Energy Consumption Measurement and Analysis in Wireless Sensor Networks for Biomedical Applications

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ABSTRACT

Energy Consumption in Wireless Sensor Networks is a fundamental issue in terms of functionality and network lifetime. Minimization of energy consumption by applying optimization techniques enables pervasive computing especially in the field of biomedical engineering. A framework for energy consumption measurement and analysis is proposed which combines a theoretical approach, a simulation procedure based on a widely used software simulator and the validation by means of a high sensitivity measurement setup. Application driven profiling of energy consumption at the node level is a useful tool for optimal function of energy consumable node components in order to improve total energy efficiency.

Categories and Subject Descriptors

B.4.4 [INPUT/OUTPUT AND DATA COMMUNICATIONS]: Performance Analysis and Design Aids - Simulation, Verification.

General Terms

Measurement, Performance, Verification.

Keywords

Energy consumption, wireless sensor networks, energy model, biomedical applications

1. INTRODUCTION

The concept of ubiquitous and pervasive human well being monitoring with regards to physical, physiological and biochemical parameters in any environment and without restrictions of activity has recently become a reality with the advances in sensors, miniaturized processors and wireless data transmission technologies. All these developments in these fields have been integrated in the rapidly emerging field of wireless sensor networks (WSN) for biomedical applications.

If the reference point is the body and the acquired signals are related to biosignals then a specific field of body sensor networks (BSN) is developed in order to describe the applications of WSNs which are ideally suited for monitoring of human body physical parameters. Pervasive healthcare systems utilizing large scale BSN and WSN technology allow access to accurate medical information at any time and place, ultimately improving the quality of service provided. Energy consumption in WSNs and BSNs sets important technological challenges in hardware design research in terms of increased battery capacities and low energy consumption electronics. Wireless sensor network node functions such as sensing, local data processing and radio communications require sufficient energy reservoirs.

Energy efficiency in pervasive computing is a key factor in functionality and lifetime. Optimization techniques enable green Wireless Sensor Networks by applying energy efficient functioning of consuming node components without limiting ubiquitous information access. Node miniaturization as a trend in wireless sensor networks is moving fast to smaller scales while batteries as the main source of power do not follow in the same pace. Energy scavenging from the node environment seems to be promising still with limited scale of applications. Fuel cells are not advancing from prototypes to mass production and solar panels are not a continuous source of power. Research activities focus on minimization of energy consumption of nodes’ electronic components by fabricating low power microcontrollers, RAM circuits, low power FLASH memories and energy efficient radio communications components. The other active front of research directions is related to low energy routing and self organization protocols while keeping other system parameters fixed.

Energy efficiency in network and node level is important parameter in network design and deployment. The volume of literature in the field of energy efficient protocols and optimization techniques is convincing about the necessity of energy consumption optimization techniques which is mainly covered by simulation tools. Energy consumption estimation techniques for wireless sensor networks can be divided into two categories, the simulation oriented and the hardware based. The last category is related to real measurements. A widely used tool for simulation is PowerTOSSIM [1], an energy consumption simulator for TinyOS [2] platform, which simulates the main hardware components of the node considering them as energy consumers into the underlying energy model.

Estimation accuracy of the simulator is reasonable with acceptable error levels although lifetime uncertainty inherent in simulator is non negligible. Limitations are mainly due to the state-based estimation extension of TOSSIM, ignoring energy fluctuation within each energy state of the node. PowerTossim is dependent on the TinyOS and nodes compatible with this widely used operating
system which is the main software suite for wireless sensor networking researchers. Software simulators are based on energy models in order to accurately predict energy consumption. Calibration and validation of energy models enhances simulator prediction relating simulation results with real measurements. Based on execution of real applications, codes and measurements, software estimators use more realistic models for the accurate prediction of actual energy consumption of nodes (AEON [3]).

While literature references suggest that the energy consumed at a transition from one energy state to another should not be neglected [4], simulators for wireless sensor networks do not take it into account. Energy consumption simulation is basic part in several simulators such as SensorSim, senQ, SENSE, SENSIM amd J-Sim with detailed energy models and in some of them battery discharge rate and relaxation is considered as well [5].

Another software simulator, which is based on instruction level power simulation (IPEN) rather than state transition energy simulator [6], was proposed. Instruction level simulation is slow, compared to state-based simulation trading off the increased estimation accuracy.

Apart from the software simulators, measurement based techniques are considered of higher order of accuracy compared to simulation based techniques. However hardware based techniques have difficulty in applying to large scale deployments of wireless sensor networks. Measuring voltage and current draw from wireless sensor network nodes at the same time and integrating the product over time is the common approach for the calculation of energy consumption. It requires expensive equipment with high sensitivity in small currents in the order of microampere (µA), a common state in wireless sensor networks of low duty cycle. Keeping voltage constant, the need for energy consumption profiling is addressed by the measurement of current.

Clamp-on current probe connected to an oscilloscope or a data acquisition card is used as a magnetic field sensor to measure current [7]. Low sensitivity of the measurement setup limits the current detection to a few milliampere (mA) making this measurement approach unsuitable for low duty cycle wireless sensor networks. SPOT [8] is based on current sensing using a shunt resistor. Voltage drop at the shunt is amplified and is driven into a voltage-to-frequency converter, with the generated pulse train output to be accumulated by a counter. Common issue in the shunt resistor case is the value of the shunt. Typical values for shunt resistors are below 10Ω (close to 1-2Ω) producing voltage drops in the order of magnitude of a few micro voltage (µV) when node is in power down state. The voltage signal is driven to an instrumentation amplifier [1] with low offset voltage and bandwidth large enough to follow the fastest signal.

Theoretical estimation of energy consumption in node level and network level is mainly focused on performance comparisons and trade off studies between various low energy routing and self organization protocol. Aggregate energy consumption for a sensor network is affected by non protocols parameters such as node density, traffic generation and transceiver and antenna characteristics [9], [10].

In this paper theoretical calculation of energy consumption is based on the timing and discrete transition of energy states acquired from the measurement stage. Energy consumption related parameters values are collected from a widely used WSN node Tmote Sky [11] and verified in the calibration stage of the energy model.

Simulation results are obtained after the calibration of the energy model by testing specific TinyOS applications with discrete and identifiable energy state transitions. A measurement scheme is designed and developed with adequate sensitivity in small currents and high energy states of the node.

Energy consumption after the application of optimization schemes is compared to energy consumption of widely used reference TinyOS applications. The technique aims at the identification of the node components with high energy consumption compared to the overall node energy consumption and the implementation of a scheme targets towards the minimization of component usage without compromising node functionality.

2. SYSTEM MODEL

Theoretical energy consumption calculation, presented in this paper, is a method composed of three parts. First the extraction of the energy consumption parameter values from the node's datasheet secondly the calibration of the energy model and thirdly the real measurements of timing for the energy state transitions that are discrete and identifiable.

Total energy consumption in node level comes up as the sum of the energy consumptions of the individual components of the node. Considering a node as a composition of various subsystems, identification of discrete energy states due to specific subsystem function results in composite energy profile consisted of superposition of individual components energy states. State transitions are energy consumable and should be taken into account in calculating the total energy consumption but it is hard to indentify in measurement stage the energy consumed during the transition.

Reference TinyOS applications are chosen based on criteria such as the incorporation of different components as the application is running in node level. Timing and energy consumption of subsystems are extracted by isolating discrete energy states and correlating each one with subsystem's function.

By examining measurement figures of current draw at constant voltage (measurement setup is explained in the appropriate section below), energy consumption values of the individual components are extracted in order to be used in the formula which calculates node's energy consumption.

As the complexity of the applications is increased and more subsystems with different energy states are involved theoretical calculation accuracy is reduced. This is due to difficulty in identifying accurate timing and discrete energy states of the individual components and because of the nature of TinyOS applications in handling the asynchronous signaling of events.

Timing is exported by the real measurements and compared to the trace file of the PowerTossim energy consumption simulator. Voltage supply is constant and equal to 3 volts.

Hence, the energy consumption formula is a function of the current draw of the microcontroller at every energy state, the current draw of the radio communication subsystem which corresponds to the appropriate function state (Transmitting, Listening), the current consumption of every individual LED and the current consumption of the other components. This is expressed in the following formula

$$E = I_{mcu} t_{mcu} + I_{led} t_{led} + I_{tx} t_{tx} + I_{rx} t_{rx} + \sum I_{i} t_{i}$$

Where V is the constant supply voltage, $I_{mcu}$ is the current the microcontroller (MCU) draws in every energy state, $I_{led}$ the current every individual led draws, $I_{tx}$ the current the radio communication subsystem draws while transmitting data, $I_{rx}$ the current the radio communication subsystem draws while listening to the channel and
the sum term denotes the total consumption of all the other subsystems (RAM, Flash, sensors) [12]. The time term with the corresponding subscript that denotes the component and its state \(t_{\text{tx}}\) denotes that the radio subsystem transmits data at the time interval equal to \(t_{\text{tx}}\).

3. ENERGY CONSUMPTION SIMULATION - CALIBRATION OF ENERGY MODEL

The energy estimation framework consists of PowerTossim, an energy sensor network simulator based on the TinyOS. The energy model is built according to the mica2 wireless sensor network node which is the default model of the simulator that is adapted to Tiny sky energy consumption component properties. Energy model is calibrated by fine tuning consumption parameter values for individual components at every energy state corresponding to the discrete and identifiable energy states in the measurement procedure. For this purpose applications with multiple discrete energy states are employed due to their simplicity in identifying the different states. Different color LEDs energy consumption as well as MCU energy states and radio communication transmit and listen states are measured and compared to the initial simulation results based on the energy model developed by incorporating datasheet parameter values. In this way, the energy model is reconfigured before applied in energy consumption simulation estimation (Figure 1).

![Energy Consumption Simulation](image1.png)

**Figure 1.** Energy Consumption of TinyOS application CntToLedsAndRfm for simulated and measured current draws at constant voltage supply

4. DATA PROCESSING AND CONFIGURATION TECHNIQUES

Apart from the reference TinyOS applications used for calibration of the simulator energy model, a series of applications are developed and tested based on TinyOS package. Oscilloscope and OscilloscopeRF typical TinyOS package applications are used in theoretical estimation, simulation estimation and measurements. Based on OscilloscopeRF, new applications are developed in order to implement and test the energy efficiency of the optimization techniques. Measurement results in OscilloscopeRF reveal the high consumption of frequent radio communication when each sensor reading is forwarded to transmission. The first application, named OscilloscopeCustom, samples an onboard sensor which in biomedical application case could be a temperature, oxygen saturation, or any slow time varying biosignal, collects 10 sensor readings in a buffer and transmits those readings in one radio message of Oscilloscope message format. An RF managing scheme is implemented in this application. Radio communication, transmitting or listening, is disabled in every round of sensor readings until the buffer is filled and then radio control is enabled in order to transmit and disabled at the end of transmission. OscilloscopeFusion is designed towards the direction of implementing on board signal processing of the sensor readings without transmitting raw data but instead transmit processed sensory data.

Data processing is application driven and it significantly reduces the amount of data buffered in the radio communication subsystem. A simple processing scheme is implemented and after its completion radio communication subsystem is enabled to transmit in broadcast fashion the result of the processing to the network and disabled again.

Disabling radio communications while other tasks run on the node causes data throughput decrease. Data exchange demand is an important parameter in numerous wireless sensor network applications and underestimation of this parameter undermines interactivity and reliability of the network.

In various low duty cycle wireless sensor network deployment’s interest is focused on monitoring phenomena with spectral content mainly in low frequencies. The application sets the constraints for the cycles of data acquisition and radio communication handling revealing a possible trade off between node - network lifetime and the ability of continuously monitoring a biosignal.

In this paper, the node perspective is examined in terms of energy consumption and optimization techniques are evaluated by the energy savings calculated and measured compared to the default scheme of data handling in reference applications.

The network implemented for evaluation purposes is a single hop in fixed positions in laboratory environment. Measurements are obtained for default transmission power of the node (CC2420 transceiver is configured to operate at the default power transmission level) and no changes in the radiating system of the node are made.

5. MEASUREMENT SETUP

The design of the measurement setup is based on the shunt resistor in series with the node. The value of the resistor is required to be small enough and considering that node's current draw in sleep energy state is in the order of microampere (\(\mu\text{A}\)), it results in a voltage drop in the order of micro volt.

![Circuit Diagram](image2.png)

**Figure 2.** Circuit designed for the measurement setup scheme

The specification of the instrumentation amplifier used to amplify the \(\mu\text{A}\) signal indicate low input offset voltage, low input offset
current, high supply range and high gain range. AD620 is chosen according to these requirements. The circuit designed is depicted in figure 2. The values of R and R_G are chosen after parametric simulation of the circuit monitoring the output voltage. Focused on the high energy state and low energy state of the node, there are two sets of parametric simulations setting I_mote in the order of 30mA for high energy state (MCU on and Radio on Listening mode) and I_mote in the order of 6uA (MCU on standby and Radio disabled) applying a safety factor to the datasheet values. In high energy states of the node, deviation of the theoretical output value of the circuit from the simulated output voltage does not exceed 2% for I_mote lower than 32mA. In contrast, low energy states (node currents in the range of some uA) deviation is high in the range of current values that is below current draw in the sleep state of the node.

Results of the simulation indicate that optimum values are R = 8.5Ω and R_G = 800Ω. The R shunt resistor of the aforementioned value seems to have a satisfactory behavior in terms of temperature compensation still lower values of shunt resistor result in slightly better sensitivity if offset voltage is being compensated.

6. PROFILING ON ENERGY CONSUMPTION

The process of optimizing the function of energy consumable node’s subsystems is based on the creation of the energy consumption profile for a specific application. Simulation results on the calibrated energy consumption model initiate the procedure of profiling the application by breaking down the total energy consumption of the node in individual energy consumptions of the node subsystems.

By processing simulation results, break down into node functions such as radio communication, sensing, led blinking, memory access, mcu operation and radio communication. Analysis on simulation data indicates that for the specified application the most energy consuming component is the radio communication subsystem because of the continuous cycle of sensing and transmission (Figure 3).

Aiming at the minimization of energy consumption and the optimization of the radio communication function of the corresponding subsystem, OscilloscopeCustom application is created buffering 10 sensor readings before transmitting as a single radio oscilloscope format message. While sensor readings are acquired radio control is disabled and enabled only when message is ready to be transmitted.

Profiling of the optimized application suggests that there is a significant energy saving due to the deactivation of the radio communication subsystem at a significant fraction of time in the time interval of tasks execution (Figure 4). This is depicted by a significant decrease in the percent of total energy consumption for the radio communication subsystem.

Further optimization implemented leads to OscilloscopeFusion application which introduces a signal processing stage over biomedical data acquired by node's sensors. The addition of logic implemented in the form of an on board signal processing technique prior to the activation of the radio communication subsystem results in a significantly reduced amount of data forwarded for transmission. Limited processing power resources as well as memory resources set a constraint factor to the complexity of signal processing methods.

Profiling of OscilloscopeFusion application (Figure 5) revealed that activating radio communication subsystem less frequently and transmitting less amount of data compared to the previous applications, is proved to be a successful strategy in order to reduce the total energy consumption in node level.

Total energy consumption has been reduced 4-6 times approximately. Nevertheless this direction is not applicable in any biosignal monitoring application since is strongly dependent on the spectral content of the signal. This approach implies though that even for high spectral content signals, energy consumption optimization techniques could improve total energy consumption by introducing a radio control and signal processing stage prior to transmitting or exchanging data.

7. RESULTS

The energy consumption of different TinyOS applications was measured by means of the measurement scheme described in section 5. Analysis of the exported data from simulations using PowerTossim that incorporates a calibrated energy model, are compared with measurement data at the reference time interval of 60 seconds (table 1).
A typical TinyOS application named Oscilloscope is included for comparison purposes. Sampling of a biosignal is taking place at the same rate as in the case of the applications under consideration and data are forwarded to the USB port connected with a personal computer without enabling the radio communication subsystem. The continuous sampling, the use of the USB port for data transfers, the flashing of LEDs as well as the power feed circuitry function of the node are the only energy consumable functions executed at Oscilloscope TinyOS application. Surprisingly, it seems that the rare use of radio communication strategy adopted in OscilloscopeFusion is in the same scale in terms of energy consumption to the continuous function of USB subsystem in Tmote Sky and the temporary data storage in flash memory. As a conclusion it is drawn that a radio control strategy along with a signal processing on board reduce the total energy consumption in node level of a wireless sensor network.

Theoretical approach was used for energy consumption calculation based on timing data obtained by the measurement procedure and energy consumption parameter values are collected from the node datasheet. Measurement results reveal that deviations of theoretical approach and simulation method from the measurement are small and acceptable for OscilloscopeCustom switching on/off radio communication between subsequent fillings of data buffer. Specifically, on board data processing of OscilloscopeFusion collects 10 sensor readings and calculates a mean value. After completing ten rounds of sensor readings and mean value calculation, data buffer is filled with 10 values ready to be transmitted which actually represent 100 sensor readings and OscilloscopeFusion enables radio communication less frequently rather than OscilloscopeCustom in order to transmit data.

Referring to OscilloscopeFusion which implements the same RF managing scheme as OscilloscopeCustom and additionally process collected data before the transmission, energy saving is significant compared to OscilloscopeRF and OscilloscopeCustom due to reduced radio communication usage.

8. CONCLUSIONS

TinyOS applications are implemented to examine the optimization technique proposed in this paper. Radio communication subsystem is the most energy consuming component of the node and energy saving can be succeeded by applying RF managing schemes without compromising data information transmitted.

<table>
<thead>
<tr>
<th>Application</th>
<th>Simulation 60 sec (mJ)</th>
<th>Measurement 60 sec (mJ)</th>
<th>Theoretical Estimation 60 sec (mJ)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Oscilloscope*</td>
<td>863.65</td>
<td>743.13</td>
<td>864.00</td>
</tr>
<tr>
<td>OscilloscopeRF</td>
<td>4440.14</td>
<td>4070.63</td>
<td>4464.00</td>
</tr>
<tr>
<td>OscilloscopeCustom</td>
<td>1151.04</td>
<td>1093.16</td>
<td>1164.00</td>
</tr>
<tr>
<td>OscilloscopeFusion</td>
<td>877.55</td>
<td>687.37</td>
<td>812.88</td>
</tr>
</tbody>
</table>

*No use of Radio Communication (for comparison purposes only)

A theoretical tool is proposed as a composite method of energy consumption estimation with current draws for the various components of the node and timing of the energy states transitions obtained by the measurement stage. A method of measurement is developed based on a shunt resistor and instrumentation amplifier stage in order to have sufficiently high sensitivity in both low energy and high energy states of the node.

A profiling stage is applied in order to identify the most energy consuming subsystems and assign node functions to subsystem functions. Identification of those functions initiates the procedure of optimization by applying techniques towards the optimal operation of the specific node functions in order to reduce energy consumption.

Results indicate a significant reduction of energy consumption at the OscilloscopeFusion application which implements RF managing and on board signal processing. This finding validates the belief of energy saving by replacing, when possible, radio communication with signal processing techniques. The constraints of this approach are defined by the limited resources of wireless sensor network nodes especially in processing power and memory. There are strong indications that these conclusions can be generalized for a wide variety of wireless sensor networks made by different manufacturers.

Improvement in accuracy of theoretical and simulation processes is related to the creation of a more detailed energy model for nodes and precise detection of energy state transitions which is expected to enhance the ability of detecting and measuring timing of every energy state.

Current TinyOS applications implemented are considered to handle biosignals characterized as slow varying time series which require low sampling rates. Suggestively at the framework of the current work some biosignals that could be handled are light, temperature, continuous glucose monitoring taking into account a monitoring application such as the variants of oscilloscope application presented. More biosignals could be monitored with the increase of sampling rate such as pulse oximetry, acceleration, electrocardiogram, electroencephalogram or electromyogram enabling pervasive computing in a wide range of assistive body centric applications.

9. FUTURE WORK

Energy consumption estimation and measurement is being extended to network level by designing and deploying wireless sensor network with multihop communication fashion and implementation of the principles described in this paper in network level. Moreover, a basic assumption adopted in this paper is the constant voltage supply in order to acquire only current draws values and calculate energy as a product of voltage, current and time. Batteries
set challenging fronts in calculating energy consumption due to recovery effect. Optimization techniques implemented for sensing high frequency biosignals such as electrocardiogram (ECG), electromyogram (EMG) complicate the energy saving schemes which are based on minimization of radio communications (Transmit or Listen) due to limited memory resources of the nodes. Signal processing methods aiming at the reduction of the amount of transmitting data without compromising information are under examination.

Low energy consumption hardware design, energy efficient protocols and optimization techniques aiming at the efficient administration of energy consuming wireless sensor networks node subsystems enable green pervasive computing.

Energy resources are critical for wireless sensor networks lifetime and lack of adequate power may compromise network functionality and reliability. Wireless Sensor networks design for specific applications is taking into account energy consumption and applies techniques to minimize consumption. Simulation and theoretical tools are proved to be essential in designing energy efficient applications and measurement results verification enhance reliability to those tools.

10. REFERENCES


