dual cell supercapacitor required for 3V operation. Therefore we consider circuits to couple a single cell 2.7V supercapacitor with a 3V source. A basic charge circuit block diagram to keep a supercapacitor trickle charged to its operating voltage is shown in Fig 2. The diagram of Fig 2. can be made to operate at quiescent currents as low as 3uA. Capacitor voltage is regulated to 2.7 volts by operation of the switch and charging intervals are determined by the load and hysterisis on the switch control. Charge current is limited by internal battery impedance and the value of R. Because the total energy dissipated in the battery impedance and R during charging is a function solely of the capacitance and the discharge state, the designer is free to choose a value of R to optimise the charge time and to reduce high current stress on the battery since the energy loss is independent of R. Inevitably applications using high current pulsed loads will use a microcontroller which would be in a minimal current sleep mode awakened by a timer. Such applications have the option of leaving the supercapacitor discharged for most of the time. The microcontroller can then activate the charging circuit well in advance, allowing the supercapacitor to fully charge prior to the load pulse burst.

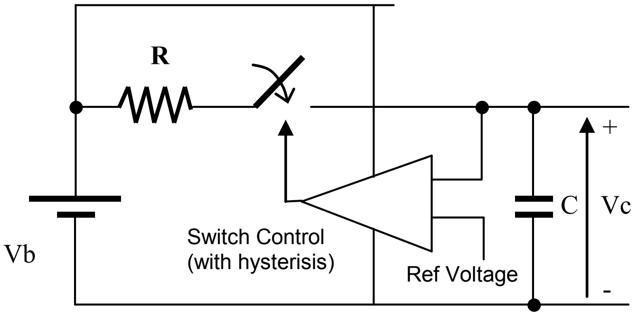

Figure 2. Button battery supercap trickle charger

5. Losses are independent of R

This conclusion is counter-intuitive, but the intuitive logic is that for higher values of R, current is less but the integration period for energy loss is longer, while for lower values of R, current is higher but the integration period for energy loss is lower.

Consider the basic circuit of Fig 3 used to charge a capacitor from a 3 volt button cell. SW1 is electronically controlled to keep the capacitor voltage below its maximum allowed value, typically 2.7 volts. R is the sum of battery impedance and any chosen external resistance lumped together.

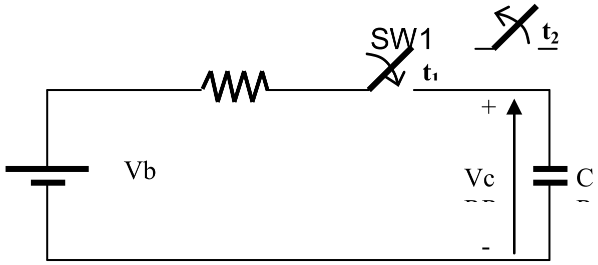

Figure 3: Simple supercapacitor charge circuit

Efficiency is important and although not obvious the energy lost in the resistor is simply a function of C and the voltage difference between V_b and V_c. There is no relation to the value of R as shown below.

5.1 Calculate Energy lost in R as V_c increases from V_{c1} to V_{c2}

$$i(t) = \frac{V_b}{R} e^{\frac{-t}{\tau}}$$

Energy dissipated in R from 0 to x secs:

$$E_R = \int_0^x i(t)^2 .Rdt = R\int_0^x i(t)^2 dt = R\int_0^x \frac{V_b^{\,2}}{R^2}.e^{\frac{-2t}{\tau}} dt$$

$$= \frac{V_b^{\,2}}{R}\int_0^x e^{\frac{-2t}{\tau}} dt$$

$$E_R = \frac{V_b^{\,2}}{R}\left[\frac{-\tau}{2}e^{\frac{-2t}{\tau}}\right]_0^x = \frac{V_b^{\,2}}{R}\left[\frac{-CR}{2}e^{\frac{-2t}{\tau}}\right]_0^x$$

$$= \frac{CV_b^{\,2}}{2}\left[-e^{\frac{-2t}{\tau}}\right]_0^x = \frac{CV_b^2}{2}\left(1-e^{\frac{-2x}{\tau}}\right)$$

Therefore energy lost in R as C charges from V_{C1} to V-$_{C2} = E_R(t_1 \rightarrow t_2)$:

$$E_R(t_1 \rightarrow t_2) = \frac{CV_b^{\,2}}{2}\left[\left(1-e^{\frac{-2t_2}{\tau}}\right)-\left(1-e^{\frac{-2t_1}{\tau}}\right)\right]$$

$$E_R(t_1 \rightarrow t_2) = \frac{CV_b^{\,2}}{2}\left(e^{\frac{-2t_1}{\tau}} - e^{\frac{-2t_2}{\tau}}\right) \quad .....(1)$$

Next find values for t_1 and t_2:

$$V_{C1} = V_b\left(1-e^{\frac{-t}{\tau}}\right)$$

$$\frac{V_{C1}}{V_b} = 1-e^{\frac{-t}{\tau}}$$

$$e^{\frac{-t}{\tau}} = 1-\frac{V_{C1}}{V_b}$$

$$\frac{-t}{\tau} = \ln\left(1-\frac{V_{C1}}{V_b}\right)$$

$$\therefore t_1 = -\tau\ln\left(1-\frac{V_{C1}}{V_b}\right) \quad \text{and}$$

$$t_2 = -\tau\ln\left(1-\frac{V_{C2}}{V_b}\right)$$

Substituting t_1 and t_2 into equ(1) gives:

$$E_R(t_1 \rightarrow t_2)$$

$$= \frac{CV_b^{\,2}}{2}\left(e^{2\ln\left(1-\frac{V_{C1}}{V_b}\right)} - e^{2\ln\left(1-\frac{V_{C2}}{V_b}\right)} \right)$$

$$= \frac{CV_b^{\,2}}{2}\left[\left(1-\frac{V_{C1}}{V_b}\right)^2 - \left(1-\frac{V_{C2}}{V_b}\right)^2\right]$$

which reduces to:

$$E_R(V_{C1} \rightarrow V_{C2})$$

$$= C\left[V_b(V_{C2} - V_{C1}) + \frac{V_{C1}^{\,2} - V_{C2}^{\,2}}{2} \right]$$

Where $E_R(V_{C1} \rightarrow V_{C2})$ is the energy dissipated in the resistor as the supercapacitor charges from V_1 to V_2.

6. Circuit Implementation of the Button Battery Supercap Charger

The circuit of Fig 4 shows one implementation using a Texas Instruments nano power TLV3012 comparator which operates down to 1.8 Volts and includes an internal 1.24 volt reference at pin 5. R4 is used to hold Q1 ON at startup when the super capacitor voltage is below the operating voltage of the TLV3012. Once the super capacitor reaches 2.696 volts the comparator output flips high and switches Q1 OFF. When the super capacitor voltage falls below 2.688 volts Q1 is switched ON. A small amount of hysterisis is applied around the comparator by R3 and R4 to reduce the switching rate of Q1 and hence reduce switching losses in the MOSFET and the comparator. The circuit draws only 3uA to 5uA once the super capacitor is fully charged. The value of R5 is chosen to limit the charge current to well below the maximum continuous discharge current specified by the battery manufacturer whilst charging the capacitor in a timely manner for the application.

For example if the maximum discharge current for the battery was 3mA then the lower limit for R would be 3 volts/3mA = 1k ohms. The maximum limit for R would be determined by the application's minimum recharge time and the chosen value for C. So long as $T_{recharge} \leq 5RC$ then the supercapacitor will have charged to 99% of the battery voltage within the allowed recharge time. In the circuit of Fig 4, the supercapacitor would be charged to 99% of V_{bat} after 5 x 2400 = 12000 secs = 3hrs 20mins.

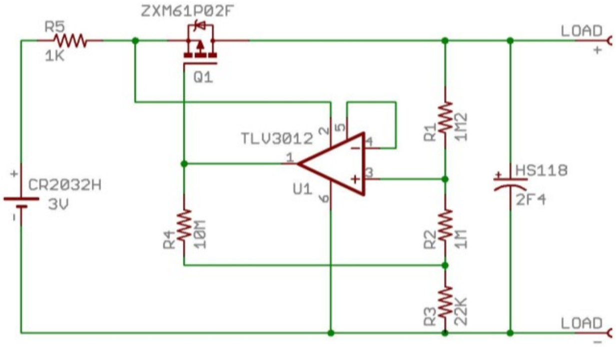

Figure 4. Button battery supercap charger circuit

7. Design Considerations

7.1 Lithium Battery Discharge Rates

It is useful to know the minimum operating voltage and load that a battery manufacturer has used to determine the battery capacity. The manufacturer will also usually quote a maximum discharge current and a standard discharge current. It is necessary to keep within these limits in order to maximise battery life. With very light loads of less than 10uA, available battery capacity is determined mainly by the size of the battery and the minimum operating voltage of the load. Reduced available capacity can be assumed if the load is greater than the standard discharge current. For these reasons, it is best to design for as light a load current as possible. Fig 5 below shows the discharge curves provided by the manufacturer for a typical CR2032 button cell with an advertised capacity of 235mAH[1]

A translation of the discharge performance of the CR2032 battery in Fig 6 shows how available capacity is affected by the minimum operating voltage of the load. As can be seen for the CR2032 battery, Fig 6 shows the available battery capacity is not significantly reduced provided the minimum operating voltage of the load is not higher than about 2.6 volts.

7.2 Steps to Determine Battery Life

a. Determine the battery voltage when the battery is at end of charge.

Battery life is determined by the time taken to reach the voltage when the battery is at end of charge, or the "flat battery" voltage. This voltage is effectively the minimum terminal voltage required at the supercapacitor for it to maintain full operating voltage to the load during the load burst sequence.

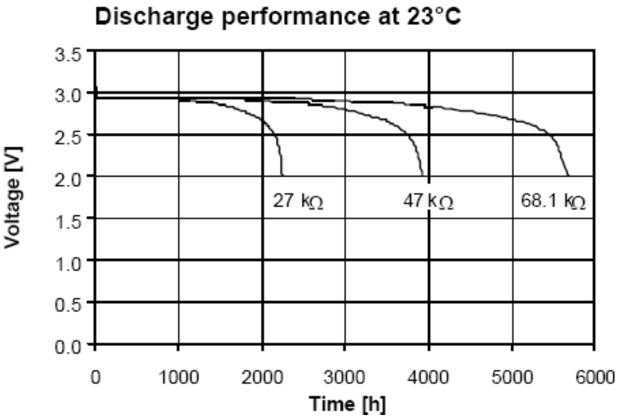

Figure 5. CR2032 discharge performance

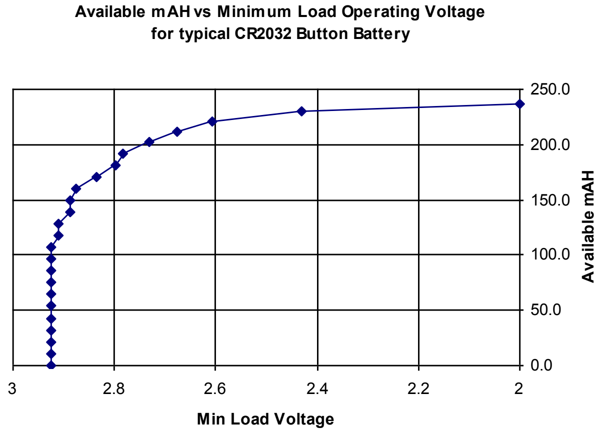

Figure 6: CR2032 capacity vs minimum load voltage

b. Estimate the available battery energy.

The available battery capacity can be estimated once the flat battery voltage is known by analysing the battery discharge curves as done above. Capacity is usually in mAh and needs to be converted to available energy by multiplying by the average battery voltage. A value for average battery voltage would be its nominal terminal voltage, however, the value is subjective and may be better chosen by looking at the discharge curve for the battery in question for the estimated average current.

c. Determine the net energy used over one charge/discharge cycle.

Four sources of energy loss need to be counted here:

1. Energy to recharge the supercapacitor.
2. Energy dissipated in the charge current limiting resistor R_{charge} as calculated in section 5.
3. Energy lost through supercapacitor leakage current and sense resistor current.
4. Energy to supply the comparator and any application quiescent current such as a wakeup timer.

d. Calculate the estimated battery run time.

Divide the available battery energy by the energy per charge/discharge cycle to give the number of cycles before the battery is flat.

7.3 Keep C on Charge OR Charge C when Needed

If the time between load events is very long then energy lost between load events by keeping the supercapacitor charged may exceed the energy required to re-charge the supercapacitor prior to each load event. Energy lost through supercapacitor leakage current and comparator supply current to keep the supercapacitor at voltage must be weighed against the energy required to charge the supercapacitor prior to peak load events. A plot of battery runtime vs period between load events will show a cross over point where it is best to change from one method to the other in order to maximise battery life. A chart for the constant current example in this paper whose profile is given in Fig 8 is shown in Fig 7.

Note that the self discharge characteristic of the supercapacitor used will have a major effect on this curve. If the supercapacitor is only charged prior to load events and isolated afterwards, then the voltage the supercapacitor has discharged to prior to starting charging for the next load event will affect the above calculation. The self discharge will depend on how long the supercapacitor has been held at voltage. We recommend you determine this by testing some supercapacitors on the bench.

7.4 Constant Current Load vs Constant Power Load

Constant load currents are those where the load current is independent of the load voltage, as long as the

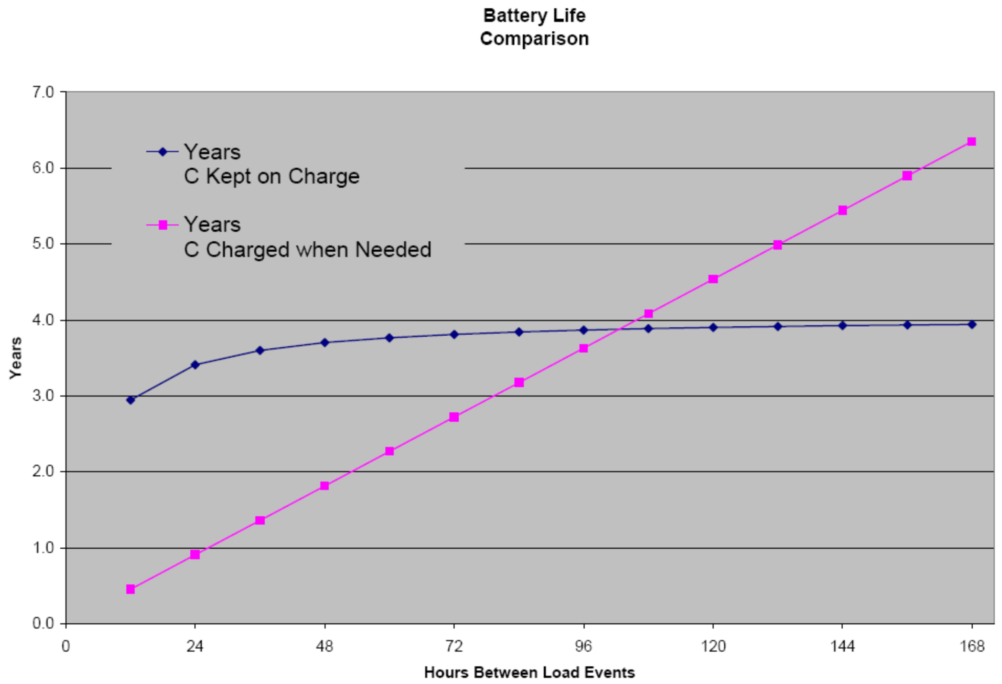

Figure 7: Battery Life depending on whether supercapacitor is always on charge or only charged prior to each load event.

Input voltage is greater than the minimum voltage the load needs to operate, typically presented by the input to a linear regulator or circuit. Constant power loads are most commonly presented by the input to a boost converter or switching regulator of one form or another. As load voltage decreases, load current increases to keep the V x I product = constant power. They typically have a wide range of input voltage and are therefore capable of using most of the stored energy in a supercapacitor and may be well supported by this type of application.

7.4.1 Estimating Battery Run Time for a Constant Current Load (C kept on Charge). Consider a transmitter taking 200ms to transmit a bust of data drawing 500mA during this time with a minimum operating voltage of 2.5 volts. The transmitter will send data once a day and between times the system goes into sleep mode with less than 1uA current draw. The supercapacitor is charged between load events.

The supercapacitor would be charged to 2.7 volts, so the maximum allowed voltage drop during the burst is 0.2 V. Assuming no ESR drop, the minimum required capacitance would be:

$$C = Idt/dV = 500mA \times 200mS / 0.2V$$
$$= 0.5F$$

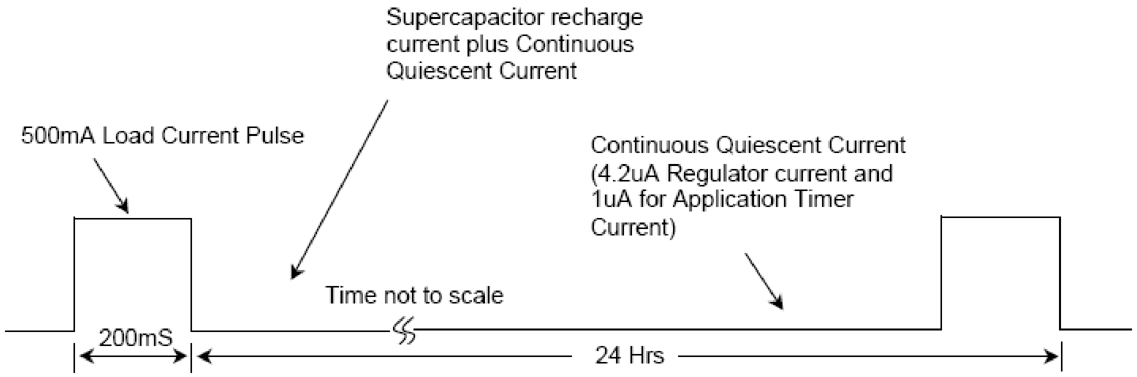

Figure 8. Example: constant current load profile

The CAP-XX HA130[2] is well suited in this case with a capacitance of 850mF and ESR of 55mOhms. The voltage drop during the load event using this part will be:

$dV = V_{esr} + dV_{cap}$ = (55mOhms x 500mA) + (500mA x 200mS / 0.85F) = 145mV

The flat battery voltage is the minimum load operating voltage plus the voltage drop as the supercapacitor discharges:

Flat Battery Voltage = 2.5V (Capacitance) + 145mV (ESR drop) = 2.645V.

The available battery capacity in this case is approximately 220mAh as taken from the graph in Fig 5 above.

Calculation of Energy Used per Charge/Discharge Cycle:

- **Energy to Recharge the Supercap**
  (Energy lost in R_{ESR} is very low and may be ignored)
  Voltage drop due to capacitance = Average Load Pulse Current x Duration/C
  = 500mA x 200mS / 0.85 = 117.6mV
  Hence V_i = 2.7 volts and $V_f = V_i - V_{drop}$ = 2.7 – 117.6mV = 2.582 volts.
  $E_{Supercap} = ½ \times C \times (V_i^2 - V_f^2)$ = 264mJ

- **Energy Dissipated in R_{charge} as C charges from V_f to V_i**

$$E_R(V_f \to V_i) = C\left[V_b(V_i - V_f) + \frac{V_f^{\,2} - V_i^2}{2}\right]$$

  (ref: Section 5)

  Note: V_b is “average battery voltage” assumed to be ≈ 3 volts.
  $E_{Rcharge} = 0.85 \times [3(2.7 - 2.582) + (2.582^2 - 2.7^2)/2]$ = 36mJ

- **Battery energy supplying Leakage, Sense resistor and any continuous Load current.**
  Sense resistor current: $I_{sense} = V_{supercap}$ / (sum of sense resistors) = 1.22uA
  Supercapacitor leakage current is typically < 1uA. Application current at the supercapacitor voltage in this case is zero.
  $E_{1Bat} = V_{bat} \times (I_{sense} + I_{leak} + I_{app})$ x Hrs Burst Interval x 3600

  E_{1bat} = 3(1.22uA + 1uA) x 24hrs x 3600 = 575mJ

- **Battery energy supplying by Continuous Current at the Battery Voltage.**
  Comparator and Ref Current: TLV3012 typically 3uA at room temp.
  Application Wakeup Timer: typically < 1uA.
  $E_{2bat} = V_{bat} \times (I_{comparator} + I_{wakeup})$ x Hrs Burst Interval x 3600
  E_{2bat} = 3(3uA + 1uA) x 24hrs x 3600 = 1.04J

Total Energy used per cycle = $E_{Supercap} + E_{Rcharge} + E_{1bat} + E_{2bat}$ = 1.9J

Available Battery Energy = Avail Bat Capacity x Average Bat Voltage x 3600
Available Battery Energy ≈ 220mAh x 3 x 3600 = 2376J

Estimated Battery Runtime (Yrs)
= (Available Battery Energy / Total Energy Used per Cycle) x Hrs Burst Interval / Hrs in a year.
= (2376J / 1.9J) x 24hrs / 8760
= 3.4 years.

7.4.2 Implementation and Battery Runtime Estimation for a Constant Power Load
(C only Charged prior to transmission)

A Class 8 GPRS transmitter working at a reduced power of 1 Watt RF takes 3 seconds to transmit its data once a week. The operating voltage of the transmitter is 3.6 volts and the efficiency of the RF PA stage is 60%. The minimum boost operating voltage is 0.9 Volts. The system architecture and load profile are as shown in Fig 9.

Operation

The microprocessor is kept in sleep mode and interrupted by an alarm previously set in the wakeup timer. The supercapacitor charger is enabled, the microprocessor sets another alarm allowing time for the supercapacitor to fully charge and returns to sleep. On the next interruption, the microprocessor sets a new alarm time, disables the supercapacitor charger and enables the boost converter and PMOS switch for the duration of the load event. All inputs and outputs on the microprocessor need to be designed for minimal or zero current load during sleep to ensure maximum battery life.

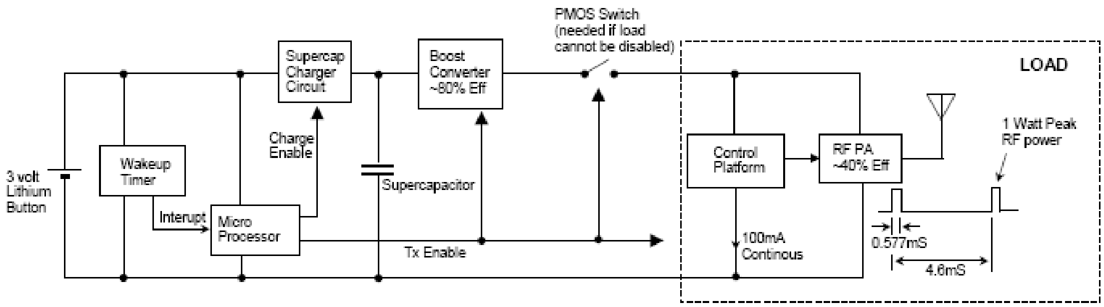

Figure 9: System Architecture: Single 3 Volt Lithium Cell Driving a 1 Watt Class 8 GPRS Load.

Power Analysis for System shown in Fig 9

Duty Cycle (D) = 0.577mS/4.6mS = 0.125

Average PA Power

= [(Peak RF Power x D)/η_{pa}] + (V_{ccpa} x $I_{control\ platform}$)

= (1 Watt x 0.125/0.4) + 3.6 volts x 100mA

= 672.5mW

Average Power Boost Input

= Average PA Power/ η_{boost}

= 672.5mW/0.8

= 840.6mW

Total Energy needed at Input to the Boost

= Average Power Boost Input x Transmit Duration

= 840.6mW x 3 seconds

= 2.522J

Calculation of Peak Current in PMOS Switch

Peak PA Current

= Peak RF Power / (V_{ccpa} x η_{pa})

= 1Watt / (3.6 volts x 0.4)

= 694.4mA

Peak Current in PMOS Switch

= Peak PA Current + Control Platform Current

= 694.4mA + 100mA

= 794.4mA

Peak Boost Output Power

= Peak Current in PMOS Switch x V_{ccpa}

= 794.4mA x 3.6 Volts

= 2.86 Watts

Peak Boost Input Power

= Peak Boost Output Power / η_{boost}

= 2.86 Watts / 0.8

= 3.575 Watts

Peak Boost Input Current

= Peak Boost Input Power / Minimum Boost Input Voltage

= 3.575 Watts / 0.9

= 4 Amps

Finding the Right Supercapacitor

In this case we will design for a final battery voltage of 2.6 Volts which from Fig 5 gives an available capacity of about 220mAH for a CR2032 button battery.

Assume we use a supercapacitor with an ESR of <100mOhms at end of life, therefore the minimum supercapacitor voltage:

V_f = Minimum Boost Input Voltage + (Peak Boost Input Current x ESR)

= 0.9 Volts + (4 Amps x 100mOhms)

= 1.3 Volts

This means the supercapacitor charged to the flat battery voltage of 2.6 Volts may drop down to 1.3 Volts over the 3 seconds of transmission and the value of C may now be calculated as follows:

$E_{Supercap} = ½ \times C \times (V_i^2 – V_f^2)$

= Total Engergy needed at Input to the Boost

Where V_i = 2.6 Volts, V_f = 1.3 Volts and total energy needed at Input to the Boost = 2.522J from above.

Therefore $C = 2\ E_{Supercap} / (V_i^2 – V_f^2) = 0.995F$

The CAP-XX HS108 part is well suited for this application as it has a capacitance of 1.8F +/-20% and ESR of 28mOhms^2.

8. Supercapacitor charge and discharge characteristics

The previous section gave an example of determining the right supercapacitor for the application. Section 7.3 explained how to decide if it was more energy efficient to leave the supercapacitor always on charge or to discharge it after each peak load event and re-charge it prior. However, in the se sections, we treated the supercapacitor as a classical capacitor, assuming the supercapacitor charges through a resistor according to

$$V = Vs(1-e^{t/RC})\ldots..(1)$$

or

$\Delta V = I_{CONST}.\Delta t/C$ for constant current charging.

Figure 10 shows how a CAP-XX HS206 charges with low levels of constant current. It can be seen that below ~50µA the supercapacitor will not charge and below 200µA there is a knee in the voltage over time curve, when theory predicts this should be a straight line. This effect is due to electrochemistry in the supercapacitor and will depend on the composition of the carbon electrode and the electrolyte used. We do not yet have a theoretical model to accurately predict this behaviour. Figure 11 shows the an estimated charge curve and actual charge curves for a population of 12 1.8F supercapacitor cells charged to 2.7V through a 2.2KΩ resistor. The classical equation (1) above is modified to:

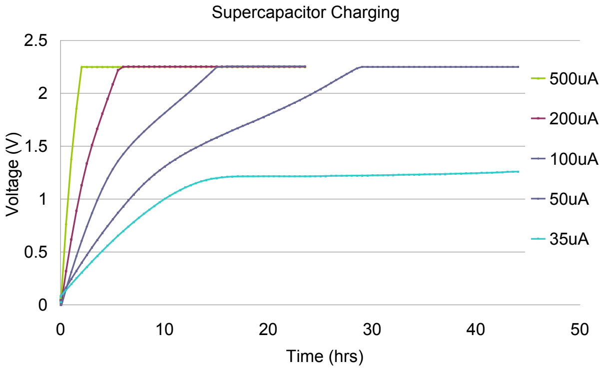

Figure 10: Supercapacitor charging at low levels of constant current.

$$V = Vs(1-e^{t/aRC})$$

where a has been empirically determined:

$$a = 6\times10^{-3}\sqrt{t} + 0.8125$$

where t is in seconds. Figure 11shows an excellent curve fit. Note that as time increases, the equation is governed by √t. Previous work at CAP-XX has shown that supercapacitor properties are affected by diffusion of ions in the pores of the carbon electrodes, so the effective capacitance for a current pulse of duration τ is proportional to √τ. This was the clue to trialling an equation governed by √t

Figure 12 shows the self discharge curves for the population of 12 x HS108 supercapacitors and two empirical curve fits. The fit labelled “Est 2” follows the classical equation where self discharge is modelled by leakage through a resistor in parallel to the supercapacitor and is given by:

$$V = Vinit \times e^{-t/RC}$$

where R = 5.5MΩ and C = 1.8F. Figure 12 shows that “Est 2” was not a very good fit. Therefore we tried another curve, labelled “Estimate” given by:

$$V = Vinit - 0.025317\times\sqrt{t}$$

While not ideal, this is a reasonable fit, especially for the first 800hrs, making this a good model where the interval between peak load events < 800hrs or ~1month.

This confirms our conclusion in section 7.3, that the user should experiment with a population of supercapacitors intended for use to determine their actual charge / discharge characteristics and modify the equations given in section 7.4 accordingly.

9. Conclusion

This paper has shown how a supercapacitor can be used to power a remote wireless sensor from a low power source such as a 3V watch battery and examined design considerations for the power architecture and selection of the supercapacitor. In particular we have focused on using a single cell organic supercapacitor due to this device type’s superior energy density and low leakage current without any need for circuitry to balance multiple cells in series. We have provided a worked example as a guide for engineers designing their system and highlighted how supercapacitor charge and self discharge behavior should be characterized to minimize energy use.

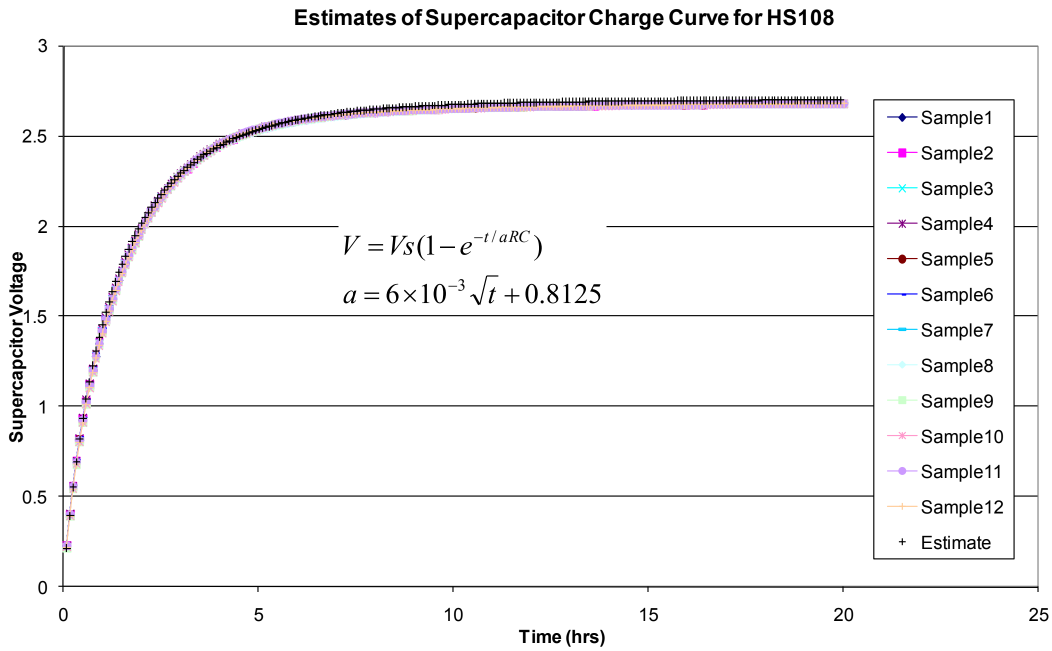

Figure 11. Supercapacitor charging does not follow the classical model

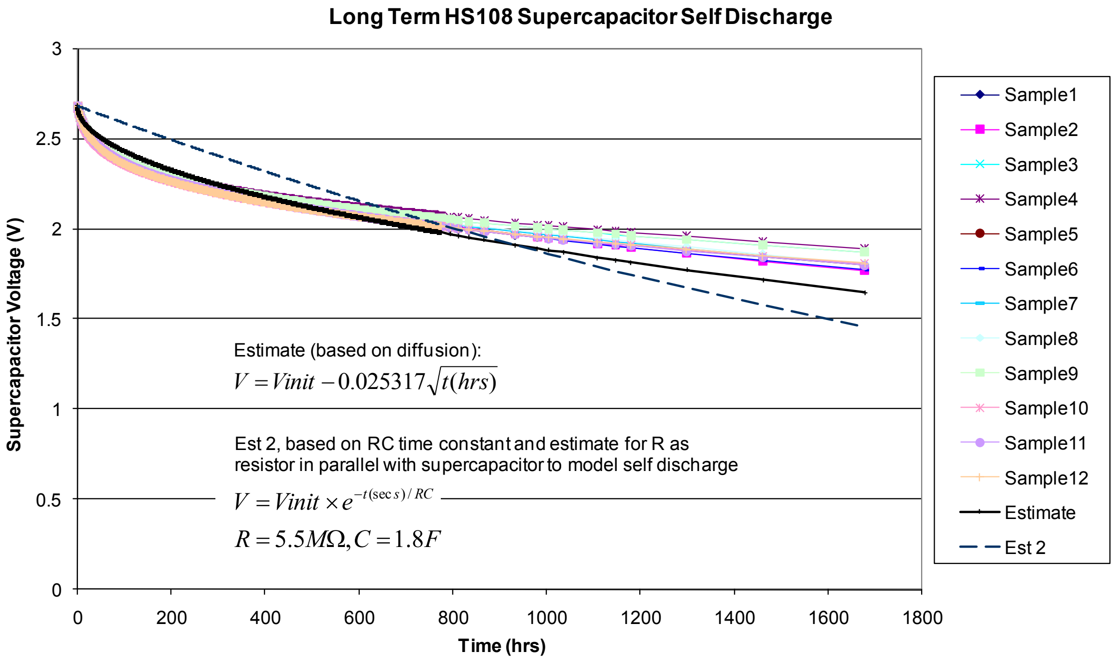

Figure 12: Supercapacitor self discharge characteristic

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