

# Energy-Efficient Wireless Temperature Sensing for Smart Building Applications

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**Abstract**—Building energy accounts for large amount of the total energy consumption, and smart building energy control leads to high energy efficiency and significant energy savings. For energy-efficient smart building applications, accurate and robust measurement of temperature via emerging wireless sensor network is imperative. Many of the temperature sensors are battery-operated. As a result, it is crucial to reduce the power of those sensor nodes without sacrificing performance and accuracy. In this paper, we propose a ZigBee-based wireless network for temperature sensing that can monitor the change of temperature in a number of distributed sensor nodes. We properly adjust the sampling period and show that the power consumption can be reduced so that the sensor can operate for a longer lifetime with sufficient accuracy. The distributed sensor nodes will gather temperature data and transmit it to central controller for further processing and intelligent thermal control. The practical implementation based on TI chips show that this sensor network for predicting temperature only causes an error of less than 1°C in different situations. The relative errors in transmission in our experiment are less than 4%, and in most cases are lower than 2%. Besides, the power consumption of this wireless sensor network can be reduced with a very minute quantity by improving data gathering and sampling period.

## I. INTRODUCTION

As the technologies of electric and automatic control developed, it is predictable that human beings are going to automate life in a smart way. Smart building is a systematic study of the application of new technologies in buildings in order to reduce energy and equipment maintenance costs while improving occupant comfort and worker productivity. As one of the critical research areas in smart building, the study on controlling the temperature automatically has gained more and more attention. Establishing a wireless sensor network which consists of sensors and controllers is a preparatory step of temperature control. The network should be able to sample the temperature at a fixed period and then transmit the temperature data for advanced processing [1] [2]. In practical application, the temperature measurement accuracy must be guaranteed and the whole sensor network should be able to work for a relatively long lifetime with only some small coin cell batteries since the users do not want to recharge the distributed sensors frequently. As a result, the sensor network should work with ultra-low power consumption and acceptable accuracy while operating in normal working mode [3].

In the issues in wireless sensor networks, one of the fundamental problems is the coverage problem, which reflects how well an area is monitored or tracked by sensors. It should be formulated as a decision problem, whose goal is

to determine whether every point in the service area of the sensor network is covered by a manageable number of sensors, and estimate the least number of sensors for a given area [4]. The lifetime of the system is also a critical issue in a wireless sensor network. Different from the lifetime of a single sensor, the communication among sensors is an important considerable factor for wireless networking. Efficient power management and scheduling can extend the lifetime of a wireless sensor network [5]. Besides, the security of a wireless sensor network is another challenging research area requiring high-level security services [6].

In this work, we establish a wireless sensor network (WSN) for ultra-low-power applications. We propose a ZigBee-based wireless network for temperature sensing that can monitor the change of temperature in a number of distributed sensor nodes. We properly adjust the sampling period and show that the power consumption can be reduced so that the sensor can operate for a longer lifetime with sufficient accuracy. The distributed sensor nodes will gather temperature data and transmit it to central controller for further processing and intelligent thermal control. Our TI-chip based practical implementation show that this sensor network for predicting temperature only causes an error of less than 1°C in different situations. The relative errors in transmission in our experiment are less than 4%, and in most cases are lower than 2%. Besides, the power consumption of this wireless sensor network can be reduced with a very minute quantity by improving data gathering and sampling period.

## II. ARCHITECTURE OF THE WIRELESS SENSOR NETWORKS

In our wireless sensor network implementation, we use CC2650, which is developed by Texas Instrument (TI) [7], as the wireless Microcontroller Unit (MCU) and use LM35DZ, developed by TI, as the temperature sensor node. The correctness of the function of the MCU and the sensor need to be tested, requiring the verification of measurement accuracy. To establish the wireless sensor network for predicting temperature in smart building, the temperature sensor is connected to the MCU as shown in Figure 1. The first consideration in our experiment is to connect the board to the sensor for supplying power to the sensor, and the voltage value can be read from the output pin. Figure 1 shows the connection between the MCU and the sensor in the WSN. The output of the sensor is an analog signal, which can be sampled by Analog-to-Digital

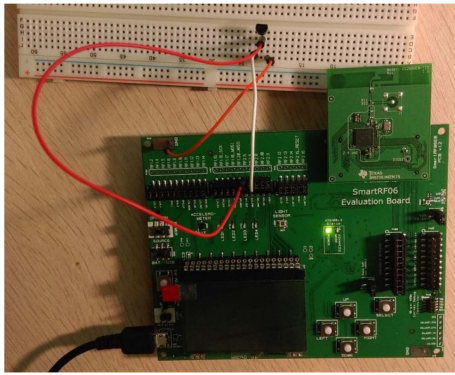


Fig. 1: Connection between the MCU and the sensor.

Converter (ADC) in the sensor controller in the MCU and converted to a digital value. It should be noted that the power supply pin is a digital output pin and the data receiver pin is an analog input pin.

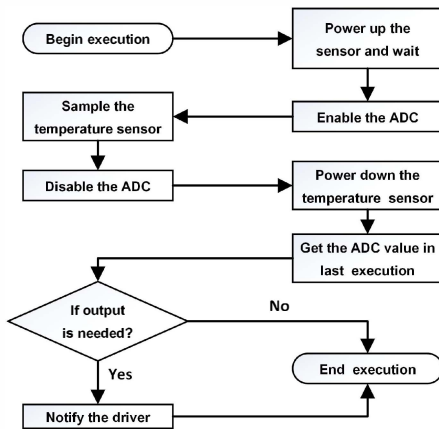


Fig. 2: The procedure of the sensor controller program.

For our wireless sensor network, the data receiver pin is connected to the ADC at first. The program in the wireless sensor network will be carried out in cycles, is shown in Figure 2. To reduce the frequency (thus power) of waking up the main CPU, there is no interrupt until the ADC value is different enough from the value sampled in the last execution. Currently, the difference between the two samples is set to be not greater than 3 (degree). Otherwise, an interrupt will be delivered to the CPU to wake it up.

Initially, the power domain, general-purpose input-output (GPIO) module and sensor controller need to be enabled and initialized. After that, the main run loop executes on the wireless sensor network platform. In the main loop the processor is waiting for an interrupt, after which a callback function will be called to wake up the main CPU. In the experiment, both the sensor and the ADC need to be turned on and off in every cycle. In our experiment, the currents of the sensor and the MCU are measured to be  $2.4\mu\text{A}$  and  $2.65\text{mA}$ , respectively. Correspondingly, the power consumptions of the sensor and the MCU are  $7.68\mu\text{W}$  and  $8.692\text{mW}$ , respectively, which reflects the energy efficiency of the developed wireless

sensor network.

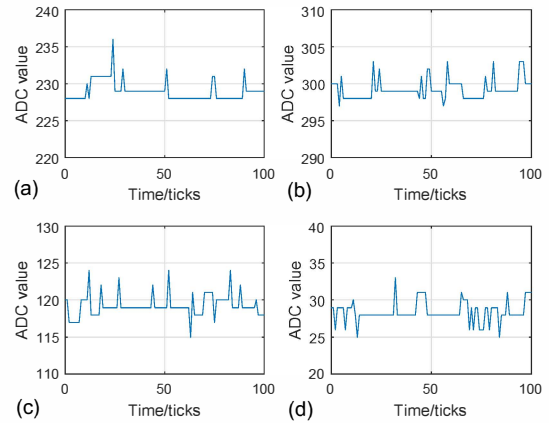


Fig. 3: The ADC value at: (a) 23°C; (b) 30°C; (c) 12°C; (d) 3°C.

It can be seen from the datasheet of the sensor that each 10mV in the output voltage value means 1°C difference for the temperature measurement [8]. In our expectation, the allowed divergence between the theoretical value and the practical one should be less than 10. Figure 3 shows the ADC values at 23°C, 30°C, 12°C and 3°C in our experiment. It should be noted that if the gap between the ADC value and the ten-times temperature values are small enough in each situation, we can claim that the experiment results are in line with our expectations. Changing temperature when the room is heating or cooling is also an important indicator for evaluating the measurement accuracy in dynamic environment. The blue curve in Figure 4 shows that the temperature of the sensor monitors is 16°C at beginning and then is increased to about 24°C in a short interval, and the red one shows the corresponding ten-times temperature values. It can be seen from Figure 4 that the difference do not exceed 10, which means that the difference between the detected and real temperatures is less than 1°C. Therefore, the measurement by the proposed architecture is considered reliable in the time-varying temperature cases [9].

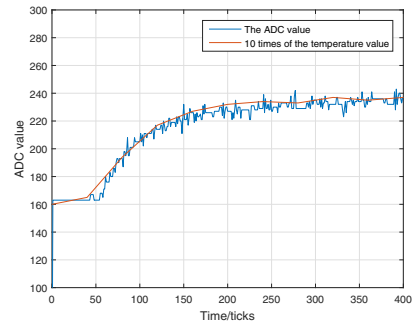


Fig. 4: Ten times the temperature value and the ADC value when heating from 16°C to 24°C.

When the sensors are arranged to monitor the temperature in a room, the communications between sensors, sensor and

controller, and controllers are essential. Figure 5 shows the schematic diagram of a wireless sensor network, which is constituted by many sensors, several controllers, the manager and gateway. In this network, temperature data is collected by sensors, and transmitted to controllers for processing. If needed, it will be sent to the processor for further analysis and application, or to the internet through the gateway. The experiment of the communication is executed on TI's SimpleLink SensorTag. In a simplified network, we test the function of the network and measure the error rate of the communication between different pairs of nodes in the experiment. The data of 10000 packets is transported in the speed of 100 packets/s from TX to RX, with distance of 15 meters. The experiment results are shown in Table I. It can be seen from Table I that the packet error rates in transmission in our experiment are less than 4% and in most cases are lower than 2%, which indicates that the wireless network meets the design specification.

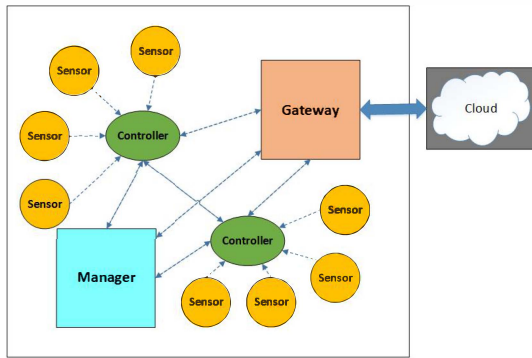


Fig. 5: Schematic diagram of a wireless sensor network.

TABLE I: Error rate in network communication test.

TX	RX	Lost Packets	Packet Error Rate (%)
control node 0	control node 1	367	3.67
control node 0	control node 2	232	2.32
control node 1	sensor node	121	1.21
sensor node	control node 1	48	0.48
control node 2	sensor node	137	1.37
sensor node	control node 2	130	1.30
sensor node	control node 2	130	1.30
control node 0	sensor node	6	0.06
sensor node	control node 0	8	0.08

### III. POWER OPTIMIZATIONS AND DISCUSSIONS

In this section, we present some optimization methods for the proposed wireless sensor network. We show that the power consumption can be reduced by adjusting the sampling period so that the whole sensor network system can operate for a longer lifetime with sufficient accuracy.

#### A. Outlier Exclusion and Storage of the ADC Value

Some temperature “outliers” may appear during the temperature measurement process due to some unpredictable factors when the whole network system is running. Figure 6(a) shows some possible outliers which are the points with prodigious difference to the surrounding ones. The outliers will increase the global error of measurement in the system. In case we

take these outliers into account in calculation, they should be withdrawn during the preprocess step. In our measurement process, if the gaps between the current temperature value and its neighbouring values are greater than 15, it will be replaced by the average value of two nearby temperature values. Figure 6(b) shows the dynamic monitoring temperature values after removing the outliers, which indicates a better measurement of the changing temperature over time [10].

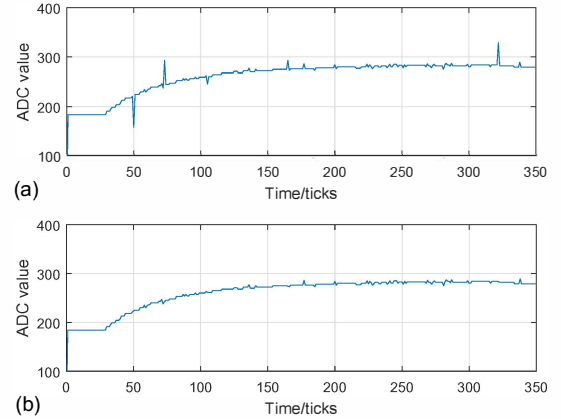


Fig. 6: The changing temperature over time: (a) before outlier exclusion; (b) after outlier exclusion.

Since the values of temperature are stored in the RAM of sensor controller, they must be read through the specific data structure defined in sensor controller studio. There are four data structures provided, in which “cfg”, “input”, “output” and “state” are used for exchanging data or storing configuration [11]. The ADC value will be delivered to the CPU when an interrupt is generated. We store the ADC value in the callback function. Whenever the main CPU is waken, the stored ADC value will be updated. To combine the outlier excluding algorithm with the store function, we need to create a global vector [v1 v2 v3] as shown in Figure 7, in order to detect the outliers and exclude them before communications. The procedure of ADC sampling and outlier excluding is shown in Figure 7. When the procedure of sampling and excluding is periodical, the temperature values will be updated continuously and can be taken out simultaneously.

It should be noted that the gaps between the outlier and its neighbours are frequently greater than 15 in the experiment. Our experiment shows that spikes appear in 38.1% of the test results. When taking the outliers into account, the average error of total measured ADC values is 4.73. When the outlier excluding method is put into use, the average error of total measurement will be reduced to 4.14. The value storage API provides convenience to other programs while bringing little extra cost to the MCU. In a complete wireless sensor network, the accuracy in data transmission will also be improved in this way.

#### B. Optimization in Power Consumption

If we turn on the sensor at beginning and never shut it down in the rest operations instead of the original working pattern,

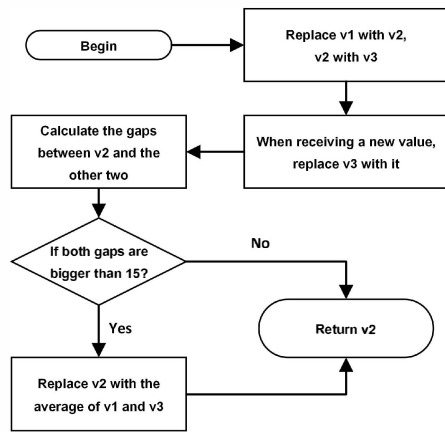


Fig. 7: The procedure of ADC sampling and outlier excluding.

the current will be  $62.6\mu\text{A}$ , about 26 times that of the former value. The on-and-off-every-cycle mode is beneficial for energy saving in sensor networks. If there are two ticks between each execution, the current is  $0.3\mu\text{A}$  and the corresponding power is  $0.96\mu\text{W}$ . It indicates that the longer the sampling period is, the more energy can be saved [12]. The MCU's working mode can be modified for different applications. In normal mode, the MCU's electric power consumption is  $8.692\text{mW}$ . In sleep mode, when the CPU is waiting for the next interrupt for energy saving, the corresponding power is  $4.78\text{mW}$ . In deep-sleep mode, when the conditional clock gate stops in addition to the state of sleep mode, the power is  $3.97\text{mW}$ . Experiments show that the sensor and ADC can work in both sleep and deep-sleep modes.

For some extreme cases, a confined room's temperature changes rapidly, which needs to be taken into analysis. For example, an ordinary air-conditioner's power consumption is  $7000\text{W}$  and is always installed in a room smaller than  $30\text{m}^2$ . In such situation, the change rate of the temperature in the space is more slowly than  $0.06^\circ\text{C}$  per second. In order to guarantee the measurement accuracy, we expect the difference between two consequent temperature values to be less than  $0.1^\circ\text{C}$ . For a tradeoff of energy saving and accuracy, the sampling tick period we choose is  $0.5\text{s}$ . In this case, the total power of MCU is  $8.16\text{mW}$  and the sensor controller's power consumption is  $0.29\text{mW}$ . The period between the ADC being turned on and off in every sampling procedure is also a significant factor of the power of the chip. It takes about  $12\mu\text{s}$  to turn on the ADC, sample the temperature sensor and disable the ADC in every cycle.

With proper adjustment in the peripheral settings, the energy consumption of a node in the network, which consists of a sensor and the relevant sensor controller, will be less than  $0.29\text{mW}$ . As a distributed node in the wireless sensor network, the performance and cost are sufficient for low power tasks. In some extreme application for sensor networks, a specially prolonged work life for each sensor node is essential. In such condition, the usual energy optimization methods are insufficient. Energy harvesting approaches need to be developed to overcome the difficulties. In the energy harvesting process, energy are collected from external sources such as the light

source, thermal source, wind source and kinetic source. The energy harvesting parts send the energy to the sensor for power consumption through the connection. Radio frequency power transfer is an approach for supplying power wirelessly to small electronic devices [13]. With the power from the local environment, the battery is not essential for a small device anymore. Thus the space of battery could be substituted by other sensors and chips.

#### IV. CONCLUSION

In this paper, we set up a wireless sensor network that can monitor the change of temperature and showed that it can collect the temperature value in a certain accuracy. The data transmission between sensors and controllers are also available and reliable in the network with acceptable error rate. With our adjustment on the data collecting and the determination of sampling period, the accuracy and power consumption of the sensor network has been optimized, so the system can work for a longer lifetime. The practical implementation based on TI chips show that this sensor network for predicting temperature only causes an error of less than  $1^\circ\text{C}$  in different situations. The relative errors in transmission in our experiment are less than 4%, and in most cases are lower than 2%. Besides, the power consumption of this wireless sensor network can be reduced with a very minute quantity by improving data gathering and sampling period.

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