

Maximizing Efficiency of Solar-Powered Systems by Load Matching

Pai H. Chou, Dexin Li and Sungjun Kim
Center for Embedded Computer Systems
University of California, Irvine, CA 92697-2625 USA
{phchou,dexinl,ksungjun}@uci.edu

ABSTRACT

Solar power is an important source of renewable energy for many low-power systems. Matching the power consumption level with the supply level can make a great difference in the efficiency of power utilization. This paper proposes a source-tracking power management (STPM) strategy that maximizes the panel's total energy output under a given solar profile by load matching. The power efficiency was validated by extensive measurement. Compared to a conventional solar powered system, our load matching strategy improves the power utilization by 114% for a portable system performing image processing and wireless communication tasks.

Categories and Subject Descriptors

C.3.8 [Computer Systems Organization]: Special-Purpose and application-based systems—*Real-time and embedded systems*

General Terms

Design, experimentation

Keywords

Solar energy, photovoltaics, power model, solar-aware, power management, load matching

1. INTRODUCTION

Solar power represents one of the most important sources of renewable energy to complement batteries in portable and autonomous devices. Examples range from satellite systems, emergency telephones, remote sensors, sun-powered radios, and space vehicles. Batteries carry a finite, relatively small amount of energy, and battery technologies have been improving at a slower rate than the increase in demand. Fuel cells may have higher energy density but are expensive. Small nuclear generators are the longest lasting and are found in space probes, but they are unsuitable for many small, disposable systems on earth where cost and safety are obvious concerns. This leaves solar power as a viable, reliable source of energy for extended operations.

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Conventional power management algorithms are driven by workload and possibly remaining energy. However, solar powered systems must also consider the output level of the solar panel for power management for several reasons. First, the solar power is not only a non-ideal energy source but also not an energy storage. This implies that the most important consideration is to maximize the utility of the solar power while it is available, instead of always minimizing power by dynamic voltage scaling. Of course, the utility can include recharging the battery, but overcharging the battery can be counterproductive.

Another problem that is of particular importance to solar panels is load matching. Solar panels, like batteries and other power sources, have internal resistance R_i . Unlike batteries, whose R_i is around 0.7–1.2 Ω , solar panels have a much larger R_i value as a function of the solar output and current drawn. Because the R_i forms a voltage divider with the load R_L , the effective value of R_L directly determines the efficiency of the solar panel. In other words, if the load R_L is not balanced with R_i , then much of the power can be wasted. If the load is matched then the system can get the maximum benefit from the available power for longer operation, more precise computation, or higher quality communication.

This paper makes the following contributions. First, we present a power source model for solar panels by a mix of analytical and empirical techniques. Second, we develop a solar-aware power management technique that complements today's workload-driven techniques for maximizing the power efficiency by load matching. We demonstrate the advantages of our technique by measurement on real hardware. Finally, this research work results in a tool that can help designers determine the optimal size and budgets for these solar-powered embedded systems.

2. BACKGROUND: PHOTOVOLTAICS

A photovoltaic (PV) cell, also known as solar cell, is a semiconductor device that generates electricity when exposed to light. When light strikes a PV cell, the photons dislodge the electrons from the atoms of the cell. The free electrons then move through the cell, creating and filling in holes in the cell. This movement of electrons and holes generates electricity. The physical process by which a PV cell converts light into electricity is known as the photovoltaic effect.

The major types of materials for building PV cells include crystalline and thin films, which differ in terms of light absorption efficiency, energy conversion efficiency, manufacturing technology, and cost of production [1]. Fig. 1 lists a comparison of PV materials.

Existing electronic models for solar cells characterize properties such as the open circuit voltage (V_{oc}), the maximum power voltage (V_{mp}), and the maximum power current (I_{mp}) in terms of the short

Material	Crystalline			Thin films		
	Single-Si	Poly-Si	GaAs	a-Si	CaTe	CuInSe ₂
Absorption efficiency	low	low	medium	high	high	high
Conversion efficiency	15-20%	10-14%	25-30%	5-9%	7%	18%
Cost	low	low	high	medium	medium	high

Figure 1: A comparison of PV materials.

circuit current (I_{sc}), which is in turn modeled as a function of the beam and diffuse irradiance, air mass (AM_a), incident angle (AOI), and panel temperature (T_c) [2, 3].

First, the short circuit current is

$$I_{sc} = I_{sc0} \cdot f_1(AM_a) \cdot \left(\frac{(E_b \cdot f_2(AOI) + f_d \cdot E_{diff})}{E_0} \right) \cdot (1 + \bar{\alpha}_{I_{sc}} \cdot (T_c - T_0)) \quad (1)$$

$f(AM_a)$ and $f(AOI)$ are functions of air mass and incident angle, respectively, and are defined as

$$f(AM_a) = A_0 + A_1 \cdot AM_a + A_2 \cdot AM_a^2 + A_3 \cdot AM_a^3 + A_4 \cdot AM_a^4, \quad \text{and} \quad (2)$$

$$f(AOI) = B_0 + B_1 \cdot AOI + B_2 \cdot AOI^2 + B_3 \cdot AOI^3 + B_4 \cdot AOI^4 \quad (3)$$

E_e is defined as the ratio of the measured short-circuit current to the short-circuit current at reference conditions.

$$E_e = \frac{I_{sc}}{I_{sc0}} \cdot (1 + \bar{\alpha}_{I_{sc}} \cdot (T_c - T_0)) \quad (5)$$

The open-circuit voltage is

$$V_{oc} = V_{oc0} + N_s \cdot \delta(T_c) \cdot \ln(E_e) + \beta_{V_{oc}} \cdot (T_c - T_0) \quad (6)$$

The maximum power is defined as

$$P_{mp} = V_{mp} \cdot I_{mp}, \quad \text{where} \quad (7)$$

$$I_{mp} = I_{mp0} \cdot (C_1 \cdot E_e + C_2 \cdot E_e^2) \cdot (1 + \bar{\alpha}_{I_{mp}} \cdot (T_c - T_0)) \quad (8)$$

$$V_{mp} = V_{mp0} + C_3 N_s \delta(T_c) \cdot \ln(E_e) + C_4 N_s \cdot (\delta(T_c) \ln(E_e))^2 + \beta_{V_{mp}} \cdot (T_c - T_0) \quad (9)$$

Parameters appearing in Equations (1) – (9) are:

- I_{sc0} , short circuit current at reference conditions
- V_{oc0} , open circuit voltage at reference conditions
- E_b , beam irradiance (W/m^2)
- E_{diff} , diffuse irradiance (W/m^2)
- f_d , fraction of diffuse irradiance (1 for non-concentrating modules)
- $\bar{\alpha}_{I_{sc}}, \bar{\beta}_{V_{oc}}, \bar{\alpha}_{I_{mp}}, \bar{\beta}_{V_{mp}}$, temperature-related co-efficients
- T_c, T_0 : current temperature and reference temperature
- δ a function of temperature
- N_s , number of solar cells

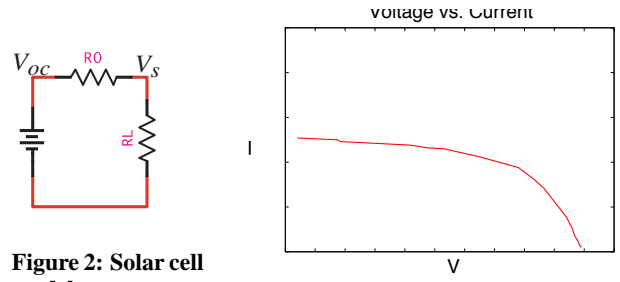


Figure 2: Solar cell model as a power source.

Figure 3: Output voltage vs. current of a solar panel.

- A_i, B_i, C_i ($i = 1, 2, 3, 4$), empirical parameters.

One observation is that, under a given reference condition with a given I_{sc0} , a user needs only one variable I_{sc} to derive the others. However, in order to determine I_{sc0} , one needs to know all the environmental parameters mentioned above, most of which are highly unpredictable and unstable. Even if I_{sc0} is determined, this model gives the upper bound of output power of the solar cells. The actual power output still depends on the load. The following section provides a circuit model that includes the load.

3. POWER MODELING

The internal resistance of solar cells is a function of both the sunlight intensity and the current drawn. Unlike batteries, whose internal resistance R_0 is about 0.7–1.2 Ω , the R_0 of solar cells has a much wider range of 10–10k Ω . As a result, some designs include a voltage regulator between the solar cells and the load circuitry. Another alternative is to use solar cells to charge a battery, which then provides the power to the load circuitry with a stable voltage.

3.1 Circuit Model of a Solar-Powered System

The solar cells can be modeled as an ideal power source and an internal resistor, concatenated with a load resistor to form a close circuit (see Fig. 2). The output voltage of solar cells is :

$$V_s = V_{oc} \cdot \frac{R_L}{R_L + R_0} \quad (10)$$

where V_{oc}, V_s are the open-circuit voltage and the observable output voltage of the solar cells, respectively. R_0 and R_L are the values of the internal resistance of the solar cells and the load resistance, respectively.

Assume ϕ is the sunlight intensity (sunlight power per unit area) that factors in all the environmental parameters like air mass, incident angle, beam irradiance and diffuse irradiance. From Equation (6), we know that V_{oc} is a function of the sunlight intensity ϕ :

$$V_{oc} = h(\phi) \quad (11)$$

Given a $R_L \neq 0$, the close circuit current is:

$$I = \frac{V_s}{R_L} \quad (12)$$

From Equation (10) – (12), by removing R_L we have

$$V_s + R_0 \cdot I = h(\phi) \quad (13)$$

Given a constant sunlight intensity, we know from [4] that I and V_s have a non-linear relation defined by the curve similar to the one shown in Fig. 3. Therefore, R_0 is not a constant, otherwise the V_s and I in Equation (13) would have a linear relation which contradicts to the empirical curves in Fig. 3.

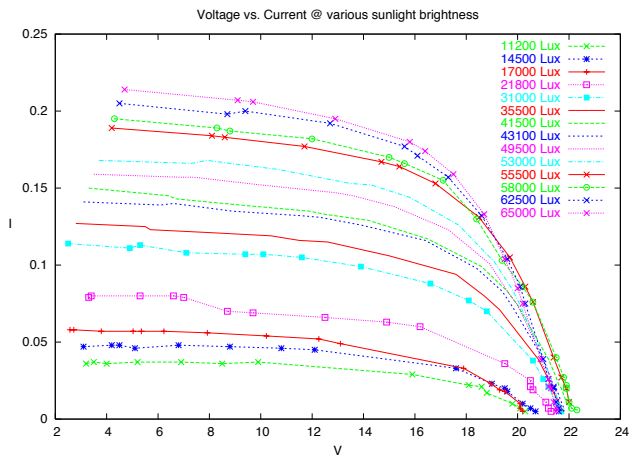


Figure 4: Load current (I) vs. output voltage (V_s) by sunlight intensity ϕ .

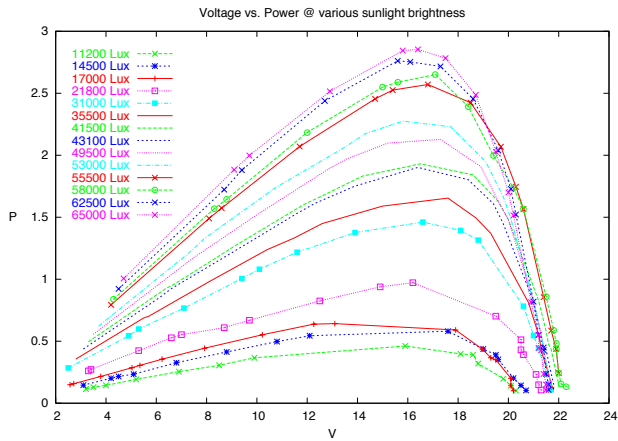


Figure 5: Output power ($P = V_s \cdot I$) vs. output voltage V_s by sunlight intensity ϕ .

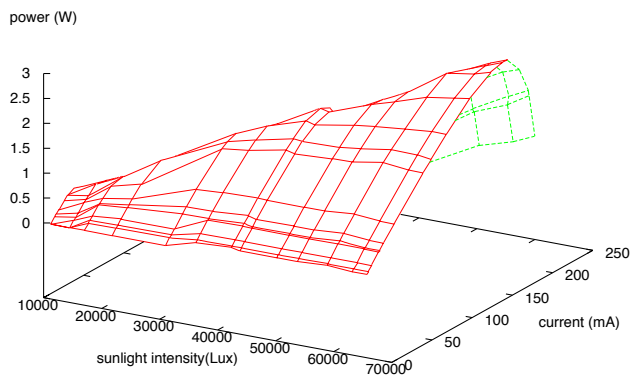


Figure 6: Output power P vs. load current I and sunlight intensity ϕ .

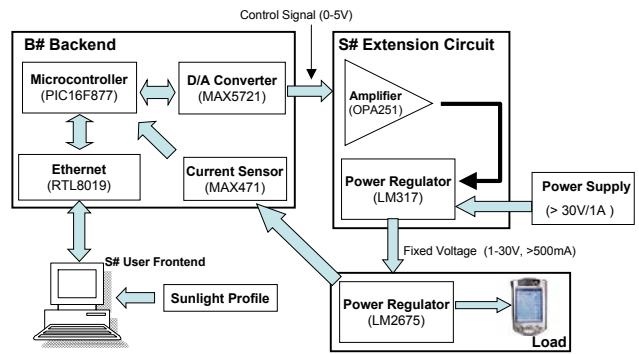


Figure 7: Block diagram of S# Emulator.

3.2 Power Model of Solar Cells

Since R_0 is not a constant, it is difficult to derive an analytical model between the output voltage V_s and the close circuit current I from Equation (13). Instead, we take a measurement approach. We vary the load resistance R_L , and measure V_s at different sunlight intensity ϕ . We obtain a family of curves in Fig. 4 showing the relationship between V_s and I at different sunlight intensity ϕ using Equation (12). Note that this model factors out the environmental parameters such as air mass and diffuse irradiance, because the sunlight intensity ϕ characterizes the actually sunlight power received by the solar panel that already factors in all the environmental parameters.

From Fig. 4 we derive Fig. 5 showing the relationship between the output voltage and the output power ($P = I \cdot V_s$). We further derive the relation between the power consumed by the load (P) and the load current (I) under different sunlight intensity values ϕ (see Fig. 6). It shows that in general the higher the sunlight intensity is, the higher power can be delivered to the load. At certain sunlight intensity, the higher the load current is, the higher power output to the load until it reaches an optimal point beyond which the power output starts to drop as the load current further increases.

4. DESIGN METHODOLOGY

Designing and testing solar-powered systems can be difficult. At the design time, without a suitable solar model a designer may either have a hard time validating the design under corner conditions or over-design the system to reassure the functional correctness while losing power saving opportunities. Field tests at the runtime are extremely challenging because it is almost impossible to reproduce the identical testing environment (i.e., sunlight strength, weather conditions). Even if it is feasible, other factors like geographical location, season of the year may also affect the testing results. Thus we develop a solar power emulator (named S#) for in-house solar experiments. In this section we introduce the S# and explain how it works for design validation. We will show in the next section how S# help design a solar-powered system with high energy efficiency by load matching.

4.1 S# Emulator

S# is a programmable smart power supply that can both simulate and emulate the electronic behavior of a solar panel. It enhances the capability of the B# Emulator [5] for versatility, wider dynamic range of output voltage and faster response time for load with higher frequencies.

The S# Emulator consists of the B# emulator back-end, an ex-

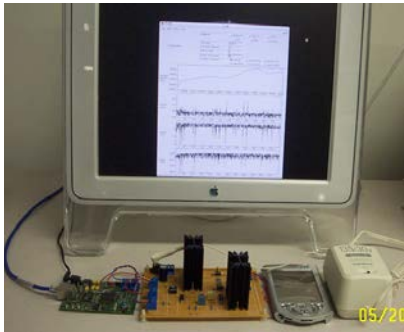


Figure 8: A picture of the S# systems.

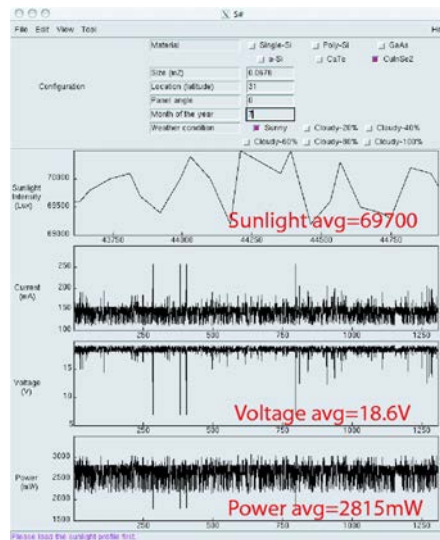


Figure 9: A current profile working under stronger sunlight.

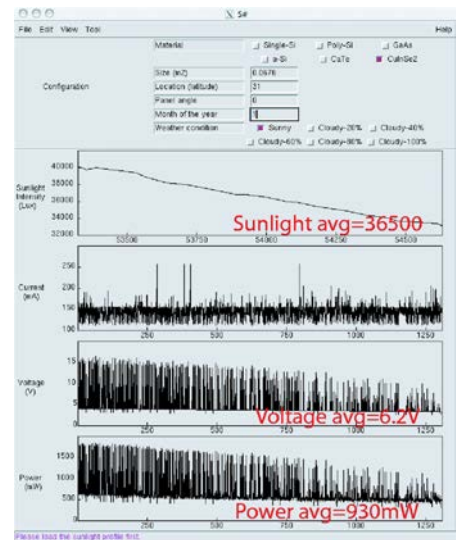


Figure 10: The same current profile working under weaker sunlight.

tension circuit and the user front-end (see Fig. 7 for the block diagram and Fig. 8 for the screen shot). The B# back-end reads the load current from the current sensor, looks up the solar model in the memory of the micro-controller and generates a control signal (0–5V) at the output of the DA converter. The solar model is implemented with lookup tables which significantly improves the response time over the slower simulation-based battery model we implemented for the B# emulator. The extension circuit magnifies (by op-amp OPA251) the control signal to a voltage level ranging 1–24V as suggested by the solar model. From the view point of the load, this voltage is as if output from a real solar panel.

The user front-end allows a user to set the S# to run either in the simulation mode or the emulation mode. In the simulation mode, S# takes a current profile and a sunlight profile as inputs, calls the built-in solar power model and generates a simulated power profile all on the host computer. In the emulation mode, a real load device is connected to the output of the extension circuit and the solar model is downloaded to the memory of the micro-controller. The S# reads the load current at the runtime and generates an appropriate voltage to drive the load. Current and voltage information is transferred to the user front-end through the ethernet interface for profiling purposes.

4.2 Power Validation

In the early design stage of a solar-powered system, a designer may already know an approximate current profile of the load and need to determine whether the solar panel can power the system both sufficiently and efficiently. The user can use the S# front-end to configure parameters of a solar panel and test the load under various environmental conditions (see Fig. 9). The material type determines the sunlight absorption and conversion rates. The panel size is proportional to the power the solar cells can output. Geographical information (latitude), time of a year (month) and weather condition (sunny or cloudy) determine the actual sunlight intensity received by a solar panel.

Given a sunlight profile and a profile of the load current, the S# tells the user how much power the solar panel can provide. The user can try various conditions which are difficult to reproduce in field tests. For instance, a current profile tested under a stronger sunlight

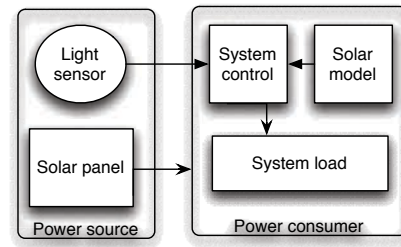


Figure 11: A block diagram of sunlight-aware design.

condition as well as under a weaker sunlight condition is shown in Fig. 9 and Fig. 10, respectively. In the former case, the solar panel constantly provides enough power to the load whereas in the latter case the solar panel outputs less and less power as the sunlight intensity drops. It is very easy for the user to identify the inadequacy of the power output (0.9W as opposed to 2.8W in the former case) which may be a clear sign of a failed design or a malfunction in the specified conditions.

4.3 Load Matching

While power validation is helpful at the design time, a better design of a solar-powered system is to build sunlight-awareness into the runtime. Fig. 11 shows a block diagram of a solar-aware system. The key point is to embed a light sensor into the power source and build a solar model and a control unit into the system. Knowing the ambient sunlight intensity, the system is able to dynamically adjust its load to match the maximum power available for the best system performance. In the next section, we will use a pre-determined set of system configurations as power modes and adjust the load current to match the sunlight intensity. The objective is to maximize the system performance with the available solar energy.

5. DESIGN EXAMPLE

In this section, we experiment an image compression and trans-

Mode	Config.	Power(mA)	T_{cpu}	T_{nic}	T_{total}
M0	206MHz+11Mbps	673	2.0	0.2	2.20
M1	206MHz+5Mbps	593	2.0	0.25	2.25
M2	206MHz+2Mbps	548	2.0	0.65	2.65
M3	206MHz+1Mbps	520	2.0	1.15	3.15
M4	103MHz+1Mbps	405	4.5	1.15	5.65
M5	51MHz+1Mbps	327	10.5	1.15	11.65

Figure 12: Power modes of iPaq 3650+NIC with reduced back-light. T_{cpu} : compression time; T_{nic} : transmission time.

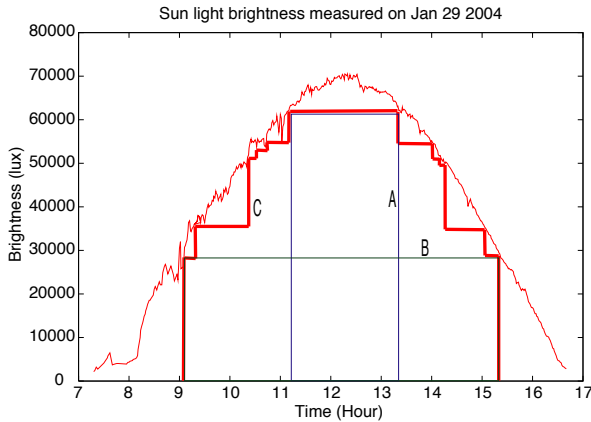


Figure 13: Sunlight intensity of a day (1/29/04, sunny, solar panel position: horizontal) and power consumption for three scenarios. A: full-on, B: conservative, C: load matching.

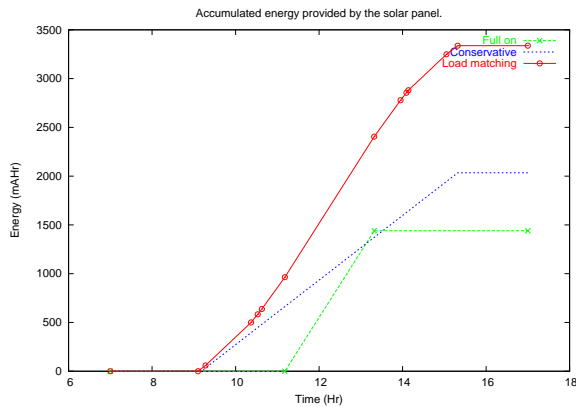


Figure 14: Accumulated energy over time.

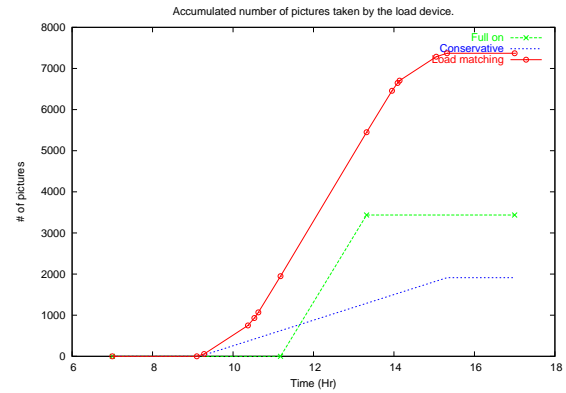


Figure 15: Accumulated performance (the number of processed images) over time.

mission application on a solar-powered handheld device with a wireless network interface. By conducting three tests using a solar panel and one test using a rechargeable battery, we show how load matching improves the system performance. In stead of tuning resistance of the load, we adjust its current level by the selection of power modes because current numbers are easier to measure and widely available from the data sheets of manufacturers.

First, we obtain a sunlight profile from a field measurement with a light meter (Extech 407026). We will use it for multiple tests below. The solar model we use is based on a thin film solar panel Siemens ST5 [6]. Second, we connect an iPaq 3650 handheld without a rechargeable battery to the S# Emulator through a switch regulator (National LM2675).

In all the tests, the handheld repetitively compresses an image (lena, 512x512) and send it out over a 802.11b wireless interface (CISCO Aironet 350). The device has six power modes (configurations of CPU speed and wireless transmission speed) listed in Fig. 12. T_{cpu} and T_{nic} are the average time to compress an image and to send an image, respectively. Note that the overhead of the operating system and the overhead of network protocol (FTP) are included. T_{total} is the average total time to process (compression + transmission) an image. We test the device in three scenarios. Scenario A assumes the device works in full-on mode - both the CPU and the NIC work at their full speeds. Since it has the highest power consumption, it works only at the noon time for about two hours. Scenario B assumes the most conservative power mode in order to keep the on-time of the device as long as possible. In Scenario C the device keeps track of the sunlight intensity and configures itself to match the potential maximum power from the solar panel (see Fig. 13).

Fig. 14 and Fig. 15 show the accumulated energy output over time and the accumulated performance in terms of the number of images processed, respectively. The handheld obtains more energy from the solar panel by load matching (red line) than in the full-on (green line) and in the conservative (blue line) scenarios. It turns out that in the full-on mode, the handheld consumes the least amount of energy due to its shortest on-time (2.16 hours). The handheld processes about twice as the number of images by load matching as in the full-on scenario. The conservative approach gives the worst outcome even though its on-time is equal to that of the load matching mainly because it needs much longer time to process an image.

A separate test is performed to first charge a rechargeable battery

Method	On time		Energy		Performance	
	(Hour)	(%)	(mAh)	(%)	(#)	(%)
Full-on	2.14	100%	1440	100%	3436	100%
Conservative	6.22	290%	2034	141%	1922	56%
Load-matching	6.22	290%	3337	232%	7369	214%
Battery	0.58	27%	391	27.1%	784	22.8%

Figure 16: Comparison of different power management schemes. Full-on: set to mode M0 all the time; conservative: set to mode M5 all the time.

(NiMH, 1600mAh) using the same solar panel. It takes about three mid-day hours on a sunny day to fully charge the battery at a charge rate of 600mAh (then we do not have enough time to fully charge a second battery in the same day). We use the battery as the only power source for the same handheld and continuously perform image compression and transmission. It reaches its cut-off voltage in only 35 minutes and has processed 784 images. This result shows that using the battery to store the solar energy and to power the handheld device is feasible but far less economical than the load matching method. Its performance is about an order of magnitude inferior to the load matching method mainly due to the efficiency loss during the energy conversion and the negative influence of the rate capacity effect and the recovery effect intrinsic to the battery which the solar panel never suffers from.

Fig. 16 summarizes the results of the three scenarios. The device working in the full-on scenario is set as the baseline. The conservative scenario uses the lowest power mode possible all the time thus maintains 2.9 times on-time of the full-on scenario. However its performance in terms of the number of images processed is only about half of the full-on scenario even though it consumes 1.4 times energy of the full-on scenario. By load matching we maintain the on-time same as in the conservative scenario and obtains much more energy from the solar panel. As a result, we double the performance of the full-on scenario. The performance of using a rechargeable battery falls far behind any of the scenarios using load matching with a solar panel. The advantage is using a rechargeable battery lies in its storage capability which is not processed by the solar panel. Indeed, this opens up a unique opportunity for power budgeting and workload scheduling with multiple kinds of power sources.

6. CONCLUSION

Due to the special characteristics of solar panels, solar-powered embedded systems must pay special attention to load matching in order to fully utilize this renewable source of power. Conventional scheme that work for rechargeable batteries do not track the wide variation in solar power and do not perform load matching. As a result they waste a consider amount of power, which can be a precious resource. Load matching requires first characterization of the solar panel's electrical properties, and second a power management policy that tracks the changes. Our result shows over 132% of usable power can be reclaimed using our power management strategy.

7. ACKNOWLEDGMENTS

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