Power Supply and Energy Management in Wireless Sensor Networks: A Literature Review

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Abstract Wireless Sensor Networks find applications in diverse fields such as military, health monitoring, security, machine diagnosis and structural integrity. All of these application areas suffer from the inevitable challenge of power management due to limited lifetime of batteries. This paper discusses the system level optimizations for power management in different configurations of Wireless Sensor Networks and the recent developments in energy harvesting techniques. The end result is to present the advantages of energy harvesting, wireless power management and power supply solutions at system level through circuit design, power aware electronics, processor optimizations and OS enhancements.

1 Introduction

Remote Monitoring through distributed networks of sensing devices finds application in a wide spectrum such as health care, environmental management, systems monitoring, military and machine diagonosis. The Wireless Sensor Network (WSN) are often highly distributed and designed to be operated in hostile (human inaccessible) environments such as inaccessible geographic terrains, radioactive environment and military supervised zones. Their distributed nature provides high resolution in data and fault tolerance to abberations [1].

The introduction of Micro-Electro Mechanical Systems (MEMS) technology overcomes volume, mass and energy barriers and allows WSN to be deployed as micro-sensor units. However, the problem with existing WSN network is their operation time. These devices are designed for operability over long lifetimes and with very limited resources (i.e. battery life). Energy efficiency of these micro-sensor nodes is therefore the utmost concern.

The motive of this research is to investigate the solutions for efficient power supply design of WSN. This can be addressed first, at the system level by efficient circuit design and software optimisation of power awareness and energy efficient communications. Second, we investigate energy harvesting (i.e., using ambient energy to power electronic microsensors) approach to scale resource availability for the micro-sensor nodes for application in hostile application areas. Energy harvesting methods reduce the dependance of the system on the battery and get rid of the need for periodic maintenance. [2]

This paper discusses the developments in power supply design methodologies and energy harvesting techniques for WSN. It starts with a description of WSN, application potentials and bottlenecks in system-level power management. Next, an overview of the design methodology for circuit-level optimisation is presented. The following section, analyses plausible energy harvesting techniques, such as wireless charging, wind energy harvesting and photovoltaic systems. Finally, conclusion presents the necessary parameters to design an optimal power supply to maximize lifetime and enhance performance of a WSN.

2 Node Power Supply in Wireless Sensor Networks

WSN is a distributed network and comprises of micro-sensor nodes. When it comes to its design, one of the main issues encountered, is the efficient utilisation of power. The power management issues can be efficiently dealt by optimisations in power supply designs at both system and software level of abstraction. And, although wireless power alternatives are still not able to replace wired sources when it comes to efficiency, operating with low data transmission and power requirements or employing far-field power delivery methods can be considered as an option.

These devices operate on scenarios where it is not possible to deliver power through traditional means (wired sources) or when relying solely on a battery system is not convenient or possible. Recent developments in energy harvesting technology from environmental sources shows potential of application in WSN. Such sources should provide energy to each node autonomously and expand their life time beyond the typical 5 years [3] and consequently finding a way around typical maintenance needs such as the replacement of batteries. The need to overcome challenges of limited lifetime of finite energy storage and autonomy calls for an alternative approach to power supply design in WSN nodes.

3 Power Supply Design Optimisations

This section discusses the power supply designs and optimisation techniques to efficiently manage the available power and consider software level optimisations and trade-off between the various sub components of the microsensor nodes.

3.1 Power Aware System Architecture

The energy consumed by the system can be variable due to workload on the processing system and latency requirements. However, the latency and data quality are not always required from a sensor network. This energy-quality trade-off can be met by Dynamic Voltage Scaling (DVS). Through DVS, we can work on reducing the supply voltage V_{dd} and the clock frequency of the processor if at an instance the workload on the processor reduces or if the computation is latency intensive. This approach can help in trading latency for energy conservation. This approach shows up to 60% reduction in energy consumption than a fixed-voltage supply. Furthermore, power consumption can be lowered by reducing the time to a few miliseconds to startup for transreceivers for communicating short packets [7].

The idea of Low Power, Wireless Integrated Microsensor (LWIM) incorporates an integrated wireless sensor subsystem capable of measurement, data computation, and Radio Frequency (RF) communication that can be demonstrated on a commercial 2μm CMOS. This is implemented by using the new approach of high-Q inductor systems which helps in improving power transceiver design by reducing the duty cycle to operate at 1 - 10 mW RF power. [8]

It is important to maintain the latency and quality while ensuring the optimum use of resources available such as battery life. Therefore, methodologies involving system partitioning, network routing protocols, low energy electronic systems, energy scalable computing techniques and low duty cycle electronics system must be considered. Dynamically reconfigurable system architectures that allow the trade-off between the energy consumption per input sample with respect to quality is an important approach in conjunction with software level optimisations. For Example, energy is inversely proportional to frequency for a fixed amount of power supply. This is because, the execution time increase is accompanied by leakage current increase. Therefore to reduce the energy consumption, it is essential to operate at low voltage. [2] Further optimisations are carried out by improvising a low duty cycle RF communication system [2].

3.2 Power Efficient Software Designs and Communication Protocols

The optimisation on the communication protocol layer paves way for flexibility of a technology and its performance measures in the long-term applications. The versatile low power media access is an important aspect of WSN and B-MAC is a protocol that efficiently introduces comparison of parameters such as reconfigurability, feedback system and possibility of bi-directional interfaces. The objective of protocols such as B-MAC is to explore its flexibility in comparison to IEEE 802.11 standard protocol and its applications in development of multi hop networks such as WSN. The B-MAC has been tested by surge, an application that produced a good amount of data with more than 98.5% efficiency in packet delivery. [9]

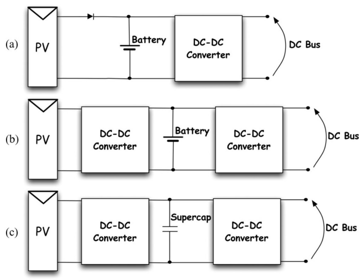
The OS directed approach to optimise power consumption led to the development of eCOS, a real-time operating system with support of frequency scaling and dynamic voltage levels in a compact sensor named AMPS running on a StrongARM processor. Furthermore, the subsequent upgrades have the potential to lower the power consumption of a sensor node 3-4 folds and at the same time allowing possibility to operate on locally harvested energy. [1]

4 Energy Harvesting Methodologies in Wireless Sensor Networks

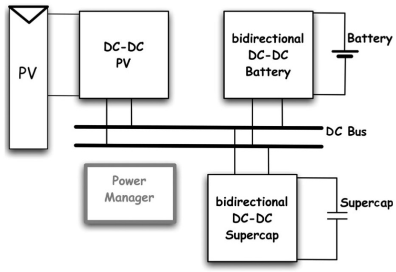
4.1 Photovoltaic Powered Sensor Networks

Harvesting energy from the sun is one of the most widespread approaches to the issue of supplying electrical energy to wireless sensor nodes. However, despite having a solar energy source, the nodes need a support structure within a network for energy storage when the energy source is irregular due to diverse situations, e.g. weather conditions. One of the approaches for photovoltaic powered WSN, is the implementation of a hybrid storage system consisting of a combination of Li-Ion batteries and a supercapacitor. Exploiting the advantages of both systems, former having a higher energy density capacity and lower costs and latter, having high charge/discharge cycles. [3].

Moreover, the behaviour of the system is revamped if a DC-DC converter is placed between the photovoltaic source and the energy storage as in figure 1a. This configuration is used in order to maintain a certain level of the voltage and current arriving at either the battery or the supercapacitor in spite of the energy harvesting fluctuations that the PV source could have. The next stage could also consist of another DC-DC converter to provide a stable voltage for the device to operate.



(a) Different configurations for power supply circuit in solar energy harvesting systems [3]

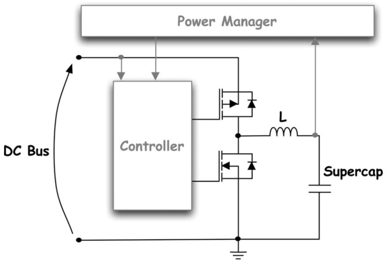


(b) Suggested circuit for energy storage management [3]

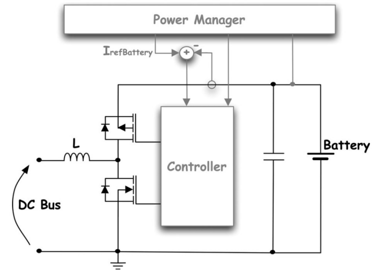
Figure 1: Energy Harvesting Configurations

Regarding the energy storage system for the sensor node, Li+ is advised over NiMH because of the longer cycle lifetime, smaller self-discharge ratio and its cycle-life is not dependent on the depth of discharge problem. The operative lifespan of the Li-ion battery used on the energy storage system for the photovoltaic based WSN, was increased by the significant reduction of the number of charge/discharge cycles (almost four times less). The proposed topology for the nodes power supply circuit is laid out in figure 1b, where 3 DC-DC converters are shown, all in parallel and arranging a DC Bus.

The DC-DC converter which is interfaced to the super-capacitor is a buck converter working in step down mode when the super-capacitor is being charged, and in step up mode when energy is been drawn off from it [3], (See figure 2a). On the adjacent, the DC-DC converter attached to the battery, is a bidirectional boost converter, this allows the battery to be on charging mode and at the same time, providing energy to the sensor node while operating, the arrangement is presented in figure 2b.



(a) Buck converter in supercapacitor [3]



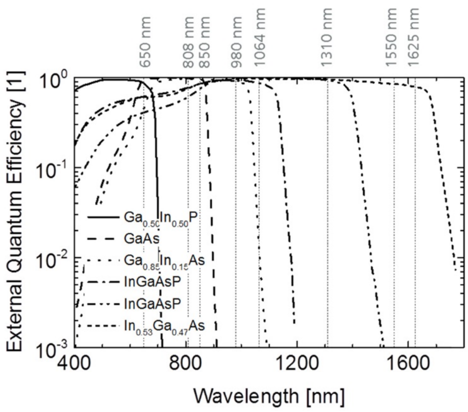
(b) Boost converter in Li-Ion battery [3]

Figure 2: Bidirectional converter for energy storage management

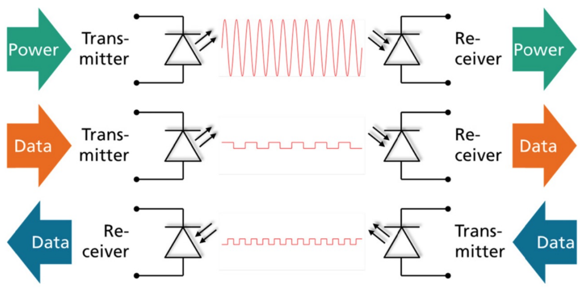
4.2 Photovoltaic Power from Lasers

The transmission of energy through optical means offers inherent advantages of galvanic isolation (lightning) and explosion protection. The basic components of the system are a monochromatic light source (Laser) and a photovoltaic laser power converter.

The convenience of using lasers as of a source of power by light is possible only after recent developments in photovoltaic materials modification. This improves light absorption properties for a specific wavelength. Some examples are shown in figure 3a for certain materials where external quantum efficiency has been measured and then a relation for specific laser wavelengths is made. Since the new photovoltaic cell no longer converts most of the solar spectrum, photon energy thermalization losses are reduced, therefore conversion efficiency rates are improved [4].



(a) External quantum efficiency vs. Wavelength for several materials used in laser power converters [4]



(b) Proposed architectue for a laser based power and data transmission wireless link from station to node [4]

Figure 3: Photovoltaic Power From Lazers

The application of an optical power transmission configuration allows to use the same power from wireless link for both power transference and information exchange between the node and the source/station. To implement this, it is necessary to count on a power transmitter and receiver, a downstream data transmitter and receiver, and a data upstream transmitter and receiver placed at the station (power source) and at the node (sensor), respectively (figure 3b). Laser diodes are mostly used, and photodiodes for the data receivers. LEDs and vertical-cavity surfaceemitting lasers are recommended for the data transmitters [10].

In Photovoltaic (PV) energy harvesting, if the materials or compound used for manufacturing the PV cells are modified, the energy absorption properties and therefore, the efficiency of the PV cell can be enhanced for specific wavelengths. This allows the use of lasers as a source of wireless power, and at the same time the use of the power input link for communications [4].

4.3 Wind Energy Harvesting

Wind Energy is another sustainable energy source for WSN. Small scale Wind Energy Harvesting (WEH) systems designed specifically to power small sensor nodes spread around wide areas face some challenges. Among them are: The low voltage (1-3 VAC) generated by turbine generator at low wind speeds; voltage drop due to diodes in rectifier stage of converter circuit; and low power harvested (in the order of mW) by a WEH system when turbine generator is not operating on ideal conditions.

With the design of a different rectifier based on MOSFETs and voltage active sensing instead of regular diodes (as shown in Figure 4), the experimental results show that the low voltage generated by a small scale wind turbine is enough for good performance. As well, the low power harvested by the small WEH system could be addressed using a boost converter to step up the DC voltage on the ac-dc converters output and resistor emulation methods using algorithms to ensure the maximum power point transference (MPPT) to the load [5]. Figure 5 provides a block diagram for the suggested circuit.

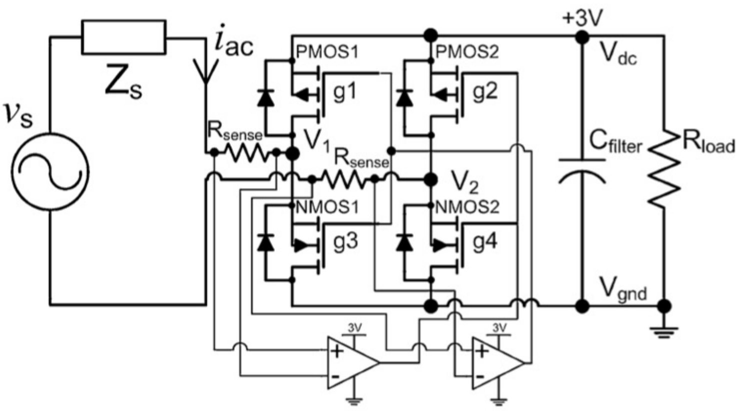


Figure 4: Schematic for full bridge MOSFET rectifier [5]

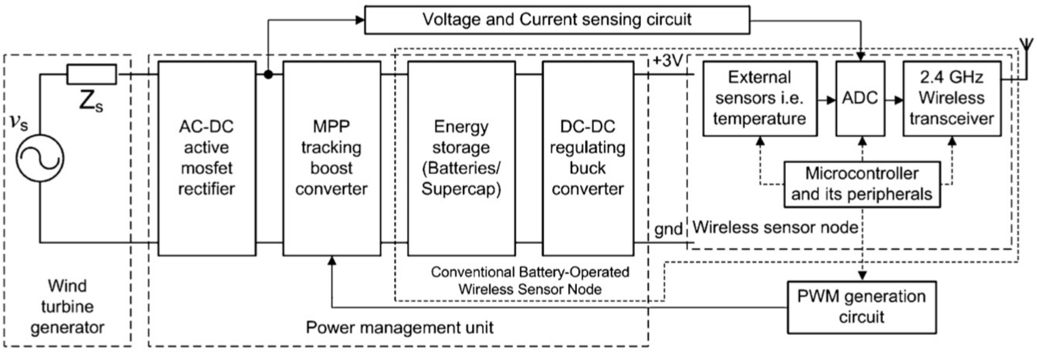


Figure 5: Block Diagram for WEH Wireles Sensor Node [5]

5 Conclusion and Recent Trends

The need for reliable and efficient power sources for WSN can be met by combining two approaches: system-level 'power-aware software'upgrade and energy harvesting.

The architectural level upgrades of system and network protocols includes power aware electronics, low duty cycle processors, OS directed optimizations [1], reliable protocol upgrades (B-MAC) [9] and RF circuit optimizations [8]. However, the challenge of reducing leakage current at the node remains. Architecture level design and IC fabrication methodologies reduce this node power consumption.

In Photovoltaic based WSN, operative lifespan of the Li-Ion battery was increased by significant reduction in number of charge/discharge cycles. As shown by Ongaro et. al. [3], the results after experimentation have demonstratee a statistical approach to size the energy storage elements are comply with simulations. Circuit design needs improvement to overcome the power challenge of supercapacitor converter. In Lazer based PV systems, modifying PV cell material optimises its light absorption properties for specific wavelengths (monochromatic light). This and interconnection of several subcells of GaAs have shown to provide 12V at the output. In WEH systems, implementing a MOSFET based rectifier system overcomes the low voltage challenges in WEH based WSN nodes.

Therefore, energy harvesting techniques implemented along with hardware and software level optimisations help improve the performance of micro-sensor nodes in WSN.

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