A High-Efficiency Dual-Channel Photovoltaic Power System for Nonvolatile Sensor Nodes

Xiao Sheng*,Cong Wang*,Yongpan Liu*,Hyung Gyu Lee†,Naehyuck Chang‡ and Huazhong Yang*
*Dept. of EE, Tsinghua University, Beijing, China, Email:{xcheng12,wang-yq05,ypliu,yanghz}@tsinghua.edu.cn
†School of Computer and Communication Engineering, Daegu University, South Korea, Email:hglee@daegu.ac.kr
‡Seoul National University, Seoul, South Korea, Email:naehyuck@elpl.snu.ac.kr

***Abstract*—With the development of the internet of things, battery maintaining of trillion sensor nodes becomes prohibitive both in time and costs. Power system with energy harvesting provides a promising solution. However, conventional energy harvesting systems with storage suffer from low efficiency because of conversion loss, storage leakage and so on. Direct supply systems without an energy buffer can achieve high efficiency, but fail to satisfy quality of service due to mismatches between energy harvesting and workloads. This paper proposes a novel dual-channel photovoltaic power system which hybrids a direct power path and a conventional supercapacitor power path. A power management unit is developed to control the channels according to real time solar condition. The nonvolatile processor enables the node system to run reliably and efficiently under varying solar profiles. We develop a simulation platform with real component parameters to validate the proposed techniques. Experimental results demonstrate up to 31.87% energy efficiency improvement under same design cost against the conventional architecture.**

I. Introduction

With the development of the internet of things, several reports [1] predict that the number of smart sensors will reach trillions. It will create a huge worldwide business, including environment, logistics, structure monitoring, home automation and etc. In a trillion-sensor world, maintaining battery for sensors becomes a prohibitive task both in time and costs. It is no surprise that energy harvesting attracts lots of recent efforts to reduce maintaining costs and to prolong the operating time of sensors.

Among various energy sources, photovoltaic (PV) cells are one of the most practical forms for electronic circuits in terms of power output, efficiency, volume and availability. Fig. 1(a) shows a conventional solar energy harvesting system with maximum power point tracking (MPPT)[2]. It tries to extract maximum power from solar panels by the MPPT converter and charges energy into the storage device. After that, the energy storage supplies power to the sensor via the output converter. This approach suffers from unexpected low efficiency between harvested energy and consumed energy by workloads. It was reported that the system-wide efficiency reaches less than 20% due to converters and storage loss [3]. Therefore, designers have to adopt much larger solar panels to compensate the energy loss, increasing both node sizes and costs.

Recently, a storage-less and converter-less solar harvesting architecture [4] has been proposed to directly supply power to the sensors. It achieves near 90% energy efficiency by eliminating energy loss from power converters and storage devices. However, the proposed architecture works in an energy-driven mode with best efforts. It cannot satisfy QoS when there are timing mismatches between harvested energy and workloads.

Conventional energy harvesting systems provide necessary QoS with low energy efficiency, while store-less and converter-less architectures achieve high efficiency in an energy-driven mode. To combine advantages in both architectures, we propose a novel high-efficiency dual-channel power supply architecture, which contains a storage-less and convert-less direct channel, an optimized "store and supply" indirect channel, as well as channel control circuits. The controller dynamically adjusts channels in four switching power modes, to maximize energy efficiency under failure rate constraints. Furthermore, we build both a simulation platform to validate the architecture. Experimental results demonstrate that the proposed architecture improve the overall efficiency by up to 31.87% over traditional supply system under same cost.

This work was supported in part by the NSFC under grant 61271269 and High-Tech Research and Development (863) Program under contract 2013AA01320 and the Importation and Development of High-Caliber Talents Project of Beijing Municipal Institutions under contract YETP0102.

II. A Dual-channel power system

The proposed dual-channel architecture is a combination of the conventional power channel (indirect channel) and the converter-less channel (direct channel), with several switches inserted in the middle. Fig. 1 compares the proposed architecture with the conventional architecture and the converter-less one. We use a supercapacitor as the energy storage, considering its lifetime is much longer than a battery. The direct channel connects the solar panel to the nonvolatile sensor node via a switch and serves as the main power source when harvested energy is sufficient. When solar power decreases or disappears, indirect channel can provide supplementary energy to satisfy the failure rate requirement. Moreover, excessive harvested energy above sensor's consumption can be stored in the supercapacitor of indirect channel to improve energy efficiency. Furthermore, we develop a power management unit (PMU) to select supply channels and tune the QoS level of the NV node dynamically. The PMU module consists of voltage/current sensing units, switching control units and a QoS controller for the sensor node. The channel control mechanism and QoS tuning algorithm try to maximize energy efficiency while satisfying the failure rate requirements.

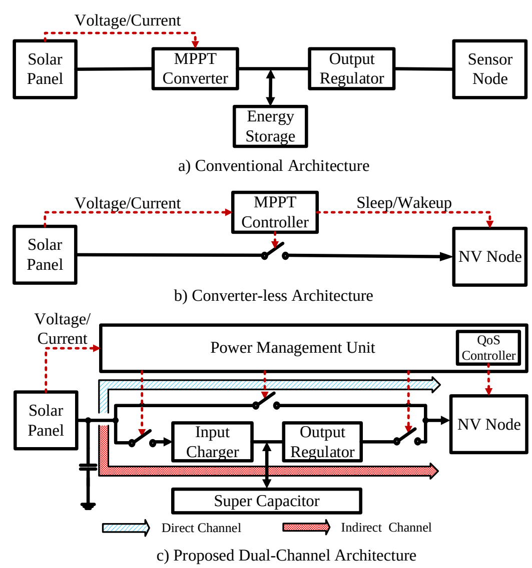


Fig. 1. Architecture comparison between conventional, converter-less and dual-channel

In Fig. 2, we propose a nonvolatile sensor node supporting dynamic QoS scaling (DQS). It utilizes the direct channel for high efficiency, while relieving reliability issues and switching overheads. The proposed node contains a sleep/wakeup driver, a nonvolatile processor and several functional units. The control signal from QoS controller adjusts working modules according to online solar irradiance. Because nonvolatile sensor nodes switch frequently between different levels, switching speed and energy are important. Compared with

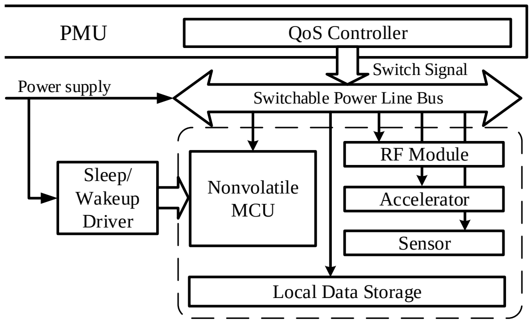
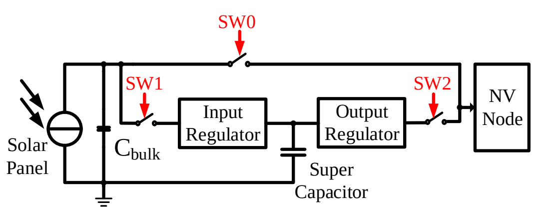


Fig. 2. Nonvolatile sensor node with different QoS levels

hundreds of milliseconds in conventional sensor nodes, nonvolatile processors provide microseconds on/off switching time and low energy overhead with emerging nonvolatile memory. Therefore, the proposed sensor node supports much higher reliability and fine-grained QoS tuning. The QoS level can be tuned by controlling the power switches to function units, thus the proposed architecture can improve the energy efficiency significantly under variable solar profiles.

According to the sensed solar irradiance level, the power management unit controls the work modes of the power system by the switches on the channels. Fig. 3 shows the operating modes of the dual-channel power system. The supply system works in "Direct" mode where the direct channel continuously supplies power to the node when the input energy matches the load consumption region. The "Direct + Charge" mode is adopted when input energy is larger than the maximum load consumption and the excessive energy is charge into the supercapacitor. The switch $SW1$ works in PWM mode to tune the average charge current to match the varying the excessive energy amount. Similarly, the "Direct + Discharge" mode is adopted when the input energy is not enough that the solar panel cannot power the node independently, such as in cloudy days. Finally, the node is powered solely by the supercapacitor when no energy is harvested or the input energy is extremely low.



Work Mode	SW0	SW1	SW2
Direct	ON	OFF	OFF
Direct+Charge	ON	PWM	OFF
Direct+Discharge	PWM	OFF	PWM
Discharge	OFF	OFF	ON

Fig. 3. Operation modes of the dual-channel supply system

III. Evaluation

We extracted the real parameters for the components in our proposed architecture, including the energy conversion efficiency and leakage energy of the solar panel, voltage regulators and the supercapacitor. Then we built a simulation platform based on them and evaluated the performance of proposed dual-channel power system. We use the recorded solar light intensity data of California in the year of 2011 and 2012 [5] as the input solar profiles. The load is a nonvolatile node which runs periodical solar irradiance sampling and transmitting tasks. The QoS controller tunes the QoS levels of the node by adjusting the duty cycle of the sensor and the RF transmitter and the node falls into sleep mode in the rest time.

Tab. I compares the energy efficiency improvements of the dual-channel architecture with conventional one under different solar panel size and supercapacitor size pairs. We can see that the the energy efficiency decreases when larger solar panel and supercapacitor sizes are adopted but the proposed architecture can achieve up to 31.87% system efficiency over the conventional architecture. Sizing up the sizes reduces the failure rate of the system because more energy can be buffered, but it also brings about more energy waste. Fig. 4 shows the detailed distribution of the conventional and proposed architecture using the setting from the fourth row in Tab. I. As we can see, over 31% energy loss comes from over charge in the conventional architecture and only 38% energy is supplied to the sensor node. Meanwhile, in the proposed architecture 27% total energy is supplied to the node via the direct channel, thus using the over charge energy to enhance the efficiency of the node to over 63%. In real applications, designers can set the sizes of the system according to the load power consumption and failure rate constraints to get best efficiency.

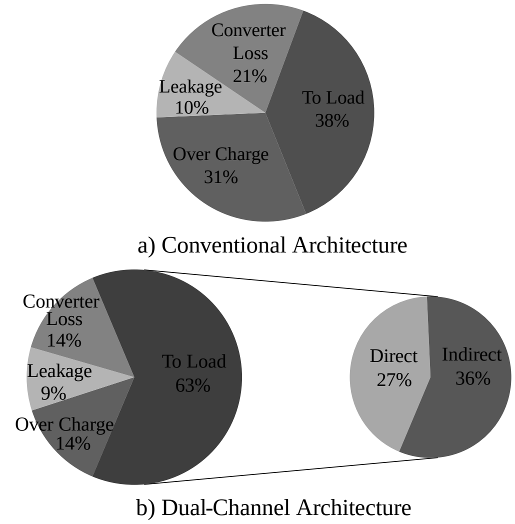


Fig. 4. Energy distribution comparison between conventional and dual-channel architecture (S=30cm^2, C=800F)

TABLE I
EFFICIENCY COMPARISON BETWEEN CONVENTIONAL AND DUAL-CHANNEL ARCHITECTURES

S/cm2	C/F	Conventional	Dual-Channel	Efficiency Gain
10	150	74.34%	86.01%	11.67%
15	250	62.83%	81.95%	19.12%
20	500	54.22%	76.89%	22.67%
30	800	39.14%	63.15%	24.01%
60	1500	19.91%	51.78%	31.87%

IV. Conclusions

Traditional supercapacitor based energy harvesting systems suffer from low efficiency due to conversion loss, leakage, etc. Harvesting systems without storage and converter can achieve high efficiency but cannot always guarantee the task failure rate requirement. This paper proposes a dual-channel photovoltaic power system to increase overall energy efficiency. We develop a simulation platform to validate the proposed technique and the experimental results demonstrate up to 31.87% energy efficiency improvement over conventional architecture under same design cost.

References

[1] J. Bryzek, "Emergence of a trillion mems sensor market," 2012.
[2] T. Esram and P. Chapman, "Comparison of photovoltaic array maximum power point tracking techniques," *IEEE Trans. on Energy Conversion*, vol. 22, no. 2, pp. 439–449, 2007.
[3] S. Liu, J. Lu, Q. Wu, and Q. Qiu, "Load-matching adaptive task scheduling for energy efficiency in energy harvesting real-time embedded systems," in *Proceedings of the 16th ACM/IEEE international symposium on Low power electronics and design*. ACM, 2010, pp. 325–330.
[4] C. Wang, N. Chang, Y. Kim, S. Park, Y. Liu, H. G. Lee, R. Luo, and H. Yang, "Storage-less and converter-less maximum power point tracking of photovoltaic cells for a nonvolatile microprocessor." in *ASP-DAC*, 2014, pp. 379–384.
[5] Measurement and I. D. Center, http://www.nrel.gov/midc/.