Autonomous Smart Sensing System for Building Energy Metering

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Abstract—Due to the potential economical and environmental benefits for smart building energy management (BEM) systems, energy efficient wireless sensor networks for BEM applications have become a major research focal area. As a fundamental step towards intelligence using electricity in buildings, a smart sensing system for building energy metering is presented in this paper. The proposed system consists of low power Tyndall wireless sensor node hardware with indoor light energy harvesting featured power supply and energy management system for long-term deployment. Evaluations of the system are conducted in a supermarket site with a total of 12 nodes operating with varying functions. The evaluation results of the energy metering system and the deployment sites energy consumption data are presented.

Index Terms—Wireless Sensor Networks, Automatic Meter Reading, Energy Harvesting

1. Introduction

Automatic Meter Reading (AMR) Systems, especially electricity meter reading has attracted considerable research interests in recent years. The main reason for such intensive research efforts is the rapidly increasing utility cost in business operations. However, the financial cost is not the only concern. The buildings energy data published by U.S. department of energy show that, in the year 2009, 40% of the total energy usage in United States is attributed to residential and commercial buildings operation [1]. The energy inefficiency of building operation has proven to be a major contributor of energy consumption and greenhouse gas emissions. How to reduce the energy consumption without compromising the operation of the building is a research focus in both academic and industrial scopes.

One aspect of these studies is to integrate smart metering and automatic control systems into target buildings. The integration of the intelligent system would substantially reduce the energy consumption. One case study shows that the addition of AMR and control system results an annual average energy saving of 23% in an office building [2]. However, the high cost of such systems limits this technology to be deployed more widely. For existing buildings, the foremost cost factor of the system is the installation. To accommodate the cable-connected system, significant changes need to be made to the original electricity installation and the building’s structure. When compare to the cable connected system, wireless connected system can greatly reduce the installation cost, making the systems more affordable for existing
buildings. Thanks to the increasing transmission reliability of the radio frequency technology (e.g. Zigbee) and also better modularity for future upgrading, the wireless AMR technology has the potential to become a widespread standard for all existing buildings in the foreseeable future.

A Zigbee based wireless sensor node Tyndall mote is presented in this paper. This low power wireless sensor system had been tested for power consumption performance in the designated AMR deployment. The results of the performance will be presented in section 2.

To operate the system in a long-term and maintenance-free manner, proposed smart sensing system needs to be a self-powered system. Hence, building environmental management (BEM) application-focused energy harvesting components have been investigated and demonstrated in this work in section 3. An energy harvesting model and the system optimization are presented in section 4. With the developed supercapacitor energy storage and maximum power point tracking (MPPT) featured power management circuit, the proposed indoor light energy harvesting module is able to provide sufficient energy for WSN at very low light level in line with many realistic deployments.

In the section 5 of the paper the system evaluation results in a local supermarket are presented. The problems discovered during the field test and the conclusions together with the future plans to improve the present system are presented in the final section.

2. Tyndall Wireless Sensor Networks

In the current WSN paradigm, the mote is a microcontroller controlled sensing module with wireless communication capability via an RF chip integrated in the module. In this AMR application, multiple sensor nodes are deployed in targeted area. The communication routed between the sensor nodes and the WSN gateway configured in a typical star network topology [3]. The structure of the AMR system is illustrated in Fig. 1 (a).

![Wireless Metering System](image1.png)  ![Tyndall Wireless Sensor Node](image2.png)

Fig. 1. (a) Wireless Metering System  Fig. 1. (b) Tyndall Wireless Sensor Node

The Tyndall wireless sensor node shown in Fig. 1.(b) is used to record and transmit the meter readings. The Tyndall mote features an Atmel Atmega1281 microcontroller and a CC2420 Zigbee RF chip. PA310 electricity meters are used to read the
electricity usage data. The gateway device illustrated in Fig 1.(a) also comprises a Tyndall mote. The communication between the RF chip and the gateway is via 2.4GHz Zigbee channels. The gateway is connected to the end user’s work station via serial cable.

Given the simplicity of the wireless communication system, the reliability requirement on the power supply in each mote is high. Any power failure on key motes will lead to critical data loss. Hence, Tyndall mote employs a low power consumption design and a duty cycling operation to minimize the power consumption and prolong the deployment lifetime [4]. During its sensing and transmitting/receiving mode, dramatically higher power is consumed than in sleep mode, the active power consumption being 3 orders of magnitude higher than its average sleep mode power consumption. The power consumption of the mote in various modes can be found in Table 1. The most efficient way of using energy in the wireless sensor nodes is asymmetric duty cycling operation. This features a much longer sleep mode time than active mode time.

<table>
<thead>
<tr>
<th>Active mode</th>
<th>Sleep mode</th>
<th>CR Li-ion Battery Leakage</th>
<th>Supercapacitor Leakage</th>
</tr>
</thead>
<tbody>
<tr>
<td>Current Consumption</td>
<td>25.6mA</td>
<td>6.2μA</td>
<td>0.5μA</td>
</tr>
</tbody>
</table>

Table 1. Tyndall Mote Power Consumption

The overall power consumption of the wireless sensor node, therefore, is determined by the active/sleep mode power consumption and the duty cycle. In another aspect, the leakage of the energy storage unit (battery or supercapacitor) is also a significant contributor to the overall average power consumption. Hence, the average power consumption can be calculated by using equation (1)

\[ P_{\text{average}} = P_{\text{active}}D + P_{\text{sleep}}(1-D) + P_{\text{leakage}} \] (1)

Where \( P_{\text{average}} \) is the average power consumption of the mote; \( P_{\text{active}} \) is the sensing and transmission power consumption; \( P_{\text{sleep}} \) is the sleep mode power consumption; \( D \) is the duty cycle; \( P_{\text{leakage}} \) is the leakage power of the energy storage unit.

For the energy metering application, when operating with a time interval of 1 minute, a CR type 300mAh coin battery based system only requires an average power of 149μW. In the case of a 2F supercapacitor used as the energy storage, the system power consumption increases to 178μA [5].

3. Energy Harvester

The targeted system operational scenario of this WSN prototype is in supermarket environment. The most common light energy sources are the overhead fluorescent lights. Efficient photovoltaic cells are essentially to harvest the energy from the fluorescent light. The voltage controlled current source behaviour of the PV cells gives relatively steady voltage output and a variable current output subject to the light illuminance. Thus, the system operation relies on the illuminance level if directly
powering the mote with the PV cells. This reliance renders the mote to be highly unreliable. Stable output voltage and current can only be achieved when an energy storage unit is used. Also as a result of the current source behaviour, the output power of the PV cell is partly dependent on the operational voltage on the PV cells. Without proper optimization, voltage on the PV cells would not operate on the maximum power point (MPP) voltage.

An energy harvester embedded system consists of five components: the light available in the environment, the photovoltaic cell, power management circuits, energy storage unit and the target wireless sensor node.

Amorphous Silicon (A-Si) solar cells are used as an energy harvesting source due to their relatively high energy conversion efficiency in indoor environments [6]. The solar cell features an amorphous Silicon deposition on glass substrate photovoltaic structure. With the tandem connections within the A-Si cells, the voltage is higher than the required 2.5V operation voltage at 200lux low illuminance. Thus, such amorphous silicon solar cells should be only connected in parallel to increase current output. Each of the solar panel features a 55 mm by 14mm dimension and composed of 4 photovoltaic P-N junctions. Characteristics of the solar panel are shown in Fig. 2 in indoor test conditions.

Fig. 2. Solar Cell Characteristics

Three illuminance levels 100lux, 200lux and 500lux are used to test the solar cells and the environmental temperature is controlled at 293K. Fluorescent light sources were used in the test to simulate the deployment site environment. Under the typical illuminance of 200lux, the energy conversion efficiency of the A-Si cells is approximately 4.5%. The output voltage when the solar cell reaches MPP is approximately 2.8V, and the maximum output power is 106μA.

In most of the energy harvesting systems, two types of energy storage elements frequently used are Lithium ion rechargeable battery and electrochemical double layer capacitors (supercapacitor). Several significant differences distinguish the supercapacitor from the Li-ion battery. (a) It has a lower energy density (energy/weight) but higher power density (energy/time) than the rechargeable battery. This allows it to be charged more quickly than the rechargeable batteries. (b) It has a much higher number of charge cycles than current battery technologies. (c) Normally,
it has more than 1 million charge cycles (deep cycles) compared less than 1000 cycles of the battery [7]. However, the high self-discharge rate is the main constraint for the supercapacitors’ long term deployment. In spite of the high leakage, the advantages mentioned above and the availability of the light energy in the deployment scenario make it very suitable in this application.

The leakage current of the supercapacitor is a very important factor for the energy harvester. However, the leakage data is often incomplete or missing from the supercapacitors manufacturer datasheet. A test was conducted on 4 different supercapacitors to investigate the average leakage current over 24 hours. All supercapacitors were pre-charged and then isolated from other circuits. The voltage drop is only due to the self discharge of the supercapacitors. The test results are illustrated in Fig. 3. The results show that the self discharge rates range from 45% to 15% every 24 hours.

![Fig. 3. Supercapacitors Self Discharge Rate Test](image)

The correlation between capacitance and self discharge rate is not linear. However, average leakage current may be fundamentally affected by the capacitance of supercapacitor. Thus, a model is required to optimize and choose a capacitance suitable for any given application.

**4. System Modelling and Optimization**

To enable the solar panel to operate continuously, an energy model is used to choose the suitable solar panel and supercapacitors. Two requirements of the system are: a) solar cells charge the supercapacitor to required level within illuminance period; b) system is ability to operate while no illuminance is available for 8 hours during night.

The operation is divided into two phases, charging phase and discharge phase. Separate models are used to explain the requirement in the two phases. Charging phase of the light energy harvesting module can be described with the following equation.

$$E_{\text{charge}} = \overline{I}_{\text{PV}} \ast (\overline{V}_{\text{PV}} - I_{\text{leakage}} - I_{\text{active}} \ast D - I_{\text{sleep}} \ast (1 - D)) \ast T_{\text{charge}}$$  \hspace{1cm} (2)

Where $E_{\text{charge}}$ is the energy stored in the supercapacitor at the end of charging time in every 24hours. $\overline{I}_{\text{PV}}$ is the average PV cell output current, $\overline{V}_{\text{PV}}$ is the average PV cell output voltage, $I_{\text{leakage}}$ is the supercapacitor normalized leakage current, $I_{\text{active}}$ is the active mode current consumption and $I_{\text{sleep}}$ is the sleep mode current consumption.
D is the duty cycle. $T_c$ is the charging time in every 24 hours (average illuminance >30 lux).

The required energy consumed in the discharge phase $E_{\text{discharge}}$ is shown in the equation (3).

$$E_{\text{discharge}} = V_{\text{avg}} \times T_{\text{discharge}} \times [I_{\text{leakage}} + I_{\text{active}} \times D + I_{\text{sleep}} \times (1 - D)] < E_{\text{charge}} \quad (3)$$

Where $T_{\text{discharge}}$ is the discharge time (8 hours) when illuminance <30 lux, $V_{\text{avg}}$ is the average voltage on the supercapacitor in discharge phase.

By combining the equation 2 and 3, the average output current of the PV cell must meet the following requirement:

$$\bar{I}_{\text{PV}} \geq [I_{\text{leakage}} + I_{\text{active}} \times D + I_{\text{sleep}} \times (1 - D)] \times (1 + \frac{V_{\text{avg}} \times T_{\text{discharge}}}{V_{\text{PV}} \times T_{\text{charge}}}) \quad (4)$$

Meanwhile, to meet the requirement (b), the following equation is used to determine the parameters of the supercapacitor.

$$\frac{C(V_0^2 - V_{\text{mote}}^2)}{2} > E_{\text{discharge}} = V_{\text{avg}} \times T_{\text{discharge}} \times [I_{\text{leakage}} + I_{\text{active}} \times D + I_{\text{sleep}} \times (1 - D)] \quad (5)$$

Where $C$ is the capacitance of the supercapacitor, $V_0$ is the smaller one of average PV cell output voltage and supercapacitor rated voltage. $V_{\text{mote}}$ is the lower operational voltage limit of Tyndall mote.

However, most of the commercial available supercapacitors with a capacitance higher than 1 F only have a voltage rating lower than 2.5 V. The operation voltage of the mote needs to be higher than 2.5 V. Due to this reason, a DC/DC converter must be used to step-up the voltage. The DC/DC converter used in this work is a Texas Instruments TPS61220 step-up Converter [8]. The topology of the energy harvester becomes to that illustrated in the Fig. 4 (a) block diagram.

This topology extends the lower operational voltage limit from $V_{\text{mote}}$ (2.5 V) to the minimal start-up voltage of the DC/DC converter (0.7 V). However, one obvious problem of the topology is the output voltage from the PV cells is limited to the voltage on the supercapacitors. For most of the charging phase, the supercapacitor voltage would be much lower than the maximum power point illustrated in Fig. 2. The PV cells, thus, would operate in a very low efficiency. Hence, a maximum power point tracking (MPPT) method is used to avoid such low efficient operation. As shown in Fig 4 (b), a secondary supercapacitor, a Schmitt trigger based MPPT circuit and a SPST switch are included in the new design. The Schmitt trigger based MPPT circuit set the dual voltage thresholds at 2.6 V and 3 V. These thresholds are within ±4% of the MPP.
The PV cells would only charge the secondary supercapacitor. Once the 3V upper limit is reached, the switch will connect the secondary capacitor to the main supercapacitor; after the 2.6V lower limit is reached, the switch would separate these two. The secondary supercapacitor would only be charged between these voltage thresholds. The test result of the MPPT circuit is shown in Fig. 5. The PV cells operate close to the MPP voltage.

\begin{align}
I_{PV} &\geq [I_{\text{leakage}} + I_{\text{active}} \cdot D + I_{\text{sleep}} \cdot (1 - D)] \cdot (1 + \frac{V_{\text{avg}} \cdot T_{\text{discharge}}}{V_{PV} \cdot V_{\text{charge}} \cdot \eta_{\text{dc}} \cdot \eta_{\text{mppt}}}) \\
\end{align}

Also Eq. (5) is rewritten due to the addition of the DC/DC converter. Where \( \eta_{\text{dc}} \) is the DC/DC converter efficiency, and \( \eta_{\text{mppt}} \) is the maximum power point circuit energy conversion efficiency.

\begin{align}
\frac{C(V_0^2 - V_{DC}^2)}{2} \cdot \eta_{\text{dc}} > V_{\text{avg}} \cdot T_{\text{discharge}} \cdot [I_{\text{leakage}} + I_{\text{active}} \cdot D + I_{\text{sleep}} \cdot (1 - D)]
\end{align}

By using the parameters analysed in section 4 and the energy models in this section, the size of the supercapacitors and the solar cells can be optimized and chosen. A prototype based on this design paradigm is shown in Fig. 6. The integrated system consists of 4 Schott solar cells, 1.5F Supercapacitors bank, TPS61220 DC/DC converter and the maximum power point tracking circuits in a topology shown in Fig. 4(b).

**5. Experimental Results**

The performance of the prototype system has been installed in a local supermarket. A voltage monitoring circuit is implemented in order to read the voltage level of the supercapacitor bank. The purposed system is used to evaluate the energy usage conditions of various areas in the supermarket. Fig. 7 shows the power consumption data of the shop floor and the voltage level on the supercapacitor bank of the energy harvester. The supercapacitor reaches the required energy level \( V_{\text{supercap}} = 2.8V \) before 22:00. Between 22:00 and 7:00, the Mote discharges the supercapacitor to 0.85V. Given the fact that TPS61220 DC/DC converter has a step-up voltage at 0.7V, the indoor light powered wireless sensor module can operate autonomously in this deployment. The voltage on the Tyndall mote is stable and the mote is under constant duty cycling condition in the entire operation time as shown in Fig. 7.
6. Conclusion and Future Work

In this research, an autonomously operated energy metering system is presented. The energy harvesting capability enables the WSN based AMR system to be installed in a “deploy & forget” manner. It shows that for the energy harvester uses supercapacitor as their energy storage, the MPPT technique should be incorporated to allow the solar cell operates near the highest energy conversion efficiency. The energy model introduced in this paper is a practical tool to understand design tradeoffs in energy harvesting systems. The model can improve the components selection and overall efficiency. With the optimized energy harvester and a low power mote, it is possible to operate continuously with 16hours low illuminance. For future work, a mid-long term energy storage unit may be integrated into the energy harvester to avoid power failure in low illuminance level for a prolonged time.

References: