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A Methodology for Designing Power Management in Autonomous Low-power Nodes

Aikaterini Kalaitzopoulou, Vasileios Konstantakos, Theodore Laopoulos

Aristotle University, Physics Department, Electronics Lab, Thessaloniki, Greece,
aikalait@physics.auth.gr, bkons@physics.auth.gr, laopoulos@physics.auth.gr

Abstract – **A methodology is presented for the development of a power management configuration, based on a microcontroller, for use in autonomous low-power systems. First, the work presents an overview of the different approaches in the literature about the appropriate considerations towards evaluating power consumed by different operations in such systems, and then proposes a new design procedure. A case study is implemented on the basis of the proposed methodology, by using conventional hardware (microcontroller, modules) in a typical application. The power consumption behavior of this case study is explored by real experimental power-consumption measurements. All the above steps form a methodology which is proposed as a general approach to power management design of low-power autonomous nodes, as usually is needed in most wireless sensor networks based on energy harvesting.**

I. INTRODUCTION

The progression of modern electronics has created the tendency to provide smart instrumentation devices characterized by a significant degree of portability. These devices may vary considerably: from recording measurement values from sensors to processing and communicating tasks. Also, these devices usually operate on battery, and in most situations the energy for recharging the battery is not plenty, thus a certain power consumption minimization during all operations is needed.

Charging the batteries of such small scale systems is based on energy harvesting. Energy harvesting is a continuously growing and rapidly increasing research area with many applications already. Harvesting systems can be met in medical, industrial, environmental applications, providing the power for operations such as measuring various parameters, alerting and security. Some details of such applications will be mentioned in several occasions below, but at this point it is suffice to say that this research subject is becoming significant among the electronics design and instrumentation area.

For such system implementation, a basic developing directive is low power consumption. Although specialized by custom specifications in each situation, this essential direction is pretty much the same and of great importance every time. So, a developer must be aware of all the necessary information related to creating and evaluating a smart low power consuming system. This means that besides the necessary computational functionality that must be implemented, the developer must be also aware of the power consumed by each module in each phase of operation.

This work is presenting an overview of the key-points for understanding and developing a low power system for such applications. The existing literature is taken into consideration in order to implement an indicative system that is to be further explored in the laboratory. Proposed techniques from the literature are either being used or neglected with cause, in order to show the usefulness of some of the published approaches to different cases.

The hardware being used is typical, because the focus of this work is on the methodology and not on the configuration actually implemented. A typical 8-bit low power microcontroller ATMEGA328P is used as a case study, equipped with a minimum number of external modules. The idea is to implement typical functions that exist in most systems either for normal operation or for power management procedures (i.e. battery voltage measurement, sensors operation, wireless links, etc). In real conditions, upon understanding several aspects of the proposed procedure, a developer is advised to make also the appropriate hardware choices (hardware/software co-design).

The proposed approach is strengthened by the use of real energy measurements held on the implemented system. These measurements will be an indication of the actual energy behavior of each individual module included in the overall configuration, of possible errors that may be detected by simply obtaining energy measurements in each phase, and of the possible need for further improvement that may arise based on the explored energy behavior.

In the next sessions, different aspects of this work will be presented as follows: In session II power management descriptions will be presented based mostly on the literature, in session III the proposed power management system is described in details, and session IV follows with real energy consumption measurements performed on an experimental system.

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II. POWER MANAGEMENT

The several aspects and key points of a power management system may be found well described in the literature. Existing research documents vary from proper hardware selection, to different algorithms related to hardware usage, and finally to variating software algorithms related to the functionality of such a system.

Firstly, in order to understand the specifications of such a system, a small description will be made of autonomous nodes (systems supplied with power from any type of harvesting), where a power management module is usually part of. Such a typical configuration in a system-on-chip design appears in Figure 1 [1]. This system is based on a central microcontroller, which is in charge of the available functionality. Also, several peripheral modules exist, mostly related to the sensor needs for proper operation, storage and processing of the measured data. It also includes a communications module to cover the communication needs of each application. Such autonomous nodes (modules, systems) are usually powered by a battery, or sometimes a super-capacitor. The harvesting subcircuitry is also included in the same chip, which won't be of any further interest in this specific work. So, according to this figure, the main focus of this work is everything besides the harvesting subcircuitry, with main focus point on the microcontroller.

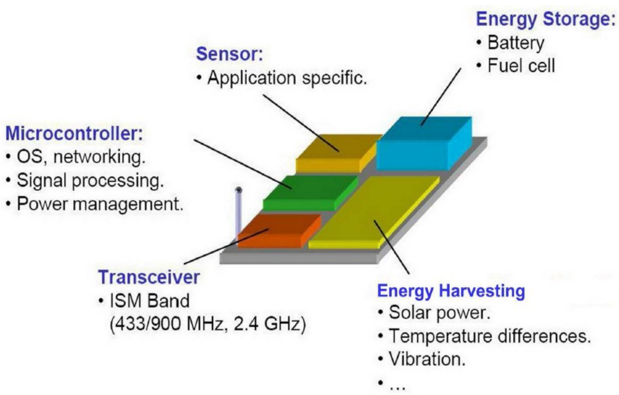

Fig. 1. Typical system-on-chip implementation of an energy harvesting system [1]

A basic step in designing such a system is the selection of hardware. A proper selection must be made for the microcontroller, for all the needed sensors and for the communication modules. Although, the above example is for a system-on-chip design, our methodology may be applied also on designing a system with discreet hardware. In [2] a thorough description of every part of a power management system is given. Complete tables-guides are presented, where they compare several modules related to their energy consumption. Separate tables are also provided for microcontroller comparison, for wireless module comparison, and for possible sensor choices. Also, some description is made for the possible battery choices and harvesting inputs that a designer may use. At the end some key points are mentioned related to techniques that are being used in the design and in the programming process of developing such a system. So, this work provides substantial information related to the first steps of a power-management design for autonomous power-harvesting systems.

The next step of a power management designing procedure is the selection of proper algorithms for implementing the necessary functionality in each situation. There are different ways of executing tasks in such systems [3]. These ways differentiate in hardware usage, and in functionality implementation, like task scheduling and usage of alternative ways of implementing functions.

For example, a developer should be aware of some basic key points of such an algorithmic procedure, like data sensing, data processing and data transmission, and be able to understand designing parameters in such categories. Also, such systems utilize large low power periods, thus the selection of a proper operating duty cycle is vital [4]. It is important therefore to have certain information about the power consumed during the execution of such algorithms, especially if there are periods (time-intervals) when power consumption is bigger than in normal operation.

Furthermore, more complex techniques can be used for the system to adapt its behavior based on available energy and necessary tasks to be executed. Task scheduling is a good way to optimize energy usage according to each set of specifications [5], with most important variations being the so-called: Lazy Scheduling Algorithm (LSA) and Energy Aware –Dynamic Voltage Frequency Scaling (EA-DVFS) [6]. Such approaches form a good basis for power management system designing, and a good source for the implementation of more complex techniques.

A last but not least step of the design procedure is the acquisition of several measurements on the system. These measurements can be separated in two different types: the operational verification and the energy exploration of the design. These measurements can be held not only at the final step of the design process, but also in the middle of it, in order to obtain feedback for redesign. The functional part is much easier to observe and to predict, because it is more straightforward related to the programming of the microcontroller. But with the energy behavior things are not that easy, especially if discreet components are being used. The designer may have every available description of the provided modules from their designers, but the combination of these modules may result in effects which are not easily predicted. Also, although the functional verification can be observed easily, the energy behavior cannot, and there are situations of possible waste of energy although the functional part appears to be correct. It is reasonably assumed then, that detailed energy consumption measurements can be important in such situations. An illustrative example of such a case appears in [7], where a microcontroller based system is evaluated in a rather high level, in terms of its energy behavior. This is a wireless zigbee system, and basic conditions are being measured like the start-up procedure, the stand-by and wake-up periods, connecting to network and simple transmits of sample data packets.

The appropriate energy consumption measurements may be held almost at any level, meaning that the focus may be not only simple modules and simple operations, but the complete behavior of the overall system as it operates normally. A lot of work focuses alternatively on simple modules, like in [2], and on simple operations like in [4]. Furthermore, the hardware being used in there is usually modern and rather expensive equipment, like high frequency oscillators, like in [4], where the power profile of a sensor is presented by the means of current waveforms.

So, the measurement set-up in [4] is convenient and quite accurate for small time windows recording, but if larger windows are needed, then the amount of data that should be processed becomes prohibitive. On the contrary, when large time windows are needed, e.g. in the scale of seconds or even more, then the measuring scheme in [7] is a better selection. In this work, the measuring scheme is the one that appears in [7] and [8], and will be explained briefly below.

All the above information form an indicative overview of the literature, and illustrate generally a typical case-study, for understanding small-size power management systems. The combined knowledge of them is necessary as design principles, in the process of creating such a system. It should be noted, that the above described literature in not only useful in autonomous systems based on harvesting, but in whatever instrumentation application is characterized by similar specifications.

III. PROPOSED IMPLEMENTATION

The proposed implementation, as already mentioned above, is an attempt to combine information from the literature, so as to develop a methodology for low power system design. The next step is to consider the basic functional operations of such systems before starting to implement a generalized version. Thus, the proposed implementation can be seen only by such an aspect: that of a typical set of characteristic functional modules. The success in extracting information about power needs of each module in this kind of effort, may lead to more specialized approaches in the future. The block diagram of the implemented system appears in Fig. 2.

The system is based on a small scale 8bit microcontroller from Atmel (ATMEGA328P). This choice is only typical and probably not optimized, and certainly there are available other (probably better) choices in terms of characteristics and consumption. Nevertheless this microcontroller is also quite modern with such criteria, like its low energy consumption, and can be a typical starting point in exploring power management configurations and design.

Besides the microcontroller, a power management system usually contains sensors, so the proposed system utilizes a temperature sensor which is inside the microcontroller and an accelerometer connected as an external sensing module. The selection of these two sensing elements is again only as a typical example of embedded sensors in combination with sensing units connected as external modules. The parameters being recorded in the proposed system may appear often in many modern applications. Temperature is met more often in many applications. Acceleration info can be used in static applications for calculating the inclination of a surface area. Also, acceleration data with some additional processing procedure is useful for calculating extra variables (speed, speed variations, etc).

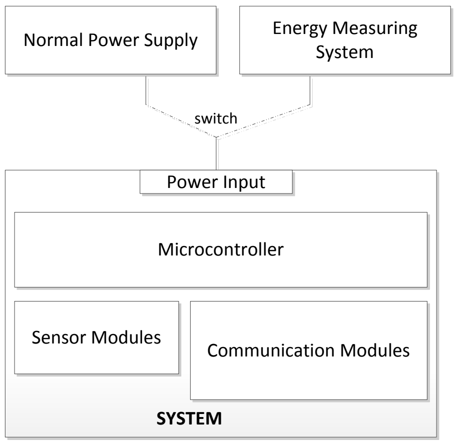

Fig. 2. Block diagram of the proposed implementation

A communications module is usually a typical part of a small-size system for automated measurements, usually wireless. A wired serial communication is used at this initial phase of this work for validating the functionality of the system, since the focus at this stage is mainly on the operating algorithm, on the microcontroller and on the sensors.

The power supply of such systems is usually a battery. The types of batteries that may be used vary, but in order to cover a large number of applications, Li-Ion batteries are selected, with a nominal value of 3.3V. So, the complete system operates at this voltage level. Again, this is not optimal, but it is a good point to begin. Of course, the battery is not easy to be used while developing the system and making measurements. So, this system is operating with a constant power supply regulated at 3.3V during the development phase, and then a battery is used to operate the designed system for evaluation in real operating conditions.

It should be noted that during experimental measurements the system is supplied with power from the energy measuring scheme used in these measurements, which is presented in [8]. The main concept of this measuring approach appears in figure 3.

The Device-Under-Test (DUT) is the complete system that is proposed in this work and it is operating normally by drawing current from the measuring system. The power consumption measuring scheme reads the variations of the supply current, and can integrate it electronically (on the basis of the number of capacitor charges/discharges) in order to result in a number indicating of the current being drawn, thus of the energy consumption of the DUT. This measuring scheme is calibrated initially by an external current source (as indicated in [7], [8]) so that for each measurement an average value can be assigned. So, a series of measurements, provide the values of average current and thus the consumption of the DUT within a specific time interval. As shown in Figure 2, a manual alternating switch is being used, either for selecting a normal power supply for the DUT, or for selecting the measuring system as the power supply.

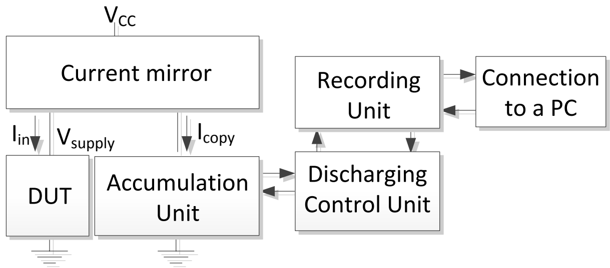

Fig. 3. Functional Block of a configuration for measuring the power consumed during a certain time interval by the Device-Under-Test (DUT)[8]

The hardware of the proposed typical system is presented up to now, and the next step is to describe the algorithm. This system is implemented by taking into consideration the needs of similar systems, as they appear in the literature. Similar knowledge has been used for the programming level. The block diagram of the resulting algorithm is presented in figure 4.

At the beginning of the algorithm, the complete hardware is initialized, meaning the microcontroller and all the available modules. After this procedure, the microcontroller goes to a deep sleep state waiting for events to wake him up. At this point, two possible events may occur. The first event is to have a specific time pass and then to wake up in order to make measurements. The second event is to have an external trigger ("a button pressed"), which will lead to a procedure where the current supply voltage is marked as nominal; that is for defining the battery's full voltage value, according to the battery being used in each case.

The important event is the wake-up event after a certain time interval. For the purposes of this work, this time has been configured to 8 seconds. In real conditions this value can even be in the scale of minutes. So, the system wakes up every 8 seconds and begins its measuring procedure. The first step always, is to measure the supply voltage. This measurement is held by the internal A/D of the microcontroller, and by measuring a portion of the supply voltage provided by an output pin of the microcontroller and a voltage divider.

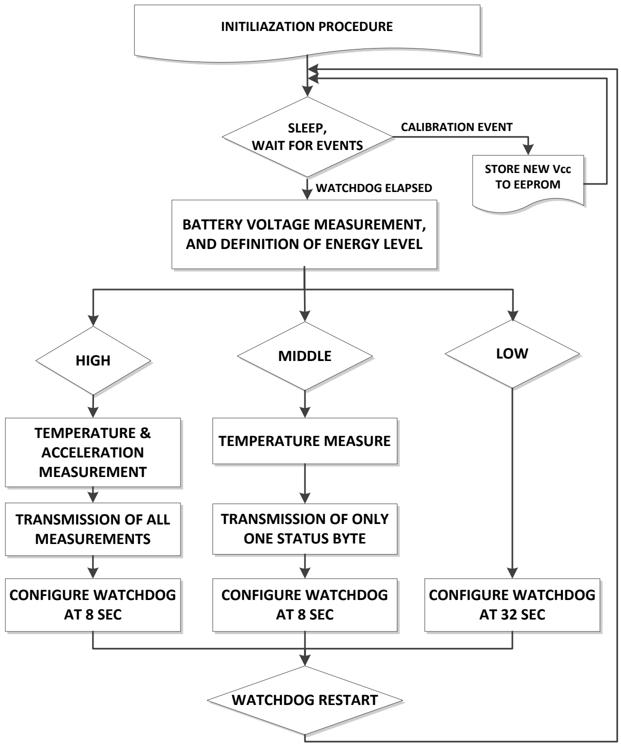

Fig. 4. Functional Block of the program running on the microcontroller

This voltage measurement is essential for defining the next possible steps of the procedure. This value is being compared with specific values which are typical for different applications. The idea is to define the available energy in the battery used as a power source, and to define what will be the parameters of the next algorithmic steps.

Three basic energy levels have been defined in this application: Full energy, reduced energy and low energy. These levels offer a basic separation, where in each case every task, a reduced number of tasks, or no tasks at all can be executed. In full energy conditions, all sensors (and external sensing units) are operating normally, all processing is realized, and eventually a full set of data is transmitted to a base station. In reduced energy situations, the measuring tasks may be reduced to neglect the less important ones, or the most consuming ones, processing is to be reduced according to the same criteria, and the transmission is held only in alerting basis, thus minimizing the amount of data to be transmitted. So, in this middle situation the system is still functioning, but only related to the most important functionality. The functionality that is considered important is related to each application and probably to the energy it requires to operate. In the “minimum energy” condition, the system switches just to a self-preserving operational status. This means that the necessary functionality is kept alive for just continuing basic operations, and everything else is turned off. The idea is to have the system waiting for conditions where more energy will be available in the future. Thus, the amount of sleep time between 2 wake-ups is increased (in this approach it is set to 32 seconds). Furthermore, upon waking up it just spends some energy to measure the battery voltage. Once the battery voltage is measured and found within normal operating scale, then the system returns eventually to its normal functionality.

In order to achieve a better result in terms of minimizing energy consumption, a change in the system’s clock has been also studied. Thus, during the operation of the described algorithm, the clock is changed according to the algorithm’s current status. This change is kept simple as a first implementation of this technique and is focused upon being on the waken-up processing part or on the sleeping part of the algorithm. So, upon waking up the clock changes to a faster value (e.g. 1MHz) and upon sleeping the clock changes to a smaller value (e.g. 250KHz or less). The effect of these changes will be presented later in this manuscript.

In order to verify the operation of this system, a small LabVIEW interface is created on a computer that is able to receive and visualize the transmitted data with the help of a serial wired microcontroller node connected to the computer. The measured sensor data and the alerting data (if any) are received and handled by it, thus confirming the different operating states of the power management system. The evaluation procedure of the proposed approach by real experimental measurement results follows.

IV. EXPERIMENTAL EVALUATION

The final step is to perform real energy measurements for the evaluation of the operation of the proposed implementation. The designed system is configured to run in different operating conditions and its operation is monitored both for qualitative and quantitative analysis.

In figures 5 and 6, typical images of the implemented measurements are illustrated, as obtained by the selected measuring scheme of [8]. In figure 5, the energy consumed during the start-up procedure is shown. Figure 6 presents a typical image of measurements being held while the power management system operates normally. As it is shown, it appears to have a wake-up period once every 8 seconds for a time window of several milliseconds, and then sleep for the rest time of the 8 seconds. One may notice the spikes being the wake-up period, and the lower values characterizing the low power period.

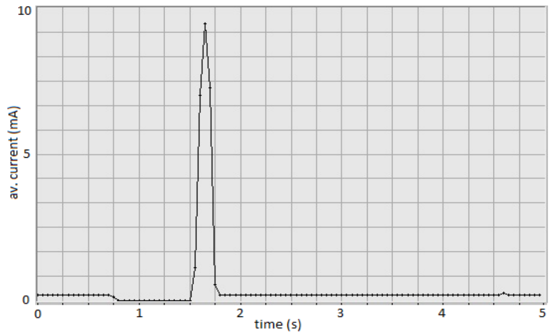

Fig. 5. The start-up procedure captured by energy measurements

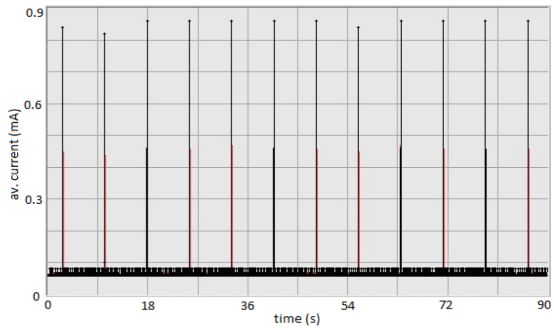

Fig. 6. The energy behaviour of the system during normal operation

So, after this qualitative small presentation, in order to make some initial energy exploration of such a system, some key characteristics are targeted, like the hardware selection, the operating voltage, the operating frequency at different time windows, and in more algorithmic terms the usage of proper low power periods. Some of these characteristics might create obvious results; nevertheless the first step in measurements is to observe also some expected behavior. According to these, the conditions that were measured appear in table 1.

At the left of this table, the conditions are being described in brief. First, the operating voltage is defined, after that the operating frequency during normal operation, then the operating frequency during low power mode, and finally whether or not low-power mode is being used while the system stands idle.

The rest of the table contains measurement results. The first column is the average measured current for the time window where the microcontroller is operating normally and the next column is the average current during low power mode. Then, energy columns are presented either of the total energy for the waken-up operation duration, or of the total energy for a complete cycle of 8 seconds, meaning both waken and sleeping time windows.

Also, the actual duty cycle is measured in all cases, with an oscilloscope, and is found to be ranging between 1% and 2%.

Table 1. Different cases of measuring conditions

OP.VOLTAGE -OP.FREQ – L.POWER FREQ -SLEEP	Active Mode Av. Current (mA)	Low Power Mode Av. Current (mA)	Active Mode Energy (mJ)	Total Energy (mJ)
3.3V -1MHz -1MHz -NO	1,145	0,978	0,0648	25,09
3.3V -1MHz -1MHz - YES	0,643	0,481	0,0623	12,39
3.3V -1MHz -250KHz- YES	0,510	0,343	0,0644	8,84
3.3V -1MHz -125MHz- YES	0,504	0,332	0,0664	8,56
3.0V -1MHz -1MHz- YES	0,565	0,419	0,0526	10,11
3.0V -1MHz -250Hz- YES	0,492	0,332	0,0578	8,02
2.8V -1MHz -1MHz- YES	0,523	0,389	0,0450	8,76
2.8V -1MHz -250KHz- YES	0,458	0,311	0,0493	7,03
3.3V -2MHz -2MHz- YES	0,929	0,891	0,0151	22,82
3.3V -2MHz -250KHz- YES	0,430	0,347	0,0320	8,91
3.3V -4MHz -4MHz- YES	0,947	0,906	0,0161	23,21
3.3V -4MHz -250KHz- YES	0,392	0,346	0,0176	8,88

So, this table presents the desired energy exploration of such a system. Several conclusions can be extracted by these experimental data, some of them expected, while others are not usually being noticed:

- Low power mode usage is critical.
- In a complete cycle of 8 seconds, the energy consumed by the idling status can be of bigger importance than the energy consumed by the normal operation window.
- Although a deep low power mode is being used, where many parts of the microcontroller close, the lowering of the clock in these low power windows improve the energy consumption.
- Lowering the operating voltage creates an obvious improve of the energy consumption
- When the normal operation clock increases to 2 and then to 4MHz, a decrease is noticed on the processing energy consumed, which in not expected. This happens probably because the processing consists of static and dynamic current contributions, and when the clock is faster, the undesired static contributions are reduced

V. CONCLUSIONS

A power management system is becoming important in modern instrumentation systems, and especially in energy harvesting systems. The designing of such a system is a procedure that takes into consideration many designing factors, such as hardware selection, hardware utilization, or algorithmic implementation. By taking these into account, a novel power management configuration has been implemented and tested. Energy consumption measurements were performed experimentally to evaluate the operation of the design and these measurements have shown certain remarkable results regarding which operation exactly consumes energy in which phase of operation. Further research work is planned once the basic operation of this design is validated aiming towards a complete investigation of the power consuming functions, operations, and modules.

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