POWER OPTIMIZATION FOR WIRELESS AUTONOMOUS TRANSDUCER SOLUTIONS

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Abstract: Low-power and small size are key demands for wireless autonomous transducer solution (WATS) systems. This demand has motivated industry and research institutions to work on various advanced small size energy systems (ES) that can efficiently deliver power to demanding applications. In order to enable low-power and consequently autonomy, power optimization at WATS system level is crucial. This paper deals with innovative power optimization techniques for two different WATS applications that transmit data at high or low duty-cycle, respectively. By applying power optimization techniques significant improvements in power consumption have been obtained. The results show the effectiveness of our low-power design techniques and power optimization approach for improving the WATS power consumption. Subsequently, the limitations of WATS applications integrating 'off-the-shelf' energy systems and low-power electronics are also revealed.

Key words: low-power, wireless, harvester, energy, autonomous

1. INTRODUCTION

This paper discusses the trade-offs between power consumption, duty-cycle and functionality for Wireless Autonomous Transducer Solution (WATS) applications. A WATS system typically contains different building blocks, schematically shown in Figure 1, where a system integration approach is needed for low-power optimization. This includes but is not limited to understanding the energy harvester and energy storage system (ESS) performances, and using ultra low-power technologies for sensing, data processing and wireless communication (see Figure 1).

Previous work focused on energy harvesters [1]-[6], batteries [7]-[9] or power management circuits [10] for WATS applications. However, whilst the topics of energy generation and conversion have been the subject of extensive research, system integration and power optimization techniques at system level have not been sufficiently addressed. This work therefore focuses on the development of two new ultra-low power WATS applications fully powered by indoor photovoltaic (PV) energy harvesters. Subsequently, the limitations of WATS applications integrating 'off-the-shelf' energy systems and low-power electronics are discussed.

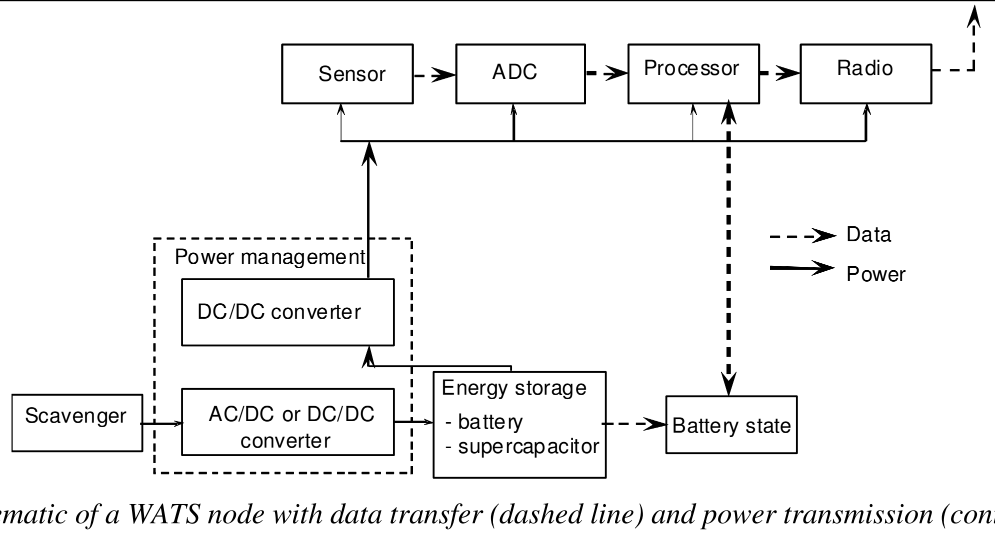


Fig. 1: Schematic of a WATS node with data transfer (dashed line) and power transmission (continuous line). The system input power is delivered by the harvester and energy storage system combination. Typical load modules are the sensor, Analog-to-Digital Converter (ADC), processor and radio.

2. WATS SYSTEM INTEGRATION

The integration of two WATS applications that transmit data at high or low duty-cycle is presented in this section. In a first case, a high duty-cycle WATS application that measures the ElectroMyoGram (EMG) signal [11] on a human body and wirelessly transmits this signal to a base station will be discussed. Secondly, a low duty-cycle WATS application that measures and wirelessly transmit a temperature measurement will be described.

2.1 General design aspects

2.1.1 Energy systems

PV harvesters and rechargeable Li batteries have been selected for both WATS applications presented in this paper, due to their maturity and durability.

In order to integrate the optimum 'off-the-shelf' available energy systems various PV harvesting and Li battery technologies from different manufacturers have been selected for testing. Based on the obtained results two PV harvesting systems [5][6] and one Li battery system [4] have been selected for integration.

2.1.2 Microcontroller (μC)

The μC selected for these applications belongs to MSP430 family from Texas Instruments [14]. The choice for this system has been motivated by his low power consumption. As an example, the power consumption equals 3 μW at 2V source voltage under the condition that the Digital Crystal Oscillator clock is still in active mode. Beside the clock module, the MSP430 integrates an on-chip 12-bit ADC and temperature sensing unit that may eliminate the need for an external temperature measurement module. This contributes to a compact and small footprint of the WATS system.

2.1.4 Radio

The low-power nRF2401 radio chip-set from Nordic Semiconductor has been used for both WATS applications [15]. This chip-set has four different modes: transmission, reception, standby and power down. The power consumption in each mode at a 2V source voltage is indicated below.

§ Reception: 36 mW
§ Transmission: 21 mW
§ Standby: 24 μW
§ Power down: 1.8 μW

2.2 Case I: design of a high duty-cycle WATS system for Body Area Network (BAN) applications

The hardware presented in section 2.1 has been further integrated in a WATS system that may serve various BAN applications. An in-house sensing unit is used for the bipolar measurement of a bio-potential signal, such as EMG. The sensing unit relies on an ultra-low-power front-end ASIC characterized by an average current consumption of 20 μA [16]. The EMG signal is measured using three off-the-shelf Ag/AgCl electrodes, places along the muscle fiber. The WATS system is programmed with dedicated application firmware which samples the EMG signals at 200Hz, organize the data in packets of 6 samples, and send them wirelessly every 33.3 ms to a base station.

The autonomy of the BAN system is enabled by a 70 cm^2 flexible PV harvester that is integrated together with the Li battery technology [4], [5]. By using two flexible patches of about 140 cm^2 in parallel a power level of about 2 mW can be generated under standard office light conditions, *i.e.* 0.003-0.01 [sun]. Subsequently, a safety circuit has been designed for protecting the battery against overcharging.

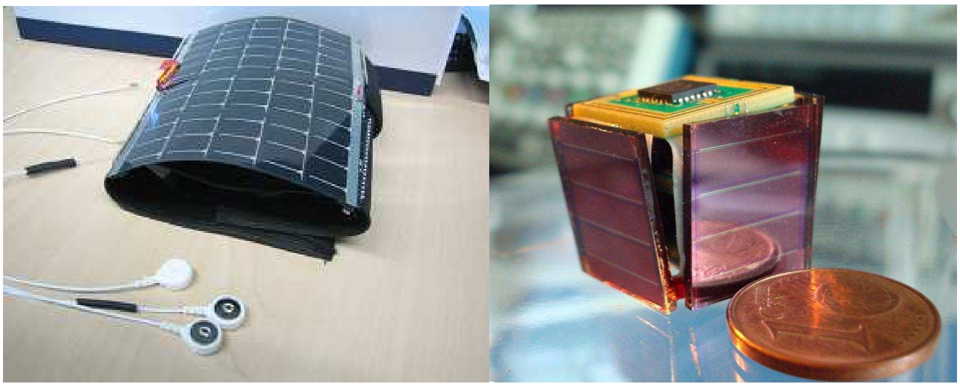
The resulting WATS system is illustrated on Figure 5a. Such a WATS sensor node shall enable long-term ambulatory monitoring of muscle activity, fatigue or power, with possible applications in sports, lifestyle, healthcare and rehabilitation.

2.3 Case II: design of a low duty-cycle sensor cube WATS application

The second case consists in the design of a WATS system for the remote measurement of ambient temperature. The on-chip ADC and temperature sensing unit integrated in the MSP430 microcontroller have been used for the temperature measurement. The system is programmed for taking a temperature measurement every 7 seconds, and transmitting it wirelessly to a base-station.

In order to enable the sensor cube system autonomy, four small-sized PV harvesters of 1.5 cm^2 [6] have been connected in series. In this case, under indoor illumination conditions, *i.e.* 0.003 sun, the generated power equals 20 μW. Similar as for the BAN EMG application a safety circuit has been designed for battery protection against overcharging.

Figure 5b illustrates the resulting WATS system, implemented as a sensor cube. Such a WATS system may be used for a variety of applications in industrial monitoring, ranging from air-conditioning units control to industrial machines temperature monitoring.



(a) *(b)*

Fig. 5: Illustration of the EMG BAN application powered by the flexible PV harvester (a) and Sensor cube application integrating PV harvesters as packaging (b).

3. POWER OPTIMIZATION TECHNIQUES

As mentioned in the previous section, the power generated by the PV harvesters under indoor illumination conditions equals 2 mW (BAN EMG application) and 20 µW (sensor cube application), respectively. In order to enable truly autonomous systems, several design and power optimization techniques have been implemented at the application level in order to match overall power consumption with the available power budget. The most important ones are briefly addressed below.

- Use know-how on the energy harvester and battery technology for designing low-power safety circuits
- Switch-off the application components, *i.e.* sensor, microcontroller and radio, by considering a trade-off between 'the power consumption requested during the component wake-up' and 'the mean power consumption during active state'
- Implement one supply voltage for the complete application by considering a trade-off between 'the quality of the data processing and transmission range' and 'the power consumption of the complete application'

As an example, figure 6 illustrates the current consumption during various modes for the BAN EMG application after applying the above power optimization techniques. The power consumption values for this application before power optimization are illustrated in Figure 7a. It follows from these figures that a factor of ten improvement in the power consumption has been achieved, where the main improvements have been obtained on the µC and ADC components power consumption. In this case, the overall power consumption of the BAN EMG system has been reduced to less than 1 mW. In order to enable system autonomy a large area PV energy scavenger was integrated (see Figure 5a). So, despite applying power optimization and integrating 'off-the-shelf' low-power electronics still a large area PV is needed (~140 cm^2) for the high duty-cycle BAN EMG application.

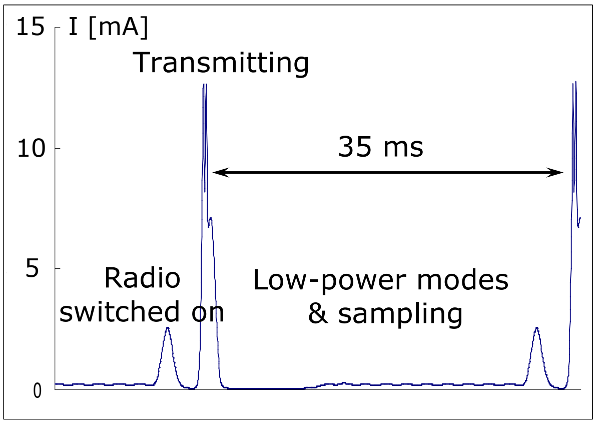
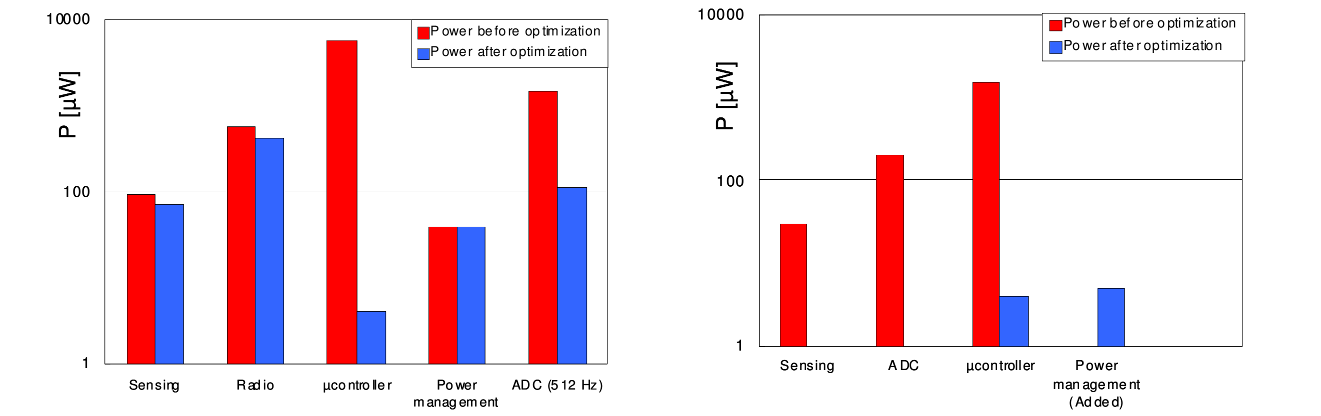


Fig. 6: Current consumption and duty-cycle for the BAN EMG application.

Similar conclusions regarding improvements in the power consumption are obtained for the sensor cube system that transmits a temperature measurement each 7 seconds (see Figure 7b). In this case, the mean power consumption has been reduced to about 10 µW, where the main power consumption improvements have been achieved on the µC, sensing and ADC components. Subsequently, a new power management circuit has been added. To the best of our knowledge, this is the first report in literature of a low-power WATS application integrating energy harvesting and Li battery with low-power electronics. As shown in this paper, autonomy for such a small size WATS application imposes strict requirements on the application duty-cycle.



(a) *(b)*

Fig. 7: Power consumption in [µW] before (red) and after (blue) applying power optimization techniques at system level for the EMG BAN (a) and Sensor cube (b) WATS applications.

4. CONCLUSIONS

The focus of this paper has been on low-power design and innovative power optimization techniques for WATS applications. Two different WATS systems for EMG and temperature monitoring have been developed. Truly autonomous performances are achieved by combining know-how on energy harvesting-energy storage, low-power electronics and application-level power optimization techniques.

The result is an important reduction in the overall power consumption, achieving 1 mW for a high duty-cycle BAN EMG application and 10 µW for a low duty-cycle sensor cube application. This paper suggests that applying power optimization and integrating 'off-the-shelf' low-power electronics are not sufficient for enabling the use of small-size energy systems for high duty-cycle WATS applications. As an example, a large area PV harvester was needed for enabling autonomy in the BAN EMG application. Future work will focus on developing ultra low-power electronics and improve the energy harvesting technology for extending the use of WATS to new application domains.

ACKNOWLEDGEMENTS

The authors would like to thank Bert op het Veld from Philips Research for the constructive discussions regarding the power management circuit. We also thank Michele Paselli and Luis Caballero from IMEC-NL for their contribution on the power optimization, systems layout and schematics and René Elfrink from IMEC-NL for performing the battery tests.

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