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Energy-Aware Sensor Node Design with Its Application in Wireless Sensor Networks Using Solar Power Harvesting

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Abstract— This paper presents the design and implementation of an energy aware sensor node, which helps in constructing energy-efficient WSNs using solar energy. Solar energy-efficient strategy, which aims at minimizing energy consumption from both the sensor node level and the network level in a WSN has been proposed. To minimize the energy consumption of the sensor node during communication, the distance between the transmitter and the receiver is estimated before transmission, and then, the lowest transmission power needed to transmit the data is calculated and determined. The sensor nodes are also set to sleep mode between two consecutive measurements for saving energy. The solar energy can be harvested and stored in batteries and amount of energy can be predicted and used.

Keywords—Energy efficiency, periodic sleep/wake-up scheme, wireless sensor network (WSN).

I. INTRODUCTION

System miniaturization, wireless communication has promoted development of wireless sensor technology.[1][2]Good progress in wireless communication has enabled its wide applications from condition based maintenance [3] to industrial system monitoring [4] and environmental sensing [5]. The number of wireless sensors, which are typically considered as a wireless sensor networks (WSN),will be deployed even more in the years to come [6], [7]. However, energy consumption still remains as a major concern as, real-life applications have rapidly increased in recent years, and this trend is expected to increase. Prior researches have studied different approaches, such as duty-cycling and data-driven approaches [8], for reducing energy consumption. Duty cycling can be achieved through sleep/wake-up protocols and media access control protocols with low duty cycle. For example, sparse topology and energy management approach has been proposed to improve the network lifetime by setting some redundant nodes to sleep mode [9]. The traffic-adaptive medium access protocol has been designed to reduce energy consumption by allowing sensor nodes to assume a low-power idle state, whenever they are not working in transmission or receiving mode [10].

Data-driven approaches can be divided into two different categories: data compression and energy-efficient data acquisition. As an example, a variable data length coding method using Walsh function was developed to compress the transmission data, and this has been proved to be effective in improving energy efficiency in signal transmission [11]. In another study, the sensor network was divided into several subsystems, and only high-level inferences are communicated between the subsystems. In this way, the energy consumption for communication decreases as the data to be transmitted decrease [12]. For energy-efficient data acquisition, an adaptive sampling algorithm consisting of duty cycling (the sensor board is switched off between two consecutive samples) and adaptive sampling (the optimal sampling frequency is estimated online) is proposed to reduce energy consumption in a sensor network [13]. Researchers have also studied other approaches for energy-aware transmission, including modulation scaling schemes [14], [15], multihop routing schemes [16], network sectioning [17], [18], and low-power hardware [19].

Later a combination of sleep scheduling with block transmission approach has been proposed to achieve energy saving in a wireless multimedia sensor network [20]. Motivated by the prior research, an energy-saving strategy consisting of node-level energy saving using adaptive radio frequency (RF) power setting and network-level energy saving through adaptive network configuration has been proposed . This paper is an extension of [21], in which the periodic sleep/wake-up scheme is added into the sensor node design to further achieve the node-level energy saving. The energy can be harvested from the environment and stored. The stored energy is then used effectively by predicting the energy available.

The remainder of this paper is organized as follows. Section II introduces the sensing scheme and the associated energy consumption estimation of the sensor node and the entire network, respectively. Section III presents the hardware and design of the sensor nodes, the design of the solar battery and its controller. The network level energy details are also presented. And finally the conclusion is drawn in section IV

II. SENSING SCHEMES

The concept of wireless sensor node implies that, except for the physical sensing capabilities, the nodes will also be able to process the obtained data and communicate the results wirelessly. In recent years, many energy conservation schemes have been proposed in the literature, which assume that data acquisition and processing have an energy consumption that is significantly lower than communication [13]. In addition, since each of the sensor nodes in the network is energy constrained and each component in a sensor node consumes a certain amount of energy, power supply becomes important to ensure proper operation of the entire WSN as the number of sensors deployed in a network grows. Hence, constructing effective network structures for the application of WSN with consideration of energy efficiency is of critical importance.

A. Energy Consumption Calculation

After sensing the environmental parameters the results should be transmitted to the central monitoring unit (CMU) or other sensor nodes. In order for two sensor nodes to communicate, the energy consumption needed for data transmission can be expressed as [22]

$$E_{\text{Tx}} = E_{e\_\text{tx}} \cdot k + \varepsilon_{\text{amp}} \cdot d^{\alpha} \qquad (1)$$

where k is the number of transmitted data bits; α is a factor valued from 2 to 5, depending on the environment of wireless transmission; d is the distance between two sensor nodes; ε_{amp} $(J/b/m^2)$ is the amplification coefficient to satisfy a minimum bit error rate to ensure reliable reception at the receiver; and E_{e_tx} (J/b) is the energy dissipated to operate the transceiver, which is given as

$$E_{w\_\text{tx}} = V_{cc} \cdot I_{TP} / K_{\text{data\_rate}} \qquad (2)$$

Where V_{cc} denotes the working voltage, I_{TP} denotes the current for transmission, and $K_{\text{data\_rate}}$ denotes the data transmission rate.

The energy consumed for receiving a data stream can be expressed as

$$E_{\text{Rx}} = E_{e\_\text{rx}} \cdot k. \qquad (3)$$

Equation (1) shows that, for a fixed distance, the energy consumed is proportional to the number of data bits. On the other hand, the longer the distance between two sensor nodes is, the more energy will be consumed.

B. Sensing Schemes

The network-level energy saving was realized mainly through the scheme, switching of the network. Two different schemes of the network are shown as follows [12].

Scheme1:

The obtained data points are transmitted to CMU from each sensor node. The energy consumption E_{dr} in this case is calculated as

$$E_{dr} = \sum_{n=1}^{N} [(E_{e\_\text{tx}} + \varepsilon_{\text{amp}} \cdot d_n) \cdot k_r] \qquad (4)$$

Where N is the number of sensors, d_n is the distance between each sensor node and the CMU, and k_r is number of data bits from the obtained data.

For example, Fig. 1 shows scheme 1 being applied to the platform of greenhouse management in which temperature is measured by the sensors. In each greenhouse, the sensor nodes acquire the temperature data and transmit the data to the CMU directly without routing and relay.

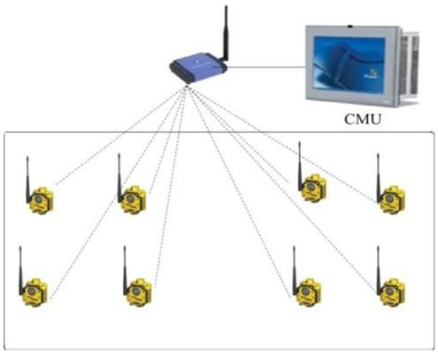


Fig.1: Scheme 1

Scheme 2: The sensors are grouped into different clusters, and the obtained data from each sensor node are transmitted to the corresponding cluster head (it is defined as the sensor node that collects the data from others in the cluster). Then, the cluster head will pack the data and transmit them to the CMU. The energy consumption E_{ds} in this case is calculated as

$$E_{ds} = \sum_{m=1}^{M} [\sum_{j}^{N_m - 1} (E_{e\_tx} + \mathcal{E}_{amp} . d_j^{\alpha} + E_{e\_rx}) . k_r + (E_{e\_tx} + \mathcal{E}_{amp} . d_m^{\alpha}). K_m] \qquad (5)$$

Where M is the number of clusters, N_m is the number of sensors in the corresponding cluster, d_j is the distance between a sensor and its corresponding cluster head, d_m is the distance between the cluster head and the CMU, and k_m

is the number of packed data bits for data transmission. For example, Fig. 2 shows scheme 2 being applied to the platform of greenhouse management in which the network is grouped into different clusters.
Here, each greenhouse is defined as a cluster, and the obtained data are transmitted first to corresponding cluster head; then, the CMU will ask the cluster heads for the temperature data.

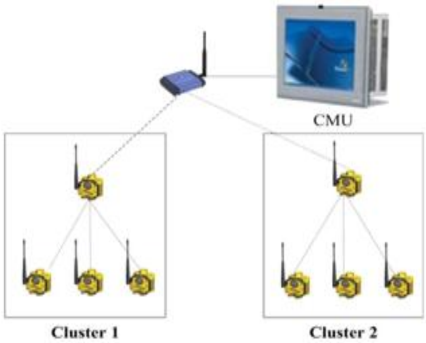


Fig. 2. Scheme 2

III. DESIGN OF THE ENERGY-AWARE SENSOR NODE

In order to provide energy-efficient sensing in a WSN, an energy-aware sensor node is designed and implemented in this section. The detailed information is described in the following discussion.

A. Communication Module

In the two sensing schemes designed for the WSN, it is assumed that the transmission power is minimized to ensure reliable reception at the receiver end, according to the communication distance between two sensor nodes. Hence, awareness of the communication power as well as the adjustability of the transmitter's output power becomes critical in performing the sensing scheme for the designed sensor node. By assuming a unit signal gain provided by antennas, the output power of the communication module is dominated by the consumption for power amplifier. To transmit 1 bit to the receiver, the output power and associated received power are expressed as

$$P_{Tx} = (\mathcal{E}_{amp}.R)\ .\ a^{\alpha} \quad (6)$$

$$P_{Rx} = \frac{P_{Tx}}{d^{\alpha}} = (\mathcal{E}_{amp}\ .\ R).\frac{\hat{d}^{\alpha}}{d^{\alpha}} = P_s\ .\ \frac{\hat{d}^{\alpha}}{d^{\alpha}} \quad (7)$$

where R denotes the data transmission rate, $\hat{d}$ and d are the estimated and actual transmission distances between the transmitter and the receiver, respectively, and $P_S = \varepsilon_{\text{amp}} \cdot R$ is the receiver sensitivity denoting the minimum signal power that the receiver can discern. From (7), it is seen that, if the estimated distance $\hat{d} < d$, then the received signal cannot be identified and the communication between sensor node fails. On the other hand , if $\hat{d} > d$(overestimation),which means a received power that is higher than receiver sensitivity, then a portion of the transmission energy will be lost on the propagation path while not affecting the results of signal reception. In this case the energy efficiency problem is translated to the effective of communication distance between two sensor nodes. Since all of the sensor nodes are equipped with both transmission and receiving capabilities, we can estimate the distance. Example , scheme 2 is applied for local data transmission from a sensor node to its cluster head, the cluster head sends a test code with maximum transmission power $P_{\text{Tx max}}$ to one of the sensor nodes in the local cluster first. By measuring the received power P_{Rx} on each sensor node, the distance to the cluster head can be calculated as

$$\hat{d}^{\alpha} \geq P_{\text{Tx max}}/P_{\text{Rx}}. \quad (8)$$

Hence, by minimizing the estimated distance for data transmission, the minimum required power to ensure data communication is expressed as

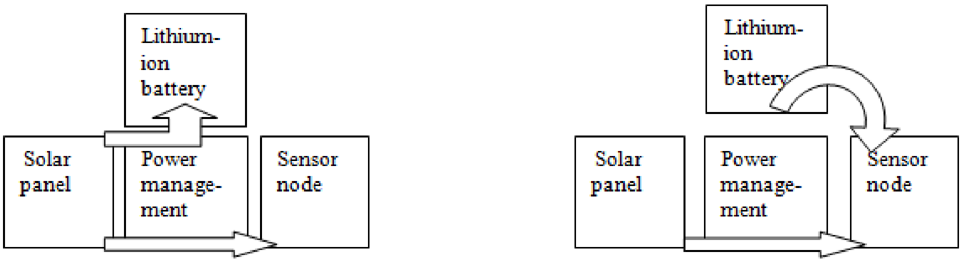
$$P_{Tx} = P_{s}.\frac{P_{\text{Tx max}}}{P_{Rx}} \quad (9)$$

B. Periodic Sleep Wakeup Scheme

The node-level energy saving is achieved through the periodic sleep/wake-up scheme. As we know if a WSN is deployed in remote fields or under harsh environments where manually recharging batteries for sensors is not feasible, one typical alternative approach for energy saving is to turn off some sensors and to activate only a necessary set of sensors while providing a good sensing coverage and network connectivity simultaneously [23]. In slowly varying parameter measurements, such as temperature, not all sensor nodes are needed to stay in active mode. Therefore, in order to save energy consumption, the sensor nodes are designed to be put into a sleep mode with a timer that determines their sleep duration. When the timer overflows, an interrupt happens, and it will wake those nodes up and will then perform measurements and data transmission.

C. Solar energy harvesting and storing

Solar panels can be used to harvest energy and this energy is stored in batteries. The stored energy can be managed and used as and when required. The power management is done using a solar power management module.



a) Charging b) Discharging

Fig 3 Energy Flow

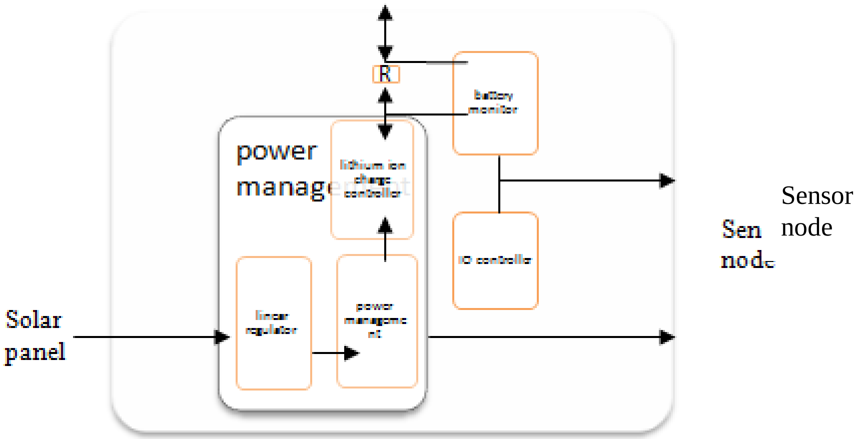


Fig 4 power management concept

Figure 4 shows a conceptual view of solar power management module. The solar power is fed into the power management component through a line regulator. For charging the battery, a controller is integrated as well. The battery current that flows in and out of the battery are monitored and logged, the battery monitor also accumulates the currents during charging and discharging cycles, hence provides precise information about energy currently stored within the battery. This information can be used to reduce the energy consumption and provide effective communication with the available energy in wireless sensor networks.

D. Network-Level Energy-Saving Realization

Although the energy consumption of each sensor node is individually minimized by its associate functional modules, the total energy consumption can be further reduced by using the appropriate sensing scheme for the whole sensor network. First, the sensor node is set to sleep mode until the timer overflows, and then, it is waked up to collect environmental parameters and waits to communicate with the CMU. Second, the proposed scheme initially estimates the minimum required transmission power P_{TX} by using the test code from the CMU or the cluster head. Then, the CMU selects an appropriate sensing scheme by comparing the total energy consumption.

By assuming a homogeneous hardware scheme for all of the sensor nodes, the variables representing distances between sensor nodes/cluster heads and CMU are aggregated by broadcasting each of the schemes and makes decision to choose the one with the best energy efficiency as the current network scheme.

In this scheme, test codes are defined as command for the sensor nodes to perform the different tasks required.

IV. CONCLUSION

In this paper, we have presented the design and implementation of an energy-aware sensor node, which can help in constructing an energy-efficient WSN through "node-level energy saving by using solar energy" and "network-level energy saving." The "node- level energy saving" is achieved by adaptive transmission power setting and by the periodic sleep/wake-up scheme, while the "network-level energy saving" is achieved by adaptive network configuration. And for efficient usage of energy, the harvested solar energy is stored in batteries and monitored. And based on the logged information, the energy can be predicted and then used.

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