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Practical Wireless Sensor Networks Power Consumption Metrics for Building Energy Management Applications

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Abstract: The power consumption of wireless sensor networks (WSN) module is an important practical concern in building energy management (BEM) system deployments. A set of metrics are created to assess the power profiles of WSN in real world condition. The aim of this work is to understand and eventually eliminate the uncertainties in WSN power consumption during long term deployments and the compatibility with existing and emerging energy harvesting technologies. This paper investigates the key metrics in data processing, wireless data transmission, data sensing and duty cycle parameter to understand the system power profile from a practical deployment prospective. Based on the proposed analysis, the impacts of individual metric on power consumption in a typical BEM application are presented and the subsequent low power solutions are investigated.

1 Introduction

The development of wireless sensor networks (WSN) technology in the last decade enables these miniaturized embedded modules to be integrated in a wide variety of applications, ranging from building energy management (BEM), structural health monitoring (SHM) to body-area network applications for human health care [1-3]. The BEM application emerges with a substantial market opportunity and high technology readiness level in recent developments. The integrated sensing and data processing units together with wireless data transmission capability give a high level of flexibility and programmability to future BEM solutions. The improved robustness of wireless communication has been evidenced by various literatures and shows the possibility of replacing most of the cable connected BEM systems in the foreseeable future [4].

Despite many advantageous characteristics of WSN, one considerable drawback is that battery powered WSN often requires frequent service intervals due to the limited capacity of the energy storage element. The maintenance cost to replace or recharge the hundreds of WSN modules (motes) in a typical office building may exceed the system cost in a relatively short period of time. Other than the maintenance cost issue, frequent power failures in key connection points of the mote network will compromise the reliability of entire system. Many research efforts have been made in order to harvest energy from environmental sources (i.e. light, wasted heat or vibration) to prolong the system lifetime [5-7]. Alternatively, many works investigate low power network protocols to save power consumption of WSN [8][9]. However, one important but less addressed issue is how to correctly understand the power consumption characteristics of mote and the critical metrics of the WSN power profile.

This paper summarizes the key issues in WSN power consumption profiles with a focus on building energy management applications. The main factors including duty

cycles, data processing and wireless data transmission power and data sensing power are individually investigated. Their impacts on the overall system performance are analyzed and quantified. The proposed power consumption metrics of WSN are aimed to help the end-users to prolong the lifetime based on existing WSN system. More importantly, design engineers can use these metrics to evaluate the power consumption performance of their future WSN system prior to device manufacture.

2 WSN in BEM Applications

Wireless sensor module (mote) is a microprocessor-controlled sensing module with wireless communication capability via an RF chip. The mote is then connected based on certain network topology and protocol. With a focus on BEM application, the integrated sensing module includes temperature, relative humidity, light and passive infrared (PIR) sensors. The connection between microcontroller and sensors are linked by I2C and ADC interfaces. Figure 1 refers the structure of mote used in BEM applications with sensors for indoor environmental monitoring tasks.

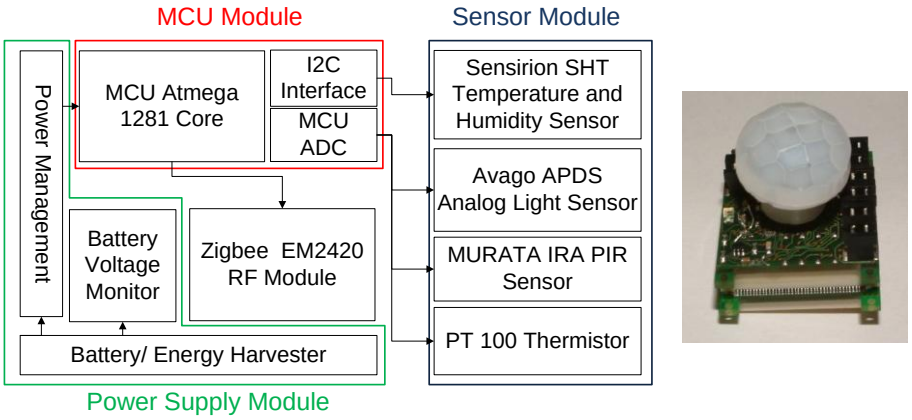


Figure 1. Wireless Sensor Node for Building Energy Management Application

The implementation miniaturizes the Atmega 1281 microcontroller [10], Zigbee EM2420 RF module [11], power supply module and 4 sensors into a 25×25×15mm mote. The motes are programmed in nesC and only require 1 Kbyte of memory.

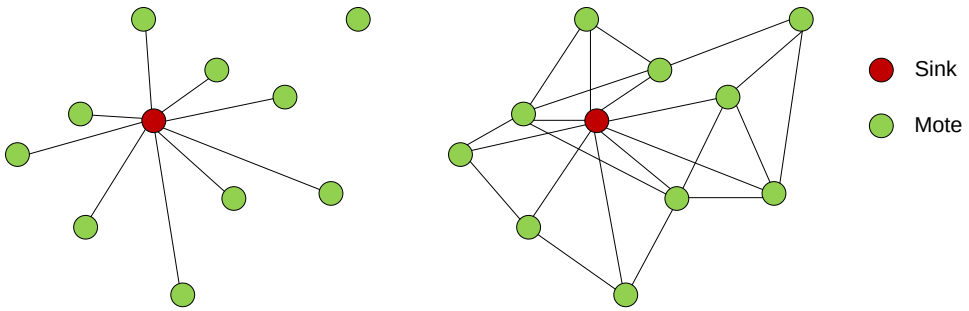


Figure 2. Star network (left) and Mesh Network (right) Topologies

Two types of network topology, star type network and mesh network, are proposed to effectively utilize the functionalities of the motes. The simplicity of star network enables relatively low energy consumption during deployment. However, for network

covering indoor area in a complex radio propagation condition, it often requires multiple “hops” via relay motes to transmit data to the sink. In this scenario, a mesh network topology is necessary to avoid increasing the number and cost of sinks.

3 Power Consumption Metrics

In this section, the power consumption metrics of mote are derived and presented from four aspects, data sensing, processing, transmission and duty cycle operation. From the user prospective, the controllable parameters of mote are important to optimize the system operative power consumption. Many other parameters are determined by components inherent characteristics. Although they can be modified from theoretical prospective, it is unrealistic to change once the device is finalized. Thus, the analysis of power consumption is focused on the parameters that can be modified by the users. The analysis is based on point to point data transmission to understand the hardware performance.

3.1 Data Sensing

The power consumption of sensors is an area less addressed in previous literatures. Due to the fact that the power consumption highly relies on the type and specifications of the devices selected during design. Although data rate, sensing resolution and measurement range are critical for the sensor design, from the power consumption point of view, the most important parameters are different. The active mode power consumption, warm up time and active mode time are of particular importance. The settle time of microcontroller integrated ADC for analogue sensor will also impact the power consumption of sensor module. Figure.3 illustrates the power profile in a sensing cycle.

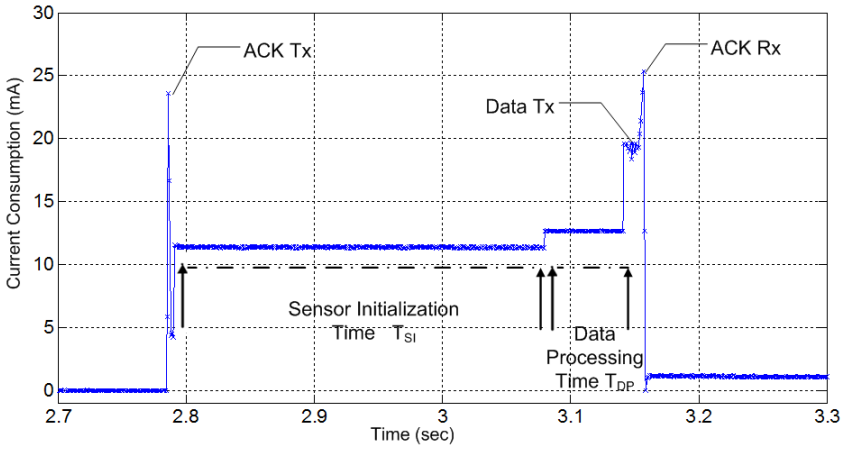


Figure 3. Power consumption profile of sensor module

In the practical sensor layer design, a universal power MOSFET is often implemented to switch off the sensors when sensing is not required. This feature generally eliminates the power consumption of sensor module in sleep mode. However, switching the power mode from sleep to active requires an initialization phase. For

analogue sensors, the initialization time is the settling time of microcontroller analog to digital converter (ADC). For digital sensors, the connection to the microcontroller is made either through an I2C interface or GPIO signal pins. Some of the digital sensors require initialization time T_{SI} significantly longer than the actual sensing time T_{DP}. Although the initialization phase consumes less power than the active mode, the extended warm up time may lead to high energy consumption if not controlled properly. In addition, due to the fact sensors need to be activated by microcontroller, the extended initialization time also significantly increases the active time of microcontroller.

	Measured RF (mW)	Measured MCU (mW)	Measured Sensor (mW)	Calculated Power (mW)	Measured Power (mW)
Initialization	1.3673	29.7964	0.4105	31.5742	31.4054
ACK	61.7566	14.786	0.2614	76.804	76.962
Data Tx	48.4873	14.5296	0.4713	63.4882	64.1361
Sensing & Data Processing	0.0008	30.2783	2.0308	32.3099	35.2189
Sleep	0.0022	0.0403	0.004	0.0469	0.0422

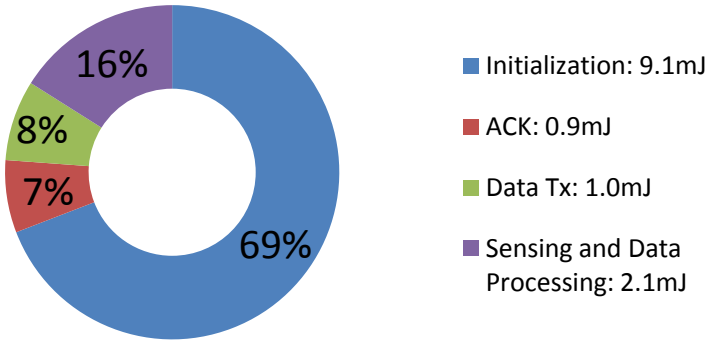


Figure 4. Power Consumption in Typical BEM Application Mote

For BEM applications, the size of the measured data is relative small. A combined data packet including temperature, relative humidity, light level and PIR data may only require 50 bytes. In some implementations, the size of the data packet is even lower [12]. The small data size and high sampling rate lead to the short active sensing time. However, there is no direct correlation between warm up time and the data packet. Figure 4 presents the actual power consumption of sensor module in a typical BEM application. In contrast of previous literature, the main impacting fact of sensor module in a practical BEM deployment is due to the proper control of warm up time of sensor. 69% of the active mode energy consumption is attributed to the sensor and MCU initialization, while only 16% of the total energy is consumed on the subsequent sensing and data processing.

3.2 Data Processing

The power consumption of actual data process only represents a friction of the total power cost. In the case of BEM application, the volume of data generated from the sensor is limited. Most of the latest microcontrollers obtain a clock speed of 8MHz. The high computation capability is only partially utilized in BEM applications. For a

significant percentage of the microcontroller operative time, the MCU device is set into idle mode in order to maintain the active mode and the capability to response to the forthcoming tasks without initialization. Although the power consumption of idle mode of MCU is lower than the data processing mode power consumption. It is still two orders of magnitude higher than the sleep mode power. In order to minimize the energy consumption, it is necessary to minimize the idle mode time in the programming and reduce the redundancy.

However, from a hardware point of view, the microcontroller is a highly integrated device. Access to the microcontroller core is infeasible from the user point of view. Two parameters can be modified to adjust the power consumption of microcontroller. The power supply voltage of micro controller is one parameter that has direct impact on the power. The minimum supply voltage of microcontroller is as low as 1.5V, however, other components e.g. sensors and RF module require higher voltage. In order to simplify the power supply design, the microcontroller is often directly connected to a 3V or 3.3V battery through a LDO type voltage regulator. The simple method doubles the power consumption in micro controller. An alternative method is to include a secondary voltage regulator to minimize the extra power consumption due to the relative high voltage from the universal LDO voltage regulator. A tradeoff between LDO efficiency loss and power saving from lower operative voltage is required to optimize the supply voltage.

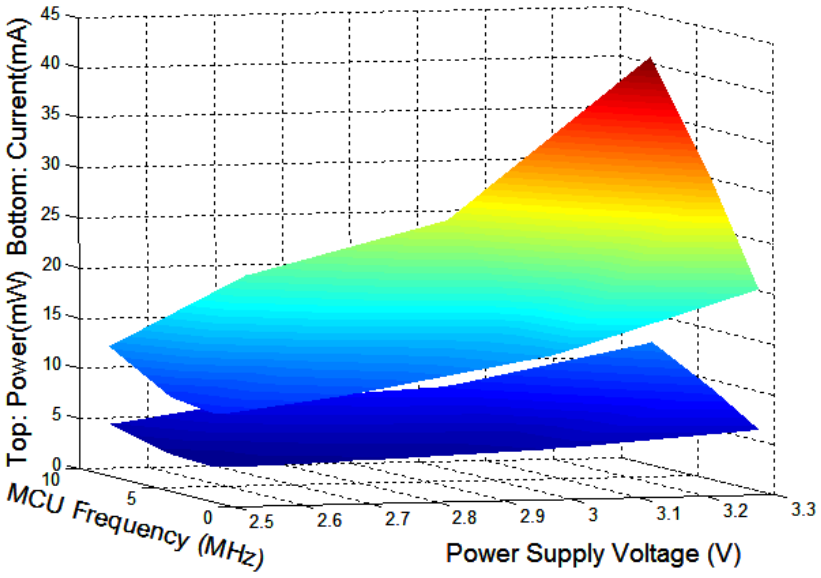


Figure 5. Atmega 128L and MSP430P435 Microcontroller power consumption profile in various supply voltage and clock frequency conditions

Another parameter that poses a substantial impact on the data processing power consumption is the MCU clock frequency. Most micro controller used in WSN applications can obtain multiple operative clock frequencies. Between different frequencies, the power consumption variation is also significant. Some MCU devices show obvious correlation between the power supply voltage, while in other devices the correlation is less significant. In this work, a former type of MCU is considered and

the correlation between the operative frequency and supply voltage is investigated and presented in Figure 5. The data sensing and data processing power consumption of a mote is presented in the following equation:

$$E_{DP} + E_{SEN} = P_{SI} \cdot T_{SI} + P_{DP}\,(f_{CLK}, V_{CC}) \cdot T_{DP}(f_{CLK}) \quad (1)$$

Where $E_{DP}\ and\ E_{SEN}$ are the energy consumptions in data processing and sensing, respectively. P_{SI} and T_{SI} are the power consumption and time of sensing initialization. Both parameters are determined by sensor device and cannot be directly modified by users. P_{DP} is the power consumption of sensing and data processing power consumption, 94% of the power consumption attributes to the MCU as shown in Figure 4. This parameter can be controlled by clock frequency of MCU and power supply voltage as the correlation shown in Figure 5. T_{DP} is the sensing and data processing time. Although it is determined theoretically by the clock frequency of MCU, the actual impact the MCU speed caused is negligible due to the small data size.

3.3 Data Transmission

A Zigbee RF module provides a maximum data transmission rate at 250Kbit/sec. For BEM applications, the small packet size of sensing data allowed it to be transmitted in a short period of time. Based on a Texas Instruments CC2420 Zigbee module, the data transmission time of a 50 bytes packet is 16msec. Although power consumption of wireless communication module is considerable higher than microcontroller in active mode, the actual energy dissipated in data transmission is substantial lower. The power consumption of communication is mainly determined by the transmission power mode. However, the chip level drain efficiency (the ratio of output RF power to total input power supply DC power) is inherently low for 2.4GHz Zigbee RF modules. The ratio is between 1% and 2% when 0 dBm transmission power is selected, whilst it drops significantly when lower transmission power is used. The low and variable efficiencies lead to the fact that the measured power consumption difference between high transmission power mode (29.7mW for 0 dBm) and low power mode (52.2mW for -15 dBm) is substantially lower than the transmission power difference (0 dBm and -15dBm). The small data packet size and resultant short transmission time enable relative low energy consumption when transmitting with maximum power mode.

Due to the low energy consumption nature of the data transmission in BEM application, the acknowledgement (ACK) packet of network protocol is considered in the power consumption analysis. The acknowledgement packet transmission time is 12msec with one transceiving ACK and one receiving ACK. The transmission power is on maximum power transmission mode to extend the transmission range. Thus, the energy consumption of acknowledgement transmission is comparable to the energy dissipated in data transmission.

To improve the data transmission reliability, when a transmission is failed or incomplete, the gateway node will send an ACK requiring a repeat transmission from the mote. Upon receiving the repeat ACK, the mote will transmit the previous data stored in flash memory. In the deployment, the mechanism is essential to maintain a

high quality of service. The repeat rate also significantly contributes to the energy consumption of mote.

The energy consumption in ACK and data transmitting of a single input single output (SISO) wireless communication is summarized in the following equation:

$$E_{ACK} + E_{data} = P_{TX}(k_{PM}) \cdot T_{TX}\left(L_D, n_p, L_{ACK}, \rho\%\right) + P_{RX} \cdot T_{RX}(L_{ACK}, \rho\%) \quad (2)$$

Where E_{ACK} and E_{data} are the energy consumption of acknowledgement and data transmitting, respectively. P_{TX} is the RF module total power consumption when a transmitting power is selected. The correlation between measured module power consumption and transmitting power is described by the coefficient k_{PM}. P_{RX} is the power consumption in receiving mode. P_{RX} is a constant value in most of current Zigbee modules and is 15-20% higher than the maximum transmitting power. T_{TX} and T_{RX} are the transmitting time and receiving mode time, respectively. The ACK packet has a single and preset data format, only the actual packet length and the repeat rate are relevant to the receiving mode time T_{RX}. In the case of transmission time, the number of data packet $n_p$and length of data packet L_D are main parameters.

3.4 Duty Cycle

To reduce the energy consumption during long term deployment, it is crucially important to operate the mote in a low power "sleep" mode when no data sensing and transmission is required. As shown in Figure 4, the sleep mode power consumption is measured at 42μW. When compared with the data transmitting power, the sleep mode power is 3 orders of magnitude lower. The requirements of BEM application allow relatively long time intervals between measurements, 5 to 15 minutes measurement intervals are often sufficient, while the total active mode time is shorter than 400msec, the mote is able to operate in ultra-low duty cycle. The total energy consumption including sleep mode power consumption is shown in the following equation:

$$E_{Total} = \left(\frac{E_{ACK}+E_{data}+E_{DP}+E_{SEN}}{T_{SI}+T_{DP}+T_{TX}+T_{RX}}\right) \cdot T \cdot d\% + P_q \cdot T \cdot (1 - d\%) \quad (3)$$

Where T is the period of one measurement including active mode and sleep mode time, $d\%$ is the duty cycle. P_q is the sleep mode power consumption.

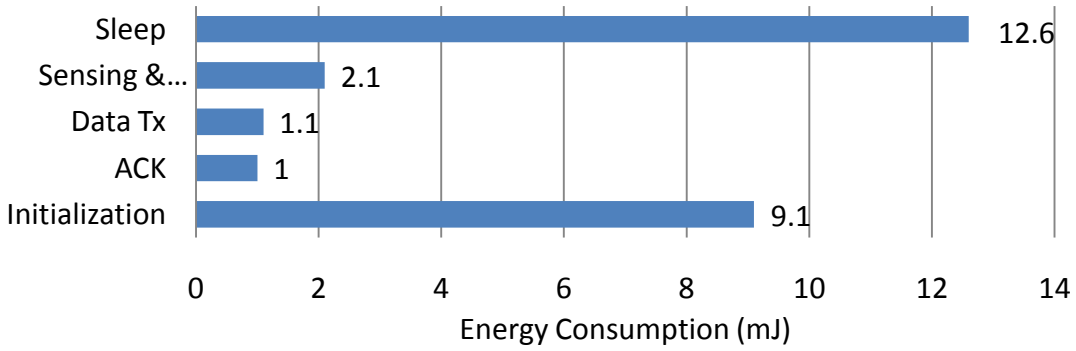


Figure 6. Power Consumption Impacts

In a case of 5 minutes per measurement and a 6% repeat rate, the total energy consumption is measured at 25.9 mJ. Figure 6 illustrates the energy consumption divided by each functions of the measurement. The sleep mode energy contributes to a significant percentage of the total energy consumption of WSN in low duty cycle applications. By improving the power regulators, adjusting impedance between power supply and ground pin and effectively isolating the sensor layers from power supply in sleep mode, the energy consumption of this mode can be further minimized.

4 Conclusions

In this paper, practical metrics of WSN energy dissipations are investigated to understand the impacts on long term deployments. The experimental results show the sleep mode and mote initialization phase power consumption have a more profound impact than data processing and wireless communication power dissipation in low data rate, low duty cycle operations such as BEM. Significantly different to previous literatures, the importance of low power wireless communication protocol is a less fundamental issue in such applications. The most important challenges to minimize the WSN power consumption are on (i) sensor initialization energy consumption (ii) power regulation of WSN in order to reduce the sleep mode power consumption.

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