Long-Duration Solar-powered Wireless Sensor Networks

Peter Corke
CSIRO ICT Centre
P O Box 883, Kenmore 4069
AUSTRALIA
peter.corke@csiro.au

Philip Valencia
CSIRO ICT Centre
P O Box 883, Kenmore 4069
AUSTRALIA
philip.valencia@csiro.au

Pavan Sikka
CSIRO ICT Centre
P O Box 883, Kenmore 4069
AUSTRALIA
pavan.sikka@csiro.au

Tim Wark
CSIRO ICT Centre
P O Box 883, Kenmore 4069
AUSTRALIA
tim.wark@csiro.au

Les Overs
CSIRO ICT Centre
P O Box 883, Kenmore 4069
AUSTRALIA
leslie.overs@csiro.au

ABSTRACT

This paper discusses hardware design principles for long-term solar-powered wireless sensor networks. We argue that the assumptions and principles appropriate for long-term operation from primary cells are quite different from the solar power case with its abundant energy and regular charging cycles. We present data from a long-term deployment that illustrates the use of solar energy and rechargeable batteries to achieve 24x7 operation for over two years, since March 2005.

1. INTRODUCTION

Sensor networks are now being deployed in a variety of situations, and each has its own unique energy requirements, sources and challenges. Our interest is in environmental monitoring for land and water systems and for tracking animals on a farm[8, 9]. Typically, environmental monitoring applications have access to solar energy during the day, the full potential of which has not been well explored in the wireless sensor network community. The following example illustrates the utility of solar power. The worst case solar insolation in Fairbanks (Alaska) is 2.12 $\mathrm{kWh/m^2/day}$ (or, about 212 $\mathrm{mWh/cm^2/day}$) (see www.solar4power.com /solar-power-insolation-window.html, for example). Assuming solar conversion efficiency of 10%, we can obtain about 21 $\mathrm{mWh/cm^2/day}$. Consider a device/application with a 1 mA continuous average current draw at 3 V. This amounts to an energy requirement of 72 mWh/day, which can be provided by less than 4 $\mathrm{cm^2}$ of solar cell. In other parts of the world with higher solar insolation, the solar cell required would be even smaller. For example in much of mainland Australia and the United States the insolation is above 5 $\mathrm{kWh/m^2/day}$.

Rechargeable battery technology has advanced to the point where NiMH batteries are now a commodity item and Li-ion batteries are only a little more expensive. Solar cell technology has been stable for a long time now and small solar panels (about $1000 - 10000\ \mathrm{mm^2}$) are also becoming commodity items. Super-capacitors are trending similarly and hold the promise of longer operational lifetime.

In this paper we challenge some of the common principles related to powering of wireless sensor nodes. We argue that solar operation is a fundamentally different problem to long-term operation from primary cells and that different design tradeoffs apply. We present the design principles of our node, the Fleck, as well as data from a long-term solar-powered deployment of a wireless sensor network monitoring the environment.

EmNets '07, June 25-26, 2007, Cork, Ireland

2. PREVIOUS WORK

Our experiment was conceived in late 2004 and commenced in March 2005. Since that time several papers on this topic have appeared [7, 2, 3, 4] but we are not aware of any similar long-term deployments. Raghunathan *et al.* [7, 2] present the design, implementation and performance evaluation of the Heliomote — a Mica2 [1] mote with a custom circuit board for solar harvesting equipped with 2 NiMH batteries and a small solar panel. They tested the device for a week and demonstrated, in principle, that their device is capable of near perpetual operation. Jiang *et al.* [3] present the design and implementation of *Prometheus* — a Telos-mote [6] based sensor node relying on solar energy, super-capacitor and Li-ion batteries. *Prometheus* varies its duty cycle based on available power. These nodes are also capable of operating for very long periods on low duty cycles from solar and super-capacitor storage alone and results over ten days are discussed. Minami *et al.* [4] present a system of battery-less sensor nodes that utilize a solar cell and a super-capacitor. These nodes adapted their operation to the level of charge available. The authors however, have not reported any results for a long-term deployment.

Solar-aware communication protocols have been mentioned in [6], while Voigt *et al.* [11, 10] present some interesting simulation-based work on solar-aware protocols.

In this paper we present results from a deployment that has run for more than 2 years, using solar cells and rechargeable batteries, and straightforward non-energy aware protocols.

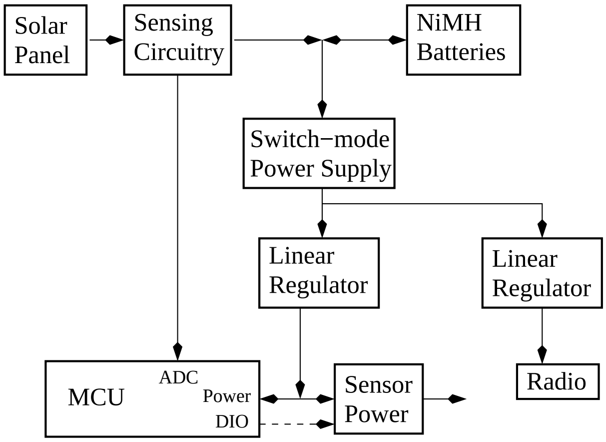

Figure 1: The power stage of the Fleck1.

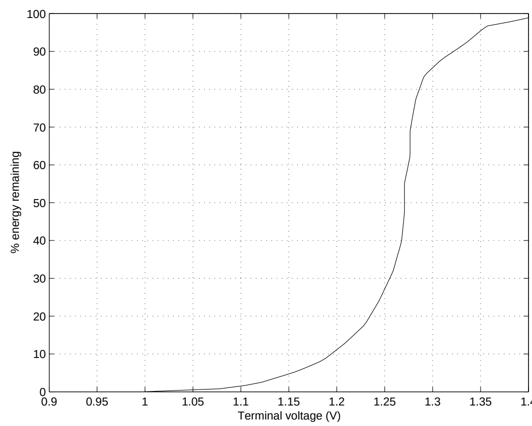

Figure 2: Battery energy remaining as a function of battery voltage (for Energizer Alkaline E91 cell).

3. DESIGN PRINCIPLES

Figure 1 shows the architecture of the power input stage to the Fleck1 [8]. This stage was designed to extract the maximum possible amount of energy from the energy source, be that a primary cell, a rechargeable battery or a super-capacitor. The downside is a small continuous current draw to drive the DC-DC converter. However many designs place undue focus on leakage current rather than the complete picture and eschew the use of power converters. Currently we use NiMH batteries, in preference to Li-ion, as they do not require a complex charging circuit.

To investigate the benefits of a DC-DC converter consider the case of a unit powered from two alkaline primary cells (Energizer E91). Typically, these cells have an initial voltage of 1.5 V and can provide 15.4 kJ (2.85 Ah) of energy. A pair of batteries connected in series can therefore provide 30.8 kJ of energy with an initial voltage of 3 V. If the electronics works down to 2.7 V (or 1.35 V per battery), as is the case of the Mica 2, then Figure 2 indicates that about 90% of energy remains in the battery. If the minimum voltage is 2.5 V, then about 25% of the energy remains. Our design uses a DC-DC converter that can work down to 1.2 V, but with a penalty of a 100 μA continuous current draw. Using the power converter results in only 4% of energy remaining.

i_{avg} (mA)	t_1 (days)	t_2 (days)
0.1	212	327
0.2	106	219
0.5	42	109
1	21	60
5	4.2	13
10	2.1	6.4

Table 1: Node lifetime as a function of current draw with (t_2) and without (t_1) a DC-DC converter.

The amount of extra energy recoverable from the batteries is thus very significant.

Now we discuss the negative aspect of this continuous current draw: 100 μA at 3 V is 300 μW. Table 1 shows the node lifetime for various average application current consumption, assuming a 3 V supply.
where t_1 is the time to live in days consuming down to 2.5V then stopping — the Mica2 approach. t_2 assumes a DC/DC converter, with the parameters given above, on top of the application's consumption. The second strategy is clearly better, and the ratio t_2/t_1 improves with increased current consumption (the leakage is less significant), but it is never worse.

For higher average current and daily solar charging patterns the benefits of the converter approach is clear. It is particularly advantageous for use with a super-capacitor. A pair of AA NiMH rechargeable batteries has a capacity of 5000 mAh or 54 kJ, but by contrast a 50 F super-capacitor charged to 3 V holds only 225 J, just 0.4% of the battery's capacity. Recovering as much of that stored energy as possible is critical.

Another important design consideration is whether there is a need for a battery at all. In Prometheus[3], for example, the battery is an "emergency" supply. However, in our environment, prolonged low light is not a problem. Solar cell failure is possible but could be detected and reported using residual super-capacitor charge before the node goes down. An emergency supply only delays the inevitable failure of a solar powered node, but adds to the complexity. However the importance of this is application specific.

Figure 3 compares the terminal voltage for two Flecks, one operating outdoors with daily charging cycles, and one operating indoors with insufficient light to charge it and which fails after 10 days. The shallowness of the charging cycle can be clearly seen.

The Fleck1, see Figure 4, is an integrated solar-powered wireless sensor node. It is a mote class device with an Atmega 128 processor and a Nordic nRF903 radio chip operating at 433 MHz for improved radio range in outdoor environments. It measures 60×60 mm. The solar panel is rated at 4 V open-circuit voltage and can provide a maximum current of 300 mA. The Fleck1 has a normal current draw of 11 mA with the radio off, 32 mA with the radio in receive mode, and 37 mA with the radio transmitting at full power (at the nominal voltage of 3.8 V).

4. RESULTS

We have a small network which has grown in size from four to fifteen nodes currently, monitoring the environment around our work-premises since March 2005. In this section

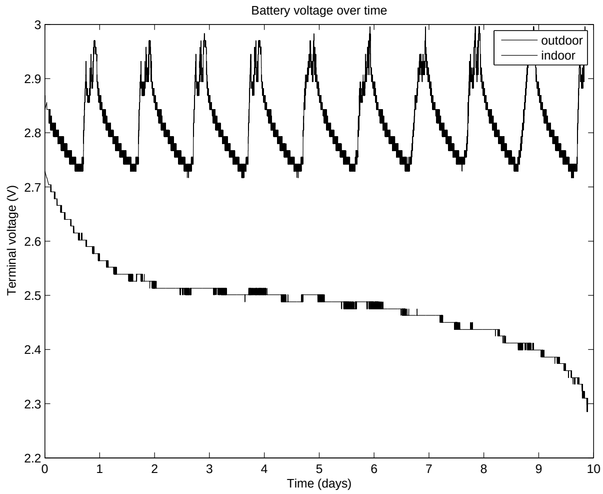

Figure 3: Comparison of battery terminal voltages for 2 solar powered Flecks, one outdoors and the other one indoors.

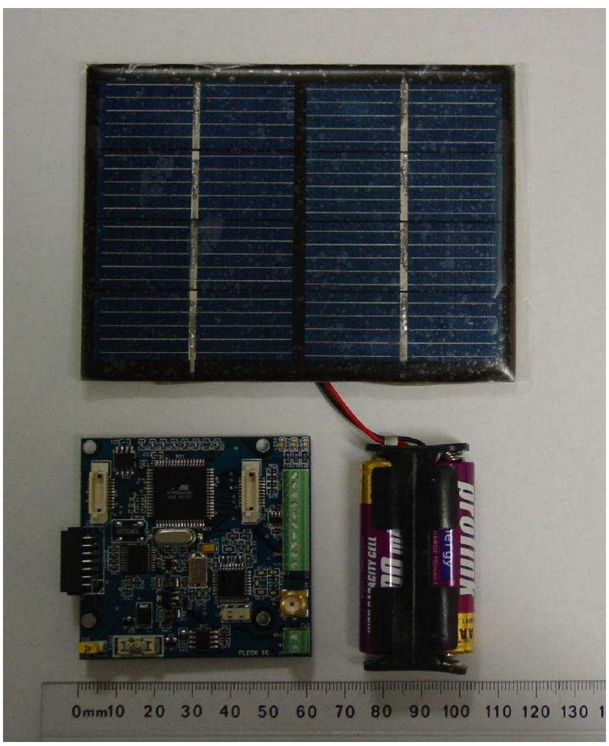

Figure 4: A complete solar-powered node: a Fleck1, two NiMH batteries and a solar panel. The solar panel measures 115×85 mm (almost 100 cm^2) and the batteries are standard AA size NiMH rechargeable batteries.

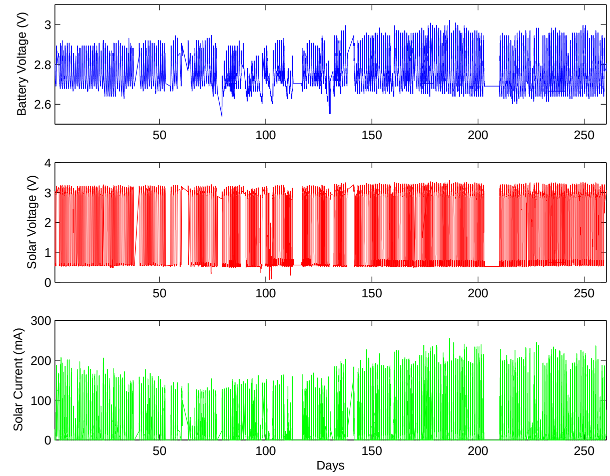

Figure 6: The solar voltage, solar current and battery voltage over a nine month period.

we present sample results from the four nodes which were in the original deployment for which we have the longest data records.

Figure 5 shows an example of one of the original sensor nodes deployed near a creek flowing through our work-site. It also shows a recent picture of another one of our oldest nodes. A new solar panel has been placed alongside to provide some indication of the degradation over the 2 years since the node was deployed. However, this degradation is cosmetic and the panel is still supplying more than sufficient power to the node.

For all nodes we continuously logged data from the solar panel and node batteries. An example of this data is shown in Figure 6, where the solar voltage and current levels as well as the battery voltage levels are shown for a single node over a nine month period. The gaps in the data which can be observed are a result of problems with our gateway not logging data rather than the network being down and includes a large outage over the holiday period in December and January.

The battery level varies from a high of about $2.9 - 3.0$ V down to about $2.65V$. According to typical discharge curves for NiMH batteries, a cell voltage of 1.3 V corresponds to a depth of discharge less than 20% indicating a very shallow discharge cycle for the batteries. Since battery life in number of charge/discharge cycles decreases logarithmically with depth of discharge, we can expect to obtain about 1000-2000 cycles from the batteries [5] (about 3-5 years). Unfortunately the batteries were routinely replaced before the two year point so we are not able to investigate this phenomenon.

An example of the characteristic relationships between battery voltage, solar voltage and solar current is shown in Figure 7 for a single node over six days. The daily charge/discharge cycle is clearly shown, where the battery voltage can be seen to slowly drop once the solar power fades away. An interesting observation was that the nightly patrols of security guard cars past the nodes resulted in small peaks in the solar voltage in the nighttime voltage troughs! Current inflow periods vary from 10 hours per day in winter to nearly 12 hours per day in summer — greatly exceeding the 6 hours per day assumption in Section 1.

Figure 5: (a) A deployed Fleck1 node in the field. (b) A recent picture of one of the oldest deployed Fleck1 node in the field. A new solar panel is also shown to provide an indication of the degradation over 2 years.

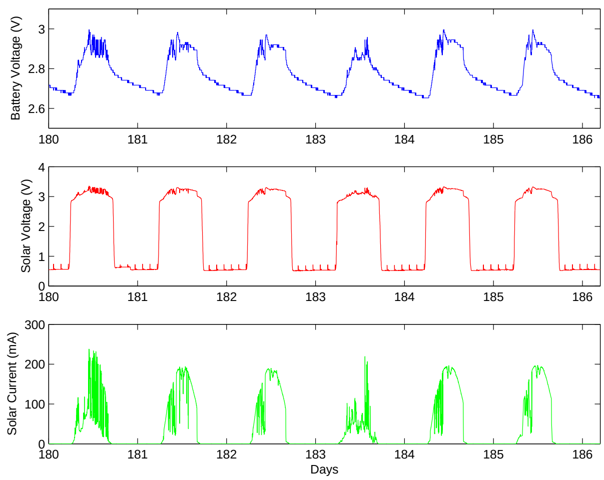

Figure 7: The solar voltage, solar current and battery voltage over a six day period.

By integrating the solar power measurements over time for each month, we are able to estimate the total solar energy received for each node for each month. This is shown in Figure 8 for four of the nodes deployed from March to November.

While there are clear trends over all nodes in relation to seasonal changes, there is also significant variation. This can be explained by the highly varied locations of each node. Nodes such as 88 are far more exposed and hence show higher energy and far less seasonal variation than nodes such as 91 which are near dense foliage. The monthly energy harvest ranges from 80 to 400 kJ which corresponds to a **continuous** average current of between 17 and 51 mA.

Our network in Brisbane (latitude $27^{\circ} S$) has a daily average number of sunshine hours[1] ranging from 6.5 to 8.5 hours. Figure 9 shows variation for one node over a three-month period which corresponds to unstable local weather conditions. The top curve shows the official sunshine hours for the city , measured 20km away from the deployment,

[1]Sunshine hours from the Australian Bureau of Meteorology and recorded using a Campbell-Stokes recorder.

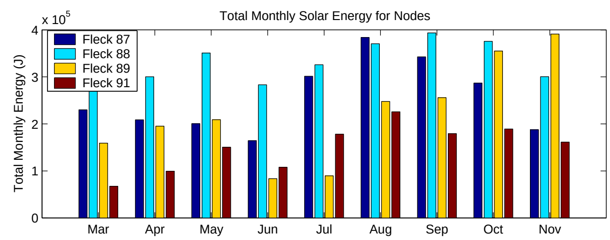

Figure 8: The solar energy received monthly by each node in the sensor network over nine months (In the southern hemisphere June/July is winter).

The second curve shows daily average power harvest and we can see some correlation. The third curve shows the daily minimum and maximum battery voltage, which tend to track each other, and the effect of reduced energy harvest can be seen. The bottom graph shows the daily number of packets received which reflects network outages and network software changes.

5. FUTURE DIRECTIONS

Super-capacitors hold the potential for much longer endurance than rechargeable cells. The experiments in this section were conducted with $2.5V$ $55F$ capacitors and a Fleck1 programmed with a simple application that broadcasts a packet containing the supply voltage once every minute and sleeps. This leads to a very low duty cycle of about 0.03%.

The top graph in Figure 10 shows the input voltage as a function of time for a fully charged capacitor and for 2 fully charged capacitors in series driving a Fleck1 running the above application. A single super-capacitor keeps the Fleck alive for over 14 hours, while 2 super-capacitors in series keep the sensor node active for over 27 hours. Since our maximum daily non-charging period is 14 hours, this should allow for perpetual operation without batteries except for prolonged periods without sunlight.

The bottom graph in Figure 10 shows the energy stored in the capacitor(s) as a function of time. The slope of the linear part of the curve is $-1.8\,\mu$W which corresponds to an energy consumption of -109.8 mJ in each cycle. Note that almost

50 J is lost within the first 2 hours as a result of leakage in the case of 2 capacitors driving the sensor node. This is about 20% of the total energy stored in the capacitors.

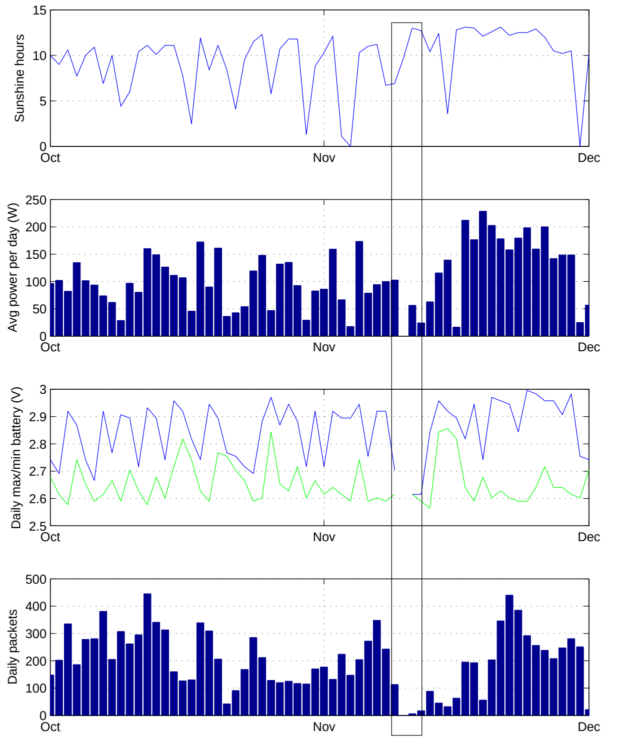

Figure 9: Details of variation in energy due to sunshine (2006). The rectangle indicates a weekend outage in the server.

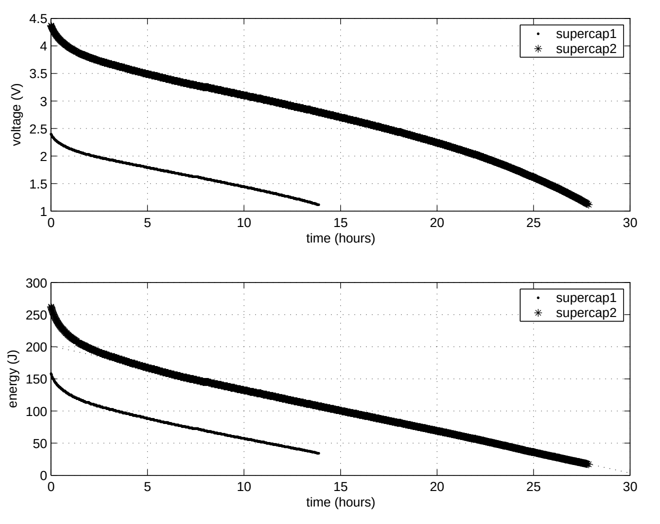

Figure 10: Discharge curves for super-capacitors driving a Fleck1. The graph at the top shows the capacitor voltage as a function of time, while the graph at the bottom shows the energy stored in the capacitor as a function of time.

6. CONCLUSION

We have discussed the design principles for a solar-powered sensor node. We argue that a DC-DC converter is critical for efficient energy recovery and that its perceived drawbacks are not significant. We also show that the daily charging cycles are shallow which should lead to long battery life. We use simple NiMH battery technology which does not require complex charging circuitry. In outdoor environments energy availability is very high, allowing significant relaxation of the severe energy constraints which have become part of the wireless sensor network mind-set. These arguments are supported by results from our small but steadily growing long-term deployment which has been solar powered since March 2005. Finally, we believe that super-capacitors alone are sufficient for energy storage and our next generation of nodes will adopt this approach.

7. REFERENCES

[1] J. Hill, R. Szewczyk, A. Woo, S. Hollar, D. Culler, and K. Pister. System architecture directions for network sensors. In *ASPLOS*, 2000.

[2] J. Hsu, S. Zahedi, D. Lee, J. Friedman, A. Kansal, V. Raghunathan, and M. Srivastava. Demo abstract: Heliomote: Enabling long-lived sensor networks through solar energy harvesting. In *Fourth International Conference on Embedded Networked Sensor Systems*, 2005.

[3] X. Jiang, J. Polastre, and D. Culler. Perpetual environmentally powered sensor networks. In *IPSN/SPOTS*, 2005.

[4] M. Minami, T. Morito, H. Morikawa, and T. Aoyama. Solar biscuit: A battery-less wireless sensor network system for environmental monitoring applications. In *The 2nd International Workshop on Networked Sensing Systems*, 2005.

[5] MPower Solutions Ltd, Scotland. *Battery Life (and Death)*. http://www.mpoweruk.com/life.htm.

[6] J. Polastre, R. Szewczyk, and D. Culler. Telos: Enabling ultra-low power research. In *IPSN/SPOTS*, 2005.

[7] V. Raghunathan, A. Kansal, J. Hsu, J. Friedman, and M. Srivastava. Design considerations for solar energy harvesting wireless embedded systems. In *IPSN/SPOTS*, 2005.

[8] P. Sikka, P. Corke, and L. Overs. Wireless sensor devices for animal tracking and control. In *1st EmNetS*, pages 446–454, 2004.

[9] P. Sikka, P. Corke, P. Valencia, C. Crossman, D. Swain, and G. Bishop-Hurley. Wireless adhoc sensor and actuator networks on the farm. In *IPSN'06*. ACM, Apr. 2006.

[10] T. Voigt, H. Ritter, and J. Schiller. Solar-aware routing in wireless sensor networks. In *Personal Wireless Communication*, 2003.

[11] T. Voigt, H. Ritter, and J. Schiller. Utilizing solar power in wireless sensor networks. In *The 28th Annual IEEE Conference on Local Computer Networks*, 2003.