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# Design and Optimization of Wireless Remote Monitoring and Control System Using the ZigBee Protocol

Jingcheng Zhang

Linköpings universitet
INSTITUTE OF TECHNOLOGY

Department of Science and Technology
Linköpings University, SE-601 74 Norrköping, Sweden

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Linköping University
Department of Science and Technology
SE-601 74 Norrköping
Sweden
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## ABSTRACT

This thesis presents the design and the optimization of a wireless remote monitoring and control system utilizing the ZigBee protocol.

From the system architecture point of view, the remote wireless monitoring and control system is mainly combined by 3 parts, the wireless sensor network, the message gateway and the web service. In order to increase the system flexibility and the re-configurability, each part communicates with each other by using the standard communication protocols.

The wireless sensor network of the system can be deployed in many different locations. The network includes the sensor module, the message relay, the control module and the network coordinator. The sensor module calculates the sensor information (e.g., temperature) periodically and sends the message to the network coordinator. If the radio link of the sensor module is not long enough to reach the coordinator, a message relay could be utilized in between to forward the message to the destination. Meanwhile, the message relay can be utilized as a control module as well. For example, when connected with the air conditioning system (radiator or ventilation), the control device can generate control signal to adjust the temperature and the relative humidity. The network coordinator is the root of the network. When the network coordinator receives the sensor information from the sensor module, it forwards the message to the connected gateway. On the other hand, the coordinator also receives the control command from the gateway. When the control command is received, the network coordinator forwards the control command to the corresponding control device of the wireless sensor network to execute the command. Generally speaking, it is the wireless sensor network part provides the sensor information and executes the control commands in the system.

The gateway works as a translator and synchronizer between the wireless sensor network and the web service. It communicates with the wireless sensor network via the connection of the network coordinator. When receiving the sensor information from the wireless sensor network, the gateway forwards the message to the web service through the Internet. On the other hand, the gateway also receives control commands from the web service. When the gateway receives the control command from the web service, it forwards the command to the network coordinator of the wireless sensor network. Moreover, the gateway also works as a local monitoring and control agent. The gateway can be utilized to monitor and control the local sensor network without login to the web service. During the network deployment, the gateway needs to be equipped for each wireless sensor network. Different gateways can communicate with the web service via the Internet at the same time.

The web service contains the sensor information uploaded from different locations. When the control command is received from the user configuration, the web service forwards the control command to the correct local server. From the user point of view, the web service is a website which can be accessed by a normal web browser. Users can register the website to apply for monitoring and control privilege. The monitoring function provides the graphical presentation of the sensor information from different locations. The control function of the system includes the ON/OFF control, temperature control and humidity control.

In order to increase the system reliability, extra optimizations are developed in different parts of the system. In the wireless sensor network, the power consumption of the battery powered sensor module is optimized. A method is discovered to manage the network topology and the message forwarding pattern. Moreover, an alternative routing algorithm is designed which could be utilized by the coordinator to communicated with the sensor network. This method is verified to be much more efficient than the original algorithm utilized by the sensor network. Finally, a general purpose communication reliability enhancement framework is developed for the wireless sensor network. It helps the wireless sensor network to handle the exceptions without interference to the sensor network applications. In the gateway part, the Internet connection status is checked all the time. When the Internet connection is broken, sensor messages sent from the coordinators are buffered in the gateway to avoid the message lost.

Finally, the remote monitoring and control system has received a nomination for the Swedish Embedded Award 2010 and been demonstrated at the Scandinavia Embedded Conference 2010 in Stockholm.

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Jingcheng Zhang,
Norrköping, September 5, 2011.

## LIST OF PUBLICATIONS

Papers included in this thesis:

**Paper 1** **Jingcheng Zhang**, Allan Huynh, Qin-Zhong Ye and Shaofang Gong, "Remote Sensing System for Cultural Buildings Utilizing ZigBee Technology", *Proceedings of the 8th International Conference on Computing, Communications and Control Technologies (CCCT 2010)*, Orlando, USA, pp. 71-77, April 2010.

**Paper 2** **Jingcheng Zhang**, Allan Huynh, Qin-Zhong Ye and Shaofang Gong, "Design of the Remote Climate Control System for Cultural Buildings Utilizing ZigBee Technology", *Sensors & Transducers Journal (ISSN 1726-5479),* Vol. 118, Issue 7, pp. 13-27, July 2010.

**Paper 3** **Jingcheng Zhang**, Allan Huynh, Qin-Zhong Ye and Shaofang Gong, "Reliability and Latency Enhancements in a ZigBee Remote Sensing System", *Proceedings of 4th International Conference on Sensor Technologies and Applications (SENSORCOMM 2010)*, Venice/Mestre, Italy, pp. 196-202, July 2010.

**Paper 4** **Jingcheng Zhang**, Allan Huynh, Qin-Zhong Ye and Shaofang Gong, "A Fully Wireless Monitoring and Control System for Protecting Cultural Heritage", *Proceedings of 20th IEEE International Conference on Collaboration Technologies and Infrastructures*, Paris, France, pp. 51-57, June 2011.

**Paper 5** **Jingcheng Zhang**, Allan Huynh, Qin-Zhong Ye and Shaofang Gong, "A Communication Reliability Enhancement Framework for the ZigBee Wireless Sensor Network", Manuscript, 2011.

The author has also been involved in the following papers but not included in this thesis:

**Paper 6** Allan Huynh**, Jingcheng Zhang**, Qin-Zhong Ye and Shaofang Gong, "Wireless Remote System Monitoring for Cultural Heritage", *Sensors & Transducers Journal (ISSN 1726-5479)*, Vol. 118, Issue 7, pp. 1-12, July 2010.

**Paper 7** Allan Huynh**, Jingcheng Zhang**, Qin-Zhong Ye and Shaofang Gong, "ZigBee Radio with External Low-Noise Amplifier", *Sensors & Transducers Journal (ISSN 1726-5479)*, Vol. 114, Issue 3, pp. 184-191. March 2010.

**Paper 8** Allan Huynh, **Jingcheng Zhang**, Qin-Zhong Ye and Shaofang Gong, "ZigBee Radio with External Power Amplifier and Low-Noise Amplifier", *Sensors & Transducers Journal (ISSN 1726-5479)*, Vol. 118, Issue 7, pp. 110-121, July 2010.

## LIST OF ABBREVIATIONS

| | |
|---|---|
| BER | Bit Error Rate |
| CSMA-CA | Carrier Sense Multiple Access – Collision Avoidance |
| dB | Decibel |
| DHCP | Dynamic Host Configuration Protocol |
| DUT | Device Under Test |
| FFD | Full Function Device |
| IC | Integrated Circuit |
| IEEE | Institute of Electrical and Electronics Engineers |
| ITN | Department of Science and Technology |
| IP | Internet Protocol |
| kbps | Kilo bits per second |
| LAN | Local Area Network |
| LED | Light Emitting Diode |
| LiU | Linköping University |
| LNA | Low-Noise Amplifier |
| LOS | Line of Sight |
| LQI | Link Quality Indication |
| LR-PAN | Low-Rate Personal Area Network |
| MCU | Microcontroller Unit |
| NWK | Network |
| PA | Power Amplifier |
| PCB | Printed Circuit Board |
| PER | Packet Error Rate |
| R | Resistance |
| RF | Radio Frequency |
| RFD | Reduced Function Device |
| RSSI | Received Signal Strength Indicator |
| Rx | Receiver |
| TRL | Through, Reflected and Line |
| TI | Texas Instruments |
| Tx | Transmitter |

| | |
|---|---|
| UART | Universal Asynchronous Receiver/Transmitter |
| USB | Universal Serial Bus |
| WLAN | Wireless Local Area Network |
| ZC | ZigBee Coordinator |
| ZED | ZigBee End-Device |
| ZR | ZigBee Router |

# Contents

# 1 Introduction

Wireless sensor network (WSN) is a hot research topic of these years. It is not only because of the challenges in the scientific research level but also due to its huge application potential. Generally, the development of WSN is aiming at low power consumption, low price and robust network. Compared with the canonical wired network, the advantage of the WSN is already presented by its name. By replacing the cable with the wireless radio signal, a WSN can provide much more communication mobility and flexibility. For example, when testing the rotation speed of an engine, a wireless sensor node mounted with an accelerometer can be placed in the spinning axis. The measured data from the sensor module can be sent wirelessly to the receiver. From the radio communication methodology point of view, two kinds of communication patterns are mainly applied nowadays, the synchronized and unsynchronized network [1]. The synchronized network utilizes the time slot method to coordinate the communication interval. It is a more power efficient WSN which even allows the message relay to go to sleep periodically. Different from the synchronized network, the non-synchronized network requires the message relay to work all the time. As a result, this type of network provides higher performance on processing sensor information. Moreover, different wireless network protocols are developed base on different communication methods. From the network topology point of view, the STAR network topology [2] is supported by almost all the communication protocols. More advanced protocol, like ZigBee, supports multi-hop mesh network [3]. As a result, the coverage of the sensor network can be largely expanded after the network establishment.

Nevertheless, the wireless sensor network is designed as a local area network (LAN). When connected with the Internet, the wireless sensor network can forward the sensor message to any place around the world. Meanwhile, the wireless sensor network can be utilized for control purpose in the deployed locations. The message relay can be connected with the control devices, i.e., radiator or ventilation. As long as the Internet is available, people at any place around the world can send control command to the wireless sensor network to control the indoor climate. As a result, this two-way communication realizes a remote wireless monitoring and control system.

The goal of the remote monitoring and control wireless sensor network introduced in this thesis is to prove that the wireless sensor network can be utilized for the cultural heritage preservation purpose with high stability. The temperature and relative humidity is the most interesting factors to be monitored and manipulated. Besides the functions, the stability of the system should be good enough compared with the wired system in the market. Additionally, the ZigBee protocol is utilized for the communication protocol of the wireless sensor network. Sicne the project purpose is to preserve the culture heritage, the system is named as the “Culturebee System”.

## 2 Fundamental of the ZigBee protocol

The Culturebee system utilizes the ZigBee [4] protocol as the communication infrastructure for its wireless sensor network. The ZigBee protocol is also the first global standard for the wireless sensor network since 2004. As shown in Fig. 1, there are four layers defined in the ZigBee stack [5]. The Physical layer (PHY) and the Medium Access Control (MAC) layer are defined in IEEE 802.15.4 standard. It includes the hardware specification and the radio transmission specification. The network layer and the application layers are defined by the ZigBee protocol. The network layer defines the methods of establishing a self organized wireless network. It also includes the routing algorithm that helps the message to find the route to the destination. The requirements of the self-healing function are also defined by the network layer. The self-healing function helps the ZigBee network to find a new route between any two nodes in the network when the original route is broken. The application layer is mainly combined by three components: the Application Support Sub-Layer (APS), the ZigBee Device Object (ZDO) and the Application Framework (AF). The WSN applications are defined in this layer.

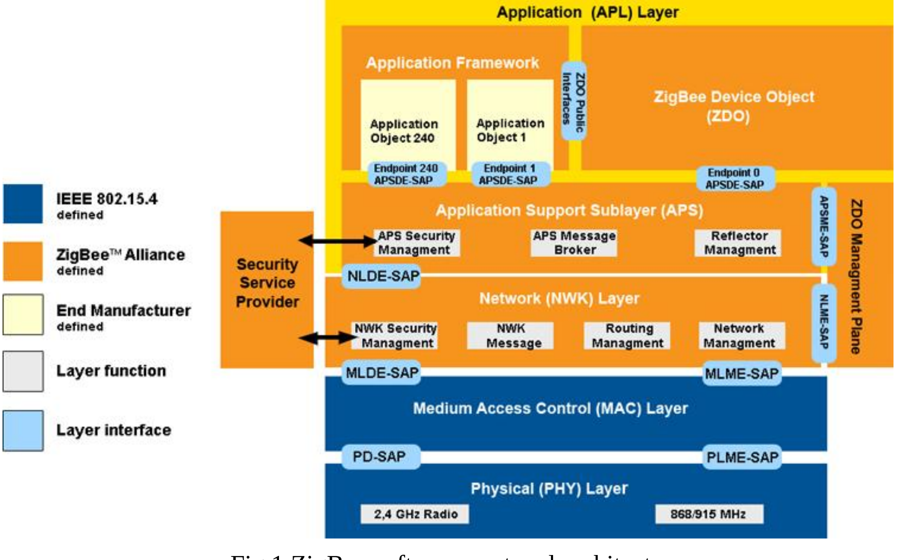



Fig.1 ZigBee software protocol architecture

## 2.1 Physical and Media Access Control layer

The ZigBee protocol utilizes the PHY and MAC layer defined by IEEE 802.15.4 standard [6]. The IEEE 802.15.4 standard defines two types of radio communication methods, the synchronized communication and the unsynchronized communication. As defined by the ZigBee protocol, the unsynchronized network is utilized by the PHY and MAC layer. In such a case, the radio part of the ZigBee router (ZR) and the coordinator (ZC) needs to be always on. Since the ZigBee radio consumes much more power compared with its sleep mode, it is necessary to provide mains power to the routers and the coordinator.

As defined by the protocol, only the router or the coordinator can adopt new network elements into the network. Fig. 2 shows the procedure of one device joining the sensor network. Originally, the network contains three devices, the coordinator C0, the router R0 and R1. When the end device E0 wants to join the network, it sends “beacon request” as a broadcast message to the network. All the network devices within the vicinity except the end devices (ZED) responses the request with the network cost. The network cost indicates the message hop from itself to the coordinator. For example, R0 and R1 response the beacon request with network cost “1” which indicates that they are “one hop away” from the coordinator. While the coordinator response the request with network cost “0”. As a result, E0 chooses the coordinator as its “parent” after it joins the network.

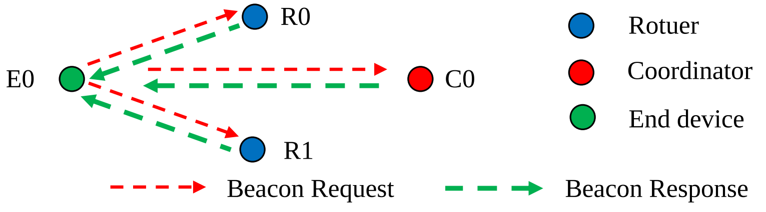



Fig.2 End device join the wireless sensor network via MAC association

## 2.2 Network layer and routing algorithm

From the function point of view, the network layer of the ZigBee protocol mainly works for two purposes. Firstly, the network layer helps the device to find the route from the sender to the receiver when sending messages. Secondly, if the original route is broken due to the link loss, the network layer helps the device to find another route so that the communication between the sender and the receiver can be resumed. The ZigBee protocol only defines the requirements of the routing method, while the AODV [7] algorithm is commonly recognized as the closest candidate that fulfills the requirement and widely utilized in different ZigBee software stacks.

Fig. 3 presents the demonstration of how the ZigBee protocol creates a new message route using the AODV algorithm. The network is combined by the end device E0, the router R0 and the coordinator C0. If E0 wants to send a message to the coordinator, it firstly forwards the message to its direct parent, R0. According to the definition of the ZigBee protocol, the end device is not allowed to participate the message routing. It is always the router or the coordinator who helps the end device to create the route to the destination device. When R0 receives the message from E0, it checks its local routing table [8]. If the entry of the coordinator destination is not found, R0 buffers the received message and start the AODV algorithm to create the route to the coordinator. The AODV algorithm starts by sending the "routing request" over the network. It is a broadcast message spreads over the entire sensor network to check if any device has the entry of the coordinator address. As shown in Fig. 3, the coordinator is just one hop away from R0, so that it response the routing request to R0. Once the route is established, the buffer message is sent from R0 to C0.

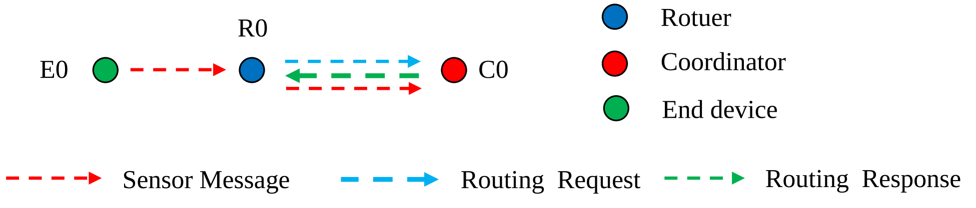



Fig. 3 ZigBee using AODV algorithm to create a new route

The same method can be utilized to repair the route between two devices. This function is also named as self-healing function. As shown in Fig. 4, E0 communicates with C0 via R0 and R1 at the beginning. For some reasons, the communication between R0 and C0 is broken. When R1 senses this problem, it issues the "routing request" to find an alternative router to communicate with C0. Since R2 is located within the communication range of R1, it response the "beacon request" of R1. In such a case, E0 communicates C0 via R1 and R2 instead.

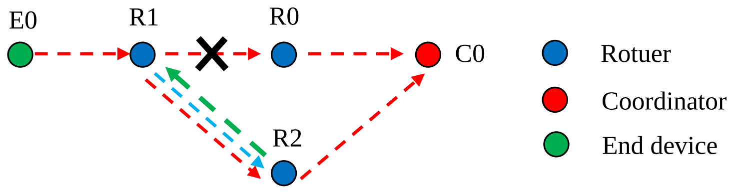



Fig. 4 Self-healing function of AODV algorithm

## 2.3 Application layer

The application layer of the ZigBee stack is composed by three components, the application support sub-layer, the ZigBee device object and the application framework. The ZigBee sensor network application is defined in the application framework. In the ZigBee protocol, each sensor application can be implemented as one logical entity, named as the endpoint. There could be more than one endpoint runs at the same time in the ZigBee stack. For example, if the end device is mounted with both the temperature and one humidity sensor. Two endpoints can be implemented in the ZigBee stack so that the temperature reading and humidity reading can be handled separately. As defined by the ZigBee protocol, each sensor network can has up to 240 endpoints.

Sometimes, the endpoint needs to configure the hardware status. This can be done via the interfaces provided from the ZigBee Device Object (ZDO). ZDO is a component which wraps the interfaces of the MAC layer and the PHY layer and provides interfaces to the endpoints. The interfaces provided to the end points are the standard interfaces defined by the ZigBee protocol. As a result, only the ZDO implementation needs to be changed when the sensor application is migrated from one ZigBee chip to another. ZDO also provides the functions that are independent of the endpoint logic. For example, the configuration of the network layer, security manager, and communication methods and so on.

The application support sub layer (APS) provides the interface between the endpoints and the network layer. When messages are received by the device, the APS layer works as a message dispatcher. It checks the endpoint ID of the received messages and forwards the messages to the correct endpoints. When the end point sends message, the

APS layer reform the package so that the message sent from the end device compliant with the ZigBee specification.

# 3 Remote monitoring and control system description

As a remote monitoring and control system, the Culturebee system architecture has high flexibility and re-configurability. The monitoring function and the control function can work separately. Moreover, if the control function works together with the monitoring function, the monitoring function can provide feedback information to the control function. As a result, a closed loop control function is established. This section presents the detailed function description of the remote monitoring and control function of the Culturebee system.

## 3.1 Remote monitoring function description

As shown in Fig.5, the wireless sensor networks are deployed in three different buildings. The end device of the sensor network is mounted with the temperature and humidity sensor. It reports the temperature and humidity information periodically to the network coordinator. The coordinator is connected with a gateway (local server) via the USB port. Once the local server receives the message from the USB port, it parses the received message and forwards the message to the web service via the Internet. All the local servers connect to the web service via the Internet. The web service is equipped with the database. Once the sensor message is received by the web service, it stores the sensor message into its database. On the other hand, the web service provides webpage based graphical presentation of the sensor data. The service can be accessed by normal web browser via address www.culturebee.se. The registered user can remotely monitor the measurement result of different buildings from the website.

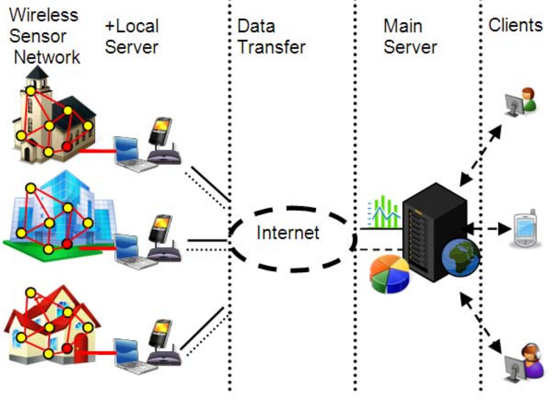



Fig.5 Culturebee monitoring function description

Additionally, the monitoring function also provides the working status monitoring of the wireless device of the network. All the devices in the wireless sensor work do the self check periodically and report the problems if occurred, e.g., low battery, chip temperature too high and so on. This function is very important for the network maintenance. Since the wireless sensor network is sometimes deployed in the place where there is no fulltime maintainer, it is good to know the network working status and solve the problem when it happens.

### 3.2 Remote control function description

The remote control function works as an add-on of the culturebee system. It can either run separately or combined with the monitoring system to perform the closed loop control. Fig.6 shows a scenario when the control system works together with the monitoring system.

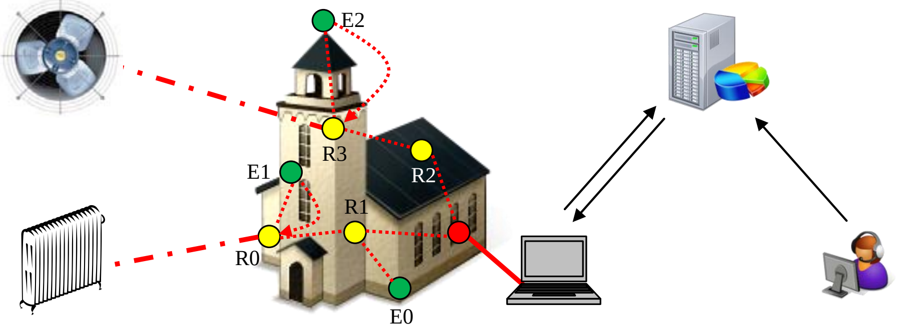



Fig.6 Culturebee remote control function description

As shown in Fig.6, the wireless sensor network is deployed in one church. Router R0 and R3 are programmed as control device which are connected with the radiator and the ventilation to control the indoor temperature and relative humidity respectively. The coordinator of the sensor network is connected with the local server. In order to get the command from the web service, the local server polls the web service periodically to retrieve the pending commands. For example, a user logs in to the web service and configures the church indoor climate as temperature 24 °C and relative humidity as 50%. The submitted command is stored at the web service until the web service receives the polling command from the local server. Once the web service receives the polling command, the web service sends the command back to the corresponding local server. When the local server receives the command, it checks its local record for the destination address of the control units sends the command. As a result, R3 receives a command which sets the relative humidity as 50% and R0 receives a command that sets temperature as 24 °C.

However, as a controller, the router does not equipped with any sensors detecting the climate change. It is the end device which can works together with the control unit. The end device sends the sensor information to the control unit from time to time so that the control unit “knows” when to start or stop the radiator or the ventilation. As a result, the closed loop control is established.

# 4 Remote monitoring and control system component description

To reduce the system dependency, the concept of “interface oriented programming” is introduced into component design of the system. The wireless sensor network communicates with the local server via the USB port. When receiving the sensor information, the coordinator just forwards the message to the USB port. On the other hand, the local server only interests about the interfaces received from the USB port. It only receives the sensor information from the USB port and does the further processing. As a result, the local server can be utilized to communicate with any system as long as the USB data format fulfills the requirement of the local server. Meanwhile, the wireless sensor network can also be easily migrated to other systems as long as the USB interface can handle the data format utilized by the sensor network. The communication control between the local server and the wireless sensor network relies on the USB protocol itself.

The local server communicates with the web service via the standard HTTP interface. Same as the communication between the local server and the sensor network, any message with the correct passwords can be accepted by the web service. As a result, any authorized network device can be utilized as the local server to communication with the web service.

## 4.1 Wireless sensor network elements

From the ZigBee terminology point of view, the wireless sensor network is composed by the end device, the router and the coordinator. From the function point view, however, the wireless sensor network elements of the Culturebee system can be categorized as the sensor module, the message relay, the control module and the coordinator.

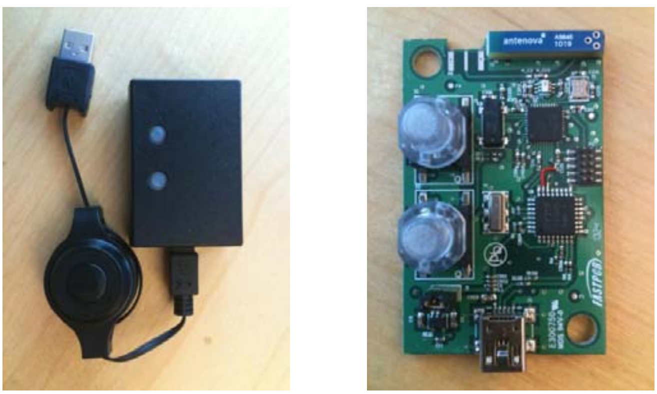
Fig.7 shows the outlook and PCB view of the sensor module. While the sensor module is enclosed with casing, the temperature and humidity sensor can be seen from the outside. Besides, there are also two push buttons and one LED which could be used to reset the sensor module and indicate the network status respectively. As shown in Fig.7 (b), the sensor module is powered by a ½ AA Lithium battery with capacity of 1.2 Ah.

Moreover, the IEEE 802.15.4 radio chip is placed at the "heart" of the PCB board. It is a radio chip together with MCU, named as CC2530.

(a) (b)

Fig.7 Hardware description of the sensor module

The module shown in Fig.8 can be used as the router, the coordinator or the control device. The device is mains powered from the mini USB port. When the device is programmed as the coordinator, the same port is used to communicate with the local server. It either forwards the message to the local server or receives the control command from the local server. If the device is programmed as the message relay, the mini USB port is only used for power supply purpose. The router can be deployed as long as the place is equipped with the power outlet.



(a) (b)

Fig.8 Hardware description of the router and coordinator

The same hardware could also be programmed as the control module. From the ZigBee point of view, a control module is also a ZigBee router, which could be utilized to participate the message routing. When programmed as a control module, the control algorithm is loaded in the program context. The control signal can be generated to control the connected device. Fig.9 shows an example that utilizes the control module to adjust two dimmable lights. The LED light density is controlled by the voltage controller. The ZigBee control module sends control signals to the voltage controller via its digital interface. Different control signals can be generated from different drivers of the control device.


Fig.9 Dimmable lamp wireless control system

## 4.2 Wireless sensor network

The wireless sensor networks of the culturebee system can be deployed in different locations. The ZigBee protocol utilized in the wireless sensor network provides self organization and self-healing features which increase the communication reliability of the sensor network. However, in order to establish a stable wireless sensor network, extra optimizations and implementations are introduced in the culturebee system. Firstly, a power saving end device state machine is implemented to control the end device operation when calculating and forwarding the sensor information. Secondly, the culturebee system utilizes the standard ZigBee command to create a self-organized closed loop control system. In this system, the end device can automatically find and match the control device which needs the sensor information. When sending the sensor information, the end device sends the message to the coordinator as well as the control device. As a result, the climate change information is returned as a feedback to the control unit. Thirdly, the communication reliability enhancement is implemented as a generic framework. It is an application independent framework which could be flexibly configured in the ZigBee stack. Finally, after the mentioned optimization, the wireless sensor network is ready to be utilized in the culture heritage environment.

### 4.2.1 Remote monitoring function design in the WSN

The end device collects the sensor information periodically and forwards the sensor information to the coordinator. In order to save the battery power, a state machine is designed to control the end device operations. In the state machine, the historical value is saved to compare with the latest sensor reading. If the difference is within the defined threshold, the end device does not send the message via the radio but go to the "sleep" mode directly.

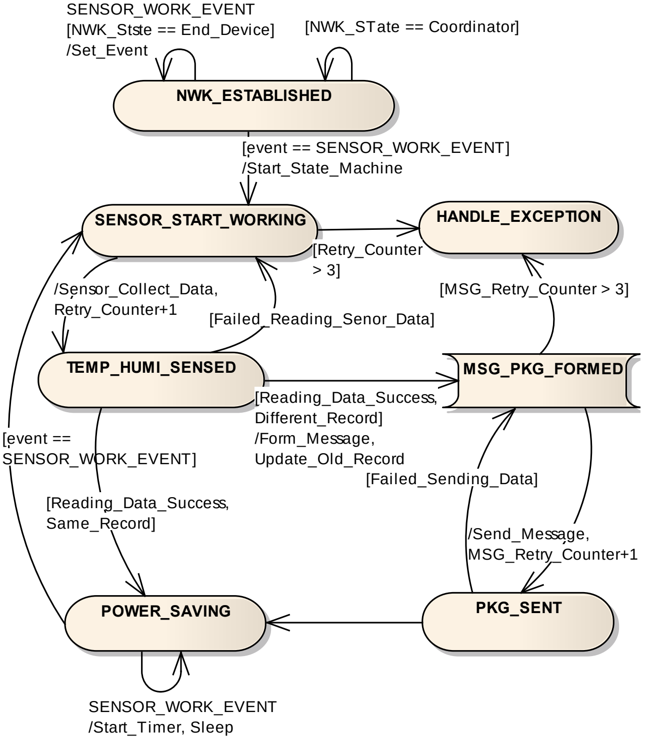



Fig.10 End device sensor operation state machine

As shown in Fig. 10, the state machine works at the NWK_ESTABLISHED when the end device successfully joins the network. Meanwhile, the SENSOR_WORK _EVENT is triggered to start state machine. After that, the sensor module tries to collect the temperature and humidity data from the sensor and jumps into the TEMP_ HUMI_SENSED state. The newly collected sensor value is compared with the "old value" stored from last time. If the "new value" is equal to the "old value" (if a threshold of, e.g., 0.3°C is configured, the application considers the temperature 24.5°C and 24.8°C are "same") the sensor module does not send out the sensor message and goes to the POWER_SAVING state. Otherwise a new message is formed and the state machine goes into the MSG_PKT_FORMED state. In this state, the end device sends the sensor data message to the network coordinator. If the message is sent successfully, the state machine goes into the PKG_SENT state and automatically jumps to the POWER_SAVING state. At the POWER_SAVING state, a timer that triggers the SENSOR_START _WORKING event is set. After that, the end device goes into the sleep mode to save power. The state machine works at the SENSOR_START_ WORKING state again when triggered by the SENSOR_WORK_EVENT. In this state, the end device begins the sensor working for the next round sensor module operation.

When storing the historical value at the state TEMP_HUMI_SENSED, it is important to assign the "old value" only at the state MSG_PKT_FORMED. This is to avoid sensor data from miss-reporting. For example, the temperature reporting threshold is set to 0.3 °C. The end device sensor detects 3 consecutive temperature changes: 11.5, 11.7 and 11.9 °C. If the "old value" is updated each time when the temperature is sensed, 11.9 °C will not be reported to the coordinator since 11.9 °C is checked against 11.7 °C and the deviation is 0.2 °C, which is within the threshold. Thus the sensor will lose the sensitivity of detecting the "smooth" temperature deviation. However, if the "old value" is only assigned when it jumps to the MSG_PKG _FORMED state, 11.9 °C will be reported since the old value is 11.5 °C, and there is 0.4 °C temperature deviation which is outside the threshold.

Furthermore, sensor module exceptions are also handled in the state machine, as showed in Fig. 10. The state machine will go into the HANDLE_EXCEPTION state when the sensor fails to collect the sensor information for three times or the sensor module fails to send out data after retrying 3 times at the state SENSOR_START _WORKING and MSG_PKG_FORM ED.

### 4.2.2 Remote control function design in the WSN

In order to minimize the deployment effort, a self-organized closed loop control network is developed for the control function enabled wireless sensor network. The "service discovery" mechanism defined in the ZigBee protocol is applied to "match" the control device and the necessary sensor module when the network start up.

The “service discovery” procedure is described in Fig. 11. As defined by ZigBee, each ZigBee network should have only one application profile [9]. Within the profile, different nodes can define different “clusters [10]” to identify its features. The clusters defined in the ZigBee node also have directions, either IN or OUT. By marking “OUT” of one specific cluster, one node identifies itself that “I provide the function of this feature!” As shown in Fig. 11, the control node and sensor node are defined within the “Control Profile”. The “Sensor Info” cluster of the control node is marked as “In_Cluster”, which means that the control node needs the “Sensor Info”. The sensor node provides the sensor reading function by marking the “Sensor info” cluster as the “Out_Cluster”. To match these two predefined interfaces, the “Match Description request” is used. The “Match Description Request” is sent from the sensor node. It is a broadcast message to all the nodes within the ZigBee network. On receiving the “Match description request”, the node will check itself if the “Sensor_Info” cluster direction is defined as “In_Cluster”. If so, a “Match Description Response” is sent from the “matched” node to the sensor node. On receiving the “Match Description Response”, the message network address is recorded in the sensor node. Once the sensor node generates a sensor message, the message is forwarded according to the recorded address.

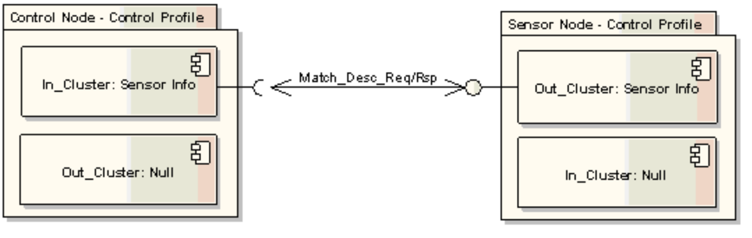



Fig. 11 Service discovery between the control node and the sensor node

The control node controls the climate by sending control signals to the real control device (e.g., radiator). Fig. 12 shows the state machine of the control node. The state machine starts by sending “Control node registration”. It is a message that used to register the control device network address in the local server. When the registration is finished, the state machine jumps to the “Registration finished” state. If the control node needs to add control algorithms to control the target device, the state machine will load the “3rd party” algorithm and jump to the “Algorithm loaded” state. The output of the algorithm execution is taken as the input for generating control signal. If there is no algorithm defined, the state machine jumps directly to “Generate ON_OFF control Signal” state. Before the state machine returns to the “Registration Finished” state, a generic interface called “On_Off_command” is invoked as the output of the control node. It depends on the control device to implement this interface.

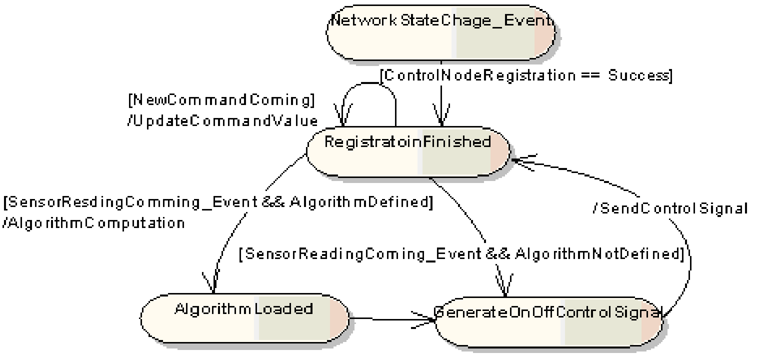



Fig. 12. Control node state machine

### 4.2.3 Communication reliability enhancement state machine

People always blame the communication reliability of the wireless sensor network when compared with the wired system. The ZigBee protocol utilizes the AODV algorithm to increase the network communication reliability. The “self-healing” function defined by the AODV algorithm can automatically find alternative message route to the destination if the current route is broken. As a result, a duplicated router is always appreciated just for redundancy purpose when doing deployment. However, people always consider about the cost when doing the deployment. In such a case, the redundancy of the network is not always available. When the communication link is broken, the end device always tried to find a new router which does not exist. As a result, the battery lifetime of the end device is reduced dramatically (roughly 2 weeks). Moreover, when the communication is broken, the sensor information is lost during the link down time. Even worse, when a new device joins the network, the communication to the coordinator cannot be guaranteed by the ZigBee protocol if the communication status is poor. The enhancement state machine implemented in the culturebee system solves these problems by utilizing the standard ZigBee command. It is a state machine that can be co-exist together with the ZigBee stack, It also provides the interface for importing new application into the framework without interfering the standard ZigBee communication. By using this framework, the communication reliability can be largely improved. The framework contains two state machines for both the end device and the router. These two state machines can work together to increase the communication reliability.

### 4.2.3.1 End device reliability enhancement state machine

The end device state machine describes the behavior of the end device under different circumstances.

- Detect the communication status of the router periodically.
- Stop the sensor data forwarding when the communication link is down
- Find a new parent if the current parent cannot forward messages to the destination
- Use the circular buffer to store the sensor data when link is down
- Upload the buffered data when the communication link is recovered
- Go to sleep mode to save battery power if “rejoining network” failed

Fig. 13 shows the state machine design of the end device. There are 4 states defined in the state machine, the INITAIL, NORMAL, SYNC and FAILURE state. The detailed descriptions are presented for each state.

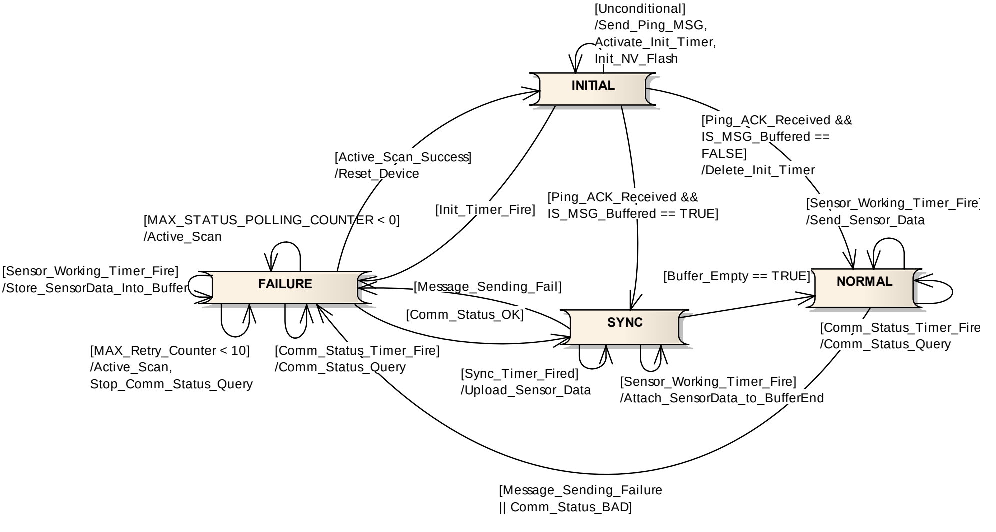



Fig.13 End device communication reliability enhancement state machine

### *INITIAL state*

The state machine starts at the “INITIAL” state after the end device joins the wireless network. In this state, the end device firstly sends a “PING” message to the coordinator. At the same time, a timer is started with the “timeout” interval of the sent “PING” message. Once the coordinator receives this “PING” message, it responses to the end device with an acknowledgement. If the acknowledgement is not received before the “Init timer” fired, the state machine jumps to the FAILURE state. Otherwise, the sensor initializes its flash memory to check if there is any buffered sensor message. If the flash memory is empty, the state machine jumps to the NORMAL state. Otherwise, it jumps to the SYNC state to upload the buffered messages.

The “PING” message is only sent when the end device joins the network. It helps the end device to establish a wireless route to the coordinator. The routers in the network are configured as never expire the route record. In such a case, the communication link from the end device to the coordinator is always guaranteed before any sensor message is sent.

### *NORMAL state*

When the end device works at the NORMAL state, it periodically collects the sensor reading, repacks the sensor message and sends the sensor message to the coordinator. The acknowledgement of the sensor information (Per-to-Per) is checked after each sensor information transmission. If the end device fails to send the message to its direct parent, the state machine jumps to the FAILURE state. Otherwise, it stays at the NORMAL state to transmit the sensor information in the next duty cycle. The end device also sends “Comm_Status_Query” to its direct parent periodically. When receiving this query, the parent of the end device responses with its communication status to the coordinator. If the parent replies the end device with “COMM_STATUS_BAD”, the end device state machine will jump to FAILURE state. Otherwise, the state machine stays at the NORMAL state.

### *SYNC state*

SYNC is the abbreviation of synchronization. In the SYNC state, the buffered messages are uploaded from the end device to the coordinator. The end device keeps message uploading until the buffer is empty. When the buffer is empty, the end device state machine jumps to the NORMAL state. During the message uploading, the end device keeps collecting the sensor information. The newly collected sensor information is appended to the end of the message buffer in order to keep the correct message sequence. Moreover, the message transmitting result is checked for each uploaded message. If the message fails to transmit from the end device to its direct parent, the state machine jumps to the FAILURE state.

***FAILURE state***

The FAILURE state handles all the exceptions happened in the end device. The end device keeps collecting sensor information in the FAILURE state, the collected sensor information is attached into the end of the circular buffer. Meanwhile, the end device sends “Comm_Status_Req” periodically. If the received “Comm_Status_Rsp” indicates the link is recovered, the end device state machine jumps to the SYNC state and synchronizes the buffered messages. A counter is also configured in the FIALURE state. The counter decreases by 1 each time if the end device fails to communicate with its direct parent. When the counter is smaller than 0, the end device believes that the current link is un-recoverable. Then the end device tries to find a new parent by sending the “Service discovery” command over the network.

### 4.2.3.2 Router reliability enhancement state machine

The router state machine is developed mainly for detecting the communication status from the router to the coordinator. The state machine disables the association capacity when the communication link to the coordinator is broken.  As shown in Fig.14, the router state machine contains three states, the INIT, NORMAL and FAILURE state.

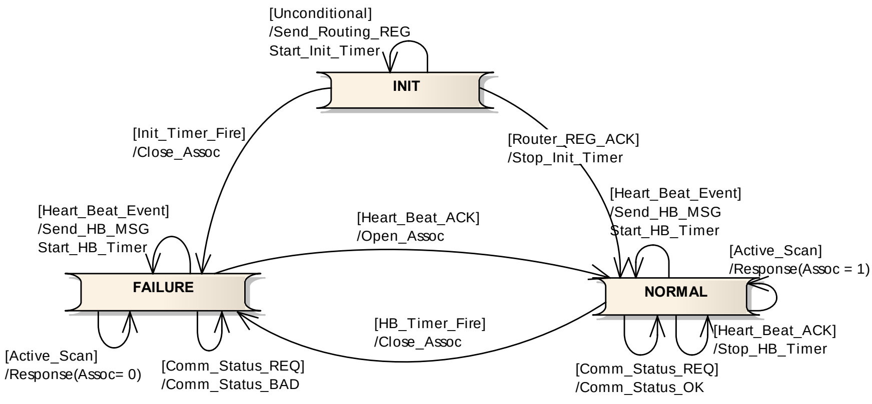



Fig.14 Router performance enhancement state machine

In the “INIT” state, the router sends out the “Router Registration” message when it starts up. Same as the end device state machine, the “Router registration” message aims to create a message route from the router to the coordinator. Once the “Registration Acknowledgment” from the coordinator is received by the router, the state machine jumps to the “NORMAL state”. Otherwise, the state machine jumps to the “FAILURE state”.

In the “NORMAL state, the router sends “Heart_Beat_MSG” to the coordinator periodically. If the “Heart Beat ACK” is received by the router, the state machine stays at the “NORMAL state”. Otherwise, the state machine jumps to the “FAILURE state”. At the same time, the router disables its “association capacity”. By disabling the association, the router stops the new device from joining the network. When the router works at the “NORMAL” state, it responses the “Communication Status Query” with “Comm_Status_OK”. It is a message which indicates a good communication link to the coordinator.

When works at the “FAILURE” state, the router always tries to repair the connection by sending “Heart Beat Message” to the coordinator. Once the “Heart_Beat_ACK” is received by the router, the state machine jumps back to the “NORMAL state” and the association capacity is reopened. If the router receives the “Communication Status Query” in the “FAILURE” state, it responses the query with the “Comm_ Status_BAD” message. It is a message which indicates that the link to the coordinator is broken. Meanwhile, since the “Association capacity” bit is disabled when the router working at the "FAILURE" state, no more devices can be adopted into the network by this router.

### 4.3 Local server software design

The local server is a gateway between the ZigBee network and the Internet. A Netbook [10] is used to run the local server software. The coordinator of the ZigBee network is connected with the Netbook via the USB port. A database is installed in the Netbook to store the local sensor readings and the control node registration information. Fig. 15 shows the software architecture of the local server. If we consider the local server as a black box, it provides the graphical user interface for data displaying. The local server also requires interfaces from the operation system, which are the serial port interface for data communication with the ZigBee network coordinator, the HTTP interface for main server – local server communication and the ODBC [x] interface for database manipulation. Each component implemented in the local server runs as a single thread and responds to each other via events.

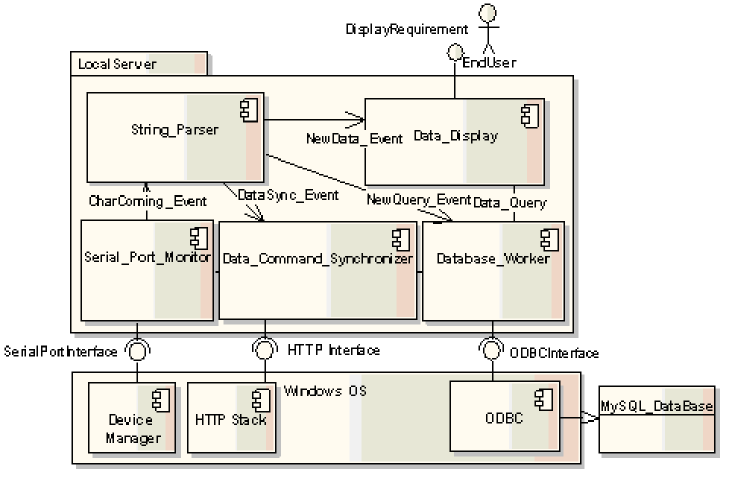



Fig. 15 Local server Software Architecture

From the function point of view, the local server is responsible for sensor information synchronization and main server command polling.

### 4.3.1 Sensor information synchronization

Once the local server receives the sensor information, it forward the message to the web service via the Internet. Fig.16 presents the while procedure of the sensor message synchronization. The "data display" component in the local serve also updates the user interface which presents the latest sensor reading.

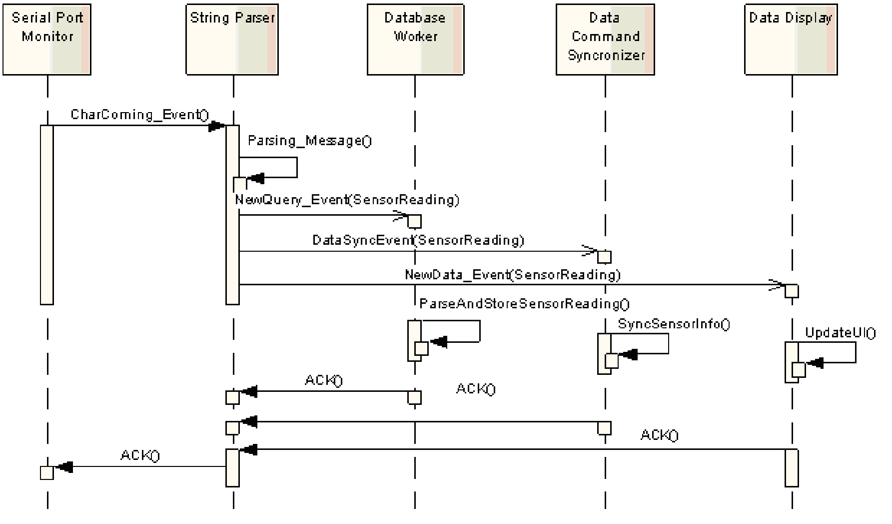



Fig. 16 Sensor information synchronization flow chart

### 4.3.2 Control command polling

When working for the control purpose, the local server sends polling messages to the web service periodically. As shown in Fig. 17, once the web service receives the polling message, the pending command is sent back to the local server accordingly. A configurable timer is set in the local server to trigger the command polling operation periodically. When the timer fired, the "Data Command Synchronizer" is triggered to send a "Command Polling" message to the remote main server via the HTTP protocol. If there are commands to the specific local server, a "new control command" message is sent back to the "Data Command Synchronizer". The command received contains the control node index and the configuration information as shown below:

**ContrlNodeIndex**:XXXX **Value**:XXXXXX

The system only recognizes the control node by its user defined index. When the control command is about to send from the local server to the wireless sensor network, the ZigBee network address of the control node is retrieved from the local server database. The control node network address is retrieved by querying the database with the control node index. The relationship of the control node index and the control node network address is recorded during the “control node registration”. The control command together with the control node network address is reorganized as a new command and sent to the coordinator via the serial port monitor component. On receiving the control command, the coordinator transmits the command to the control node specified by the network address.

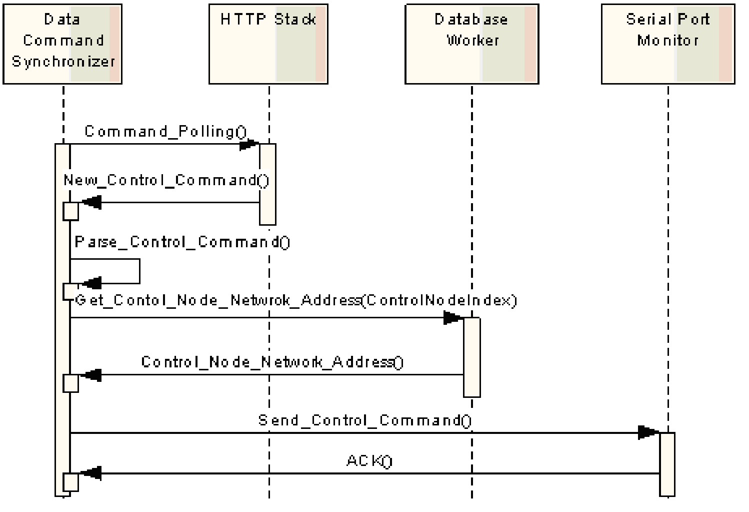



Fig. 17 Local server command polling flow chart

### 4.4 Web service

From the user point of view, the main server provides the graphical data representation. The data can be sorted according to the user command. From the sensor network and local server point of view, the main server provides the interfaces for data synchronization. Fig. 18 shows the main server architecture. The main server is built above the “LAMP” (Linux + Apache + MySQL + PHP) infrastructure and provides dynamic web service [12].

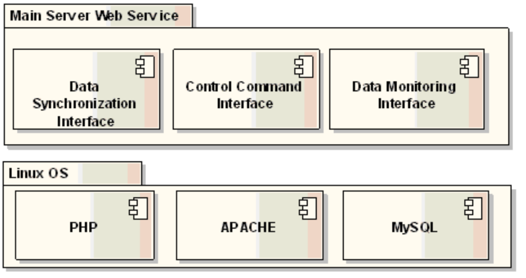
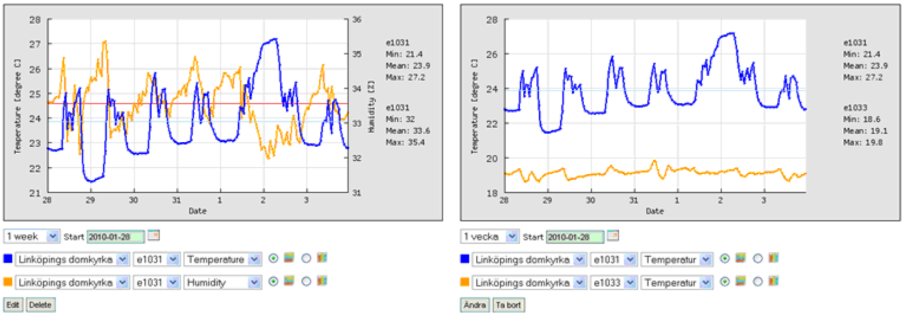



Fig. 18 Main server architecture.

As shown in Fig.18, the “Control command interface” and the “Data monitoring interface” provides the webpage to the end user to issue control command and monitor data. The data monitoring results and the control user interfaces can be observed from the address www.culturebee.se. Fig. 19a is the screen cut of the monitoring function from the main server. There are two curves in the diagram representing temperature and humidity respectively. Node “e1031” is the ID of the end device located on the reception desk in Linköping Cathedral [13], one of the biggest churches in Sweden. People can also compare the temperature or humidity by selecting different sensors in the list box. As shown in Fig. 19b, the temperature measurement is compared between “e1031” and “e1033”, which are located on the reception desk and the corridor in Linköping Cathedral, respectively.




a) Temperature and humidity monitoring b) Temperature comparison

Fig. 19 Screen cut of the monitoring function from the main server

The main server control function user interface is shown in Fig. 20. Two kinds of control modes are defined, which are the “General Control” mode and the “Accurate Control” mode. The “General Control” mode is applicable for the churches controlled by only one control device. The average temperature and humidity are measured and fed back to the control node. Therefore, the church climate is controlled "generally". For the churches equipped with multiple control devices, the "Accurate Control" mode can be applied. Users can issue control command for each control node separately. In such a way, the church climate is controlled "accurately".

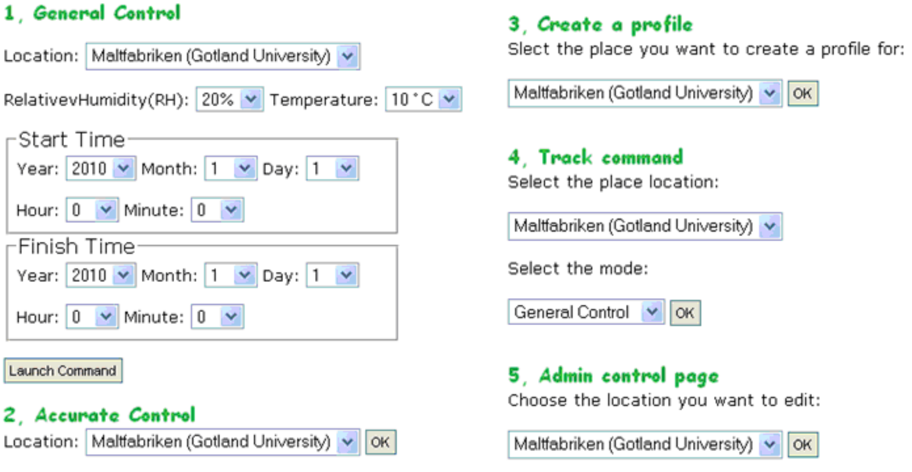



Fig. 20 Control function user interface of the web service

The "Data synchronization Interface" component is designed for main server – local server data synchronization. The interfaces provided from this component are shown in Fig. 21. Each interface is implemented as a PHP file. When the local server wants to send data to the main server, it sends a SOAP [14] message to the corresponding PHP file via the Internet. Once the interface receives an incoming message, it creates a software SOAP server to handle the message. Four interfaces are implemented for data synchronization purpose. The "Sensor registration interface" is invoked when a new sensor want to register the matching relationship with the control node. The "Control node registration interface" handles the "Control node registration" message. The "Sensor information synchronization interface" handles the sensor reading information. The "Control command interface" is responsible for command synchronization from the main server to the local server. When the local server invoking the "Control command interface", a "location name" parameter is sent to the main server as well. The main server will forward all the commands related with the specific location to the local server. Once the message is successfully handled, the software SOAP server is destroyed.

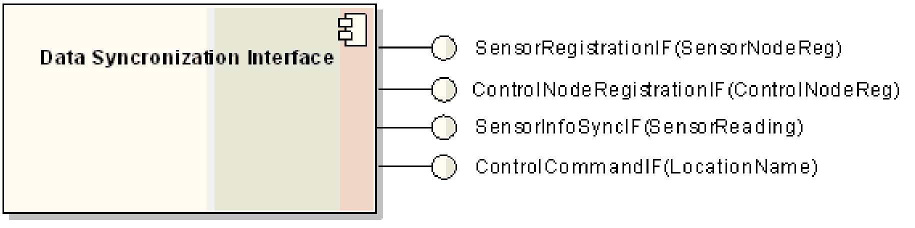



Fig. 21 Web service interface.

# 5 Summary

A remote monitoring and control system is implemented. It is a system that has high flexibility. In the wireless sensor network part, the battery life time of the end device is optimized. Communication reliability enhancement is developed as a generic framework which is ZigBee protocol compliant. The gateway is implemented as a Windows based application. It utilizes the database technology to increase the duplicity of the system and also implement the buffer mechanism to handle the situation when the internet connection is lost. The web service can be accessed as a normal webpage. From the web page, users can remotely monitor different locations. User can also issue control command from the web service.

# 6 Future work

The future work can also be done in the area of the wireless sensor network optimization and new application development.

In order to optimize the wireless sensor network, the idea is to implement a “synchronized ZigBee sensor network” so that the router can also go to sleep mode. Once implemented, the router can also be powered by the battery. According to the definition of the ZigBee protocol, the coordinator and the router should always be mains powered. However, due to the fact that the ZigBee network is a low data rate network, the router is turned on in vain for most of the time. One of the ideas is that to turn off the power of the router when the router is not used and switch on when necessary. This could be done by connecting an external MCU to switch ON/OFF the regulator of the router. Different synchronization algorithms could be verified by using this module to optimize the network performance.

Another future work is to expand the culturebee system into applications other than the culture heritage preservation. Although the culturebee system is designed originally used for culture building preservation, it is a system that could be utilized in other application areas, i.e., industry monitoring, agricultural automation and so on. The requirements and challenges are different from different application areas. In order to expand the application area, the culturebee system needs to be under many different field tests.

# 7 Summary of the included papers

**Paper 1**

**Remote Sensing System for Cultural Buildings Utilizing ZigBee Technology** by Jingcheng Zhang, Allan Huynh, Qin-Zhong Ye and Shaofang Gong, Proceedings of the 8th International Conference on Computing, Communications and Control Technologies (CCCT 2010), Orlando, USA, pp. 71-77, April 2010.

A wireless remote sensing system using the ZigBee standard is presented in this paper. The concept of this system is utilizing ZigBee network to carry and transmit data collected by sensors and store them into both local and remote database. Thus, users can monitor the measured data either locally or remotely. Especially, the power consumption is optimized to extend the life time of the battery driven devices.

Contribution: Prove the concept that the remote monitoring system can be utilized for the cultural heritage preservation purpose. The battery lifetime of the wireless sensor module can be up to 10 years.

**Paper 2**

**Design of the Remote Climate Control System for Cultural Buildings Utilizing ZigBee Technology** by Jingcheng Zhang, Allan Huynh, Qin-Zhong Ye and Shaofang Gong, Sensors & Transducers Journal (ISSN 1726-5479, Vol. 118, Issue 7, pp. 13-27, July 2010.

In this work, a wireless solution of remote climate control for cultural buildings is presented. The system allows users to use web service to control climate in different buildings. The wireless sensor networks deployed in the buildings receive the control commands and manage the indoor climate. The whole system is modularly designed, which makes possible an easy service extension, system reconfiguration and modification. This paper includes the system overview and the software design of each part within the system.

Author's contribution: Prove the concept that the wireless sensor network can be utilized in the cultural heritage environment for remote control purpose. A self-organized closed loop control system is implemented for accurate control and save power.

**Paper 3**

**Reliability and Latency Enhancements in a ZigBee Remote Sensing System** by Jingcheng Zhang, Allan Huynh, Qin-Zhong Ye and Shaofang Gong, Proceedings of The Fourth International Conference on Sensor Technologies and Applications (SENSORCOMM 2010), Venice/Mestre, Italy, pp. 196-202, July 2010.

In this work, methods to improve the reliability and optimize the system latency of own-developed ZigBee remote sensing system are introduced. The concept of this system utilizes the ZigBee network to transmit sensor information and process them at both local and remote databases. The enhancement has been done in different parts of the system. In the ZigBee network part, the network topology is configured and controlled. The latency for message transmitting is optimized. In the data processing part, the network status check function and data buffer function are introduced to improve the system reliability. Additionally, the system latency is measured to compare it with that from the Ad-hoc on demand distance vector algorithm used in the ZigBee standard.

Author's contribution: Design a method for control the ZigBee network topology rather than self organization. Add a buffer mechanism in the system to improve the message forward reliability. Implement the wireless sensor network status monitoring function for the wireless sensor network maintenance purpose.

**Paper 4**

**CultureBee – A Fully Wireless Monitoring and Control System for Protecting Cultural Heritage** by Jingcheng Zhang, Allan Huynh, Qin-Zhong Ye and Shaofang Gong, Proceedings of 20th IEEE International Conference on Collaboration Technologies and Infrastructure, Paris, France, pp. 56-61, June 2011.

This work presents the design and implementation of a component based wireless remote monitoring and control system. Firstly, the design of each component in the system and the communication between them are presented. Secondly, the system optimization is introduced. Instead of the original message routing algorithm, an own developed routing method is applied in the wireless sensor network part. The applied routing method is especially optimized for cultural heritage preservation applications. Finally, in the test result section, the battery life time calculation result, network performance test result and remote monitoring field test result are also presented.

Author's contribution: Implement a new routing algorithm for the communication from the coordinator to the sensor network device. Implement a flash memory based circular buffer which could be utilized for the end device when the radio link is down.

**Paper 5**

**A Communication Reliability Enhancement Framework for Wireless Sensor Network Using the ZigBee Protocol** by Jingcheng Zhang, Allan Huynh, Qin-Zhong Ye and Shaofang Gong, Manuscript, June 2011.

This work presents the framework that enhances the communication reliability of wireless sensor network using the ZigBee protocol. The paper begins with the introduction of common communication problems caused by the broken links between the sensor module and the message relay, or between different message-relays. Extra message hand shake mechanisms are added to solve the mentioned problems. Based on the solutions to different problems, a general purpose reliability enhancement framework is developed. The framework contains two state machines for both the sensor module and the massage relay. These two state machines can work together with the ZigBee protocol to enhance the network communication reliability. Moreover, the battery lifetime of the sensor module under link loss is considerably increased after the enhancement.

Author's contribution: Implement a ZigBee protocol compatible framework for the enhancement of the message forwarding reliability. The framework defines the operations of the ZigBee sensor network when the radio link is down. Moreover, the battery life time during the radio link down time is considerably increased by running the framework.

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