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Design and Implementation of an Indoor Positioning System Based on Wireless Sensor Networks

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Abstract: The positioning technologies play a crucial role in the application of wireless sensor networks. In this paper, based on research TI CC2530 chip and ZigBee protocol stack, using Received Signal Strength Indication and the trilateration positioning technology, the wireless sensor network indoor positioning system was achieved. Take CC2530 chip as the control core, the system hardware was realized and ZigBee 2007 / PRO protocol stack was amended. RSSI technology was used for distance measurement, and finally the blind node positioning was implemented by trilateration method. Has been tested, the system is able to achieve indoor node localization features, and has a certain practical significance. *Copyright © 2013 IFSA.*

Keywords: Wireless sensor networks, Indoor positioning system, ZigBee 2007 / PRO protocol stack, Trilateration, Positioning algorithm.

1. Introduction

Wireless sensor network is formed by a large number of randomly distributed sensor nodes, a self-organizing network of collecting, processing, and forwarding information in the coverage area [1].

ZigBee technology, as a new low-cost, low-power, low-rate short-range wireless sensor network technology in recent years has been widely used in environmental monitoring, smart home, automotive electronics and industrial control the amount of data transfer rate less demanding situations [2-3]. The positioning technologies play a crucial role in the application of wireless sensor network, indoor positioning technology is relative to the outdoors or in the field in terms of positioning technology, generally applied to the inside of the building, such as: libraries, warehouses, and other. Some literatures theoretically study the localization algorithm and do the simulations, not for actual design [4-6]. This paper describes the indoor positioning system hardware using TI CC2530 chip as the control center, and software based on ZigBee 2007 / PRO protocol stack design.

Firstly, ZigBee 2007 / PRO was tested and improved for the design flaw. Then, calculate the distance between blind node and reference nodes by measuring the receiving signal strength, and determine blind node coordinate using the trilateration measurement or maximum likelihood estimation algorithm.

2. System Structure and Hardware Design

The system consists of three types of nodes: the coordinator node, reference nodes and blind nodes, which are using the TI new generation chip CC2530 as the master chip. The system structure diagram is shown as Fig. 1 [7].

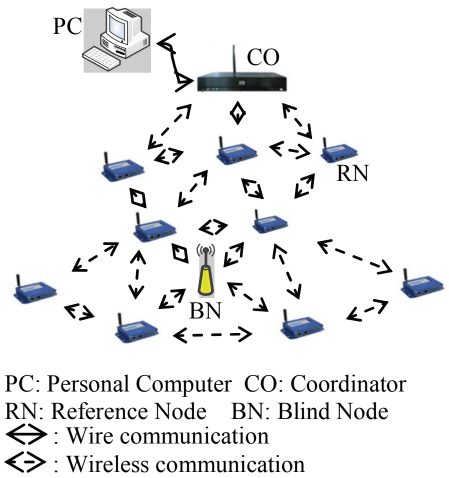

Fig. 1. The system structure diagram.

CC2530 is an IEEE 802.15.4 compliant real system-on-chip, to support proprietary IEEE 802.15.4 and ZigBee and ZigBee PRO and ZigBee RF4CE standard. It integrates a 2.4 GHz RF transceiver, enhanced industry standard 8051 MCU, up to 256 kB programmable FLASH, 8 kB of RAM and provides a set of extensive peripheral set (including two USART, 12-bit ADC and 21 universal GPIO). At the same time, CC2530 can be equipped with TI standard compatibility or proprietary network protocol stack (RemoTI, Z-Stack or SimpliciTI) to simplify the development, its RF transmitter output power is 4.5 dBm and receiver sensitivity of -97 dBm [8]. The hardware block diagram is shown as Fig. 2.

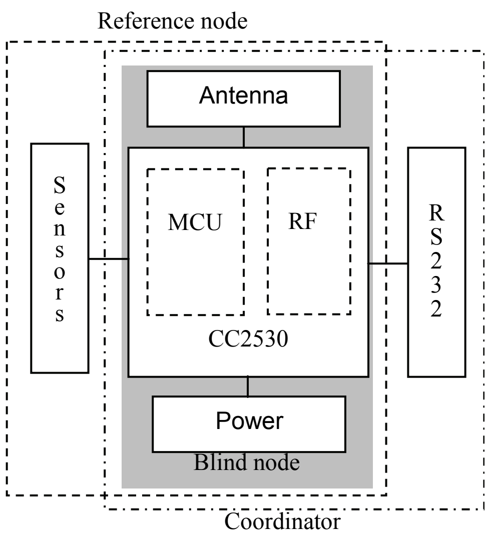

Fig. 2. The system hardware block diagram.

The node hardware consists of the CC2530, antenna, power supply, sensors and RS232 communication module. The function of coordinator is to establish, maintain and manage the network, and communicate with the host computer PC. Therefore, the hardware of the coordinator includes CC2530, antenna, power supply and RS232 communication module. CC2530 chip is used as the control core of the hardware and the RS232 module is used to communicate with the host PC. The reference node has to maintain the network, routing, and also has the function of detecting the ambient temperature, humidity, smoke alarm. Its hardware includes CC2530, antenna, power supply and sensors module. The sensors module is composed mainly by the temperature and humidity sensors and the analog-to-digital conversion circuit. Due to output signal from the sensors is inconsistent with the input signal to MCU, the sensors output signal should be carried out analog-to-digital conversion after signal conditioning, and is sent to the MCU for processing through photoelectric isolation, in order to improve the anti-interference performance of the system. The blind node includes CC2530, antenna, and power supply module. It receives the location information from the reference node, completes the location algorithm, and sends out its own location information at the predetermined time interval.

3. ZigBee 2007 / PRO Protocol Stack

Based on the ZigBee 2007 protocol stack specification, the ZigBee 2007 / PRO protocol stack is developed for the new generation chip CC2530. The agreement IEEE 802.15.4 standard as the basis for communication, the protocol uses the OSI seven-layer structure model. It defines the physical layer (PHY) and media access control layer (MAC) standards; ZigBee Alliance defines network layer (NWK), the application layer (APL) and the security service specification of ZigBee protocol.

In the protocol stack, there is a bug of the associated list management that each node can only have 32 sub-nodes. It is found that the reference node does not automatically update the associated list when the number of child nodes is changed. For example, a reference node having 25 child nodes (blind nodes or other reference nodes) should update its association list after 10 sub-nodes leave. But the protocol stack does not provide this functionality and remain the original network associated list. If there are other 10 sub-nodes need to be joined this reference node, the number of the child nodes will be 35 and over 32. The other child node can not join the network according to the definition.

At this point, there is only one solution to re-program the code. It is explained as follows on TI website. The maximum number of devices that can be supported by one router or coordinator (i.e. associated devices) is 32. This is because we use a 32-bit bit-mask to keep track of assigned addresses. Therefore, the NWK_MAX_DEVICE_LIST should be set to 32 maximum [9].

The coordinator and the reference node associated lists are corrected to solve this shortcoming of the original protocol stack in this paper. After the correction, the system defines the total number of associated list is 32, the number of the reference node 25, the blind node number is defined as 7. The pseudocode of the association list management process is shown in Fig. 3.

```
/*Association list management process*/
  If networking success
  If the number of the coordinator associate list has reached the upper limit
      Delete the coordinator Associate list
End if
  If the number of the reference node associate list has reached the upper limit
      Delete the reference node associate list
End if
  If the number of the blind node associate list has reached the upper limit
      Delete the blind node associate list
End if
      Delay
End
```

Fig. 3. The association list management process.

4. Application Software Design

4.1. Coordinator Workflow

Based on the TI ZigBee 2007 / PRO protocol stack, application software was designed. Firstly, the coordinator creates a network, whose PAN ID is less than 0x3fff, according to the specified channel. Reference nodes and blind nodes join the network and get 16-bits networks address assigned by the coordinator.

Coordinator creates, maintains and manages WSN, and communicates with host PC through the RS232 serial interface, with the reference nodes and blind nodes through the WSN at the same time. It receives the command from the host PC and sends PC the blind node location message string BN_POSI_ANS and the reference node configuration message string RN_CONFIG, which includes its network address, coordinates and collecting data from sensors module. There are three commands from PC: the coordinator restart command string CO_RESET, getting all the reference nodes configuration information command string PC_RN_CONFIG, and gaining the specified reference node configuration information command string PC_A_RN_CONFIG. When coordinator receives CO_RESET command, then restart the network immediately. When the coordinator receives PC_RN_CONFIG command, broadcast this command to the whole network; when receives PC_A_RN_CONFIG command, send this command to the specified reference node. The same time, the coordinator receives the data in the network, and adds them to the pre-defined data stream. When length of the data stream reaches the specified length of the data stream, the coordinator uploads them to PC for analyzing and processing. The pseudocode of the coordinator data transmission process is shown in Fig. 4.

```
/*The coordinator data transmission process*/
Create network
L1: IF receive the command from PC
IF the command is CO_RESET
  Reset the coordinator
End if
IF the command is PC_RN_CONFIG
  Broadcast PC_RN_CONFIG to the whole network
End if
IF the command is PC_A_RN_CONFIG
  Send PC_A_RN_CONFIG to the specified reference node
End if
End if
IF receive the data from the network
  Add the data to the pre-defined data string
IF length of the data string reaches the pre-defined length
  Upload the data string to PC
End if
End if
  Goto L1
End
```

Fig. 4. The pseudocode of the coordinator data transmission process.

4.2. Reference Node Workflow

Reference nodes join the network, and broadcast its own configuration information RN_CONFIG actively. Then the reference node waits for receiving network information, which includes two commands PC_RN_CONFIG, PC_A_RN_CONFIG from the coordinator and positioning request message string BN_ASK_ANS from the blind nodes. When it receives PC_RN_CONFIG and PC_A_RN_CONFIG commands, send itself configuration message string RN_CONFIG to the coordinator. When it receives BN_ASK_ANS command, send RN_FIND_ANS message string to the blind node, which sends the positioning request. RN_FIND_ANS from the reference nodes includes its own coordinate information and RSSI values of the received signal. The pseudocode of the reference node data transmission process is shown in Fig. 5.

```
/*The reference node data transmission process*/
Join the network successfully
Broad RN_CONFIG
L1: IF receive the data from the network
      IF it is BN_ASK_ANS
  Send RN_FIND_ANS
End if
      IF it is PC_RN_CONFIG or PC_A_RN_CONFIG
  Send RN_OWN_CONFIG
End if
End if
  Goto L1
End
```

Fig. 5. The pseudocode of the reference node data transmission process.

4.3. Blind Node Workflow

Blind nodes join the network, and broadcast its positioning request message string BN_ASK_ANS. Reference nodes within the communication range receive location request message from the blind nodes, reply the RN_FIND_ANS message string including RSSI value of the received signal. Blind nodes receive the response message, start positioning operation to obtain their own coordinates and send BN_POSI_ANS message string to the coordinator. Coordinator receives the blind node positioning result information uploads it to the host computer to process [9].

5. Positioning Algorithm Design

Positioning algorithm is implemented in the blind node, and only the calculated position information is transmitted, rather than all used data. This localization algorithm is based on the RSSI technology. It is tested that RSSI measurement value is nearly linear relationship with signal input power through measurement study by TI laboratory. The received signal strength is a function of the transmission power and the transmission distance which is between the receiver and sender. It will decrease with the increase of the distance, the formula (1) is as follows:

$$RSSI = -(10n\log_{10} d + A) \tag{1}$$

In the formula (1), the parameter n is the signal propagation constant, also called the propagation coefficients. The parameter d represents the distance between the sender and the receiver. Parameter A represents the signal strength when the distance between the receiver and the sender is 1 meter.

It is very simple when the ideal formula is used to calculate the signal strength, but some uncertain factors need to be considered in the real environment. Most of the uncertainty is caused by the hardware, but they are often corrected through software processing method in order to increase the accuracy.

We usually use simple RSSI filtering method, including the feedback filter and average filter method. The former filter only uses a portion of the most recently received RSSI value for calculating, less data is required, but increase the new positioning calculation time delay [3]. The latter is the most basic filtering methods, but it needs to send a lot of packets and increase the burden of network traffic. Average filtering basic formula is as follows.

$$RSSI = \frac{1}{n}\sum_{i=0}^{n} RSSI_i \tag{2}$$

The improved average filtering algorithm is used in this paper. The blind nodes poll each reference node three times, and receive the RSSI value five times from each reference node each poll. Polling results over three times, in accordance with the principle of majority last RSSI values are obtained.

After the distance value from three or more reference nodes is obtained by calculating formula (1), the blind node can use the trilateration method or maximum likelihood estimation method to calculate its coordinate. Assume that the coordinate of the blind node is x and y, and the coordinates of three reference nodes are (x1, y1), (x2, y2), (x3, y3), the calculated distance value to the reference nodes are respectively d1, d2, d3. The trilateral measurement formula is as follows.

$$\begin{cases} (x-x_1)^2 + (y-y_1)^2 = d_1^2 \\ (x-x_2)^2 + (y-y_2)^2 = d_2^2 \\ (x-x_3)^2 + (y-y_3)^2 = d_3^2 \end{cases} \tag{3}$$

By the formula (3), the blind node coordinate can be obtained by the formula (4).

$$\begin{bmatrix} x \\ y \end{bmatrix} = \begin{bmatrix} 2(x_1-x_3) & 2(y_1-y_3) \\ 2(x_2-x_3) & 2(y_2-y_3) \end{bmatrix}^{-1} \begin{bmatrix} x_1^2-x_3^2+y_1^2-y_3^2+d_3^2-d_1^2 \\ x_2^2-x_3^2+y_2^2-y_3^2+d_3^2-d_2^2 \end{bmatrix} \tag{4}$$

The pseudocode of the positioning algorithm process is shown in Fig. 6.

```
/*The positioning algorithm process in the blind nodes*/
    Join the network successfully
 L1: Transmit BN_ASK_REQ
 Receive RN_FIND_ANS
 Store RSSI value VRSSI from the reference node
     If transmission count is less than 5
   Goto L1
 Else
 Average the RSSI for this polling
 Sleep 300ms
     If polling count is less than 3
   Goto L1
 Else
   Get RSSI value in accordance with the principle of majority
   Calculate the distance with formula (1)
   Calculate the coordinates with formula (4)
 Send BN_POSI_ANS
 End if
 End if
End
```

Fig. 6. The pseudocode of the positioning algorithm process.

6. System Testing and Conclusion

Host computer (PC) software is implemented with the vs2008 tools, which is visual interface based C++ MFC application framework. The testing environment is at a floor of a building. The diagram of testing nodes distribution is shown in Fig. 7.

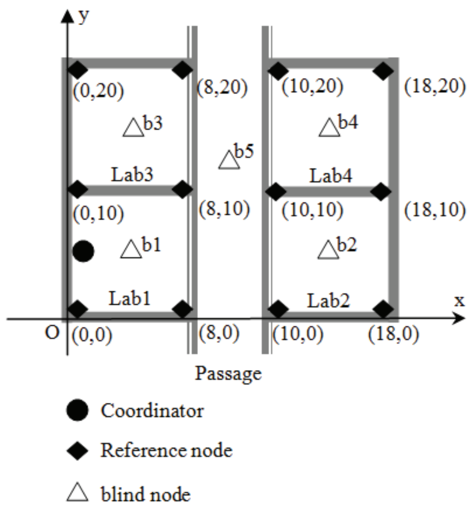

Fig. 7. Diagram of testing nodes distribution.

The test nodes are placed according to Fig. 4, 100 times testing have done and 100 testing results are averaged, the last positioning results are shown in Table 1. The average absolute positioning error is 0.49. Test results prove that the system can complete indoor positioning coordinates of the blind node, have practical application of significance. It was also found deficiency in the system.

Table 1. Indoor positioning test results.

No.	Real Coordinates	Positioning Coordinates	The absolute positioning error
b1	(4,5)	(3.75, 4.80)	0.32
b2	(14,5)	(14.31, 4.65)	0.47
b3	(4,15)	(3.85, 14.95)	0.16
b4	(14,15)	(13.55, 15.16)	0.47
b5	(9,12)	(8.97, 11.90)	1.03

First of all, in a laboratory environment, the effective transmission distance of the node is less than 30 m, and we must increase the number of the reference nodes to extend the communication range. Secondly, the positioning accuracy of the blind node depends on the reference node distribution density, the greater the density the higher the accuracy, which is not conducive to reducing the cost of the practical application of the positioning system. Third, there will be a lost package and blind node can't join the network within a period of time because the test environment is more complex and the wireless network is not very stable, the experiment proves that we get much better communication quality when the nodes were placed in a certain height position. Therefore, to improve the quality of wireless communication and the node positioning accuracy will be future research directions.

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