A DYNAMIC THERMAL MANAGEMENT IN BUILDINGS FOR COMFORT ENHANCEMENT AND ENERGY CONSERVATION: FROM SENSOR NETWORKING TO USER PARTICIPATION

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A Dynamic Thermal Management in Buildings for Comfort Enhancement and Energy Conservation: from Sensor Networking to User Participation

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CERTIFICATE OF ORIGINALITY

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ABSTRACT

Nowadays, buildings occupy a significant portion of global energy consumption. Sustainable efforts and measures have been carried out to reduce the energy consumption in buildings. Yet, buildings are not only a shelter for people, they also serve to provide people with comfort and safety; otherwise, turning off every power consuming equipment can maximize the energy conservation. Balancing the energy consumption and human comfort is challenging since it is hard to evaluate the satisfaction of occupants.

This thesis presents a user-participatory framework, and models the thermal comfort of individuals by using mobile devices with minimal manual input. The framework connects with the building management system (BMS) to adjust the temperature setting; the mobility of underlying controllers is thus important to the framework applicability. An asynchronous-response design is developed to dewiring existing controllers into wireless while keeping the communication protocols intact. A modular design for wireless data plane is used to selectively prioritize and schedule data transmission in case of link quality and throughput variations. The feasibility of the design is tested by comprehensive experiments and field deployments in the University.

A temperature-comfort correlation model is developed to estimate the individual comfort based on a collection of parameters and sensors data. In addition, a setpoint optimization algorithm is developed to find out the temperature that maximizes the group comfort. Field experiments in the University and a commercial office show the improvement of thermal comfort by 63% and 33.8% respectively, while reducing 18% of energy consumption in the experiment of commercial office.

Keywords: Building Management System, BACnet, Participatory sensing, Thermal Comfort, Mobile Application, Strategy-proof.

LIST OF PUBLICATIONS

Conference Papers

1. **Abraham Hang-yat Lam** and Dan Wang. "Carrying my environment with me: A participatory-sensing approach to enhance thermal comfort". In *Proceedings of the 5th ACM Workshop on Embedded Systems For Energy-Efficient Buildings*, BuildSys'13, pages 21:1-21:8, New York, NY, USA, 2013. ACM.

2. **Abraham Hang-yat Lam**, Yi Yuan, and Dan Wang. An occupant-participatory approach for thermal comfort enhancement and energy conservation in buildings. In *Proceedings of the 5th International Conference on Future Energy Systems*, e-Energy'14, pages 133-143, New York, NY, USA, 2014. ACM.

3. Liang Zhang, **Abraham Hang-yat Lam**, and Dan Wang. Strategy-proof thermal comfort voting in buildings. In *Proceedings of the 1st ACM Conference on Embedded Systems for Energy-Efficient Buildings*, BuildSys'14, pages 160-163, New York, NY, USA, 2014. ACM.

Demos & Posters in Conference

1. **Abraham Hang-yat Lam**, Dan Wang, and Daniel Wai tin Chan. Demo: BACChat: A building automation control client for sensor data collection. In *INFOCOM IEEE*'11.

2. Qinghua Luo, **Abraham Hang-yat Lam**, Dan Wang, D.W.-T. Chan, Yu Peng, and Xiyuan Peng. Demo abstract: Towards a wireless building management system with minimum change to the building protocols. *In Proceedings of the ICCPS*'12.

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CHAPTER 1

INTRODUCTION

In recent years, people have been paying more attentions to energy conservation around the world. In the United States, around 46% of the total energy consumption is consumed by buildings [1]. In Hong Kong, commercial buildings account for more than 65% of energy consumption of the city [2]. Having envisaged that the energy consumption of buildings will substantially increase, governments of different countries have adopted various measures, formulating energy policies to combat with the energy issue.

To maximize energy saving efforts, one may simply turn off all the air-conditioning and electrical appliances. Nevertheless, buildings are not only served as a shelter, but it also aims to provide occupants with a safe and comfort environment [62] [52]. Occupants of buildings are playing a significant role in the energy consumption of buildings, especially their habits and behaviours have strong correlations with the energy consumption [52]. Besides, they have a certain level of comfort threshold to the change of ambient conditions, a well balance of the energy consumption and human comfort have long been studied. An intelligent and dynamic control of system equipment are thus required to realize different proposals.

1.1 Emergence of intelligent buildings

Intelligent building has been proposed in the past decades to enhance occupants' comfort. In doing so, it automates the equipment configuration and decision-making process by detecting and learning users' behaviours and habits from their daily environments [62] [94]. Various kinds of sensors are installed, detecting human activities and carrying out the corresponding control and adjustment wisely. While it revolutionizes the context of building controls by actively taking humans factors into consideration, humans are still passive under the current design; the actual perceptions of people are being neglected [54] [48] [67].

In built environment discipline, the current practice to obtain occupants' levels of comfort is mainly by surveys and field studies. However, surveys are normally conducted in once-off and the result is normally context-dependent [34], which only reflect shallow information and perhaps instant feedback of occupants. In addition, it fails to indicate the correlation between the change of ambient conditions to the levels of comfort to occupants. Considering the effectiveness of collecting data via questionnaires, occupants usually have low incentives to provide detailed information because they perceive the questionnaire simply as a service feedback to facility management. As such, the data collected by the questionnaires is not able to reveal useful implications regarding the factors affecting occupants' comfort [54] [38].

Aside from surveys, there are field studies and simulations in laboratories. In the laboratories, different scenarios can be simulated by controlling the parameters of temperature, humidity, air flow rate, etc. with the use of a climatic chamber. Numerous sensors are used to capture precise change of the internal environment of chamber and models can be trained to enhance the accuracy of estimation. Despite the fact that it provides a more comprehensive, finer view and rigid evaluation than that in field studies, the former practice is still questionable for its applicability since humans possess with heterogenous habits, metabolic rates, airflow and temperature sensitivities [34] [48]. Recent studies have further shown that cultural and racial factors also influence the comfort levels [34]; therefore, a sustainable study and ongoing feedback of occupants are important and essential, and the intermediary between building systems and humans has become a new research frontier [52].

With the high penetration rate of mobile electronic devices like smart phone to date, these mobile devices have facilitated in capturing, classifying and transmitting various

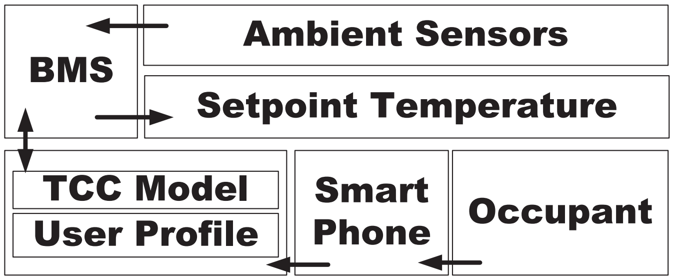


Figure 1.1: High level idea of OPTC workflow

kinds of data, e.g., user's location and movement. As such, a user-based participatory sensor network can be formed from bottom-up to collect, analyze and aggregate the local knowledge of users in the individual level [22]. It provides a low-cost ubiquitous intermediary [54] that is suitable for human-building interface [67]. In this thesis, the participation of occupants is important for modeling and supporting the proposed framework; therefore, a user-participatory approach using smart phones is adopted with the consideration of its benefits regarding cost, system availability and functionality. More details are discussed in Chapter 4.

1.2 Participatory sensing for human comfort

The approach of participatory sensing provides a gateway for physical systems to acquire and capture ubiquitous data directly from individuals and groups of people. An occupant-participatory thermal comfort (OPTC) framework is designed in this thesis to connect humans with the building systems by the interface of mobile devices. A temperature-comfort correlation (TCC) model is used to transform the thermal preference of humans into numerical setting of physical system. Considering the incentive of occupants providing feedback, the framework is designed to be model-driven. The high-level idea of the design flow is illustrated in Figure 1.1 and summarized as follows:

1. Each occupant is given a profile, in which their feedback are recorded and trained in the TCC model.

2. Occupants submit their feedback using mobile devices to the OPTC server.
3. The sensors data from BMS provide ambient information for the TCC model.
4. The TCC model determines the optimized setpoint temperature with the highest satisfaction of occupants, and configures the temperature accordingly via BMS.

To correlate the thermal comfort of occupants with the actual conditions of building, it is essential to acquire the real-time ambient sensing. In the design of HVAC system, each floor of building is divided into *zones*; each zone can be individually controlled by the corresponding thermostat [48]. Ideally, more sensors can provide a finer information and optimized temperature control to suit the actual need of occupants, which in turn helps train the model more precisely. To do this, additional controllers are needed to connect new sensors and carry out the system adjustment accordingly. However, significant amount of work will be involved for the enhancement of control and sensing granularity, such as system re-configuration, engineering work and labor input. Worse still, the wiring and deployment work of cables to an operating building will definitely pose various technical challenges and management difficulties from administrative perspective, which will greatly reduce the incentives of facility management to leverage the system potentials. A wireless system is a promising solution in this regard.

1.3 Smart sensors for BMS applications

The emergence of wireless sensor network (WSN) in the past decade has led to massive deployment of smart sensors into buildings. They are mainly used for i) energy measurement, ii) environmental sensing and iii) human activities detection [63]. A key prerequisite for reducing the energy consumption is to first understand energy distribution of a building. Unfortunately, most of the contemporary buildings are not able to provide a fine-grained visibility to the energy consumption due to huge installation cost and complicated design of electrical circuit [33]. Smart sensors are used as cost-efficient alternative in different circuit levels to provide detailed information of energy consumption [57].

Aside from energy consumption, smart sensors are also deployed at different areas of building to collect ambient information [54] [44] [66], such as temperature, relative humidity and CO2 level. These information are studied and correlated for better control of indoor environmental quality (IEQ) [49] and identified abnormal air-conditioning like hot spots and cold spots of areas in buildings. Occupancy information can be sensed by smart sensors to provide automated control of lighting, air-conditioning etc. at different zones and rooms [48]. The collected information is trained to formulate models that can help enhance occupant's satisfaction while staying in building.

Besides the stand-alone applications, smart sensors can also be adopted into several parts of a BMS: i) sensors, ii) network, and iii) controllers. For BMS sensors, this can be easily replaced with smart sensors, they are equipped with various kinds of sensing functions like temperature, relative humidity and luminance. They help provide a finer view of sensors information, and enhance the close-loop feedback to controllers. For the network of BMS, additional wireless routers and switches can be used to relay the data of controllers to the network; hence, adopting wireless in this part is simple as long as the network topology is well-planned. For the controllers, they are intermediates of sensors and network, and are directly controlling the system equipment and processing the sensors data. The distance between controllers can be long and across rooms and floors; dewiring the controller cables and turning into wireless is fruitful and desired since it can save most of the time and cost in the BMS. Details will be discussed in Chapter 3.

1.4 Challenges of development

A BMS maintains a distributed architecture in controlling various building systems. Hundreds of application-specific controllers known as direct digital controls (DDC) are installed in buildings to provide precise control and automation for the operation of building equipment. The DDCs are working in close-loop according to a set of predefined control programs [48] with the feedback of sensors and actuators, where the sensors and actuators are installed at different areas or inside the equipment of buildings. In fact, the chief function of BMS is to maintain the operation of building equipment, ensuring the equipment operating at normal conditions, e.g., the air damper openness is adjusted to achieve the target temperature of a room. In contemporary design of BMS, human's perception is not considered in the control program of system. More specifically, no sensors can reflect the real perception of occupants. This can explain the reasons of massive complaints from occupants to facility management every day. From application point of view, the current BMS only serves the space of building, but not the target group of people in building; therefore, the systems are working at sub-optimal conditions; both the energy consumption and comfort of occupants are not carefully studied and considered.

There are many studies and designs proposed to resolve these shortcomings, and yet they are facing nontrivial challenges. Firstly, the design and operation of a building are intrinsically unique, functional-specific and custom-designed [66], hence no portable solutions can be applied to all buildings. The diversified building equipment from vendors pose difficulties to work along with different vendor-specific functions and properties [62]. The BMS of a building is delivered *as-is* after the construction stage and testing and commissioning (T&C) period; the lack of flexibility and rigid design requirement have hindered the extensibility of systems. Moreover, the configuration of system is also complicated, thereby reducing the applicability.

Secondly, with a view to enhancing the occupant's comfort, one has to first acquire their actual perceptions. However, humans have inconsistent perceptions from time to time. Worse still, there are conflicts between occupants' choices and perceptions to environment. Taking thermal comfort as an example, two individuals under in same room may have diverging sensations toward the room temperature. As such, it is important to consider and resolve any possible conflicts of occupants. On top of these, other concerns like system intrusiveness and privacy of the design should also be considered.

1.5 Research Framework

The core part of this thesis closely works with a BMS, it generally consists of four equivalent *Open Systems Interconnection* (OSI) layers [10], i) the *physical layer*, ii) the *data link layer*, iii) the *network layer*, and iv) the *application layer*. The research framework of this thesis is thus presented in align with the collapsed OSI model as shown in Figure 1.2.

The first direction of the framework is bridging the communication between the proposed framework with the existing BMS. Building Automation and Control Network (BACnet) is the dominant communication protocol in BMS to date. Hence, an application program BACChat [96] is designed initially to enable the communications of BMS. The details are presented in Chapter 3.

With the motivation to increase occupants' comfort and optimize the energy usage [62], a significant amount of work in computer science has prevailed. These include the deployment of WSN in buildings, the design of novel and value-added services seeking to achieve specific objectives, e.g., design energy conservation schemes, and provision of a finer view of energy consumption and human comfort enhancement.

While the contemporary design of DDC in BMS is based on wired connections, a wireless solution can provide cost-efficient and value-added features to occupants. In Chapter 3, an *asynchronous-response* framework is proposed partially replacing the wired connections of controllers into wireless. This approach is adopted using smart sensors, directly connected with the wired DDC. The detailed discussion is presented in Chapter 3.

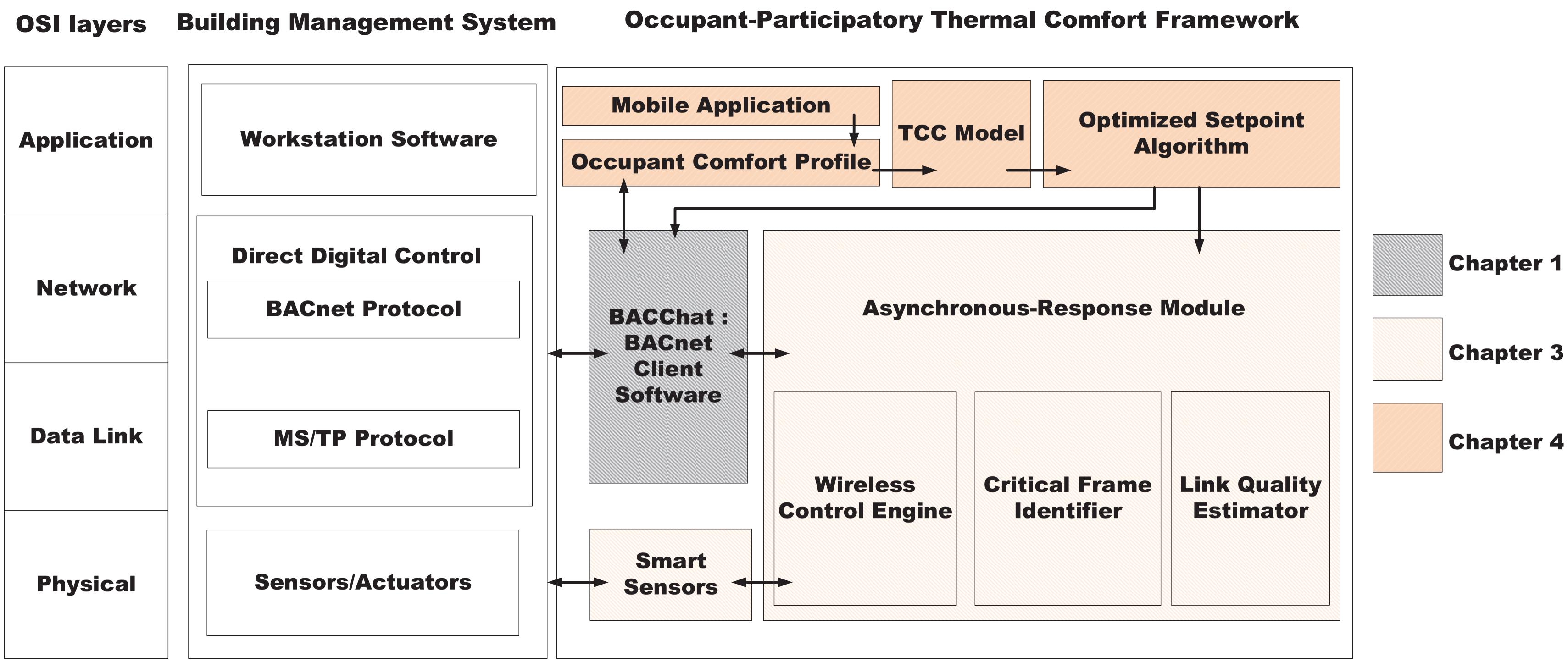


Figure 1.2: Research Framework

1.6 Summary of Contributions

To present the key contributions of this thesis in concise and precise, the following part groups the main contributions into two complementary directions: i) the design of asynchronous-response framework for BMS (Chapter 3); and ii) the occupant-participatory thermal comfort (OPTC) framework (Chapter 4).

For the asynchronous-response framework of BMS:

- Provided an open-source BMS communication package that enabled the research community to develop further applications with the essential connection of BMS. (Refer to Chapter 3.2.1.)

- Provided comprehensive studies to the existing wired BMS protocol and identified the deterministic factors for a wired BMS to successfully convert into wireless. (Refer to Chapter 3.5.)

- Designed the transmission algorithm that could convert a wired BMS into wireless without modifying the upper layer protocols. It provided a new and innovative insight for the development of wireless BMS from legacy system. To the best of the author's knowledge, this was the first work that has taken a real operating BMS as testbed and applied successfully without interrupting the existing BMS operation. (Refer to Chapter 3.5.2 and 3.8.)

- Provided comprehensive simulations and comparisons to the design of asynchronous-response framework were conducted. The result and experience could both be applied into other domains that inspire more innovative applications and future work. (Refer to Chapter 3.7.3.)

- Conducted real-world experiments and confirmed the feasibility and applicability of the design. It provided an alternative for a wired BMS to work in parallel with a wireless BMS. A hybrid option was proposed for a wired BMS to incrementally convert into wireless, and short-term deployment for specific purpose. (Refer to Chapter 3.8).

For the occupant-participatory thermal comfort (OPTC) framework:

- Designed an innovative user-participatory framework to enhance the thermal comfort of people in buildings. The design was model-driven and based on the predicted mean vote (PMV) model and adaptive comfort model of built environment discipline. (Refer to Chapter 4.4.)
- Developed an individual dynamic temperature-comfort correlation (TCC) model that was able to transform the ambient condition into thermal comfort index of people. It also translated the subjective preferences of humans into the physical settings of system context. The model considered the relationship of different physical characteristics of people and the change of metabolic rates at different periods of time. (Refer to Chapter 4.5.)
- Developed the setpoint temperature optimization algorithm (SOA) to compute the optimal setpoint to a group of people that maximized their overall thermal comfort. (Refer to Chapter 4.6.)
- Conducted simulations and comparisons of different body mass index (BMI) ratios of people using one-year real classroom schedule, and evaluated the potential thermal comfort improvement. (Refer to Chapter 4.7.)
- Conducted real-world experiments in a commercial office and university, the results showed an average of 63% and 33.8% thermal comfort improvement. (Refer to Chapter 4.9.)
- Evaluated the balance between energy conservation and human comfort. In the experiment, the OPTC scheme was able to save 18% of energy consumption of the air-conditioning terminal units while maintaining the thermal comfort of occupants. (Refer to Chapter 4.9.3.)

- Studied the existing user feedback schemes and found most of them were not strategy-proof that might implicitly encourage people to submit false-vote. The strategy-proof voting scheme was provided for the vote of thermal comfort, which is useful to be applied into other contexts requiring the feedback of users. (Refer to Chapter 4.10.)

CHAPTER 2

RELATED WORK

This thesis focuses on the research work of building-related systems and applications. The role of buildings in this part is presented from the perspective of cyber-physical system (CPS). CPS is a promising research paradigm recently that integrates the computation capacity with the physical process of system to deliver reliable services and controls [68]. The applications cover a wide range of domains, such as battlefield surveillance [92] [26], road and air traffic monitoring [92] [99], environmental control and energy conservation [18] [85] [84], medical device and monitoring system [59] [69]. Building is one of the major frontiers and is discussed as follows.

There are enormous sensors and sensing peripherals deployed and installed in buildings to monitor and control the physical systems of buildings [48] [15]; however, they are mainly installed for monitoring the operating equipment and sensing the conditions of indoor environment (e.g., temperature, humidity and CO2 level) [29]; it is yet to be sufficient to carry out new applications given their limited functions and spatial constraints. With the advent of wireless sensor network (WSN) in recent years, not only does it mitigate the problems of insufficient sensors data, but it also enriches the functionalities and widens the scope of applications.

Since buildings occupy a large portion of worldwide energy consumption nowadays, there are massive work done in this criteria. Occupants play a key role in the energy consumption of commercial buildings [54], a finer view towards the consumption is thus indicative and useful. Numerous work has been done that aims to provide multi-dimensional views to the energy consumption [33] [61] [57] [70]. Jiang et. al. [57] developed the wireless meters *ACme* at plug-load level to monitor and measure the energy consumption of individuals, and proposed a thorough energy auditing in [58]. Experimental studies were conducted to learn the behaviours of individuals toward energy consumption by evaluating the effectiveness of conveying energy-related information [74] [53]. Samuel et. al. [33] presented their energy-harvesting approach by utilizing the load current to power the meters intermittently. Kim et. al. [64] made use of the ambient signals from appliances, placing the sensors nearby to estimate the energy consumption without connecting the actual appliances. Aside from energy issue, the classical coverage problems of WSN have also been studied [58]; more than 30 power meters were installed to form an energy load tree to breakdown the energy consumption. The authors acknowledged the importance of meters grouping and assignment.

2.1 Study of Building Management System

With the increasing importance and requirement to building operations and services provisions, a BMS is expected to deliver high qualitative and value-added services to proliferate its capacity and function. To apply the results and insights from prior studies and models, it is more fruitful if these research work can be fed into existing building systems. It is worth noticing that there is no single BMS works and controls alike perfectly. The variations in building design, functions, orientations and characteristics all contribute the differences of BMS architecture and the operation and maintenance (O&M). This increases the difficulties and challenges to provide a portable solutions to apply those novel applications.

To articulate the previous work on BMS, the related illustrations are divided into two dimensions: i) design of BMS architecture, and ii) development of applications.

2.1.1 Design of BMS Architecture

A variety of previous studies has been proposed to re-architect the BMS. Starting with the minimized touch-up in upper layers, a server is normally placed in-between the proposed applications system with the legacy BMS, where the communications between them are bidirectional; the building information is sent from BMS to the application server and the feedback (or decision controls) from these application servers are relayed to BMS [67] [48] [17] [54] [15] [87] [13].

Besides the top-down approach, previous studies have been conducted in relation to the existing architecture of BMS. Luo et. al. [72] demonstrated their asynchronous framework that could partially free the wirings between the wired controllers with the upper-layer protocols intact. Andrew et. al. [66] simplified the complexity of equipment designation in BMS; application programming interface (API) was developed, enabling the building applications to be portable between buildings without requiring the re-structuring of BMS points and prior knowledge to the communication protocols being used.

2.1.2 Development of Building Applications

With the increasing concerns to the quality of indoor environment, a considerable amount of work has been done on harnessing the BMS architecture and data to develop different applications. For the sake of network traffic for massive sensors data, various approaches were proposed to compress messages content [66] [28] [15] [87] [56] between the server and BMS. Stephen et al. [28] presented their design of *sMAP*, using RESTful web service to facilitate the physical information collection (e.g., sensors and actuators data). They defined the lightweight Javascript object notation (JSON) on top of HTTP to minimize data communication. They then scaled up the design by integrating the data sharing and services of building devices [29]. Sensor Andrew [87] was developed with uniform approach to access heterogeneous smart sensors and actuators of building equipment; a push-based communication model with XML-type messages was developed to enable different users and agents to collect the sensor data. BuildingDepot [15] was designed for a scalable and distributed data storage and access of sensor data from BMS. It consisted of several components and connectors to link up users services with the physical sensor data and network.

Occupancy detection sensors have been substantially studied to minimize energy usage for zones or rooms that are left unoccupied for a period of time [37] [13] [36] [73] [71]. Chen et. al. [24] presented their non-intrusive approach to infer occupancy based on the energy consumption patterns from electric meters [71]. The sensors trained an occupant's daily working time so that the provision of heating and air-conditioning services are just good enough to suit one's need while saving energy . Circulo [41] was presented with same rationale on the tap water to heater: the system aimed to save the unused water being wasted before the hot water came out.

Some other related work on buildings include a large-scale residential sensing system [50]; using energy storage to reduce energy bills [77], cyber-physical computing on thermal energy usage [16] and bill reduction with room usage management [85].

2.2 Human-centric applications in buildings

In the buildings context, it is generally agreed that the chief objective is to provide a safe and comfort environment for occupants [9]. While the safety issues can be addressed by regular checking and close monitoring by reliable alarming systems, these measures cannot improve the comfort level of occupants [48] [67] [38]. Ironically, occupants have not been taken into consideration to the control-loop of BMS, since the current system lacks of channels to acquire their perceptions [67] [48] [54]. Occupants' complaints regarding the HVAC system have been frequently received even staying in state-of-the-art buildings [48] [38] [54] as occupants' behaviours and preferences are dynamic in nature [53]; and these issues are influenced by a collection of factors [67] [48], it is not feasible to apply the results merely from simulations or ad-hoc surveys so as to achieve an optimal balance of human comfort and system energy efficiency.

To acquire the actual perception of occupants, the approach of participatory sensing has been adopted. It acts as a gateway for physical systems to acquire and capture ubiquitous data directly from individuals and groups of people through the mobile devices [39]. With proper deployment and configuration, it leverages the power of exploiting meaningful data and infers complex phenomena to the group of people that in interested. The following part discusses the user-participatory approach in the buildings application.

2.2.1 User-participatory approach in buildings

A trend of cross-disciplinary research on occupant-building relations has emerged in recent years. Jazizadeh et. al. [54] introduced the human-building interaction framework that targeted to enhance comfort of occupants while reserving energy consumption. However, the main challenge was translating the subjective preferences of users into the context of quantitative control systems. In this regard, Gao et. al. [44] [45] presented the design of an intermediary platform between humans and system, and compared different models in optimizing the setpoint temperature and energy conservation. Following the direction of work, there are end-user participatory applications adopted [67] [55] [48] [38] [54], where mobile devices like smartphones are used to acquire occupants' thermal preferences along with the sensors data collected in buildings. This thesis adopts this direction of work to collect the users' feedback for modeling the levels of comfort. Details are discussed in Chapter 4.

CHAPTER 3

WIRELESS SENSOR NETWORK IN BUILDING APPLICATIONS

3.1 Overview

A BMS is the spinal cord of a building that responsible for the monitoring and controlling of several systems [48], including the lighting system, the heating, ventilating and air-conditioning (HVAC) system, fire and alarm system, escalators and lifts services. With the increasing concerns of safety and comfort to the people in buildings, the level of automation has risen steadily over the past years and in the midst of revolutionary change in terms of technology and extent of system control.

A typical architecture of BMS is shown in Figure 3.1; the components required to process the controls and functions in automated systems are hierarchically organized [75]. The controls and computation are managed by the direct digital controls (DDC). Right next to the DDCs are the sensors for recording system status of BMS. These include temperature sensors, flow meters, control valve status, smoking sensors, motion detectors etc. The DDCs are normally mounted into a control cabinet at the room with the equipment that under control. The edge DDC is connected to the Ethernet and relays the information received from DDCs underneath to the network.

A BMS workstation is installed into a building to provide real-time status and overview picture of BMS. Facility management operators can thus directly interact and control the BMS via the workstation. The close proximity of the control cabinet to the BMS workstation reduces the amount of cabling required. In a typical commercial building, it is approximately 1.2 km of cable [75].

A typical BMS is centralized control with distributed network controllers, it can be basically divided into three essential levels, i.e., the *equipment* level, the *controllers* level and the *network* level. To harness the operation data of the BMS, some buildings adopt two additional levels, i.e., the data processing level and the analysis level as shown in the workflow diagram in Figure 3.2.

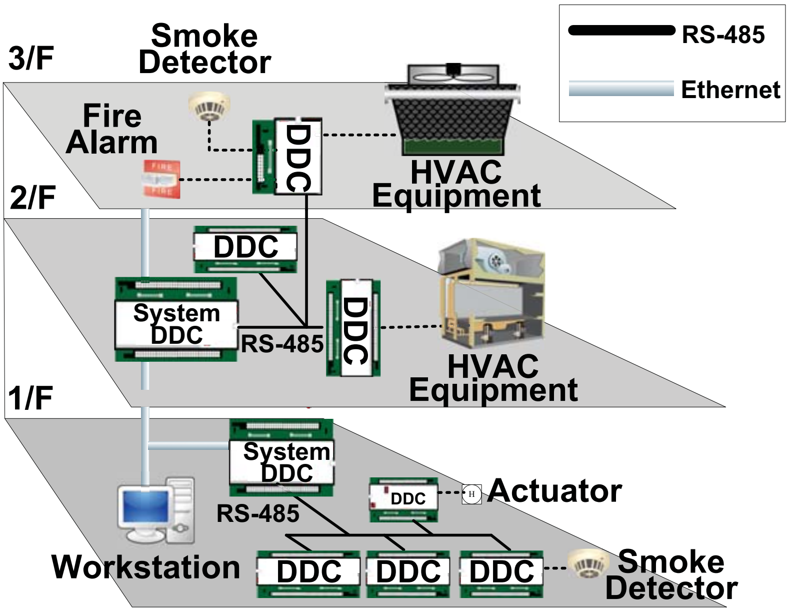


Figure 3.1: A typical BMS architecture

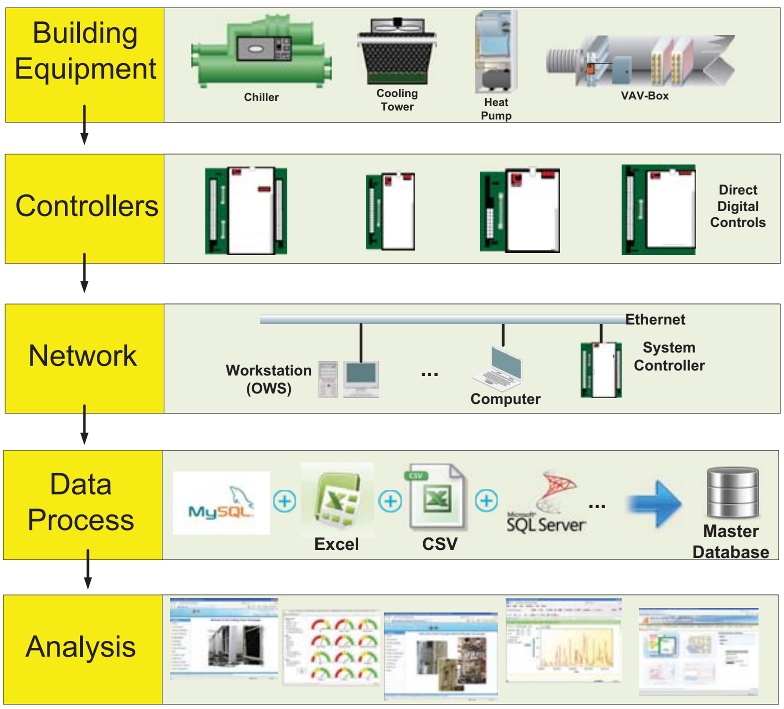


Figure 3.2: Workflow of BMS

3.2 Design for Wireless BMS

Conventional BMS has been developed for ages and has a comprehensive suite of standard protocols for various systems to communicate with each other at different levels. Building Automation and Control Networks (BACnet) [10] is one of the most common protocols today. It clearly defines the communication approach and algorithm between systems of building (e.g., lighting, air-conditioning system and pumping systems), the Direct Digital Controls (DDCs, i.e., the data "relays") and the workstation computer for facility operation.

With the increasing concerns to the indoor environment, there has been a great interest to develop smart and wireless (or partially wireless) BMS systems. Substantial costs can also be saved from wiring and cabling, and the time and labors involved for maintenance [47]. A wireless system can save the labors and materials cost as high as 30% [3] and provide a higher flexibility for installation. Besides, it also helps extend sensors coverage that is unapproachable under wired system [83].

Different wireless applications for buildings have been proposed. For example, the energy auditing and metering systems using wireless sensor networks [57] [30]; occupancy detection systems [76] [14] [71] for energy-saving measures, and occupant-participatory approach has also been proposed to enhance the thermal comfort of people in buildings [48] [67]. Besides these systems that support various services, there are also studies to integrate building services [56]. A comprehensive representative is the building operating system services (BOSS) [29], which has re-architected the existing layers of BMS. In building services industry, many off-the-shelf hardware components that support wireless communications are available (e.g., ZigBee, CAN2GO [3], Daintree Networks [12]); however, these products only perform wireless communications at the edge sensing devices, i.e., the connection between the sensors and controllers.

While these systems provide advanced features, they are either developed for specific purposes, e.g., short-term study and measurement, and run as an *ad-hoc* supporting system, or they are holistic solutions making nontrivial changes to the existing BMS that may take time to become a standard for being adopted and deployed. On the other hand, there is a need of systems in buildings that can 1) gradually replace some parts of the existing wired BMS into wireless (e.g., building retrofit), 2) temporarily adding building devices into existing BMS upon certain events, and the system can be restored afterwards (e.g., indoor air quality measurement), or 3) integrate the newly developed applications (e.g., temperature control using smartphone [48] [67]) with existing BMS when needed.

A common feature of these wireless systems is that it is able to work with the existing BMS, i.e., the wireless system that can support current protocols which originally designed for wired systems. This thesis focuses on this area and presents a design of a wireless sensing system that can convert the underlying wired system of buildings into smart and wireless without changing the upper-layer communication protocols.

From the experiment, a straightforward replacement of wired system into wireless by using wireless modules upon the communication port are impossible due to two unique challenges: 1) one has to maintain the control plane of the upper layer protocols in operation. Unfortunately, it is shown that this cannot be realized due to the time constraint of protocols that are difficult to meet using wireless links. Moreover, such constraints cannot be achieved by simply increasing the bandwidth of the wireless communication; and 2) the throughput and quality variations in wireless communications are worse than that of wired system. The data plane of the upper layer protocols has to be maintained while satisfying the default protocol requirements.

3.2.1 Development of BMS communication program BACChat

In this thesis, the communications between the proposed designs and BMS are indispensable. Hence, a program package with graphical user interface (GUI) *BACChat* is developed as shown in Figure 3.3 to enable the reading and control properties of a BMS. Though the communication protocol BACnet is an open standard, the client-side soft-

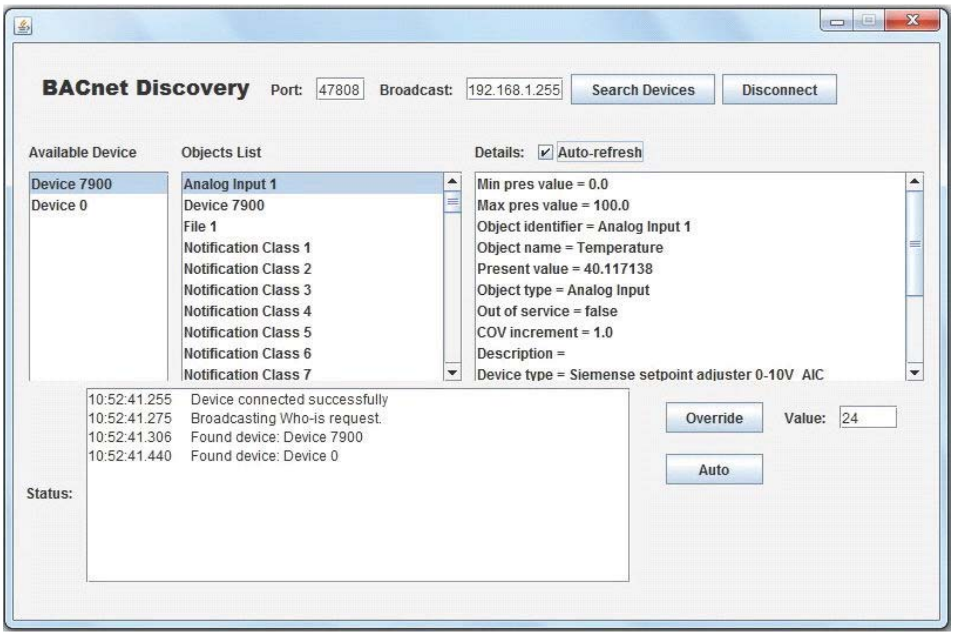


Figure 3.3: BACChat program for BMS communication

ware is mainly developed by the industrial vendors (e.g., Johnson Controls, Siemens and Honeywell), and it lacks the flexibility to control and monitor the data streamed from the DDCs directly.

BACChat can read the real-time status and values of the BMS, e.g., the room temperature sensor of a specific room, while it is also able to command and override the current setting of equipment configuration. Once BACChat is connected to the network, it broadcasts the BACnet service *Who-Is* to the network. When other BACnet-compliant controllers hear the *Who-Is* service, they will reply with their object ID and list the services they support.

All the devices found by the BACChat will be listed in the device list and the response time will be shown in the status box. Users can further read the objects list of the chosen device and select the requested point and thus obtaining the live readings.

BACChat is written in JAVA and the package is being used throughout this thesis to help execute the corresponding communication with the BMS. Besides the BACnet devices discovery and property readings, it is also able to override the current setting of the DDCs. For example, configure the setpoint temperature of a room. This function is especially useful for research purposes.

BACChat is released as open-source and available in [96].

3.3 An asynchronous-response framework for wireless BMS

3.3.1 Design Objectives

In this chapter, a novel *asynchronous-response* scheme is proposed to realize the dewiring design from a wired BMS into wireless. The term "asynchronous" refers to the approach in data exchange during the communication process between two stations or machines, where the request from one station is sent to another without interfering and interrupting its existing connection to current network. An application example is the AJAX (asynchronous JavaScript and XML) technology used in HTTP communication between the client and server. To the best of the author's knowledge, this thesis is the first to adopt the asynchronous-response approach to a BMS.

In this chapter, it is shown that the proposed design is able to maintain the control plane of the upper layer protocols intact, and it can achieve the same functionality of the control plane to that of the wired scheme. A modular design for wireless data plane is used to selectively prioritize and schedule data transmission in case of link quality and throughput variations. The critical frames are first identified and sent with a higher priority. For the majority regular monitoring frames, an online algorithm is developed for a transmission sequence that maximizes the throughput while maintaining system application fairness.

The scheme is evaluated through 1) experiments using real DDCs, which connected with smart sensors under real operating BMS. The experiments proved the effectiveness of the proposed asynchronous-response scheme; 2) a comprehensive simulations to show the scalability of the algorithms; and 3) a field deployment of the system, integrated into the existing BMS of a University, and it was tested and operated successfully during the 5-hour deployment.

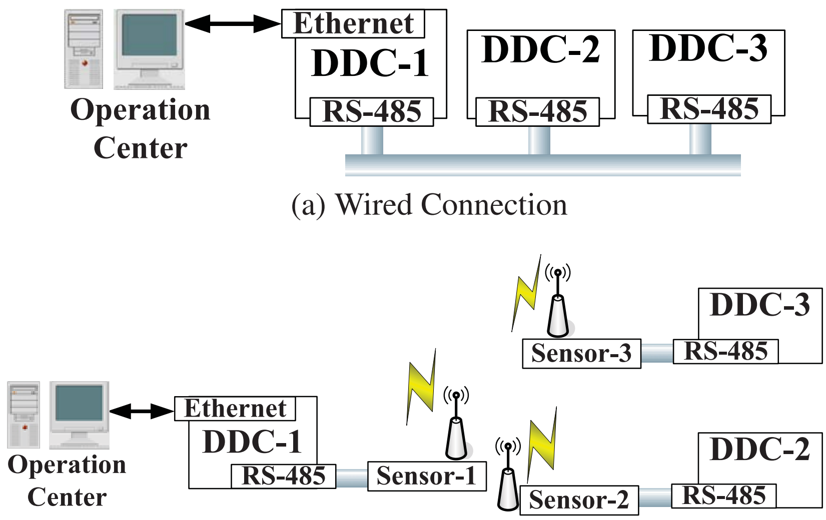
The remaining parts of this chapter proceed as follows. In Section 3.3.2, the BMS background and taxonomy used in this thesis are discussed. An overview to the design is discussed in Section 3.4, the design details on the asynchronous-response module and the wireless data transmission modules are discussed in Section 3.5. The implementation details, which are imperative for effective system operations are presented in Section 3.6. The evaluation to the proposed system is carried out in Section 3.7 with simulations. The real-world deployment is shown in Section 3.8.

3.3.2 Background of BMS

A BMS is responsible to control and monitor the mechanical and electrical equipment of a building as shown in Figure 3.1, which the physical signals are measured by sensing devices. These sensing devices are passive sensors (e.g., smoke detectors). To make the presentation clear, the passive sensors in BMS are named as *sensing devices*, and the active smart sensors that have the ability of processing, storage and communication are named as *sensors* in this thesis.

The sensing devices are connected to *controllers* known as Direct Digital Controllers (DDC), which form the hardware backbone of BMS. There are two types of DDCs: system DDCs and field DDCs. System DDC is usually more powerful in terms of computing and processing capacities, and it relays the data from field DDCs in lower layers to the Ethernet. The connections between DDCs are using RS-485, which is a common industrial standard. On top of RS-485 connection, the protocol used for DDC communications is MS/TP (Master Slave/Token Passing), and each DDC within the network has two defined roles, either *master* or *slave*. A token is passed in the network and a DDC can only send request or command frames when it holds the token. MS/TP is stipulated in BACnet, which is the most dominant communication protocol in BMS nowadays [10]. Building equipment and sensing devices from different manufacturers can thus communicate with each other using BACnet.

In a typical BMS, several parts are wire-connected. Firstly, the edge controllers that con-



(a) Wired Connection

(b) Wireless Connection

Figure 3.4: Converting wired connection to wireless

nect to the network is using Ethernet and is thus wire-connected. However, the Internet connection is usually well-planned in advance during building construction and requires less flexibility and effort to become wireless. Secondly, the DDCs and the sensing devices are also wired. There are different kinds of sensing devices (e.g., motion sensors and temperature sensors); they are passive and the connection is point-to-point. Besides, converting this part into wireless is vendor-specific and these sensors can be replaced by smart sensors easily.

Thirdly, the connection between DDCs are also wired. In actual application, the distance between DDCs can be long (across floors as shown in Figure 3.1), and therefore, converting this part into wireless has many advantages in terms of cost and flexibility. Yet, it also faces non-trivial challenges. This part is the focus of this chapter.

3.4 An Overview of the Design

Figure 3.4(a) illustrates the original wired connection of DDCs, and Figure 3.4(b) shows the design in replacing the wired connections between controllers with wireless sensors. Noted that there is no modifications and additional configurations required to the existing DDCs.

As shown in Figure 3.4(b), the communication links between DDCs are via the connected smart sensors using RS-485. The experiment proved that a straightforward replacement of wired connection using smart sensors does not work. First, of each frame sent by a DDC, there is a tight time constraint, i.e., if the frame is not received (or response) before the time-out requirement, it is considered expired. In MS/TP protocol of BMS, it is 10-bit propagation-time of RS-485 communication. While such delay can be easily satisfied under a wired connection, in wireless links such as 802.15.4 or 802.11, the processing and propagation delay make it impossible to meet such delay (1500-bit time delay was measured in the experiment). Moreover, such delay cannot be improved by increasing bandwidth. This introduces difficulty in maintaining the control plane of the upper layer MS/TP protocol. Second, the transmission of wireless is slower and less stable than a wired network. Thus, the data throughput may temporarily exceed the wireless link capacity. This affects the data plane.

In this chapter of thesis, a novel asynchronous-response scheme is proposed. A sensor communicates with the DDC it connected to (or call attached) based on the MS/TP protocol. The communication method is shown using the example of DDC-1 and DDC-2 of Figure 3.5. When DDC-1 sends a frame (refer to Figure 3.4), sensor-1 relays the frame to Sensor-2 instantly using the wireless adaptor.

In the meantime, to fulfill the MS/TP time constraint of frame response, Sensor-1 will send a frame to DDC-1 concurrently so as to maintain the connection before the response timeouts. The response is *asynchronous* to the request sent to Sensor-2. Sensor-2 relays the request to DDC-2 that originated from Sensor-1 and replies Sensor-1 when it has received the response frames from DDC-2.

A wireless BMS framework is developed using a modular design as shown in Figure 3.6. The asynchronous-response module reads frames from RS-485 and processes the control frames. It passes all the outgoing frames to the wireless transmission modules for further process/transmission.

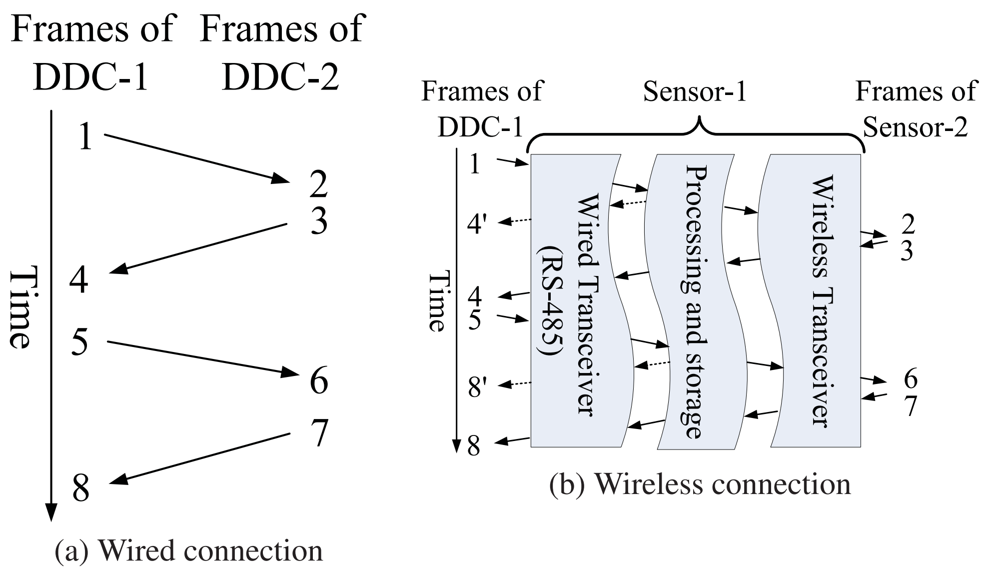


Figure 3.5: Timing sequence of asynchronous response

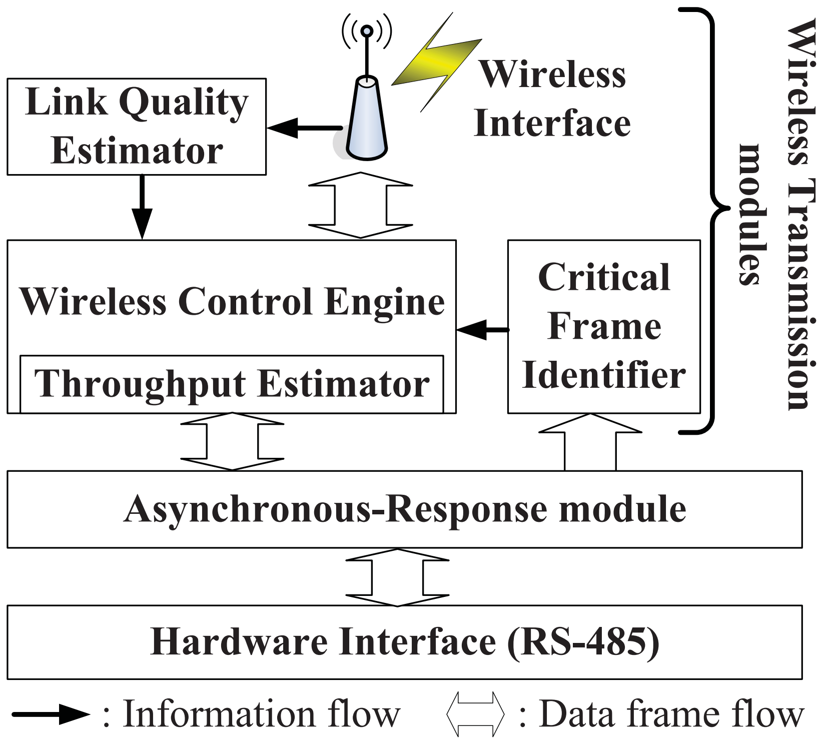


Figure 3.6: A modular framework

In application, the network traffic of wireless link may exceed its capacity, hence it has to schedule the data frames and ensure the application requirements are met (e.g., timely update to the readings of the sensing devices). A set of wireless transmission modules are thus designed as follows.

- **Link quality estimator module**: to monitor the wireless communication quality, i.e., when the wireless link quality experiences deterioration, frames will be retransmitted.

- **Critical frame identification module**: to identify critical alarms from both the traffic pattern and application frames and assign a higher priority for critical events such as fire alarms from BMS sensors.

- **Wireless control engine**: to monitor the data traffic of other modules and process data scheduling and transmission assisted by throughput estimator.

The current design omits a routing module, which is important if the communication range is long and relays are needed. In this part, the focus is on the main challenge to remain the upper layer protocols intact, and the routing module will be left for future work.

3.5 Design Details

3.5.1 The Asynchronous-Response Module

The details of the MS/TP protocol are as follows. The frame format is shown in Figure 3.7. In the original design, each DDC has an unique address; and hence in the design, each sensor is assigned an address that associated with the DDC.

There are eight defined frame types in MS/TP and grouped into two categories, i.e., the 1) link or system maintenance frames; and 2) data transmission frames. For the sake of conciseness, the following items only highlights some of the important frames with its type id.

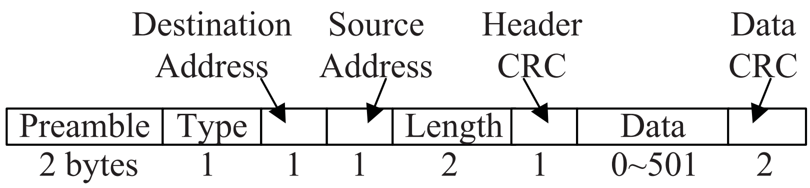


Figure 3.7: MS/TP frame format

- **00 Token** (link maintenance): is used to pass the network mastership to the destination node as only the token holder can send data. *In the proposed design*, when Sensor-1 receives *00 Token* from DDC-1, it first checks if there are valid data frames asynchronously received and stored. If yes, it sends these data frames to DDC-1. Sensor-1 returns *00 Token* to DDC-1 after it sends all the data.

- **02 Reply to Poll For Master** (link maintenance): is used to reply the *Poll For Master* frame and inform the network that this node wishes to enter the token ring. When a DDC (e.g., DDC-1) sends *01 Poll For Master* to its successor node (e.g., DDC-2), it will reply *02 Reply to Poll For Master* if it exists. DDC-2 can continue this process to check its successor node. *In the proposed design*, Sensor-1 will periodically send *01 Poll For Master* to its successor Sensor-2 asynchronously; and when Sensor-2 receives this command, it will send to DDC-2 to check its livelihood. When sensor-1 receives command *01 Poll For Master* from DDC-1, it replies *02 Reply to Poll For Master* directly if it has received the reply in previous round.

- **05 BACnet Data Expecting Reply** (data transmission): is used by master nodes to convey the data frame which expects reply.

- **06 BACnet Data Not Expecting Reply** (data transmission): is used by master nodes to convey a data frame that does not expect reply.

These two frame types are used for data transmission. *In the proposed design*, Sensor-1 sends *07 Reply Postponed* to DDC-1 when it receives *05 BACnet Data Expecting Reply*. In the meantime, it relays this command to the sensor according to the destination address in the frame. When a sensor receives *06 BACnet Data Not Expecting Reply* it relays this command to the sensor according to the destination address in the frame.

- **07 Reply Postponed** (data transmission): This command is used by master node to defer sending a reply to a previously received *05 BACnet Data Expecting Reply* command. *In the proposed design*, when Sensor-1 queries Sensor-2 and Sensor-2 queries DDC-2, Sensor-2 can receive *07 Reply Postponed* when the data of DDC-2 is not ready (For example, DDC-2 does not get data from its associated sensing devices, e.g., a temperature sensor). A tricky part here is that Sensor-2 will *not* send *07 Reply Postponed* to Sensor-1 as it knows that Sensor-1 has already asynchronously sent a it to DDC-1. Sensor-2 will also pass the token to DDC-2 by sending *00 Token*; otherwise, DDC-2 does not have the right to send data. In case DDC-2 is not ready, DDC-2 will pass the token back to Sensor-2 (see previous explanation on the token). The token passing continues between Sensor-2 and DDC-2 until the data are ready.

In Section 3.5.1, the analysis shows that the wireless asynchronous-response module achieves the same functionality to a wired system under the MS/TP protocol. The e-valuation in Section 3.7 and 3.8 also showed that the asynchronous response module successfully supports system operation. In the followings, the asynchronous-response module is shown that it can be operated resemble to a wired system.

Among the time-out constraints of a MS/TP network, the following two constraints may be affected after adopting the asynchronous-response module:

1. T_{reply_delay} : The maximum time a node can wait after receiving a frame that expects a reply before sending the first octet of the reply or Reply Postponed frame: 250 milliseconds.

2. $T_{reply\_timeout}$: The minimum time without a *Data Available* or *Receive Error* event that a node must wait for a station to begin replying to a confirmed request: 255

milliseconds.

To the first constraint T_{reply_delay}, the *asynchronous-response* module replies a *Reply Postponed* frame immediately to the network, and so it is able to fulfill this timing requirement easily. To the second constraint, assume there is k-hop distance between the source and destination devices, the delay time of routing the frame is $T_{routing}$, the response time of the wireless MS/TP device is $T_{target\_response}$ and the propagation time of each hop is $T_{wireless\_propogation}$.

The reply time T_{reply} of data frame can be calculated as follows:

$$\begin{aligned} T_{reply} = T_{target\_response} + 2 \times (k-1) \times T_{routing} \\ +(2 \times (k-1) + 2) \times T_{wireless\_propogation} \end{aligned} \tag{3.1}$$

If $T_{reply} < T_{reply\_timeout}$, it means that the current T_{reply} meets the second timing constraint.

The theoretical transmission rate of ZigBee is 250kbps, and the maximum frame length of MS/TP is 509 bytes, the receiving and transmission time of one MS/TP frame is thus less than 16ms. The propagation rate of wireless is about 3×10^8m/s, and the distance between two wireless MS/TP device is less than 300m as specified by standard, thus the propagation time of frame is about 0.001ms. As shown in timing constraint 1, the $T_{target_response} < 250$ms, hence the second timing constraint can be fulfilled easily. The k-hop can be calculated as follows:

$$\begin{aligned} T_{reply} < T_{reply\_timeout}, \text{ where } k < (T_{reply\_timeout} + \\ 2 \times T_{routing})/2 \times (T_{routing} + T_{wireless\_propogation}) \end{aligned} \tag{3.2}$$

In other words, if the parameters are able to meet the constraints as mentioned above, the wireless asynchronous-response is able to work alike to the conventional wired M-S/TP system. The evaluation in Section 3.7, 3.8 also shows that the asynchronous-response module successfully supports the control plane and system operation of the buildings.

Besides the non-intrusive asynchronous-response approach, other alternatives may be used to maintain the connection of controllers. The controller may release the time-out constraint and keep the token on-hand until the feedback is received; however, this intrusive approach will violate the requirement of keeping the controllers protocol intact. Moreover, the modification of timeout constraint will affect the controllers of the whole network, which the design can hardly become revertible for temporary adoption purpose.

3.5.2 The Wireless Transmission Modules

A wireless link is assumed to work slower and less stable than a wired link. Noted that the network traffic of BMS, especially the averaged data traffic is moderate and steady. This is the key factor that determine the design to be successful. From the experiment, it is observed that the network traffic of BMS is manageable by the wireless capacity.

For link quality variations, the data scheduling and priority approaches are adopted to achieve successful data transmission. In short, the network traffic of BMS can be classified into two categories: 1) data traffic for regular monitoring of the sensing devices; and 2) data traffic for emergency report. The wireless transmission module is presented and shown how these traffic are supported.

Critical Frame Identification

There are emergent events in BMS. More specifically, BMS receives emergent messages from the DDC when a certain pre-defined situation occurs, e.g., room temperature is above 140°F (60°C). When such emergency happens, the corresponding DDC uses critical frames to report the workstation computer. The critical frame identification algorithm (CFI) is developed to identify these reports and assigned a higher priority to the critical frame during transmission.

There are two CFI methods to identify the critical frames: 1) reading directly from the frame of data fields; and 2) using frame pattern recognition.

Specific Data Fields: In the MS/TP frame, there is a "service choice field". For critical events, this field will be labelled with 1, 2 or 3, meaning security events, critical events or fire events respectively. By reading this field, it can trivially identify critical frames; however, it violates the framework layering since it requires reading the content directly.

Pattern Recognition: In some applications, the data field of the frame may be encrypted and thus non-readable, hence, the critical frames can be identified using the pattern recognition approach. Since the data frame pattern in BMS is stable, an example is shown in Figure 3.8. The size of critical frames is obviously different from other regular frames. This is reasonable as the traffic in BMS is regulated routinely to specific building with regular monitoring procedures and intervals. The pattern recognition scheme is discussed as follows.

The frame length is used as the parameter to differentiate critical frames from regular frames. Since the data pattern of frame varies with buildings, a controlled training process is needed in advance. During this period, the system needs to be run for a period of time where no critical events exist, and all the regular frames length are being recorded. After that, whenever the frame length is different from the training set, it will be treated as critical frame. The experiment in section 3.7.2 showed that both two CFI methods are able to achieve 100% accuracy.

Link Quality Estimation

Wireless link management has long been a research topic. As far as token passing protocol is concerned, there is no serious interferences and collisions. Yet, there is still link quality deterioration. Numerous methods can detect link quality change. Based on hardware, there are RSSI [91], LQI [93] and SNR [40] where in software, there are PRR [89], RNP [23], ETX [31] and ETF [88].

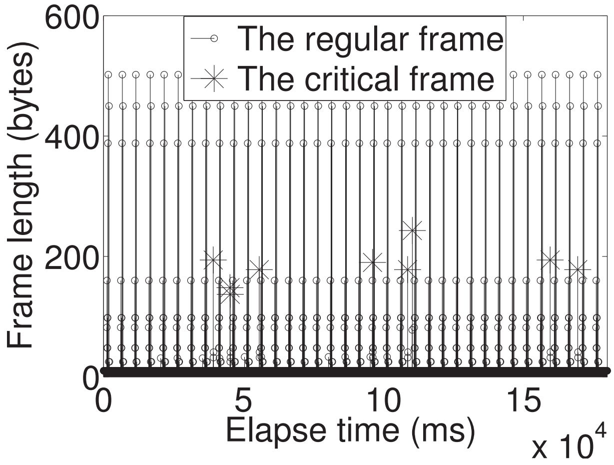


Figure 3.8: Critical frame identification

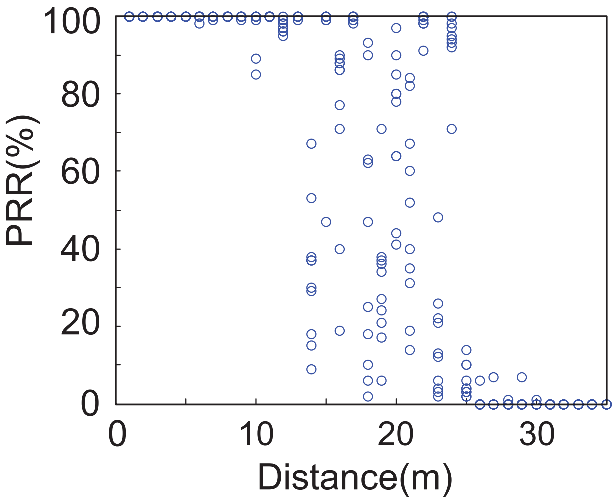


Figure 3.9: PPR and distance correlation

The design requires a lightweight scheme since the CPUs of sensors are loaded with many tasks and their processing capacities are not robust to handle complicated schemes. In this thesis, the expected number of transmissions over forward links (ETF) is chosen for link quality measurement as this module suits the proposed framework and provides accurate index to the wireless control module. Moreover, ETF does not require additional hardware and complicated computation. It can be calculated by the packet reception ratio (PPR) of a forward link d_f [88], where $ETF = 1/d_f$.

An indoor test is conducted and the result of the correlation between PPR and distance is shown in Figure 3.9. To handle the link quality deterioration, retransmissions of frames are allocated; and the number of retransmissions is determined as follows.

Let r be the number of retransmissions and $\mathcal{L}$ be the ETF. The ETF can be estimated mainly from the asynchronous broadcast beacons. It is unlikely to have dramatic change as the link distance is normally fixed in application.

To compute an expected frame success rate Δ, we have

$$1 - (1/\mathcal{L})^r \geq \Delta \Rightarrow r \leq log_{1/\mathcal{L}}(1 - \Delta) \tag{3.3}$$

A threshold $\mathcal{R}$ is put on r. If $r > \mathcal{R}$, the sensor indicates that the link is broken and cannot send any data into the link. The workstation computer is thus unable to get any data frames from this DDC, and a disconnected icon will be shown in workstation software [4]. A threshold is used to prevent sensors from overloaded with retransmissions.

Noted that the proposed scheme handles link variations and provides information to the wireless control module if the selective data transmission is needed. There may have interferences from other systems of BMS or equipment that using the same wireless spectrum, especially in times of serious wireless link deterioration; however, these discussions are out of the scope of this thesis.

Wireless Control Engine

A BMS receives regular updates from the the sensing devices of DDCs, e.g., every 10 seconds. The wireless control engine has a throughput estimator sub-module which monitors the traffic intensity from the application layer. If the data traffic is less than the residual wireless capacity, all frames will be transmitted.

Considered when the data input from RS-485 is greater than the output of wireless link, let V_{in} be the data input speed and V_{out} be the data output speed. The details on computing V_{in} and V_{out} are discussed in Section 3.6.2. Since $V_{in} > V_{out}$, part of the frames will be selectively transmitted while others will be dropped. From the application point of view, it is acceptable to increase the update interval of the sensing devices, e.g., from 10 to 2 seconds; however, two specific requirements have to be achieved:

1. *fairness:* all the sensing devices should be able to increase equally; and

2. *importance:* it should be able to achieve the closer interval by allowing to compensate a longer interval from the others. It is a common design from the perspective of security and safety purposes for some highly secured areas of building.

The fairness requirement is firstly discussed. In a typical BMS, each DDC connects to tens or even hundreds of sensing devices. The readings of multiple sensing devices can be combined into one single data frame. Since the polling rate from workstation to DDC is generally fixed, the data frame is thus also steady to the frame size. As such, the fairness among sensing devices can thus be guaranteed.

The transmission of frames can be divided into *cycles*. Each data frame is assigned with a serial number in each cycle and their frame lengthes are different (refer to Figure 3.10 (a)). Under the wired network, each cycle transmits in the same sequence, e.g., in Figure 3.10 (a), each cycle transmits 10 frames with same orders; however, under the wireless network, each cycle may not have enough capacity, and thus it has to fully utilize the transmission capacity in each cycle and each frame generally has equal interval of cycles. For example, in Figure 3.10 (b), the whole data frame are divided into 10 frames with an interval of about 2 cycles shown in the transmission schedule.

The transmission schedule of frames is discussed as follows.

Let $F_i, i \in \{0, \cdots, N-1\}$ be the frames where N denote the total number of frames, and $l_i \in \{0, \cdots, N-1\}$ be the length of frame F_i, L_C be the maximum bytes that a cycle can send in wireless communication, $\mathcal{P}$ be an arbitrary period consists of $\mathcal{C}$ cycles and L_k be the total amount of bytes transmitted in cycle k. Let $L_m = \sum_{k \in \mathcal{C}} L_k$, T_i be the total number of times F_i is transmitted in $\mathcal{P}$, $\mathcal{T}$ be the pre-defined threshold to bound

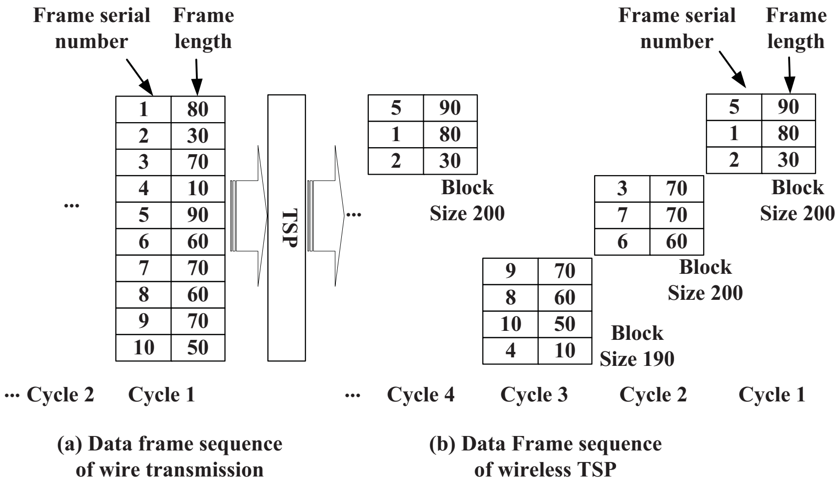


Figure 3.10: Data frame transmission

the difference of T_i, $\forall i, j, |T_i - T_j|$, i.e., the fairness.

Definition 1. *The Transmission Sequence Problem (TSP): Find a transmission sequence for F_i, $i \in \{0, \cdots, N-1\}$ in any arbitrary period $\mathcal{P}$ that can be divided into $\mathcal{C}$ cycles, such that the total transmission $L_m = \sum_{k \in \mathcal{C}} L_k$ is maximized and the difference of the frames F_i transmitted is bounded by $\mathcal{T}$.*

Theorem 1. *TSP is NP-hard.*

Proof. The TSP is reduced to the bin packing problem as follows, which is proven to be NP-hard. The bin-packing problem is defined as: given a bin size V, and a list of $a_1, a_2, ..., a_n$ of items to pack, find an integer B, and B partitions of $S_i \subseteq \{1, 2, \cdots, N\}$, where $\sum_{i \in S_k} a_i \leq V(k = 1, 2, \cdots, B)$, find the minimal of B.

For each instance of the bin packing problem, an instance of transmission sequence problem is constructed as follows.

For each bin size V, creates $L_C = V$; for each item size a_i, creates frame length $l_i = a_i$. Let $\mathcal{T} = 0$, this indicates that each frame can only show up equally. This is the key of the proof as now it only needs to consider the approach to transmit N different frames in a minimum number of cycles. Let $\mathcal{P}$ be the period of the minimum number of cycles that transmit N frames.[1] Clearly, to find the minimum $\mathcal{C}$ is the same as to find a minimized

[1]To be more rigid, this should be transformed into a decision problem where given $\mathcal{P} = i$, determine

B. This means that if TSP is solved, the bin-packing problem is solved. □

An online algorithm for TSP is needed. In this chapter, the offline algorithm will first be developed, and it will then be extended to online version afterwards. The offline algorithm adopted follows the First Fit Decreasing (FFD) algorithm that used in bin-packing problem [60]. The principle of FFD algorithm is to firstly sort all the items into descending order, and then use a greedy method to put the items into bins. The proposed algorithm in this thesis follows the same rationale by first putting large frames into cycles. In each round of iteration, it checks the number of times a frame transmitted so that $\mathcal{T}$ is never violated. The online algorithm also applies the offline algorithm for each cycle, which is shown in Algorithm 1.

The requirement of fairness is per DDC-based. In application, there may have priority requirement for important zones of building and thus require a short interval of updates. A longer timeout can be provided to DDCs with such requirement so that it can send more data in each cycle. More specifically, let $\mathcal{N}$ be the number of DDCs, and $p_i, i \in \{1, \mathcal{N}\}, p_i > 0$ denotes the priority of the i-th DDC. The lower the priority is, the longer timeout the DDC has. Assume t_r is the update interval, and timeout u_i of the ith DDC is set to $u_i = \frac{(1/p_i)\times t_r}{\sum_{j=1}^{\mathcal{N}} 1/p_j}$.

Algorithm 1 $TSP()$

Input: $F_i, l_i, L_C, \mathcal{T}$
Output: $\text{Bin}_k, L_k, k \in N$

```
1:  T = {T_1, T_2, ..., T_i, ..., T_N} = {0}
2:  k = 0, Bin_k = ∅, L_k = 0,
3:  l' = sort(l) = {l_q, ..., l_i, ..., l_p}
4:  F' = {F_q, ..., F_i, ..., F_p}, T' = {T_q, ..., T_i, ..., T_p}
5:  for (i = 1 to N) do
6:      for (k = 1 to N) do
7:          if (L_k + l'_i ≤ L_C) and (T'_i − T'_min < 𝒯) then
8:              Bin_k = Bin_k ⋃ F'_i, L_k = L_k + l'_i, T'_i = T'_i + 1
9:              break
10: return(Bin_k, L_k)
```

whether N frames can be transmitted. This is taken for granted for the sake of conciseness.

Lemma 1. *The complexity of algorithm TSP() is O(N^2).*

Proof. The complexity of the quick sort subroutine is O($N \log(N)$) and the complexity of nested loop structure is O(N^2). Consequently, the complexity of TSP() is O(N^2). □

3.6 Implementation Details

3.6.1 Fast Forward of Frame Transmission

In this thesis, the smart sensor Arduino with the I/O Expansion shield is chosen [5], which can directly support RS-485 communication to read the MS/TP frames and process the data frames of DDCs in wireless. The difference between the speed of wireless interface (which is slow) and CPU (which is fast) is huge and causes the CPU of Arduino cannot process the MS/TP frame within the timeout constraint. As a result, the Arduino becomes unstable and sometimes malfunction if the data transmission is handled frame-by-frame. Noted this is typical to smart sensors and not only to the Arduino.

To solve this problem, the *fast forward strategy for frame transmission* is proposed. More specifically, instead of sending the data frame-by-frame, the CPU is managed to send the data byte-by-byte to the wireless interface. Since the CPU processing time is much faster than the wireless interface, the time interval between each byte is negligible. From the data transmission point of view, its neighboring sensors are still able to read the data in frame-based. With the design of fast forward frame transmission, the data communication between the smart sensors and also DDCs can thus be carried out.

3.6.2 A Wireless Token Ring Network

In the contemporary wired BMS, the DDCs are physically connected in daisy-chain topology. When a DDC broadcasts a frame, other DDCs at same network will receive the frame. In converting to wireless, it is important to ensure that each of the DDCs is still able to listen to others and capable to handle interferences and collisions. The

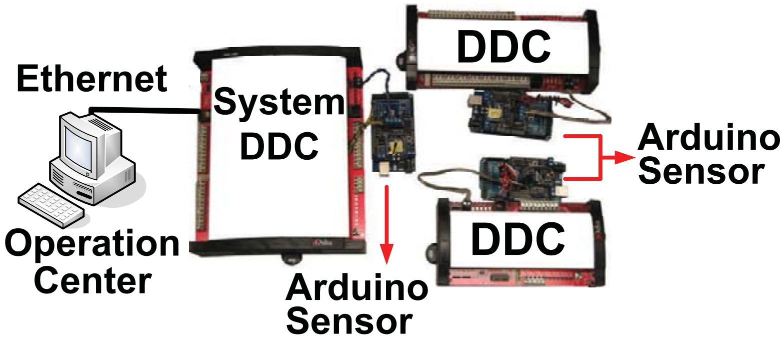


Figure 3.11: The experiment set up

approach of unicasting between sensors by using a wireless token ring is adopted in this design. A sensor can send data only when it obtains the token. Noted that this token ring should not be confused with the token passing protocol used in MS/TP of BMS among the DDCs.

The implementation of computing V_{in} and V_{out} are described in Section 3.5.2. V_{out} is computed by the wireless interface speed multiplied with a piece of token time in this wireless token ring network. V_{in} is computed by the total amount of data frames in a

3.7 Performance Evaluation

cycle divided by the cycle length time.

The proposed system has been evaluated by experiments, simulations, and real-world deployment. The experiments evaluated system functions that are difficult to simulate, e.g., the asynchronous-response module and also the system performance under real environment. The simulation shows the scalability and details of the algorithms, e.g., the wireless control engine. A field deployment of the proposed system was conducted on campus.

3.7.1 Experiment Setup

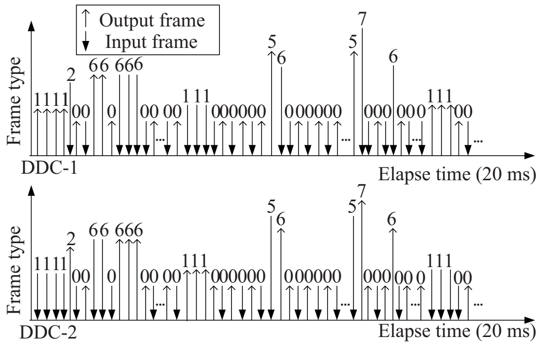
The hardware used in the experiment are shown in Figure 3.11. There were three DDCs from Delta Controls [4], of which one was a system DDC and others were field DDCs. Each DDC was connected with the Arduino Mega 2560 sensor using RS-485 as discussed in Section 3.6. The wireless module adopted was XBee [5], which used IEEE 802.15.4 wireless communication. A PC was installed with the BMS software ORCAview 3.33 [4], which could monitor and control the DDCs under the same network. The system DDC connected to the workstation via Ethernet, and communicated with other DDCs using the MS/TP protocol.

The incoming and outgoing traffic in system DDCs were originated from ORCAview, and was used to simulate the data traffic of BMS in the experiment. Noted the DDC hardware and workstation software were all off-the-shelf products.

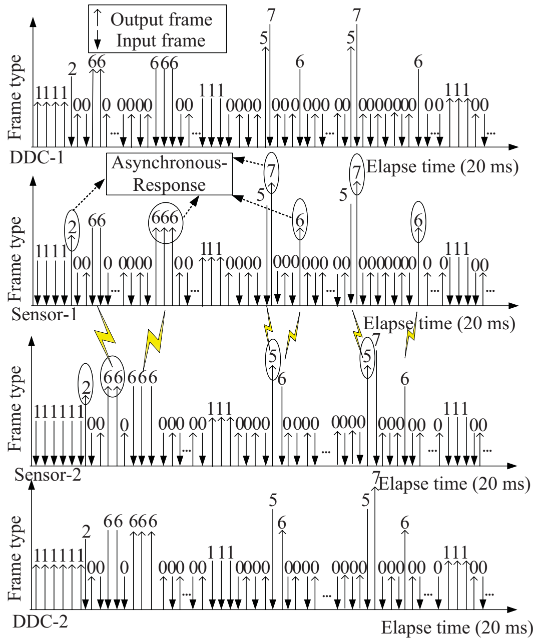
During the experiment, the PC and system DDC were placed at a fixed location, where the three DDCs were 10 meters apart from each other. The default transmission power was set to 0 dBm. The preliminary measurement upon the link quality with different distances was conducted ranging from 5 to 40 meters. One field DDC and system DDC were intended to put out of sight to each other. The result in Figure 3.9 showed that there was a sharp decrease in the packet reception rate near the distance of 25 meters. The detailed calculation is described in section 3.5.2.

3.7.2 Experiment Results

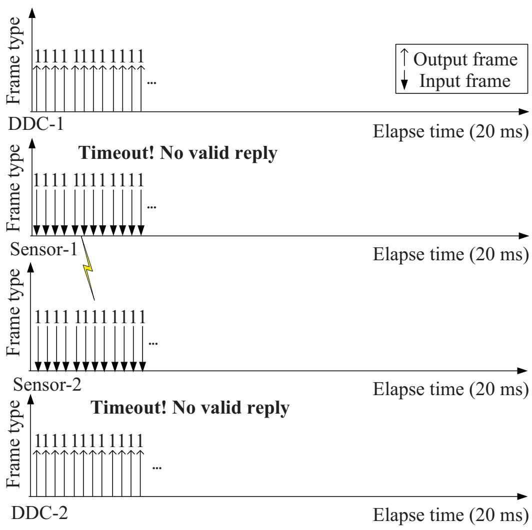
The experiment results of the asynchronous-response module are discussed in this section. Figure 3.12 shows: 1) command sequence of the original wired system, 2) command sequence of the wireless system after using the asynchronous-response, and 3) command sequence of the wireless system that without using asynchronous-response. To be fair, the three scenarios carried out the same operations. Each frame is represented by an arrow and the number on top of each arrow is the command type of the frame as



(a) The frame sequence of two DDCs



(b) The frame sequence of asynchronous-response framework



(c) The frame sequence of directly wireless replacement

Figure 3.12: The frame sequence of different system.

discussed in Section 3.5.

In Figure 3.12(a), the upper and lower part figures showed the command frames of DDC-1 and DDC-2 respectively. In general, it is observed that the communication begins with a few **01 Poll for Master**, followed by token **00 Token** acquisition. Then, data transmission frame of **06 BACnet Data Not Expecting Reply** begins and followed by token passing, poll for master and again data transmission with **05 BACnet Data Expecting Reply**.

The four figures in Figure 3.12(b) showed the commands of DDC-1, Sensor-1, Sensor-2 and DDC-2 respectively. The *asynchronous-response* frames are labelled with circles to the command type number. For example, when DDC-1 sends **01 Poll for Master**, Sensor-1 replies with **02 Reply Poll for Master** asynchronous and relays this command to DDC-2 (via Sensor-2). Also, Sensor-1 sends **07 Reply Postponed** to maintain the operation if it does not receive on time data reply from DDC-2 (via Sensor-2).

Figure 3.12(c) is used for comparison purpose that without using the asynchronous-response module. Obviously, the communication brokens soon after few commands transmission, which was due to the lack of valid reply before timeout.

The ratio between the number of asynchronous-response frames and MS/TP frames is shown in Table 3.1. It is shown that when the update rate of sensing device increases, the ratio drops. This is due to most of the asynchronous-response frames are used to support data frames.

The performance study of the system is discussed as follows. As the application data frames are originated from DDCs, it cannot be arbitrarily managed. As a result, the simulations to the unbalance of data transmission between the the wired and wireless modules by changing the baud rate of wireless transmission was carried out.

Figure 3.13 shows three different wireless throughputs under the update intervals of 15 seconds, 5 seconds and 1 second respectively. Noted that different update intervals

Table 3.1: Asynchronous-response ratio

Refresh time	5s	10s	30s	60s
AR ratio	2.5%	1.27%	0.64%	0.32%

represent different traffic intensities from the application layer, in which 1 second incurs the highest traffic volume. In Figure 3.13(a), the traffic throughput was 126.5 Kbits at all baud rates as the traffic intensity is small and thus the wireless module is able to transmit all the data frames.

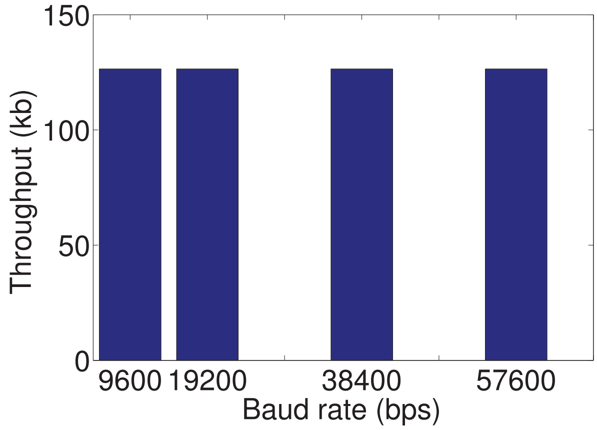
In Figure 3.13(b), when the baud rates were set to 38400 bps and 57600 bps, the throughput was remained at 126.5 Kbits. However, when the baud rate was decreased, the throughput also decreased obviously. This was due to the wireless control engine activated and frames were adjusted once the output capacity was less than the input traffic flow.

Besides, it is observed that the case of capacity almost used up when the baud rate was set to 19200 bps, only 95 Kbits was transmitted, which was the full capacity under 5-second update rate. This situation can be observed clearly in Figure 3.13(c) where the application layer traffic was the highest.

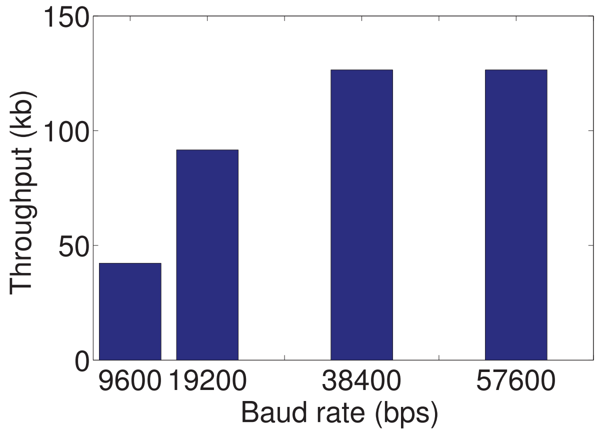
Figure 3.14 showed the actual wireless throughput rate (Kb/s) in corresponding to the absolute throughput (Kb) in Figure 3.13. When there was less data to transmit (Figure 3.14 (a)), the throughput rate was the same (84300bps) under any baud rates. The throughput rate increased while the amount of data increased, but it was bounded by the baud rates (Figure 3.14 (b)(c)).

The study of different link qualities are as follows. The proposed system performs retransmission under poor link conditions is discussed previously in Section 3.5.2. In Figure 3.15, it is observed that with the retransmission scheme, the PRR was improved significantly.

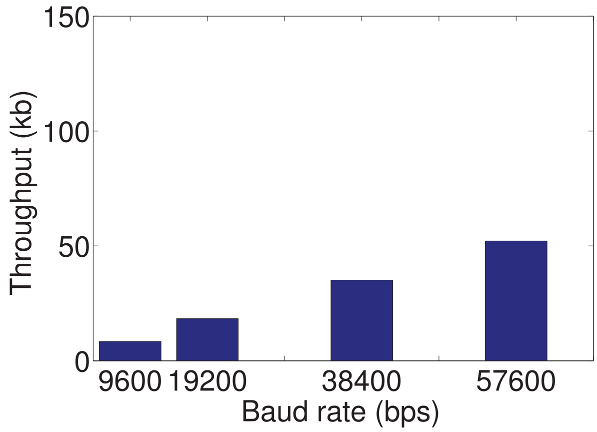
The identification of critical frames is also evaluated. By using the workstation software



(a) 15-second

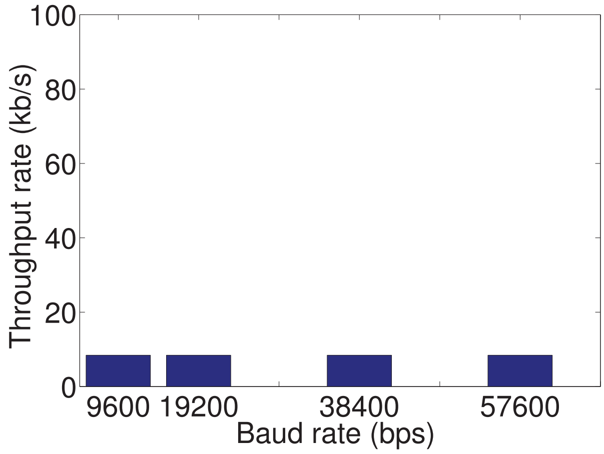


(b) 5-second

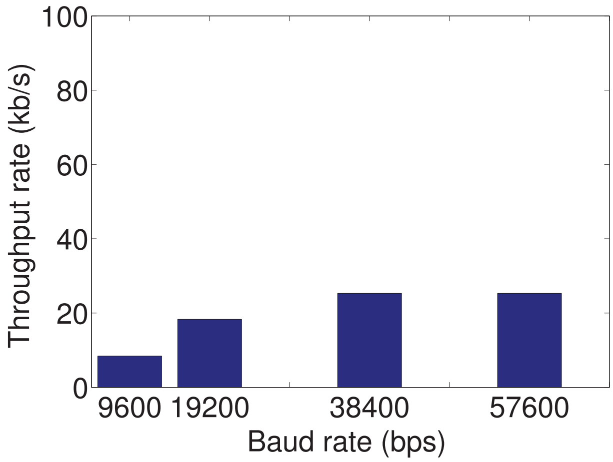


(c) 1-second

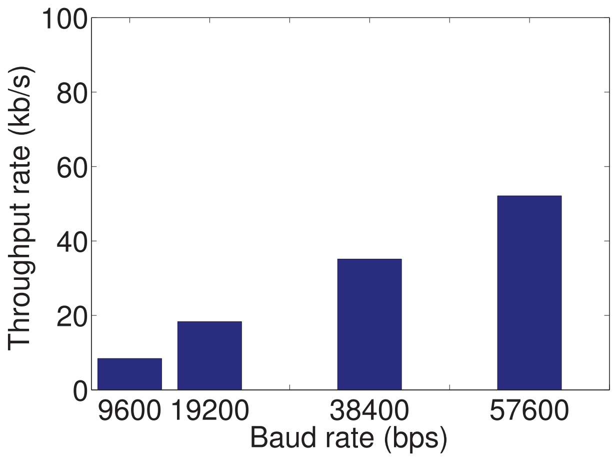
Figure 3.13: The update interval to the throughput of different baud rates



(a) 15-second



(b) 5-second



(c) 1-second

Figure 3.14: The update interval to the throughput rate of different baud rates

ORCAview [4], the temperature is simulated to the input of DDC. Firstly, an alarm was created and set to the temperature which over 140°F (60°C) in the workstation. The update rate was set to 10 seconds and the value of the virtual temperature was programmed into random so as to create random alarms from the workstation. As such, when the value is greater than the specified temperature, an alarm critical frame will be emerged and transmitted. The experiment was run for three hours and the results were compared with the actual results in workstation.

Figure 3.16 shows the results of the two proposed CFI methods, i.e., by using specific data fields and pattern recognition. It is not surprising to see that using specific data fields can achieve 100% identification rate as it read directly from the payload. When using frame length pattern recognition, the identification rate improved when training

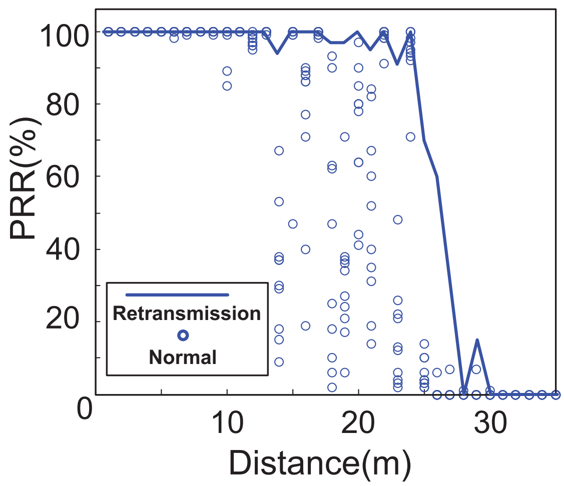


Figure 3.15: PRR under different link quality

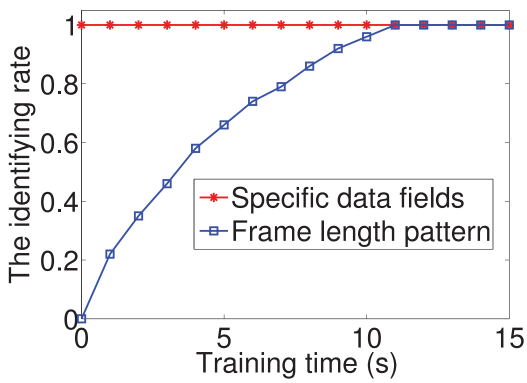


Figure 3.16: CFI rate at different training time

time increased. After 10 seconds of training time, the identification rate also achieved 100% accuracy. In practice, it is good enough if the training time is 2 to 3 times of the update interval.

3.7.3 Simulation

Simulation Setup

The objective of simulation is to evaluate the performance of the proposed scheme under different conditions, which cannot be evaluated via experiments. The lengths of the data frames were randomly created between 50 to 503 bytes, which resembles to the actual frame lengths in MS/TP. The baud rates of XBee were set to 1200, 2400, 3600, $\cdots$, 9600 and 19200 bps respectively. The data traffic sent to wired link were set between 0.5 to 8 times to the baud rate of XBee. The update intervals of the sensing devices t_r were set to 2, 5, 10, and 30 seconds respectively. The token timeouts t_o were set to 1s, 2s, $\cdots$, 9s. This t_o represents the time slice a DDC can send the data when it holds a token. The default baud rate of XBee were set to 1200 bps, the total data traffic sent was 8 times to the baud rate of XBee; the baud rate of the wired link was 19200 bps, $t_r = 15$s and $t_o = 1$s, the data quality is 0 dBm and $\mathcal{T} = 5$.

The main evaluation metrics of the design are fairness and throughput ratio R, which is defined as the ratio between wireless throughput and data traffic generated from the wired link. R is used to remove the inconsistence of the absolute value of the throughput. The results were compared with 1) sequential transmission and 2) random transmission (when the wireless capacity is less than the traffic of the wired link).

Simulation Results

In this part, the simulation results are discussed by first evaluating the throughput ratio. In Figure 3.17, the throughput against different update intervals are shown. Obviously, the smaller the update interval (i.e., more frequent updates), the higher the data traffic

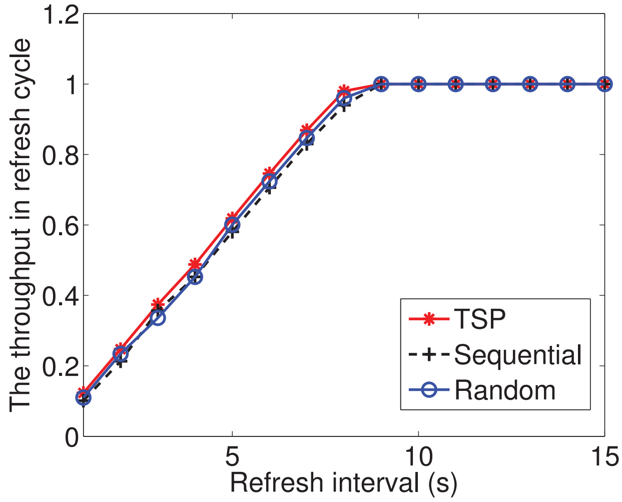


Figure 3.17: System throughput with different update intervals

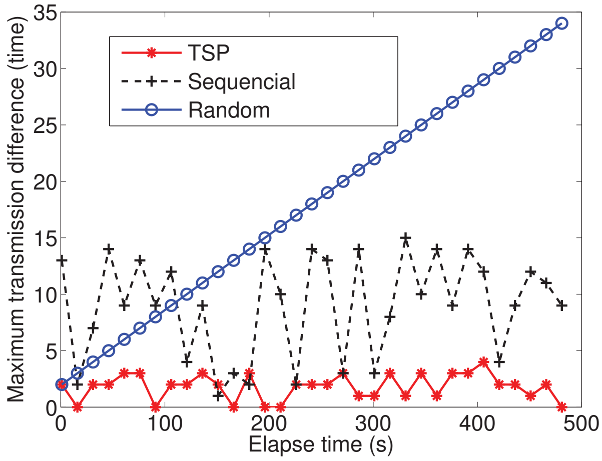


Figure 3.18: Difference of the frames transmitted

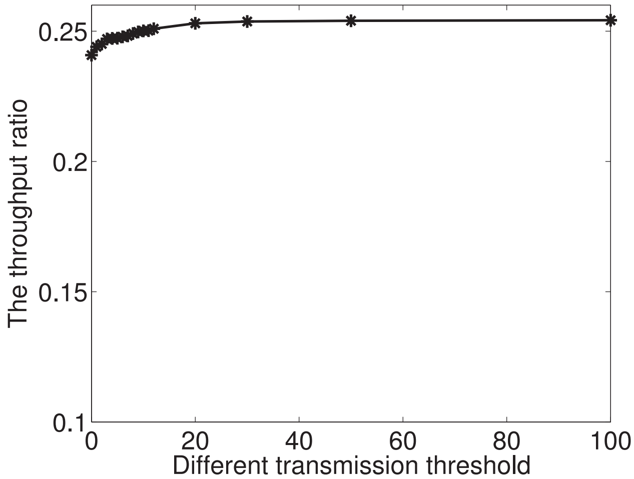


Figure 3.19: Throughput ratio under different $\mathcal{T}$

load. It is clearly that if the update interval t_r is small, the throughput ratio is also small, e.g., when $t_r = 4$ seconds, the throughput ratio is 0.47. It is due to fact that not all the frames can be sent completely with the tight interval. On the contrary, when $t_r = 9$ seconds, all the frames can be sent completely with throughput ratio of $R = 1$. In short, all the three schemes - *TSP*, *Sequential* and *Random* performed with equal throughput ratio. This is reasonable as there is no constraint upon the wireless transmission.

In Figure 3.18, the three transmission schemes of the difference in maximum transmission of each frame are compared, i.e., fairness. It is observed that the maximum transmission difference of TSP was peaked at 5, which was the default threshold; while the schemes of *Sequential* and *Random* [25] were much larger. Specifically, the transmission difference under the scheme of *Sequential* increased with the elapsed time as it always transmitted the first few frames.

To study the sensitivity of the throughput ratio to frame transmission threshold $\mathcal{T}$, the value of $\mathcal{T}$ was studied and the result is shown in Figure 3.19. It is cleared that the throughput increases with a larger $\mathcal{T}$ though the increment is not significant. While a large $\mathcal{T}$ may bring freedom in frame selection, it affects the last "bin" only. Hence, from a system point of view, the proposed algorithm is good enough as compared to other advanced algorithms.

Besides the study of single DDC, the relationship between the throughput ratio and the number of DDCs is also evaluated as shown in Figure 3.20. The total system throughput ratio increases when the number of DDCs increases. The ratio becomes stable when there are 15 DDCs given that the update interval is 15-second and the timeout of wireless token ring is 1-second. The wireless capacity is fully utilized and the system throughput is maximized at this state, as the further increase of DDCs does not enhance the throughput ratio.

In Figure 3.21, the number of DDCs is simulated to 10 and the effect of different update intervals are studied. The result shows that the wireless capacity is obviously less

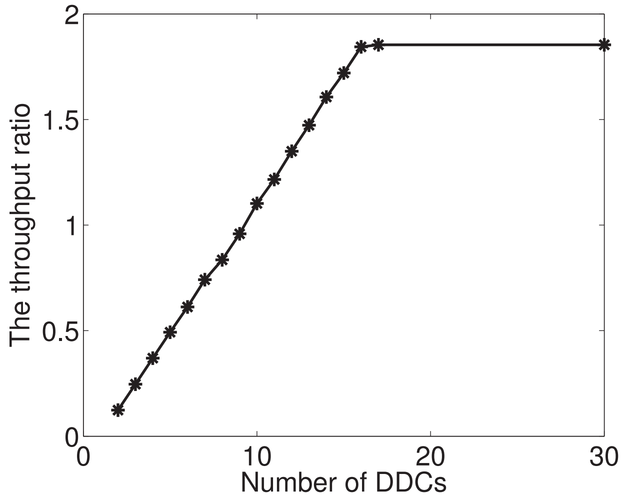


Figure 3.20: The throughput under different numbers of DDC

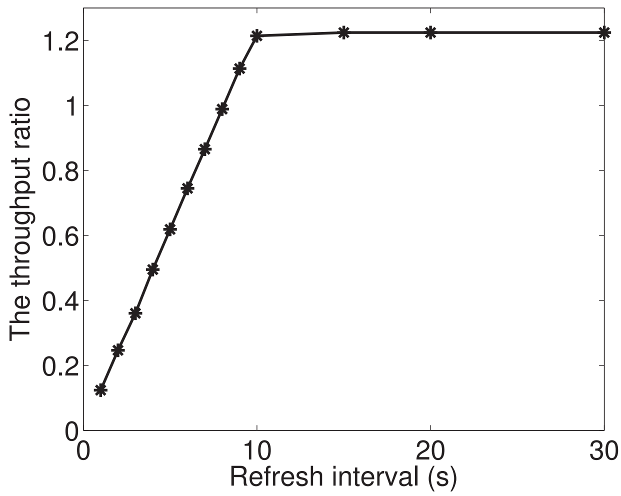


Figure 3.21: The throughput ratio under different updates rate

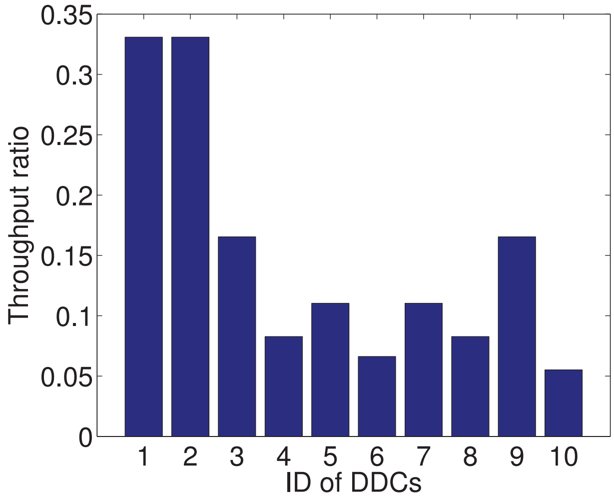


Figure 3.22: The throughput under different priorities

stringent than the previous 15 DDCs, and the system throughput ratio increases with the increase of update interval. The throughput ratio remains the same when the refresh interval is 10-second or more as the wireless capacity is fully utilized at the interval of 10-second.

In Figure 3.22, the throughput ratio and fairness of 10 DDCs with different priorities are studied. A set of priorities are randomly assigned to the DDC of ID 1 to 10 with the priorities of 1, 1, 2, 4, 3, 5, 3, 4, 2 and 6 respectively. The result shows that the throughput ratio of each DDC is closely related to their assigned priorities, and the DDCs with highest priorities (i.e., DDCs 1 and 2) have the highest throughput ratio while the least priority (i.e., DDC 6) has the lowest throughput ratio.

3.8 A Deployment Experience

The following part discusses the deployment of the design in real environment. The proposed system was deployed on the 4th floor of the F-building in The Hong Kong Polytechnic University. The floor plan is shown in Figure 3.23, and the original system is shown in Figure 3.24. Due to the experiment was conducted on an operating BMS, the facilities management office only provide a 5-hour timeslot for experiment. Although the experiment was not conducted for a long period, the system was chosen to run from 11:00a.m. to 4:00p.m. within the office-hour, which was more representative in reflecting the actual BMS operation during this period of time. The deployment photo is shown in Figure 3.25

There were 8 DDCs on the 4th floor and each of them was controlling a VAV (variable air volume) box and other sensing devices. One DDC was used to control the PAU (Primary Air-Handling Unit) that used to supply fresh air to the whole floor. The 9 DDCs were connected to a system DDC, which were then connected to the BMS network via Ethernet. In this experiment, two Arduino smart sensors were used, one connected to the DDC that controlling the PAU and another one connected to the system DDC. The

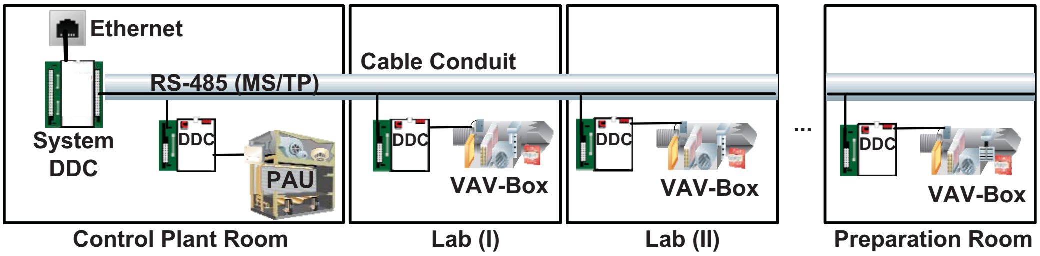


Figure 3.23: The floor plan of deployment environment

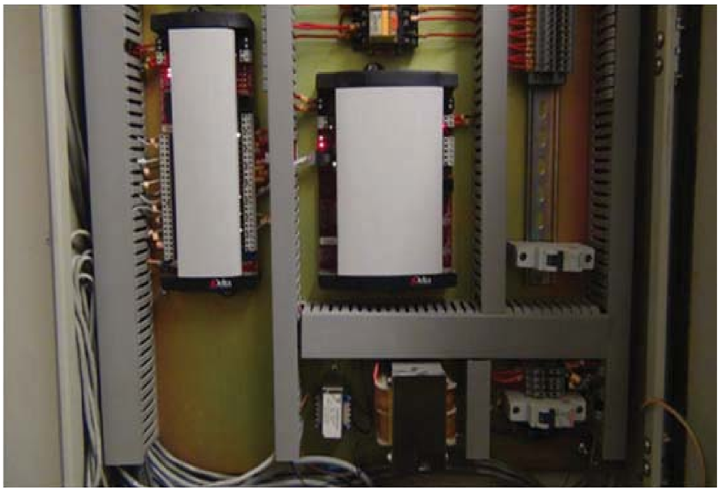
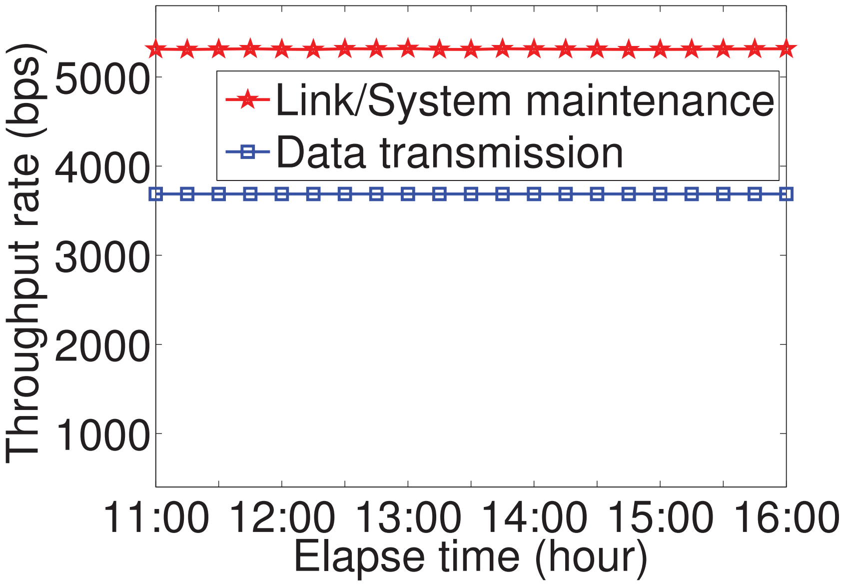
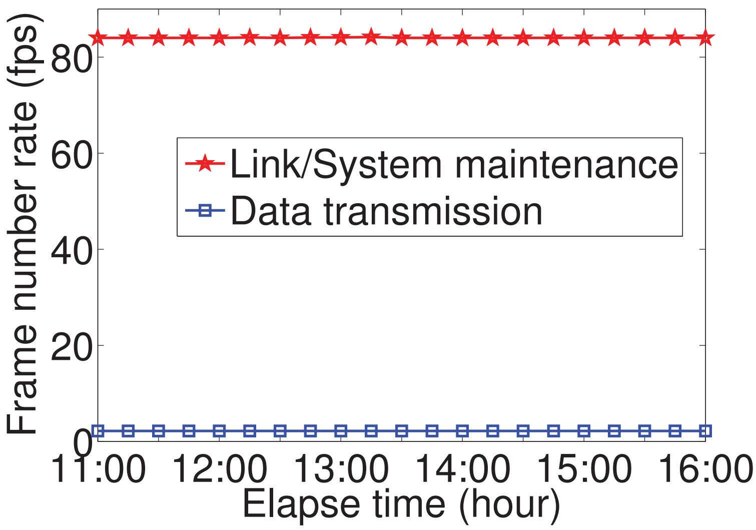


Figure 3.24: Original wired MS/TP system

Figure 3.25: Wireless deployment



(a) System throughput rate



(b) Frame rate of system

Figure 3.26: Throughput rate and frame rate of the system

baud rates of both Arduinoes were 57,600 bps.

During the experiment, the system operated smoothly without interrupting the normal operation of the BMS. The network traffic and the number of frames were captured in every 15 seconds, and the frames were categorized into data transmission frames and link/system maintenance frames as discussed in Figure 3.26(a) and 3.26(b). From the experiment, it is observed that 1) the traffic of BMS was stable; and 2) control packets dominated during the communications. The number of link/system maintenance frames and throughput rate were 38.2 times and 44.07% more than the data transmission frames respectively. Since the traffic pattern of BMS is intrinsically steady, the proposed design may also be able to apply into other BMS trivially.

3.9 Summary of chapter

In summary, this chapter shows a design which can convert an existing wired building management system into a (partial) wireless system without modification on the existing BMS communication protocols. The key approach is an asynchronous-response scheme that can support the upper layers protocol stack and a modular framework to support selective prioritization and scheduling of data frame transmission.

From the system point of view, the design can help extend the BMS network by installing new controllers and thus new senors that connect to these controllers. This approach can be carried out incrementally without affecting the existing network topology and is easy to get deployed into the systems of building. The design can be used for temporary purpose and can be restored trivially.

The evaluation of the design has been conducted by experiments, simulations and real-world deployment. It has been proven that the asynchronous-response design can work successfully with existing BMS. The design and deployment experience are useful for on-going research studies, e.g., the issue of wireless signal deterioration by the interference of building systems, the use of different wireless standards and spectrums can affect the data link quality. These studies provide useful performance indicators for the current design, and can enhance the system applicability.

CHAPTER 4

OCCUPANT-PARTICIPATORY FRAMEWORK FOR THERMAL COMFORT AND ENERGY CONSERVATION

4.1 Overview

Buildings have long been the major energy consumers in different countries and cities. In the United States, around 46% of the total energy consumption is consumed by commercial buildings [1], of which heating, ventilating and air-conditioning (HVAC) system constitutes 35%-40% of energy consumption in a typical commercial building. In Hong Kong, where the industry sectors are small, commercial buildings account for more than 65% of energy consumption of the city [2]; HVAC system also dominates the energy expenses. It is reported in the Office Segment of Hong Kong 2013 that 53% of energy was consumed in room conditioning [2]. As a result, there is a number of recent studies have proposed the idea of energy conservation by managing the HVAC systems operation [16] [35].

While there are lots of discussions and measures for energy reduction, the quality of services is always in top priority. Humans spend more than 80% of their daily time in buildings [32], therefore, the condition of indoor environment can affect the health of occupants and their productivities. Smart and intelligent buildings are proposed that aim to reduce building operation and electricity costs, improve indoor air quality and enhance human comfort. Currently, occupant's feedback is discrete from the actual operation of HVAC system, occupants dissatisfaction to the air-conditioning services are common, e.g., too cold or too hot. A fixed setpoint temperature is normally assigned and applied to different zones of buildings depends on various factors, e.g., the functionalities of zone, occupancy schedule, number of people and building orientation.

In fact, it is challenging to set a fixed temperature that suits everyone's need, since people can hardly have unanimous thermal sensations even though they are under the same environment [34], e.g., a thin person may prefer a higher temperature, whereas a fat person prefers a lower one. Another challenge is that people are insensitive to numerical expression of temperature [38], one may not be able to differentiate the actual differences between 24.5 °C and 23.5 °C; therefore, asking people questions like "What is your favourite temperature?" and set accordingly is not feasible, there are gaps between the system inputs and human sensations that seek to fill in this thesis.

In this chapter, the design of occupant-participatory feedback framework is proposed to bridge the gap between user feedback and system. The challenges of balancing the thermal comfort and energy conservation is discussed in Section 4.2; the introduction of thermal comfort and predicted mean vote model are illustrated in section 4.3. The proposed occupant-participatory thermal comfort (OPTC) framework is presented in Section 4.4, the temperature-comfort correlation (TCC) Model is discussed in Section 4.5; simulations and experiments in commercial office and University are presented in Section 4.7 and 4.9 respectively. The strategy-proof thermal comfort vote of occupants are studied in Section 4.10.

4.2 Energy conservation and thermal comfort in buildings

In recent years, people have been paying more attentions to energy conservation. The largest sectors of energy consumption are commercial buildings, residential houses, transportation, and manufactory industry. As such, energy conservation has become the common studies in cross-discipline.

Obviously, one can simply turn-off all the power-consuming equipment such as HVAC system, and thus maximizing the energy conservation. Nevertheless, the HVAC systems is designed to provide a comfort indoor environment for occupants in buildings. However, complaint minimization, rather than energy conservation, is the top priority of buildings and building operators. Therefore, it is important to take human thermal comfort into consideration.

The current practice of supporting human thermal comfort by building operators is to apply a fixed setpoint temperature. These temperatures are derived from large-scaled field surveys or laboratory experiments. Such recommendation provides the building operators with reference in temperature settings and assists them to cope with complaints.

To minimize the number of complaints, these recommended temperatures are usually very conservative (i.e., the setting is on the low temperature side) and uniformly apply to the entire building unless special requests are made. However, this traditional practice has led to massive waste of energy. In addition, a lower temperature does not necessarily reflect better human thermal comfort. Besides, it is difficult for occupants to adjust the temperature on their own in many high-end buildings with the installation of the centralized HVAC system.

As opposed to fixed setpoint strategy, there are proposals on dynamic control of the HVAC systems. One direction is to detect human presence. If a room is not occupied, the air-conditioning of the room will be turned-off. Various detection objectives and solutions have been proposed in previous studies [13] [14].

In this chapter, another direction on dynamic control of the HVAC systems is explored. Rather than passively detecting human presence and their comfort levels, a user participatory approach is taken in which occupants can provide inputs. More specifically, occupants can actively provide feedback on the comfort level with the use of their mobile devices like smartphones.

The idea is simple, yet for a participatory design to success, there are several challenges:

1. Incentives of occupants are important. The design should be as non-intrusive as

possible. Requiring occupants to provide feedback via their mobile devices every time they stay in a room will possibly discourage participation of people. Besides, it is of great importance to protect one's privacy.

2. Occupants are insensitive to the numerical expression of temperature [38]. For instance, one may not be able to differentiate the actual differences between 22.5°C and 24.5°C. However, current building management system (BMS) requires numerical values for calculation and comparison. Therefore, it is necessary to have a context-aware translation.

3. It is possible to have multiple occupants in a room, thus an optimized aggregation of different comfort levels is needed;

4. It is necessary to develop a system consisting of data collection, smartphone application, interaction with building controls for air-conditioning adjustment, etc. Many of these challenges are similar to those of typical participatory sensing systems [95] [27], but are specific in the built environment discipline.

4.3 Introduction to Thermal Comfort

Thermal comfort refers to the *condition of mind* that expresses *satisfaction* with the thermal environment [11]. The term "condition of mind" implies the nature of thermal comfort is subjective, and "satisfaction with the thermal environment" implies the existence of thermal comfort levels of human towards the environment.

There are tremendous discussions to measure and compute the thermal comfort of people. It can be summarized into two directions [20]: heat-balanced approach and adaptive approach. The heat-balance approach is first proposed by Fanger [86] which the physiology of thermoregulation is used to identify the range of comfort temperature in a building. He later proposed the Predicted Mean Vote (PMV) model, which has become the international standard ISO7730 and industrial standard [11].

As specified in [11], the condition of thermal comfort is said to attain when at least 80% of occupants are satisfied with the thermal environment. PMV model is used to predict such condition based on several personal and environmental factors. The details of PMV are discussed as follows.

4.3.1 Predicted Mean Vote

To quantify people's thermal sensation, ASHRAE adopts a seven-point thermal sensation scale as shown in Table 4.3. Each of the point (-3 to 3) corresponds to different levels of comfort. PMV is an index used to predict the mean response of a large group of people according to this sensation scale [11]. It considers six factors, including metabolic rate, clothing insulation, air temperature, radiant temperature, air speed and humidity.

The first two factors are personal-dependent, whereas the latter four are environmental-dependent. While the PMV index helps quantify the thermal sensation of one, critiques for its impracticality to real-world situation have limited its application and affected the accuracy. For example, metabolic rate and clothing insulation can hardly be obtained without detailed measurements and modelings. Also, the radiant temperature and air speed are normally not sensed by BMS. In actual applications, most of the factors apart from air temperature and humidity are assumed with constant values, causing the prone-to-error results. [38].

The accuracy of the PMV is further studied from the dataset obtained from [32]. All the field studies data are retrieved from buildings with HVAC system, they cover more than 20 countries with different climate zones and seasons. The focus is on the difference between the PMV values and the Actual Mean Vote (AMV) from more than 10k people. Surprisingly, the result shows in Table 4.2 indicates that PMV is not able to reflect the actual thermal sensation of the interviewees, there is as large as 2-point difference in the upper 80-percentile. There have been tremendous discussions to the inaccuracy of the PMV model [20] [34] [32], since this is not the focus of this chapter, the details are

Table 4.1: 7-point thermal sensation scale

Point	Sensation
+3	Hot
+2	Warm
+1	Slightly Warm
0	Neutral
-1	Slightly Cool
-2	Cool
-3	Cold

Table 4.2: Result of RP-884 database

Percentile	$\lvert PMV - AMV \rvert$	DTR
95	2.7	16.88
90	2.38	14.73
85	2.16	13.5
80	2	12.6
75	1.86	11.8

skipped here.

4.3.2 Standard of Thermal Comfort

With the worldwide field studies, ASHRAE provides the guidance and illustrates the comfort zone of humans based on the PMV values between -0.5 and +0.5 using the modified psychometric chart [11]. It assumes humans have activity levels with metabolic rates between 1.0 met and 1.3 met, and clothing insulation between 0.5 clo and 1.0 clo. Although the assumption of metabolic rates and clothing insulations have again limited its applications, the concept of comfort zone provides insights to the proposed system design of this chapter.

For instance, even different people have totally different preferences to the A/C setting, it is still possible to find the *optimized temperature* as humans have a certain levels of threshold (i.e. range of comfort zone) to temperature. Also, there can be trade-off between the extent of comfortability and the number of people, e.g. 10 people with "Slightly Cool" (-1) thermal sensations may prefer than 5 people with "Warm"(-2) and other 5 with neutral (0).

In recent work of thermal comfort, outdoor temperature has been found to play a key role that affects people's thermal sensation, known as *adaptive model*. Field studies show that there is a strong relationship between the outdoor temperature with PMV values [32] [34]. Therefore, the outdoor temperature is incorporated as a parameter in this design.

The proposed system does not merely correlate the outdoor temperature with user's thermal sensation, it has also modeled the dynamic change of occupants favourite temperature which may vary with time. For instance, a person comes back from outside with 33°C is likely to prefer the temperature as low as possible to cool down her body instantly.

In application, a person may feel cold when she sits and works in front of a computer for several hours. Hence, the proposed design does not treat each occupant's preferred temperature as static as PMV does, rather it considers the duration a user stays at the place. Details of the formulation and design will be discussed in the next section.

4.4 Occupant-Participatory Thermal Comfort (OPTC): An Overview

In this chapter, a smartphone application for occupants is developed to provide their feedback (or in other words, to vote) regarding their thermal sensations to the indoor environment of buildings. The smartphone application is able to directly communicate with the BMS and thus the room setpoint temperature is adjusted accordingly. Each vote of the occupants will be recorded along with the current environmental data, e.g., indoor room temperature and outdoor temperature, to formulate that occupant's thermal comfort model. The temperature adjustment of the room can thus be model-driven most of the time with minimizing the intrusiveness to the occupant, therefore, the occupant is not expected to keep submitting their votes all the time.

In the system design, there is a OPTC server to store the data collected from each occupant, including her thermal comfort profile. The possible privacy concerns are clarified firstly in this regard. In this design, each occupant is required to register an account with her email address and agrees a set of rules, e.g., allow the system to collect her thermal comfort information. If one does not register, her thermal preference will not be taken into the consideration of the temperature adjustment. Based on the experiments conducted, it is found that all occupants have registered. The post-experiment survey revealed that people in the experiments were not so much concerned about their thermal preferences being recorded. Instead, they were more concerned that they would be left out for the setpoint adjustment in a room sharing with multiple people.

In this section, an Occupant-Participatory Thermal Comfort (OPTC) framework is developed as shown in Figure 4.1. There are four main modules:

1. **Temperature-comfort correlation (TCC) model**: the objective of TCC model is to establish a correlation (or profile) between the indoor and outdoor temperature with the comfort index of each individual occupant;

2. **Setpoint optimization module**: based on the TCC model, setpoint optimization module computes the optimal setpoint temperature for occupant(s), especially for multiple occupants;

3. **Event monitor module**: the event monitor module collects data from the existing environment (e.g., indoor, outdoor temperature) and occupants information for two purposes: to trigger decision making in setpoint optimization, and to gradually train the TCC model;

4. **Building controller module**: After setpoint optimization module makes an adjustment decision, the building controller module communicates with the BMS to change the setpoint of the room.

The TCC model is developed interdisciplinary with the field of built environment. However, the thermal comfort models in built environment discipline are complicate and difficult to be implemented in real environment. Besides, the traditional thermal com-

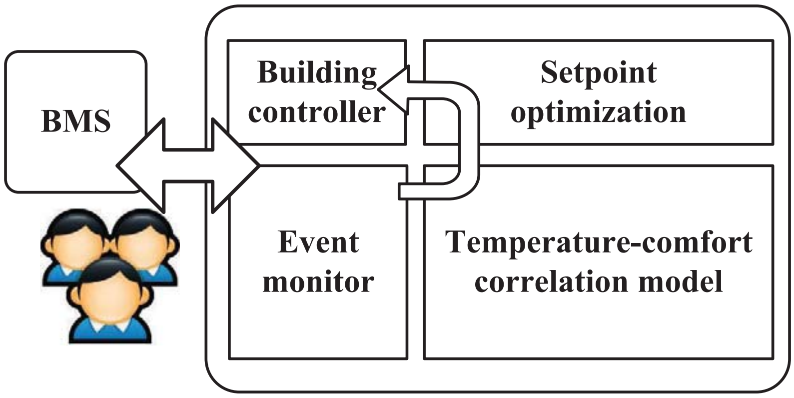


Figure 4.1: Overview of OPTC

fort models require tremendous field tests and laboratory experiments, which laboratory equipment like climate chamber to simulate different climatic conditions are used. On the contrary, the TCC model is designed to rely on daily collectable data only, e.g., indoor and outdoor temperature, and additionally occupants feedback regarding the thermal preference. Implicitly, there is expectation that more feedback will be collected at times when people are experiencing discomfort. The feedback of each user is saved into her own profile for modeling, hence the setpoint temperature adjustment can be model-driven most of the time. Details are shown in Section 4.5.

The setpoint optimization module determines the setpoint adjustment. For example, when some pre-defined events happened (e.g., indoor/outdoor temperature change and occupants' comfort index are collected, etc.), the setpoint optimization module will then be triggered. It translates the inputs from event monitor module and the TCC model into a decision for room setpoint adjustment. More importantly, an algorithm is developed to compute the optimized setpoint temperature when there are multiple occupants sharing the same space/room. The details are demonstrated in Section 4.6.

Event monitor module collects all the required data and responses accordingly. To collect the thermal preference of one, a smartphone application is developed based on the comfort index as shown in Table 4.3. The fuzzy preference is translated into computable numerical values. The details are elaborated in Section 4.8.

In building controller module, decisions made by the setpoint optimization module are passed to the BMS, which is discussed in Section 4.8. The remaining parts of this chapter are organized as follows. The TCC model is discussed in Section 4.5, and validated by the TCC model by conducting a series of field experiments with the occupants. The setpoint optimization algorithm is then presented in Section 4.6. In Section 4.7, a comprehensive set of simulations are shown using the TCC model. A comprehensive evaluation to a large set of occupants with different physical characteristics, and the energy saving with various room configurations and sets of simulated occupants are also evaluated. The implementation of the proposed system is then presented in Section 4.8. In Section 4.9, two sets of experiments are conducted, one in a university and the other one in a commercial office. These experiments serve to validate the simulation results.

4.5 Temperature-Comfort Correlation (TCC) Model

In essence, a model indicating the levels of comfort of a person is needed, given the indoor and outdoor temperature with the specified time are known. It can then determine the setpoint temperature accordingly. As discussed before, there are many models from the discipline of built environment [43] [46] [81] [42] [86], but the accuracy of these models largely rely on real-time measurement of the occupants and the surrounding environment, where special laboratory equipment are needed.

The model proposed in this section is formulated following the rudimental laws of metabolism, which is based on the discipline of built environment. In this model, three different sets of parameters are carefully categorized: 1) parameters that can be collected in one time, e.g., the age, gender, height, weight, etc. of the occupant. These information are one-off and collected during the time of registration; 2) parameters that change with time, but can be collected by non-intrusive sensors, e.g., indoor or outdoor temperatures; 3) parameters that are hard to collect using daily sensors; and these parameters can be trained collectively by the votes and other parameters.

Table 4.3: 7-point thermal comfort index

Point	Sensation
+3	Hot
+2	Warm
+1	Slightly Warm
0	Neutral
-1	Slightly Cool
-2	Cool
-3	Cold

In the following parts, thermal comfort is firstly linked with quantifiable (numerical) values. Afterwards, the thermal preference of user is developed with the proposed model. Finally the model is validated using real-world experiments.

4.5.1 Thermal Comfort Metric

To quantify thermal comfort, a seven-point *thermal comfort index* is adopted from the American Society of Heating, Refrigerating and Air-conditioning Engineers (ASHRAE). This index scales from -3 to 3 and links the thermal comfort from cold to hot as shown in Table 4.3.

From the occupants perspective, this index is easily comprehensible to reflect her thermal sensation, i.e. she can vote either hot or cold. From the built environment perspective, a value of 0 indicates that an occupant reaches *thermal neutrality*, meaning the heat generation and heat loss of the occupant is in the state of equilibrium. A negative index implies that the rate of heat loss is greater than the heat produced from the body of occupant. Hence the occupant feels cold. The smaller the index, the more uncomfortable the occupant feels. When the index of an occupant is between -1 (Slightly Cool) and 1 (Slightly Warm), the occupant is regarded as comfort. This index range $(-1, 1)$ is defined as the *comfort zone* by ASHRAE [11].

4.5.2 Model Development

An initial model is first developed and details are discussed. In the initial model, the thermal comfort is a function of indoor temperature T_i of room i, outdoor temperature T_o and the elapsed time t a person stays at the space/room. The thermal sensation is determined by the balance of heat gain and loss of human body. Let $G(t)$ be the heat gain and $L(T_i, T_o)$ be the heat loss. Thus, the thermal comfort $C(T_i, T_o, t)$ is:

$$C(T_i, T_o, t) = G(t) + L(T_i, T_o) \tag{4.1}$$

In next part, the high level ideas will firstly be presented, followed by the details of model $G(t)$ and $L(T_i, T_o)$.

In general, the amount of heat generated is primarily settled by metabolic rate. It is affected by the physical activity (PA) of people [51], e.g., a person has a higher metabolic rate during walking; a lower rate after staying sedentary. When the PA of a person changes, e.g., sit down after running, her metabolic rate changes accordingly. Thus, the occupant experiences a change of thermal sensations at same environment. Moreover, the speed to the change of metabolic rate differs among individuals. In $G(t)$, metabolic rate changes is considered as the elapsed time t after occupant enters a room.

The amount of heat lost is determined by indoor temperature and clothes insulation. In application, the clothes insulation can hardly be to obtained. However, from the results of field studies [78], it is shown that the effect of clothes insulation can be reflected by outdoor temperature. Intuitively, when the outdoor temperature is higher, occupants are likely wearing less clothes, and hence prone to a higher rate of heat loss. In this regard, they prefer a warmer indoor environment. Thus, the indoor temperature and outdoor temperature are used as determining variables in $L(T_i, T_o)$.

	Men	Women
Sedentary	1.0	1.0
Active	1.25	1.27

Table 4.4: Physical activity factor

Heat Generation Modeling

According to [65,90], heat production is proportional to physical activity, whereas metabolic rate adjusts according to physical activity. To estimate metabolic rate of an occupant, the Estimated Energy Requirement (EER) model [82] is adopted, which is proposed firstly by the Institute of Medicine (IOM) that used to estimate a person's daily average of dietary energy intake to maintain her energy balance. It considers gender, age, height, weight and physical activity of people. EER is shown as follows:

$$EER = k_1 - k_2 \times Age + [PA \times (k_3 \times W + k_4 \times H)] \tag{4.2}$$

Here, k_1 is a constant related to gender and age. k_2 is a constant related to age. k_3 and k_4 are constants related to weight (W) and height (H) respectively. The PA coefficient is related to the physical activity and varies with genders. As the change of metabolic rate of a person from outdoor to indoor is interested, the coefficients of two physical activities are considered: *active* and *sedentary*. The coefficients of active and sedentary for male and female are shown in Table 4.4. The details of other coefficients can be found in [82].

As stipulated in [51] [11], metabolic rate changes smoothly after physical activity changes. To obtain the corresponding EER at time t, the EER is formulated into:

$$EER(t) = \begin{cases} \frac{(EER_s - EER_e)}{t_c}(t_c - t) + EER_e & t < t_c \\ EER_e & t \geq t_c \end{cases} \tag{4.3}$$

Here, EER_s and EER_e are EER of a person at active state and sedentary state respectively. t_c is the time required by a person to recover from active to sedentary. Beyond t_c, EER is assumed to remain as the metabolic rate becomes steady. Figure 4.2 shows the EER of a male and a female with different ages, heights and weights.

Noted that t_c is a parameter that is difficult to obtain from daily sensors. It differs from person to person as well. Intuitively, even if two people have the same weight, they can still have different muscle-fat ratios. In built environment, t_c is normally estimated using laboratory equipment. As mentioned, t_c is trained using the votes from occupants.

As described, heat production is proportional to EER, and thus:

$$G(t) = a_1 \times EER(t) + b_1 \tag{4.4}$$

Here, a_1 is the activity sensitivity and is associated with t_c, and b_1 is stable comfort preference. Linear regression is used to process data in period $t \in [0, t_c]$. Combined with Eq. 4.4, Eq. 4.1 can be written as:

$$C(T_i, T_o, t) = a_1 \times EER(t) + b_1 + L(T_i, T_o)$$

With Eq. 4.3,

$$C(T_i, T_o, t) = \hat{a} \times t + \hat{b} + L(T_i, T_o) \qquad t \in [0, t_c] \tag{4.5}$$

where $\hat{a} = -a_1(EER_s - EER_e)/t_c$ and $\hat{b} = a_1 \times EER_s + b_1$.

From Eq. 4.6, $L(T_i, T_o)$ is computed given the values of T_i and T_o. Thus $C(T_i, T_o, t) - L(T_i, T_o)$ is linear to t because the unknown parameters ($\hat{a}$, $\hat{b}$) in Eq. 4.5 are constants. When an occupant votes, T_i, T_o, t are recorded and the vote of thermal comfort index v. Ideally, the predicted index from the model equals to the index voted from occupant, which means that $C(T_i, T_o, t) = v$ is expected. Linear regression technique can then be used with collected data $\langle T_i, T_o, t, v \rangle$ to obtain $\hat{a}$ and $\hat{b}$. Finally, a_1 and b_1 can be computed from $\hat{a}$ and $\hat{b}$ since EER_s, EER_e and t_c are known.

Heat Loss Modeling

For heat loss, there are comprehensive findings from field studies [32] [81] showing a noticeable relationship between the outdoor temperature and human thermal comfort. The correlation is formulated as $T_c(T_o) = a_2 + b_2 \times T_o$, where T_c is the comfort temperature

Table 4.5: Category of BMI

Category	BMI Range
Underweight	$<$18.5
Normal	18.5-25
Overweight	$>$25

function of outdoor mean temperature, a_2 is a constant related to comfort temperature and b_2 is the correlation between outdoor temperature change and comfort temperature change. In other words, this model assumes the occupants prefer higher indoor temperature when the outdoor temperature increases. In this chapter, the model in [21] is applied, where a_2 is set to 17.8 and b_2 is set to 0.31.

As stipulated in the standard [11], the range of temperatures for comfort zone is $7°C$. This means that when indoor temperature increases from $T_c(T_o) - 3.5°C$ to $T_c(T_o) + 3.5°C$, the comfort index changes from -1 to 1. Since $L(T_i, T_o)$ is a linear function of T_i, k can be computed as $k = 7/2$. Thus, R can be calculated as $R = 3 \times k = 10.5°C$, which is the boundaries for the comfort zone of a person. The heat loss model is thus:

$$L(T_i, T_o) = \begin{cases} 3 & T_i - T_c(T_o) \geq R \\ k(T_i - T_c(T_o)) & -R < T_i - T_c(T_o) < R \\ -3 & T_i - T_c(T_o) \leq -R \end{cases} \tag{4.6}$$

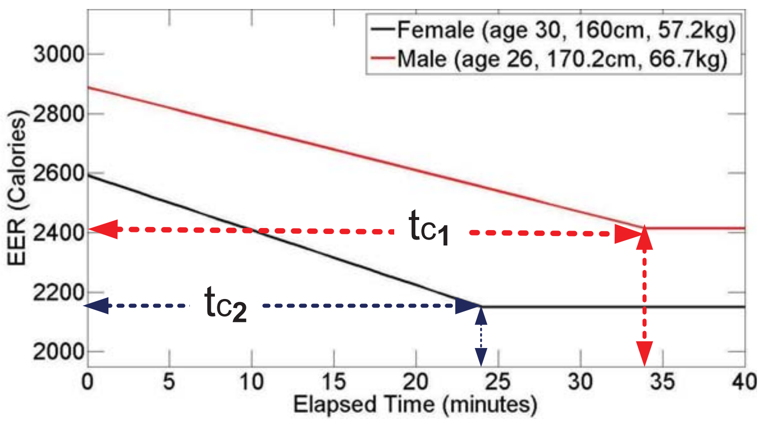
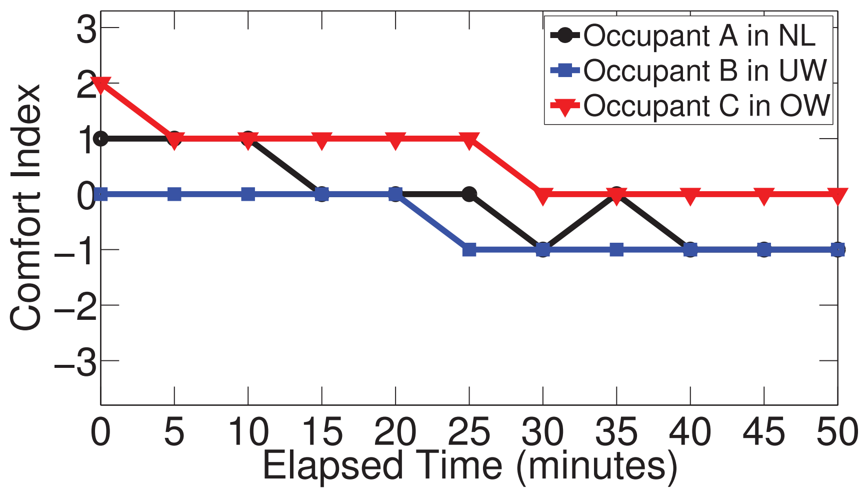
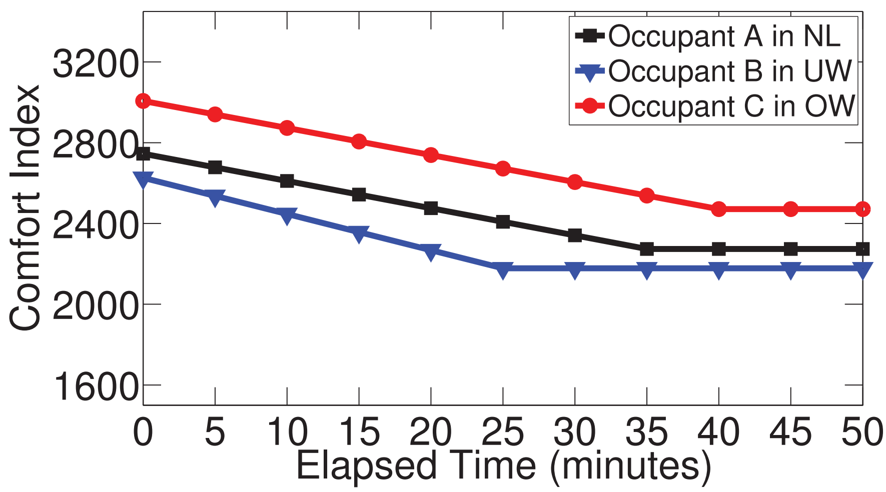


Figure 4.2: The EER example of two people

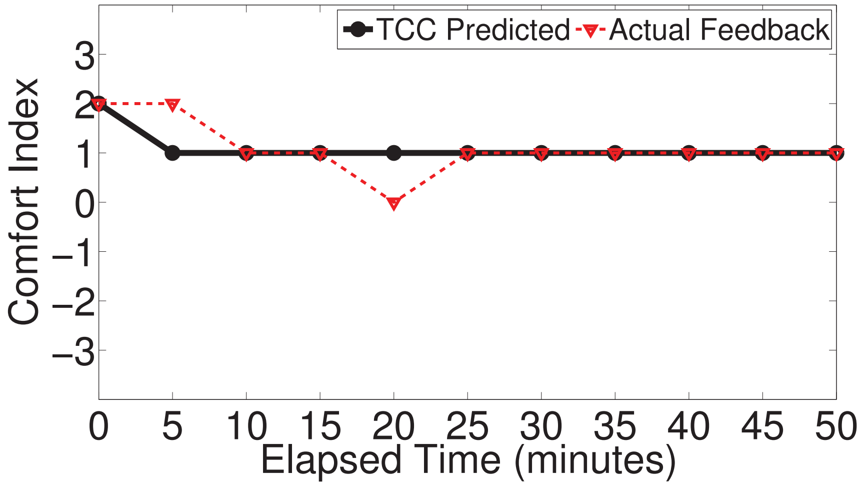


(a) Comfort index

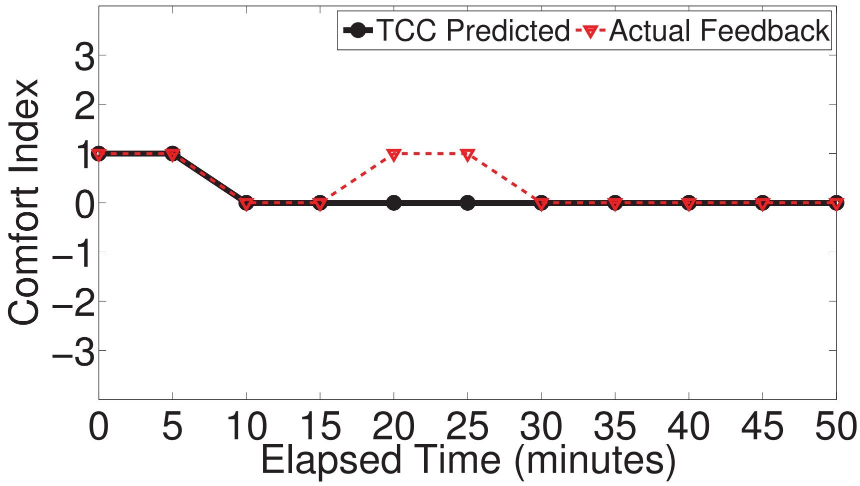


(b) EER

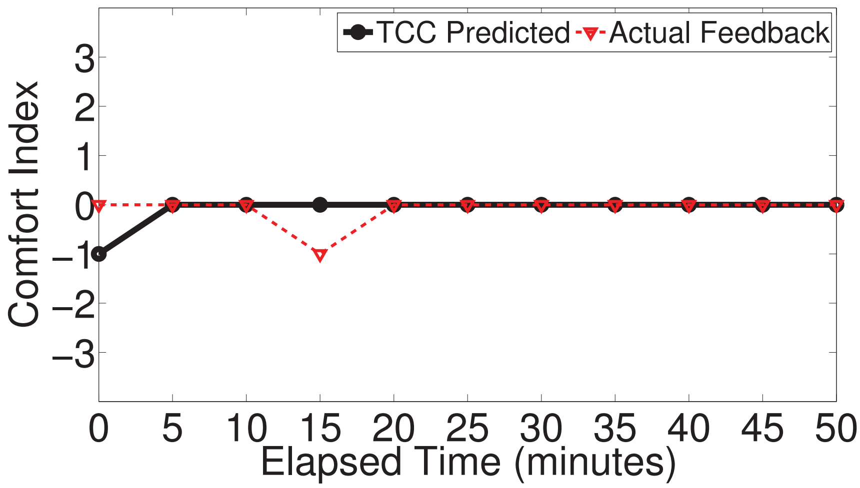
Figure 4.3: Connection between EER and Comfort index



(a) OW group



(b) NL group



(c) UW group

Figure 4.4: TCC model validation under different BMI groups

4.5.3 Model Validation

A series of field experiments were conducted to validate the model. One experiment was conducted in a commercial office for five consecutive days, and 13 occupants were invited to participate in this experiment. The profile of each occupant was created using the TCC model and trained for three consecutive days. For the remaining two days, the comfort index from the TCC model were compared with the actual feedback of occupants.

Referring to the World Health Organization (WHO) [6], occupants were classified into three categories according to their body mass index (BMI): i) underweight (UW), ii) normal (NL), and iii) overweight (OW). The formula of BMI is as follows, and the BMI index of each group is shown in Table 4.5.

$$BMI = \frac{Weight(kg)}{(Height(m))^2} \tag{4.7}$$

In this experiment, the number of occupants in UW, NL and OW were 3, 8 and 2 respectively. Each round of training was carried out at the time when occupants arrived the office from externals of building. In each round of training, a fixed setpoint temperature was assigned, and occupants were asked to submit their feedback at 5-minute interval. The setpoint (indoor) temperatures were set from 20 °C to 25°C, with 0.5 °C increment in each training.

The key parameters of the TCC model for training were a_1, b_1 and t_c for each occupant. Linear regression was used to estimate the comfort index of each occupant from the TCC model that collected during the training period. The comparisons between the TCC model and the actual feedback of occupants are shown in Figure 4.4. The accuracy for OW was 78%, NL was 75% and UW was 67%. The maximum error of the comfort index was only 1. The result indicates that the TCC model is capable to estimate the comfort index of the three occupants.

Noted that the heat loss is primarily determined by the clothing materials of occupants, and in the TCC model, this is determined by the outdoor temperature (which is translated into approximately the clothing of an occupant). The heat generation, however, depends on the metabolic rate of an individual and this differs across different occupants (one may recall our three training parameters a_1, b_1 and t_c are all for heat generation).

The details of EER are as follows. Figure 4.3a shows one of the training rounds, where one occupant is selected from each BMI group: occupant A from OW, occupant B from NL and occupant C from UW. Their change of EER are shown in Figure 4.3b. Figure 4.3a and 4.3b indicate that there is a strong correlation between the change of EER with the comfort index of occupants. More specifically, occupants A, B and C have diverging comfort indices at the beginning: A and B are warm and slightly warm respectively, and C is neutral. Their differences can be explained by the EER_s values, which are 3100, 2350 and 2100.

Noted that the thermal sensations of occupants changed with time, e.g., occupant A became neutral after 30 minutes, whereas B and C started to feel cool after 40 and 25 minutes, respectively. It is worth noticing that the thermal sensations of B and C were close to each other as their EER_e were close to each other. The result verifies the connection between EER and comfort index of a person.

4.6 The Setpoint Optimization Algorithm

As specified in the standard of thermal comfort, at least 80% of people is required to stay within the comfort zone, i.e., between -1 to 1 of comfort index. To achieve this, it is important to identify a setpoint temperature that can yield the highest comfort levels of people. In this part, a setpoint optimization algorithm (SOA) is developed to find out the optimized setpoint temperature that maximizing the number of people staying within the comfort zone. Due to the possibility of highly diverging thermal sensation of people, this algorithm seeks to find out the highest group thermal comfort with *best effort*, but the result is not guaranteed to meet the requirement of standard. The details are discussed as follows.

The algorithm is shown in Algorithm 2 with three input parameters: $\mathbb{O}$, r and T_o. The parameters description are as follows. $\mathbb{O}$ is the set of occupants in a room; r is the threshold percentage of occupants within the comfort zone (e.g., 80%); T_o is the outdoor temperature. For every occupant $j \in \mathbb{O}$, there is a corresponding TCC model C_j and a elapsed time t_j after occupant j enters the room.

The algorithm first identifies the comfort temperature of each occupant, and then followed by computing the optimized setpoint temperature iteratively for all occupants. In each iteration, a candidate of setpoint temperature is determined and check whether this temperature satisfies the thermal comfort requirement of all occupants. If it fails, the set of occupants is re-determined and proceeds next iteration. In other words, a candidate of setpoint temperature T^* is firstly calculated by minimizing the sum of comfort index of all occupants. Then the number of occupants who are thermally comfortable is counted, denoted as N. If the target requirement (more than $r|\mathbb{O}|$ occupants are satisfied) is met, the optimized setpoint T^* is found. Otherwise, an occupant whose preferred temperature is the farthest from the candidate setpoint temperature is eliminated since the objective is to satisfy as many occupants as possible.

4.7 Simulation

4.7.1 Simulation Setup

The system was evaluated into two different scales. Firstly, a classroom with different occupants' profiles was simulated in a small scale. Secondly, the academic calendar from The Hong Kong Polytechnic University (denoted PolyU thereafter) was adopted to evaluate in a large scale. The system was compared with fixed setpoint strategy.

In the simulation, the occupant profiles were created based on the results from the experiment in Section 4.5.3 model validation. One occupant from each BMI category was

Algorithm 2 The Setpoint Optimization Algorithm

Input: $\mathbb{O}$, r, T_o
Output: T^*

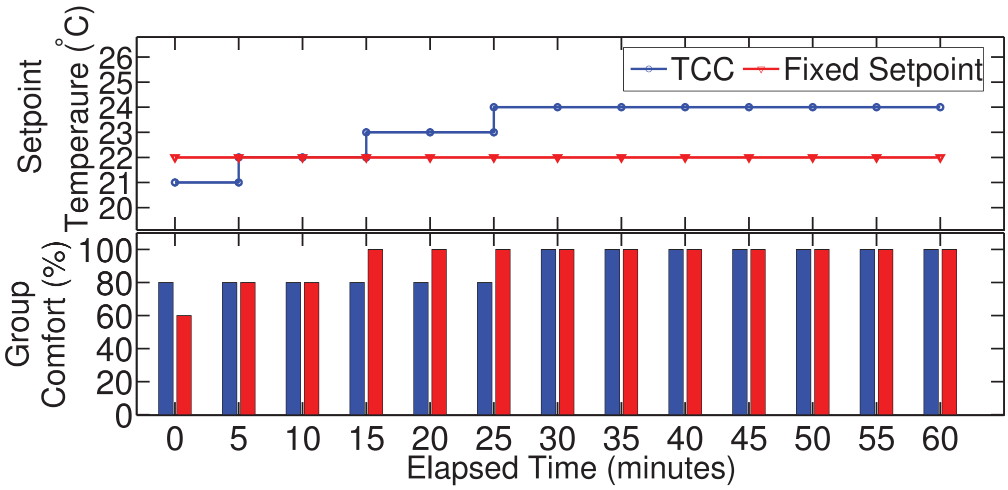
$T^* \leftarrow \emptyset$;
for $\forall j \in \mathbb{O}$ **do**
  $T_j^* = \arg\min_T |C_j(T_o, T, t_j)|$;
while true **do**
  $T^* = \arg\min_T \sum_{j \in \mathbb{O}} |C_j(T_o, T, t_j)|$;
  $N = 0$;
  for $\forall j \in \mathbb{O}$ **do**
    if $|C_j(T_o, T^*, t_j)| \leq 1$ **then**
      $N = N + 1$;
  if $N \geq r|\mathbb{O}|$ **then**
    break;
  else
    $\mathbb{O} \leftarrow \mathbb{O} \setminus \{\arg\max_{j \in \mathbb{O}} |T^* - T_j^*|\}$;

randomly chosen. The profile of an occupant was denoted as [a_1, b_1, t_c]. Thus, profiles from occupant in OW category, NL category and UW category are [0.0027, -4.99, 30], [0.0041, -7.08, 40] and [0.002, -2.5325, 25] respectively.

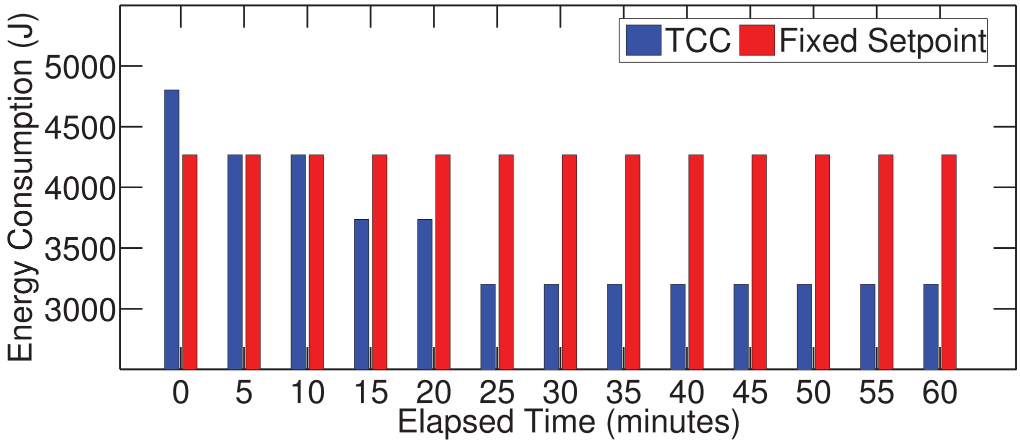
For the simulation in a classroom, two groups of occupants were created, which were named as group A and group B. Each group consisted of 100 occupants and each class lasted for an hour. The ratio of OW:NL:UW in group A was 1:7:2; whereas group B was 1:1:3. The outdoor temperature was assumed 30^oC and the fixed setpoint temperature was set to 22°C.

For the PolyU data, there were over 950 classes in every weekday. The system was evaluated with one year data, and the classes repeated every week. The outdoor temperature data of Hong Kong in 2013 was acquired from The Hong Kong Observatory [7]. From the field measurement, PolyU applied a fixed setpoint temperature of 22°C in summer period (May to October) and 24°C in winter period.

To compare the energy consumption, the energy-temperature correlation model $P = |\frac{\lambda}{M}(T_i - T_o)|$ is adopted [97]. Let P as the energy consumed by HVAC system in one-second, λ as the conductivity of that particular classroom. Intuitively, the larger the λ, the less the heat preservation is being trapped into the room. M is the energy transformation ratio of HVAC system used to indicate the energy efficiency of HVAC system. Again, T_i is the actual room temperature, and T_o is the average outdoor temperature. The model assumes that in a given room, $\frac{\lambda}{M}$ is fixed, and thus more energy is consumed when the room setpoint temperature is far away from the outdoor temperature. The values of λ and M for classrooms at PolyU were referred to [97], where M was 0.14 for all classrooms. The 155 classrooms details of PolyU main campus are summarized in Table 4.6. For the simulation in a classroom, the parameters of the 100 seats classroom were taken.

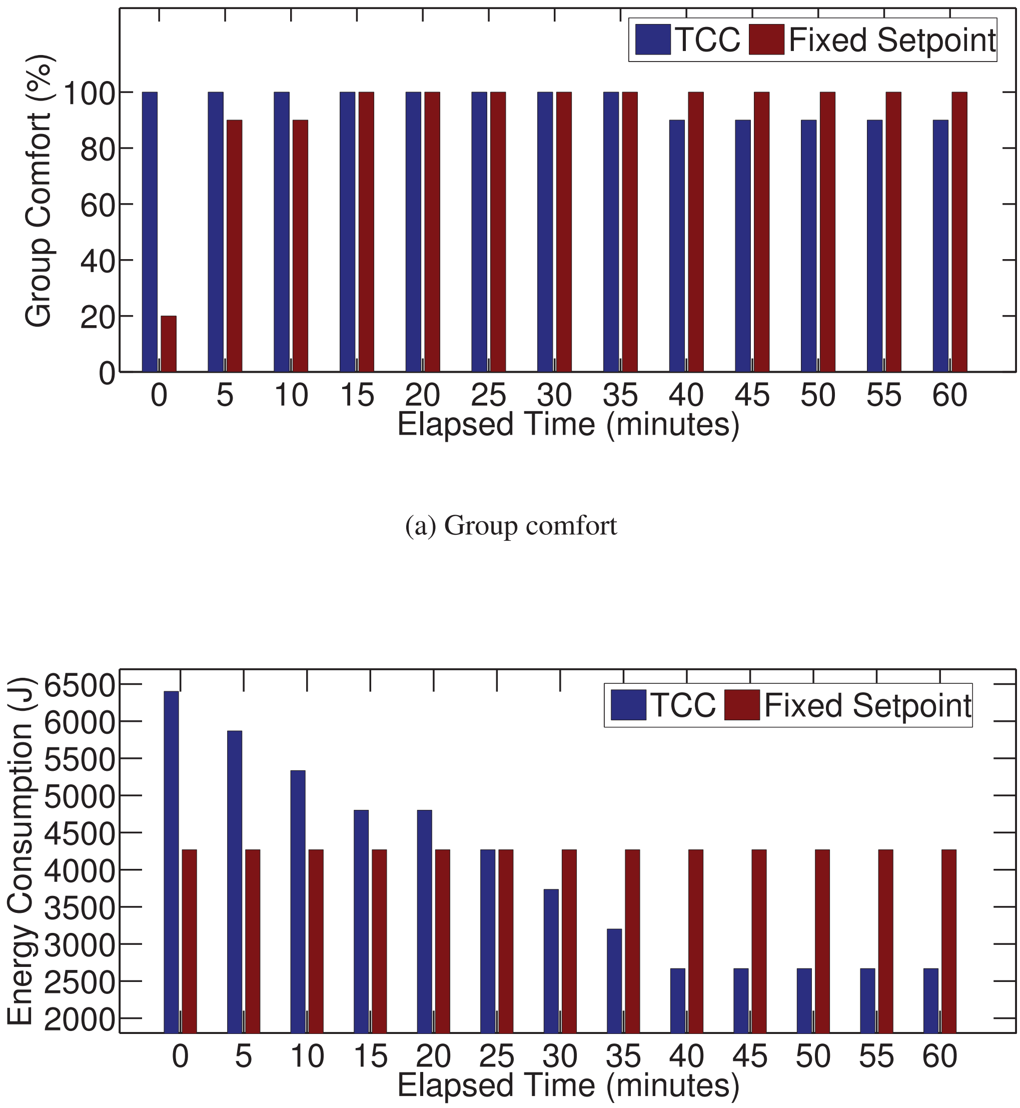


(a) Group comfort



(b) Energy consumption

Figure 4.5: Group A simulation results



(a) Group comfort

(b) Energy consumption

Figure 4.6: Group B simulation results

Table 4.6: Classroom at PolyU

Seats	No.	Size ($L \times W \times H, m$)	λ ($J/s \cdot K$)
20	8	$4 \times 5 \times 3$	70.5
40	42	$8 \times 5 \times 3$	118.5
60	67	$6 \times 10 \times 3$	162
80	10	$8 \times 10 \times 3$	201
100	4	$10 \times 10 \times 3.3$	249
150	17	$10 \times 15 \times 4$	375
200	5	$15 \times 14 \times 5$	533
300	2	$15 \times 20 \times 6$	765

4.7.2 Simulation Results

Classroom simulation result

Figure 4.5 shows the result of group A. With the starting setpoint calculated by OPTC at 21°C, it progressively increases with time and higher than the fixed setpoint, which is 22 °C after 15 minutes. It can be seen that OPTC achieves group thermal comfort requirement($\geq$ 80%) all the time, while fixed setpoint fails to meet the requirement in the first few minutes.

The energy consumption is shown in Figure 4.6b. Since fixed setpoint does not changes its setpoint, its energy consumption is steady. For OPTC, when the setpoint is changed, the energy consumption drops dramatically. For the last 40 minutes, OPTC consumes only 35% of the energy of fixed setpoint. As a whole, there is a reduction of 16.5% energy consumption under OPTC.

The result of group B is shown in Figure 4.6. Compared to that of group A, the group thermal comfort under fixed setpoint is far from satisfaction when the class begins. Only 20% of the students are within the comfort zone. In contrast, OPTC brings all the students stay within the comfort zone for more than 60% of the time, and it maintains 90% of group comfort for the students in class. From the results, beside the large differences of energy consumption between OPTC and fixed setpoint, it is obvious that group B saves more energy. It can be explained by the ratio of UW is more than the OW in group

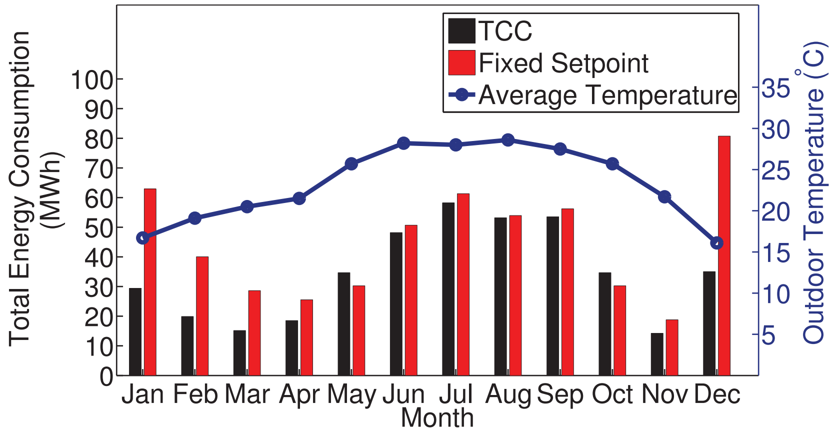


Figure 4.7: Energy consumption in one year

B, which the setpoint temperatures from OPTC are generally higher than group A.

Simulation of annual energy consumption

The result of monthly energy consumption is shown in Figure 4.7. The maximum and minimum averaged monthly temperature were 14°C and 31.1°C respectively. OPTC outperformed the fixed setpoint approach in 10 months with an exception in May and October. During summer period, the difference between OPTC and fixed setpoint were approximately 5%. However, this difference enlarged rapidly when the outdoor temperature was dropped, especially at its bottom in January and December, the fixed setpoint consumed twice than the energy of OPTC. In comparing with the fixed setpoint, OPTC saves 23.1% annual energy consumption.

4.8 Implementation Details

A prototype of OPTC was implemented in buildings. The system workflow is shown in Figure 4.8. The system was deployed in an OPTC server. The event monitor module in OPTC server collects data from the environment and occupants. After the optimal setpoint temperature is calculated, the building control module requests the BMS to command the setpoint temperature. To collect data from occupants, a mobile application is developed to enable the occupants to provide their thermal feedback and base rooms for the OPTC server. Besides collecting data from the occupants, the OPTC server communicates with the BMS for two objectives: 1) to collect the indoor temperature and the outdoor temperature; 2) to control the indoor temperature of a room. The detailed discussion is as follows.

4.8.1 A Mobile Application for Occupants

The mobile application collects the following information:

1) Occupant identity information; as discussed before, the system requests occupant registration. This registration is one-off and collects data such as weight, age, gender of the occupants. Recalled from Section 4.5, these information are needed for the TCC model.

2) The occupants are required to register their base rooms as shown in Figure 4.9a. This registration is also one-off. If the occupant has only one base room, all the computations and adjustments will be based on this room. Noted that in this situation, the setpoint temperature still requires adjustments from time to time, and primarily non-intrusive. If the room hosts multiple occupants, the setpoint optimization algorithm needs to be applied. If an occupant has multiple base rooms, then the system needs to update her location from time to time. To minimize the inputs from the occupant, the location can be obtained either from her meeting schedule, or a location detection algorithm can be applied. In a commercial office setting, an occupant usually has a limited number of base rooms. This makes the challenge for the location detection algorithm reasonable. The detailed location detection algorithm is out of the scope of this thesis. In Section 4.9, the experiment is solely confined to the single room case.

3) Occupants feedback from their votes; when the computed setpoint temperature from the comfort model is not able to meet the satisfaction of occupant, she can submit her vote as feedback using the mobile application shown in Figure 4.9b.

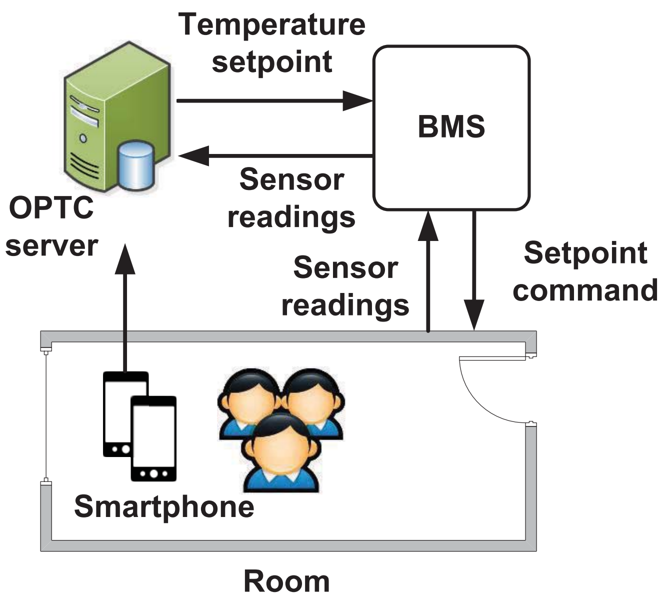
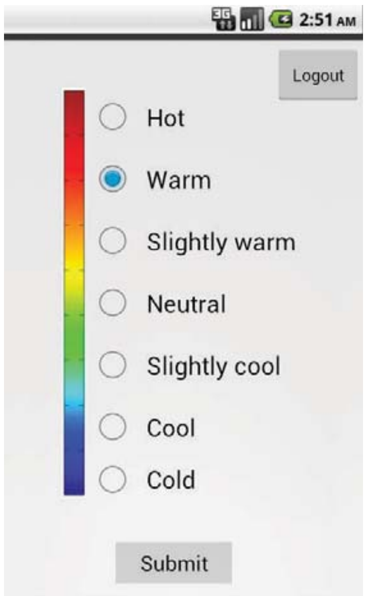


Figure 4.8: The system workflow of OPTC

(a) Location selection



(b) Voting screen

Figure 4.9: The mobile application for occupants

4.8.2 Data Collection and Temperature Control in Building

In a typical HVAC system, there are thousands of sensors to monitor the equipment status and condition feedback from the serving areas [29]. The temperature sensors are normally mounted on walls or at the ceilings of room. There are also sensors installed outside the buildings to collect outdoor ambient information such as humidity, temperature, etc. Both of these sensors information are sent to BMS via BMS network. In the design of OPTC, it requires the parameters of indoor and outdoor temperature. Since these data are available in the existing BMS, thus it can be retrieved directly from the BMS [48].

Besides the data collection at BMS, the system needs to control the setpoint temperature of rooms. This function is realized through the Building Automation and Control Networks (BACnet) protocol [10] of the OPTC framework [72]. Given that BACnet is the most dominant communication protocol in BMS today, the system is able to be widely adopted into different buildings.

4.9 Experiment

4.9.1 Experiment Setup

The experiments were conducted in The Hong Kong Polytechnic University and a A-class commercial office. In the university, the air-conditioning of lecture theaters were controlled by the BMS, and the lecture theatre in the experiment had a capacity of 130 people at the Y-core building.

For the commercial office of the experiment, the provision of air-conditioning was 24/7, the floor plan and the size of rooms are shown in Figure 4.13. There were 5 individual rooms (room A to E) and 3 meeting rooms (room 1 to 3).

The OPTC server was set up on campus and connected to both the BMSes of campus and office using virtual private network (VPN) since the campus network was located in

Intranet. To collect the votes of students, the mobile application was used as discussed in Section 4.8.1.

The system was evaluated through three performance metrics: 1) the improvement of thermal comfort of occupants; 2) the missing rate in satisfying group thermal comfort. The threshold of 80% was adopted following the ASHRAE standard; and 3) energy conservation.

4.9.2 Experiment results in the university

The experiment was conducted during a three hours lecture in the University. 87 students participated in the experiment, and the outdoor temperature was 31.4°C. According to the result of pre-measurement, the university has a fixed setpoint temperature of 21.5°C. The experiment lecture was divided into two one-hour sessions, where the fixed setpoint approach was applied in the first session, and the TCC approach in the second session.

Before the class, students were guided to install the smartphone application. They were instructed to provide feedback for their thermal sensations (as shown in Table 4.3) at an interval of 10 minutes. To develop the TCC model of each student, students' age, height and weight were also collected respectively.

Results of different group comfort under the fixed setpoint and the TCC modeled setpoint are shown in Figure 4.10. The x-axis is the elapsed time starting from the students arriving at the lecture theater. The y-axis of the upper part of the figure is the corresponding setpoint given by the fixed setpoint approach and the proposed TCC approach; and the y-axis of the lower part of the figure is the overall feedback of students.

The two different setpoint approaches were compared at here. In the experiment of fixed setpoint approach, more than 85% of the students were not at a comfort condition when they were just arrived the lecture theatre. In other words, their comfort indices were outside the comfort zone. 25 students even voted 3, and only 5 students voted thermal neutrality. At the time of 40 minutes, fixed setpoint has achieved its highest group comfort, which is still only about 40% of the students.

The model was then applied by firstly creating their profiles using the TCC model with the given data. The students were categorized into three groups according to their BMIs. One student from each group was selected and their comfort indices and EER were shown in Figure 4.11a and 4.11b respectively. It was not surprising that students in OW group had a higher EER_s, followed by the student in NL group, who had a relatively mild change of EER with time. The student from UW group had both the highest and least EER_s and EER_e respectively in comparing with other groups.

To compare the improvement brought by the TCC model, the setpoint temperature was adjusted via the OPTC server after the 10-minute break of the second-hour experiment session. Students were again told to vote at every 10 minutes. In Figure 4.10, when the elapsed time was between 0 and 10 minutes, the TCC setpoint (22°C) was again slightly higher than the fixed setpoint, and the difference enlarged between 10 to 30 minutes. The result showed that there was a great improvement to their levels of thermal comfort as compared with the default fixed setpoint at 21.5°C. Only 9 students (10.3%) were not at the comfort zone in the first 20 minutes, and later reduced to 5 students (5.7%) after 30 minutes. Based on the result, the proposed TCC approach was able to achieve 80% group comfort throughout the whole period. As compared with the group comfort before the TCC model was applied, there was an average of 63% thermal comfort improvement to the students in the experiment.

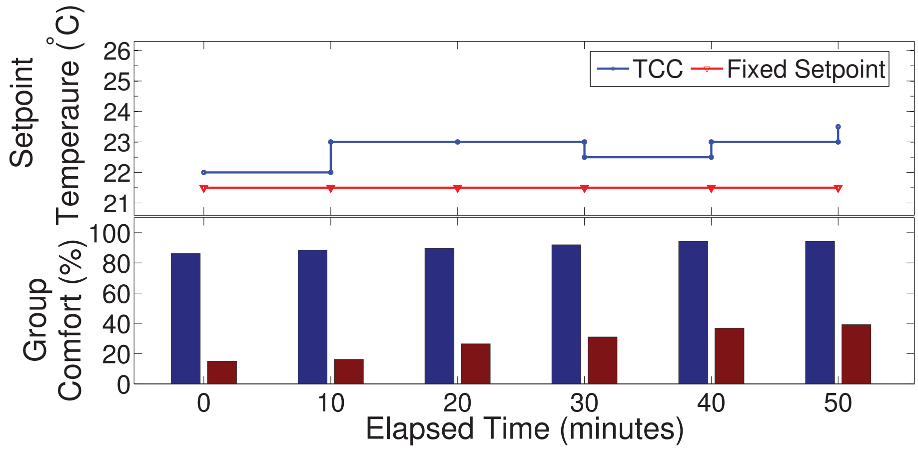
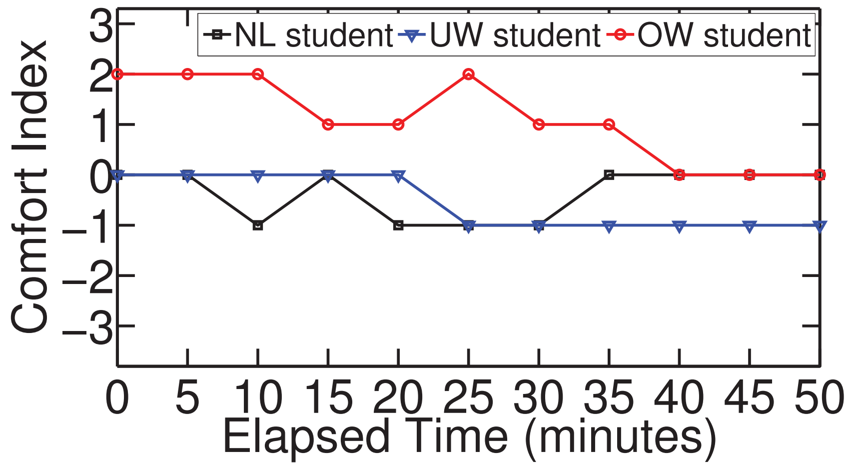
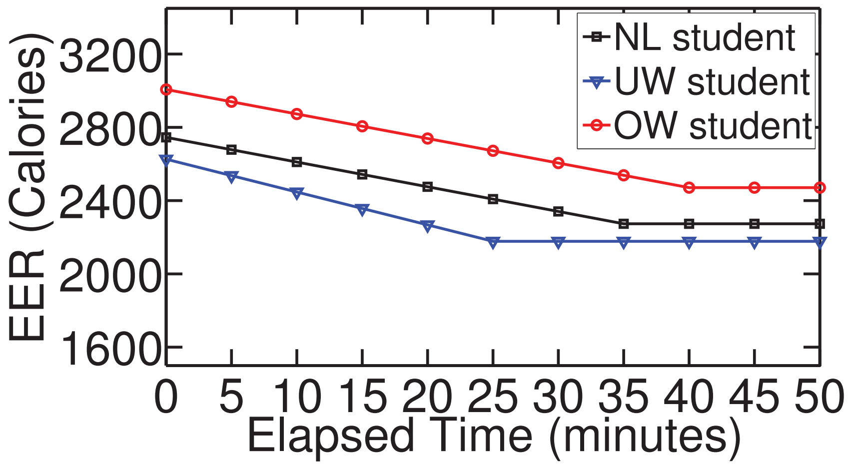


Figure 4.10: Setpoint temperature and group comfort

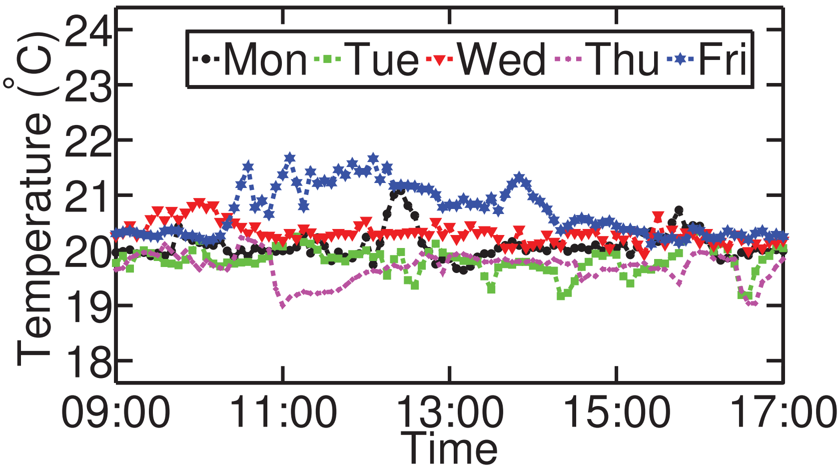


(a) Comfort index

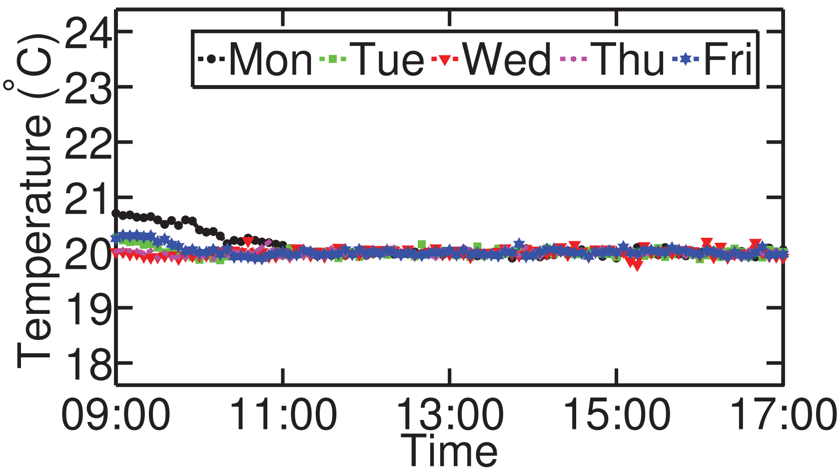


(b) EER

Figure 4.11: Students from different BMI groups



(a) Room B



(b) Room E

Figure 4.12: Temperature of two office rooms

4.9.3 Experiment results in a commercial office

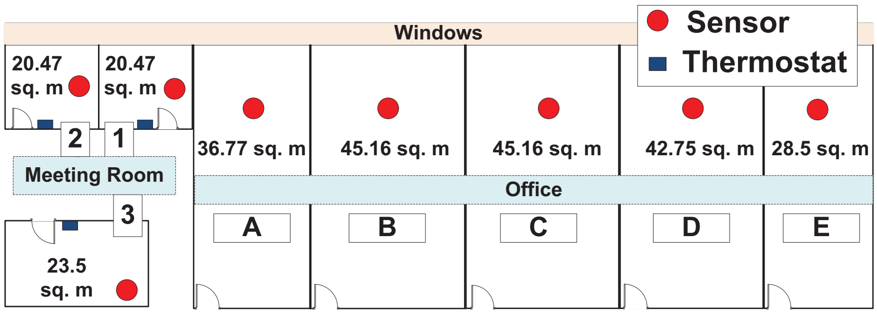


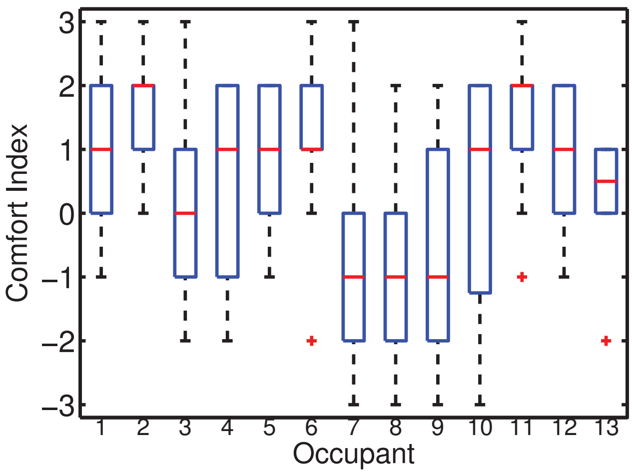
Figure 4.13: Floor plan of office

In this part, the experiment conducted in commercial office was discussed. To study the existing indoor temperature and occupants comfort, three temperature sensors at different rooms were initially deployed for three weeks to study the trend of temperature change under different outdoor temperatures. It was then followed by two five-day sessions, one for the fixed setpoint approach and one for our TCC approach.

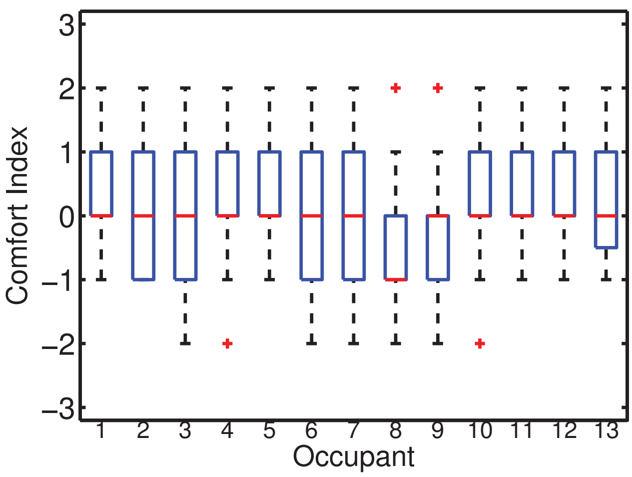
Before going into the analysis, there were several interesting observations. Firstly, it was observed that rooms with more people (e.g., room B with 13 people) experienced more significant temperature changes than rooms with less people (e.g., room E with 2 people). Figure 4.12a and 4.12b illustrate this phenomenon in room B and E respectively from one sample day during working hours.

Secondly, the temperature differences within the room can have 2.5°C differences, and such differences may constitute to occupant discomfort. By tracing the reasons, it was found that areas with printers and computers were the main culprits for a warmer temperature; and during noon time, the areas near windows were affected by the sunlight and thus created a small warm zone.

These findings show that the placement of temperature sensors directly affecting to the control accuracy of BMS and thus the room temperature. The number of sensors and location should be carefully considered; otherwise, occupants will be modeled with bias.



(a) Before using OPTC



(b) After using OPTC

Figure 4.14: Feedback from office experiment

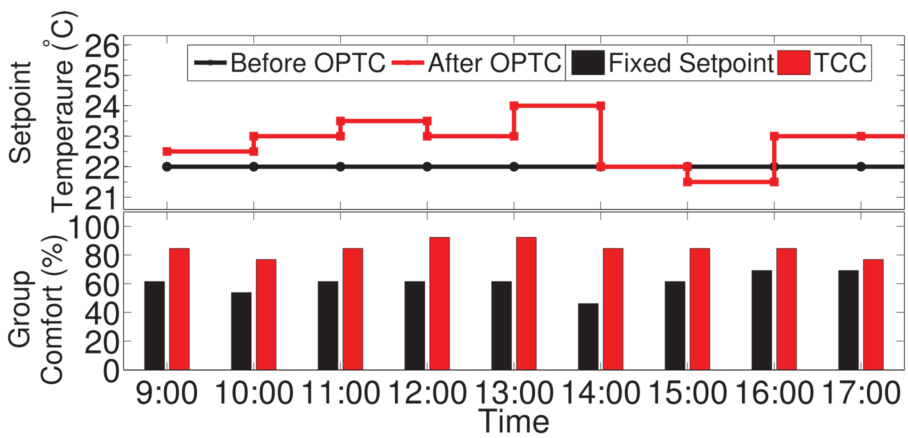


Figure 4.15: Setpoint and group comfort in office

Surprisingly, it was also observed that it took approximately 4.5 minutes in average for a room to reach its setpoint temperature. From the discussion with building services engineers, it takes time for the setpoint adjustment since the chilled water and the air flow from the air-conditioning terminal units (e.g., fan coil unit and variable air volume box) need time to work together to attain the desired setpoint. This time-lag varies with building designs and air-conditioning systems. As such, in the experiment, the setpoint temperature was determined by the TCC model at every 5-minute.

Room B was chosen in the experiment as it has the highest and most steady occupancy. Two smart sensors TelosB were additionally deployed in room to provide a finer temperature measurement. The default setpoint temperature was fixed at 22°C (summer period) by the facility management of the building. Two five-day (Monday to Friday) measurements were carried out, and the fixed setpoint approach was studied in the first measurement. Occupants were invited to provide with their feedback using the smartphone application anytime when they felt there was an obvious change to the thermal sensation.

There were finally a total of 403 votes collected, which were fairly distributed from the 13 occupants. The results are shown in Figure 4.14a. The central red line is the median, and the height of the box is the inter-quartile range of the votes, where the top and bottom of the boxes are the 75^{th} and 25^{th} percentile of the votes. Extreme data that are considered outliers is shown using the “whiskers”, i.e., with a “plus” sign.

There were dissatisfactions from the occupants to their existing fixed setpoint temperature. Around 45% of the votes were outside the comfort zone, and 7 votes (7.4%) were even at the extreme comfort index (-3 or 3).

It was then deployed into the OPTC for comparison. With the previous feedback and information of occupants (i.e., age, weight and height), the TCC model was built for each occupant. Another five-day experiment was conducted and 334 votes were collected.

The results are shown in Figure 4.14b. There was a major improvement of the occupant thermal comfort. 89% of the votes were within the comfort zone and no votes was in the extreme range (-3 or 3). There were 115 votes with thermal neutrality and they were fairly distributed from the 13 occupants. 12 occupants had a median of comfort neutrality, compared with 1 in our first week experiment. The overall improvement was 33.8%.

One of the experiments day is further displayed in timeline format as shown in Figure 4.15. There are two parts in the figure. The upper part shows the setpoint adjustment under fixed setpoint approach and our TCC approach. The lower part shows the group thermal comfort from the votes of occupants. The average outdoor temperature was 30.52°C during the day of experiment, with a diurnal difference of 3.17°C. Obviously, the TCC model has maintained a higher level of thermal comfort to the occupants than the fixed setpoint as shown in the group comfort percentage. Noted that the fixed setpoint failed to meet the target of group comfort during that experiment (i.e., 80%), whereas the TCC model was able to achieve 70% of the time meeting the requirement.

Beside the improvement of thermal comfort, there is also better energy performance. With the baseline of setpoint temperature at 22°C, there was an average of 1.75°C setpoint increment during the experiment period. Studies indicate that one-degree setpoint difference yields around 10% difference on energy use [8]. More specifically, considered the energy input for the air-conditioning terminal units (kWh),

$$\sum_{i=1}^{n}\left\{\left(\frac{\dot{m}_i c \Delta T_i}{\eta_i \cdot COP} + P_{f_i}\right) hr_i\right\}, \tag{4.8}$$

where $\dot{m}$ is the air mass flow rate (kg/s), c is the specific heat capacity of air (kJ/kgK), ΔT is the difference between supply and return air temperature (K), η is the heat transfer efficiency of the air-conditioning unit using chilled water, P_f is the operating fan motor power, COP is the coefficient of performance of the central chiller plant and hr is the cooling duration (hours).

The energy input was calculated by using the operating logs of BMS with 5-minute interval (i.e., hr = 1/12). By assuming that the operating conditions were the same during the experiment, it can be derived that the OPTC scheme was able to save 18% of energy consumption of the air-conditioning terminal units.

4.10 Strategy-proof to thermal comfort vote

In previous section, the occupant participatory approach is used to collect the real-time feedback of thermal comfort from occupants, so as to determine the right setpoint temperature to the conditioned area. The results from current studies have shown that a participatory oriented approach is superior in energy conservation, thermal comfort, etc. Thus, it is expected that further advanced schemes may be proposed. Nevertheless, one hidden assumption for all these occupant-participatory approaches is that the occupants are trustworthy, i.e., they do not "game" the system with false feedback/votes. It would become a crucial problem for the occupant-participatory approaches to succeed if this is not true. However, the current participatory schemes may have implicitly encourage occupants to have incentives to submit untruthful votes, i.e., thermal comfort in this Chapter. For example, for the average scheme proposed in [38], one may vote extreme values to affect the overall result for her own preferred temperature. In the computation of linear regression in [67], the scheme will become invalid when collecting false votes. Therefore, one can cast false vote and seek to shape with unreal thermal preference.

These participatory schemes proposed can be summarized into two main directions. One view is to consider it as a security problem. In this direction, users submitting false votes may be identified as attackers. This may not be appropriate in most scenarios as the false-vote users are not trying to attack the system, but to manage some individual gains.

Another view is to consider it as an incentive problem. In this direction, a voting scheme that guarantees truthful votes is said to be *strategy-proof* and the target of this approach is to design a strategy-proof voting scheme that avoids the user incentives to submit false votes [98]. This strategy-proof voting scheme also needs to guarantee the fairness, i.e., no single person should dominate the whole and major preferences should be chosen instead. In this section, the focus is on designing this strategy-proof voting scheme. Although the voting schemes are widely studied by many work [19] [80], this thesis is the first one to design the strategy-proof voting scheme in building environment [98]. The main challenges are: 1) the complex models in buildings, and 2) the imprecise nature of models in buildings.

In this section, the abstract of the strategy-proof framework for thermal comfort voting will first be presented rigidly in buildings (Section 2). Under this framework, the voting schemes in buildings can be classified into two types, i.e., *individual-based* and *group-based* voting schemes. The votes from occupants are usually not numerical temperatures, but their thermal sensations from cold to hot instead. Individual-based voting abstracts the scenarios where the numerical thermal comfort models are estimated by occupants' thermal sensations first, and then all numerical models join in the decision-making precess of the adjusted temperature. Group-based voting abstracts the scenarios where the group vote is decided first and then this group vote is used to estimate the adjusted temperature. In the followings, it shows the conditions for the existence of the strategy-proof voting schemes (Lemma 2), i.e., the occupants' temperature preferences should be single-peaked. Intuitively, the temperature farther away from the most preferred temperature makes occupants feeling worse. The strategy-proof voting mechanisms for both individual-based voting (Section 3.2) and group-based voting (Section 3.3) are then provided. Finally, an evaluation through simulation (Section 4) is conducted.

4.11 Basic Model

In this section, a set of occupants $\mathcal{N}$ that sharing the same conditioned space and the air-conditioning system is considered. Let the total number of people as $N = |\mathcal{N}|$, and they can reflect their levels of thermal comfort by the voting scheme as discussed in previous part, which is the 7-point thermal comfort index. Let the corresponding index of the vote for occupant $i \in \mathcal{N}$ as $v_i \in \{-3, -2, -1, 0, 1, 2, 3\}$. In practice, some occupants may not vote for their thermal comforts, hence it is reasonable to assume these occupants are staying at thermally neutral.

The index of thermal comfort is usually estimated by models and used to set the optimal or desired room temperature. The function $P_i(T, \Delta)$ is established to estimate the thermal comfort of occupant i under the room temperature T, where Δ represents other parameters excluding room temperature T. In this thesis, the focus is on the dynamics of room temperature and other fixed parameters Δ, thus the estimated function can be simplified to $P_i(T)$. The estimated thermal comfort function $P_i(T)$ is usually increasing under the current models since higher room temperature always means warmer thermal comfort. Noted that the estimated thermal comfort models may be built for all occupants $\mathcal{N}$, instead of each individual occupant. Under this case, each occupant has common estimated function $P_i(T) = P_{\mathcal{N}}(T)$.

Under the occupant-participatory approach, these thermal comfort models are trained by the occupants' actual votes. Denote the vote for occupant i under the room temperature T_0 as $v_i(T_0)$. The adjusted thermal comfort model, denoted as $\widetilde{P}_i(\cdot)$, is assumed to satisfy the following property.

Property 4.11.1. *For any temperature T, the adjusted thermal comfort model satisfies:*

$$\widetilde{P}_i(T)\begin{cases} \geq P_i(T) & \textit{if } P_i(T_0) < v_i(T_0), \\ \leq P_i(T) & \textit{if } P_i(T_0) > v_i(T_0). \end{cases} \tag{4.9}$$

The intuition for this property is that if one's vote is much larger (smaller) than the predicted thermal comfort, the predicted thermal comfort index for the adjusted model should be also larger (smaller) so as to be closer to the actual vote. This property is usually satisfied by the current works [67] [38] [11].

The BMS reacts to the votes of occupants by changing the room temperature with new temperature settings. The desired room temperature or requirement for each occupant may not be fully satisfied. The target room temperature are determined by the votes from whole occupants in company. $F(\mathbf{v})$ is used to represent this new temperature setting under current temperature T_0 when considering all requirements, where $\mathbf{v} = (v_1, \cdots, v_N)$.

There are generally two methods to obtain the best room temperature setting. One is to estimate the desired room temperature first and then determine the best room temperature according to the desired room temperature from all occupants. This method is known as *individual-based* voting scheme. Under this case, the decision-making mechanism is presented as $M(\mathbf{P})$, where $\mathbf{P} = (P_1, \cdots, P_N)$.

Another method is known as *group-based* voting scheme, it determines the group vote from all occupants' votes first and then estimate the room temperature according to this group vote. $V(\mathbf{v})$ is used to represent the decision-making mechanism for the group vote. In either case of methods, each occupant may have incentives to game the system with false vote. The truthful voting system is defined as follows.

Definition 4.11.1. *A voting system is strategy-proof if* $U_i(F(\widetilde{v}_i, \boldsymbol{v}_{-i})) \geq U_i(F(\boldsymbol{v}))$ *for any* $i \in \mathcal{N}$ *and any* $\boldsymbol{v}_{-i} \in \{-3, \cdots, 3\}^{N-1}$*, where* $\widetilde{v}_i$ *is the truthful vote for occupant* i*.*

Definition 1 states that a voting system is strategy-proof if voting truthfully always obtains the highest utility for each occupant. When the voting scheme is non-strategy-proof, each occupant may obtain more utility with false vote. This may result in both waste of energy and worse thermal comfort. An example is used to demonstrate the strategy-proof and non-strategy-proof scheme.

An example: Occupant A, B and C's optimal room temperatures are 23°C, 25°C and 26°C, respectively. Higher or lower temperature than its optimal temperature may result in worsen thermal comfort. Firstly, consider the average scheme, i.e., the setpoint temperature is the average of all required temperatures. Then, the setpoint is 24.7°C if each occupant votes truthfully. From occupant A's point of view, if she votes 21°C, then the temperature setting is 24°C given the truthful votes for occupant B and C.[1] Thus, occupant A benefits more if she votes untruthfully. This indicates that occupants has incentives to vote untruthfully and thus average scheme is non-strategy-proof.

Now, consider the median scheme, i.e., the setpoint temperature is the median of the required temperatures. When each occupant votes truthfully, the setpoint temperature is 25 °C. If occupant A casts false votes, e.g., 21 °C, given the truthful voting for occupant B and C, the median temperature is still 25 °C. Similarly, occupant B and C obtain no more benefit with untruthful votes. This indicates that the median scheme is strategy-proof.

4.11.1 Practical non-strategy-proof examples

The current work always assume that the occupants provide truthful feedback, however, the voting schemes designed by them are always non-strategy-proof. In the followings, two non-strategy-proof examples corresponding to individual-based voting scheme and group-based voting scheme are presented.

An individual-based example: The work in [67] demonstrated an individual-based model to set temperature dynamically. The proposed thermal model, is trained by four parameters (T_{in}, T_{out}, t, v), where T_{in} is the indoor temperature, T_{out} is the outdoor temperature, t is the elapsed time that the occupant entered the room and v is the value of vote. This thermal comfort model, denoted as $C_i(T_{in}, T_{out}, t)$ is increasing with T_{in}. The work [67] obtained the optimal air temperature by solving the following problem:

$$\max_{T} \#\{i| -1 \leq C_i(T, T_{out}, t_i) \leq 1, i \in \mathcal{N}\}, \tag{4.10}$$

[1]Although each occupant votes her thermal comfort, instead of temperature directly, we can still transfer the thermal comfort to the temperature.

where $\#Z$ denotes the cardinality of Z. Denote the optimal air temperature as T^*. For each occupant $j \in \{i| \, |C_i(T^*, T_{out}, t_i)| > 1\}$, if the occupant provides truthful vote, this vote has no impact on the decision process of the optimal air temperature. Yet, when if false vote is casted such that the training process makes the new thermal comfort model satisfying $|C_i(T^*, T_{out}, t_i)| \leq 1$, the vote can affect the optimal setpoint temperature and make it closer to the desired temperature. This indicates that the method in [67] is non-strategy-proof.

A group-based example: The work [38] demonstrated one dynamic temperature setting under the group-based voting scheme. It collected the whole votes and calculated the average thermal comfort index, i.e., $V(\mathbf{v}) = 1/N \sum_{i \in \mathcal{N}} v_i$ as an adjustment for the PMV model proposed. This PMV model can be simplified as the expression $PMV(T_{air} + T_{offset})$ when one considers the parameters except T_{air} and T_{offset} as constants. The work [38] determined the optimal setpoint temperature by the following equation:

$$PMV(T_{air} + T_{offset}) + V(\mathbf{v}) = 0. \tag{4.11}$$

Since the PMV model in ASHRAE [11] is increasing function in respect to $T_{air} + T_{offset}$, there exists $T_{air} + T_{offset} = PMV^{-1}(-V(\mathbf{v}))$. It means $T_{\mathcal{N}}(V) = PMV^{-1}(-V)$ and $F(\mathbf{v}, T_{air}) = PMV^{-1}(-1/N \sum_{i \in \mathcal{N}} v_i)$. Under this case, $F(\mathbf{v}, T_{air})$ is a decreasing function of v_i. Assume the truthful vote for occupant i is $\widetilde{v}_i$. Then, for any occupant i that satisfies $|\widetilde{v}_i| < 3$, we have

$$\begin{cases} U_i(x) > U(\widetilde{v}_i) & \text{if } 0 < \widetilde{v}_i < x \text{ or } 0 > \widetilde{v}_i > x, \\ U_i(x) \leq U(\widetilde{v}_i) & \text{if } 0 < x \leq \widetilde{v}_i \text{ or } 0 > x \geq \widetilde{v}_i. \end{cases} \tag{4.12}$$

According to definition 1, the voting scheme in [38] is non-strategy-proof. The occupants under such system have incentives to provide false votes.

4.12 Strategy-proof Voting Schemes

As discussed in previous discussion, occupants have incentives to cast false votes. This motivates the participatory design to consider a strategy-proof voting systems. In this section, the existence of strategy-proof voting schemes will firstly be demonstrated, and followed by the design of the strategy-proof voting schemes for the individual-based and group-based scenarios.

4.12.1 Existence of Strategy-proof Voting Schemes

Assume that the optimal temperature to an occupant is i. Recall that the closer thermal comfort index to the zero point, the more thermally comfortable to that occupant. The preferred temperature for occupant i can be calculated as:

$$T_i = \arg\min_{T} |P_i(T)|. \tag{4.13}$$

Since the thermal comfort model is continuously trained with occupant's vote, the preferred setpoint temperatures obtained from this model are thus be affected by the occupant's votes as well. The function $T_i(v_i)$ is used to represent the preferred room temperature at room temperature T_0 for occupant i with vote v_i. Then, this preferred room temperature function satisfies the following lemma.

Lemma 4.12.1. *$T_i(v_i)$ is non-increasing with vote v_i*

Proof. Considered the estimated thermal comfort $v_i = P_i(T_0)$ and one actual vote v_i'. Without loss of generality, assume that $v_i \leq v_i'$. Denote the new estimated thermal comfort function as $P_i'(T)$. According to property 1, $P_i'(T) \geq P_i(T)$. Since $P_i(T)$ and $P_i'(T)$ are increasing functions, hence $\arg\min_T |P_i'(T)| \leq \arg\min_T |P_i(T)|$. That means $T_i(v_i') \leq T_i(v_i)$. Thus, the proof is finished. $\square$

Lemma 4.12.1 indicates that voting warmer releases the information of a low desired room temperature. The intuition is that the trained thermal comfort model by higher vote makes the thermal comfort index under each temperature higher (Property 1). Since the thermal comfort model is an increasing function, the zero point shifts left resulting in lower desired optimal room temperature. This lemma is also true if one considers the preferred room temperature of whole occupants, instead of individual occupant, i.e., $T_{\mathcal{N}} = \arg\min_T |P_{\mathcal{N}}(T)|$. That means $T_{\mathcal{N}}(V)$ is also non-increasing with V.

Different room temperatures may result in different utilities for one occupant. The function $U_i(T)$ is used to represent the utility for occupant i when the room temperature is changed to T under the current temperature T_0. Denote the optimal room temperature setting under current temperature T_0 as $\widetilde{T}_i$. Assume that the utility for occupant i satisfies the following *single-peaked preference*[2], i.e.,

$$\begin{cases} U_i(\widetilde{T}_i) > U_i(y) \geq U_i(x) & \text{if } x \leq y < \widetilde{T}_i, \\ U_i(\widetilde{T}_i) > U_i(x) \geq U_i(y) & \text{if } y \geq x > \widetilde{T}_i. \end{cases} \tag{4.14}$$

The intuition of the single-peaked preference is that there exists one preferred temperature that maximizes the occupant's utility. Further away from this preferred temperature indicates lower utility for this occupant. This assumption is natural since warmer or colder temperature makes the occupant more uncomfortable.

Denote the truthful vote for occupant i under temperature T_0 as $\widetilde{v}_i$. Assume that the model built based on occupants' truthful votes can discover the optimal room temperature under temperature T_0, i.e., $\widetilde{T}_i = T_i(\widetilde{v}_i)$. Since $T_i(v_i)$ is non-increasing with v_i, the utility U_i also satisfies single-peaked preference with respect to occupant's vote, i.e.,

$$\begin{cases} U_i(T_i(\widetilde{v}_i)) > U_i(T_i(y)) \geq U_i(T_i(x)) & \text{if } x \leq y < \widetilde{v}_i, \\ U_i(T_i(\widetilde{v}_i)) > U_i(T_i(x)) \geq U_i(T_i(y)) & \text{if } y \geq x > \widetilde{v}_i. \end{cases} \tag{4.15}$$

Lemma 4.12.2. *If the occupants' preferences for temperature are single-peaked, there exist at least one strategy-proof voting scheme.*

Proof. Define one strictly increasing function $Q : [T_{min}, T_{max}] \to [-3, 3]$ with inverse function $Q^{-1}(v)$. This can be a linear function. Consider new utility function $\tilde{U}_i(v) = U_i(Q^{-1}(v))$ and new decision-making function $D(\mathbf{v}) = Q(F(\mathbf{v}))$. Noted that $U_i(T)$ is single-peaked function with respect to T. Then, $\tilde{U}_i(v)$ is also singe-peaked function with respect to v. Noted that $D : [-3, 3]^N \to [-3, 3]$. [79] states that when the decision-making function D is median function, $\tilde{U}_i(D(\tilde{v}_i, \mathbf{v}_{-i})) \geq \tilde{U}_i(D(\mathbf{v}))$ for any $\mathbf{v} \in [-3, 3]^N$, where $\tilde{v}_i$ is the truthful vote for occupant i. That means $U_i(F(\tilde{v}_i, \mathbf{v}_{-i})) \geq U_i(F(\mathbf{v}))$ for any $\mathbf{v} \in [-3, 3]^N$. Thus, according to definition 1, the proof is done here. □

[2]The single-peaked functions are not limited to the ones with single peak. The functions with single continuous set, all points in which are peaks, are also included. Here, the middle point of the set is treated as the single peak.

This lemma states that the single-peaked temperature preferences are the guarantee of the existence of the strategy-proof voting scheme. In fact, if the preference of each occupant is not constrained, the strategy-proof voting scheme does not exist.

4.12.2 Individual-based Voting Scheme

Under the individual-based voting scheme, the thermal comfort models are trained first, i.e., **P**, according to the occupants' votes **v**. After that, a decision-making mechanism $M(P_1, \cdots, P_N)$ decides the optimal room temperature. In this section, the decision-making mechanism $M(P_1, \cdots, P_N)$ is designed to guarantee the strategy-proof characteristic for the individual-based voting scheme.

Considered the median function, denoted as $\pi(a_1, \cdots, a_N)$, and defined by:

$$\pi(a_1, \cdots, a_N) = m, \tag{4.16}$$

if and only if $\begin{cases} \#\{i|a_i \leq m\} \geq \lfloor N-1 \rfloor/2+1, \\ \#\{i|a_i \geq m\} \geq \lfloor N-1 \rfloor/2+1, \end{cases}$ where $\#Z$ denotes the cardinality of set Z. Note that $\pi(a_1, \cdots, a_N)$ is one of the a_i. When N is even, there are two medians. Without loss of generality, the median function is assigned with one of the median values with half probability.

Theorem 4.12.1. *The individual-based voting scheme is strategy-proof if:*

$$M(\boldsymbol{P}) = \pi(\arg\min_T |P_1(T)|, \cdots, \arg\min_T |P_N(T)|). \tag{4.17}$$

Proof. Under this decision-making mechanism, $F(\mathbf{v}) = \pi(T_1(v_1), \cdots, T_N(v_N))$. Considered the linear increasing function $Q : [T_{min}, T_{max}] \to [-3, 3]$, we have:
$Q(\pi(T_1(v_1), \cdots, T_N(v_N))) = \pi(Q(T_1(v_1)), \cdots, Q(T_N(v_N)))$. That means $Q(F(\mathbf{v})) = \pi(Q(T_1(v_1)), \cdots, Q(T_N(v_N)))$. Denote $v_i' = Q(T_i(v_i))$ and $\tilde{U}_i(v) = U_i(Q^{-1}(v))$. Then, $\tilde{U}_i(v')$ is single-peaked with respect to v'. Thus, the decision-making function π makes $\tilde{U}_i(\pi(\tilde{v}_i', \mathbf{v}'_{-i})) \geq \tilde{U}_i(\pi(\mathbf{v}'))$ for any $\mathbf{v}' \in [-3, 3]^N$, where $\tilde{v}_i'$ is the truthful new vote for occupant i, i.e., $\tilde{v}_i' = Q(T_i(\tilde{v}_i))$. Then, for any $\mathbf{v} \in [-3, 3]^N$, we also have $\tilde{U}_i(\pi(Q(T_i(\tilde{v}_i)), \mathbf{v}'_{-i})) \geq \tilde{U}_i(\pi(\mathbf{v}'))$. Noted that $Q(\pi(T_1(v_1), \cdots, T_N(v_N))) =$

$\pi(Q(T_1(v_1)), \cdots, Q(T_N(v_N)))$. Then, we have:
$\tilde{U}_i(\pi(\mathbf{v}')) = U_i(Q^{-1}(Q(\pi(T_1(v_1), \cdots, T_1(v_N))))) = U_i(F(\mathbf{v}))$.

Similarly, $\tilde{U}_i(\pi(Q(T_i(\tilde{v}_i)), \mathbf{v}'_{-i})) = U_i(F(\tilde{v}_i, \mathbf{v}_{-i}))$. Then, we obtain that $U_i(F(\tilde{v}_i, \mathbf{v}_{-i})) \geq U_i(F(\mathbf{v}))$ and thus the proof is completed. □

Theorem 4.12.1 demonstrates a decision-making mechanism that makes the individual-based voting scheme strategy-proof. This strategy-proof voting scheme first obtains the preferred temperature from each occupant. Then, the median temperature of the desired temperatures from all occupants is set to be the optimal room temperature by the decision-making mechanism. This individual-based voting scheme also satisfies the fairness requirement, i.e., the chosen temperature is preferred by majority of occupants. The single-peaked temperature preferences guarantee that the median preferred temperature is always preferred by more than half of occupants, compared with any other temperature.

4.12.3 Group-based Voting Scheme

Under the group-based voting scheme, a decision-making mechanism $V(\mathbf{v})$ decides the group vote V. After that, the group-based voting scheme obtains the optimal room temperature $T_N(V)$ based on the group vote.

Theorem 4.12.2. *The group-based voting scheme is strategy-proof if:*

$$V(\boldsymbol{v}) = \pi(v_1, \cdots, v_N). \tag{4.18}$$

Proof. Denote the new utility function $\tilde{U}_i(v) = U_i(T_N(v))$. Since $U_i(T)$ is singe-peaked with respect to T, $\tilde{U}_i$ is also singe-peaked with respect to v. According to [79], the decision function $V(\mathbf{v}) = \pi(v_1, \cdots, v_N)$ under the new utility function is strategy-proof, i.e., $\tilde{U}_i(\pi(\tilde{v}_i, \mathbf{v}_{-i})) \geq \tilde{U}_i(\pi(\mathbf{v}))$ for any $\mathbf{v} \in [-3, 3]^N$, where $\tilde{v}_i$ is the truthful vote for occupant i. That means $U_i(T_N(V(\tilde{v}_i, \mathbf{v}_{-i}))) \geq U_i(T_N(\pi(\mathbf{v})))$ for any $\mathbf{v} \in [-3, 3]^N$. Thus, $F(\mathbf{v})$ is strategy-proof and the proof completed here. □

Theorem 4.12.2 demonstrates that the group-based voting scheme is strategy-proof if the median vote of all occupants' votes is chosen as the group vote by the decision-making mechanism. The optimal temperature can be obtained by the estimated thermal comfort model trained by this group vote. The group-based voting scheme only guarantees the majority preference for the median vote, but not for the optimal room temperature obtained from this vote. The reason is the seven-point thermal comfort index may not reflect occupants' accurate preferences of temperatures.

4.13 Simulation Results

In this section, the performance of the proposed voting schemes is evaluated by simulation . The occupants' thermal comfort state is considered as linear model, which is adopted by the standard [11]. According to the standard, the temperature range for comfort zone[3], i.e., thermal comfort index within $[-0.5, 0.5]$, is $[22.75°C, 26.25°C]$. Then, a linear model is built for the general thermal comfort as $P_{\mathcal{N}} = 2/7(T - 24.5)$. The preferred temperature for each occupant is assumed to follow Gaussian distribution with mean temperature $24.5°C$. Since the predicted percentage dissatisfied (PPD) value, defined by the percentage of occupants with thermal comfort index outside $[-0.5, 0.5]$, under the predicted mean vote (PMV) model during comfort zone is still 20%, it can be estimated that the standard variance is 1.37. Usually, errors happened when the occupant's thermal comfort is by estimation. Assume the occupants follow the Gaussian distribution $G(0, \sigma)$, and based on the thermal comfort index under specific room temperature, each occupant votes for their thermal comfort. The index of the vote for each occupant is assumed to be the integer value nearest to its own level of thermal comfort.

Figure 4.16 demonstrates the PPD with various numbers of occupants. Generally, both the group-based voting scheme and the individual-based voting scheme with $\sigma = 0.5$

[3]The comfort zone is decided mainly by six parameters. In this simulation, we take average values for parameters except air temperature.

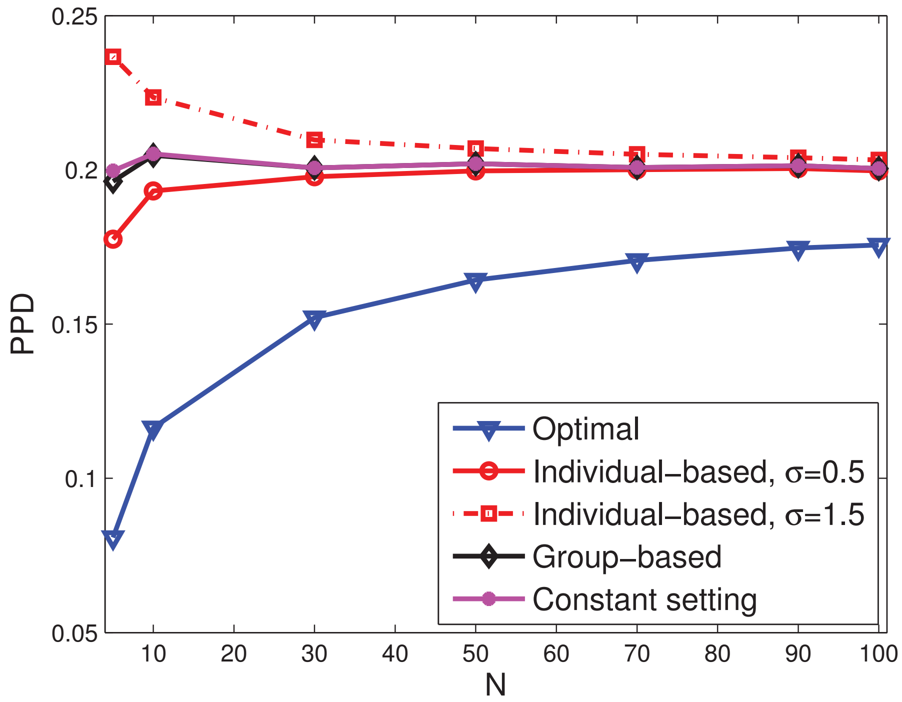


Figure 4.16: PPD vs. number of occupants

have lower PPD, compared with constant setting. The improvement is reduced when the number of occupants increase. The individual-based voting scheme with $\sigma = 0.5$ has lower PPD than group-based voting scheme. This PPD of individual-based scheme increases when the estimated error is large, e.g., $\sigma = 1.5$. The PPD of optimal setting is much smaller than both individual-based and group-based voting schemes. For instance, the PPD of optimal setting is only 0.08, while the individual-based scheme with $\sigma = 0.5$ has 0.18 and the group-based scheme has 0.2. The result motivates the incentives to improve the performance of individual-based and group-based schemes in the future work.

4.14 Summary of Chapter

This chapter first presents the background of thermal comfort, and the current problems in the temperature setting that suffered most of the facility management. The main challenges to the assignment of setpoint temperature today are that human perception can hardly be understood due to the subjective nature and varying preference of people. Besides, the current models of thermal comfort are not directly usable for the HVAC system setting; there are input parameters mismatch.

This chapter first studies the existing thermal comfort schemes from built environment, and proposes an occupant-participatory thermal comfort model framework that seek to transform the human comfort into a quantifiable and optimized setpoint temperature. The TCC model is developed according to the feedback of thermal comfort of an occupant under different physical factors that follow the EER model, and relates the heat production of one with the physical activity and external environment. The 7-point thermal comfort index from the ASHRAE is adopted, and the participatory design of using mobile devices to collect the occupant's thermal preference is developed.

With the individual-based TCC model, the algorithm of group-based setpoint optimization model that seeks to maximize the number of occupants staying in comfort zone is also proposed. With the field experiments in a commercial office and University, the results showed that the model is able to enhance the group thermal comfort while bringing the energy-saving opportunity.

On top of the models, the problems of providing false votes from occupants are also studied. In Section 4.11, the incentives and conditions for occupants to submit false votes are demonstrated, and the strategy-proof voting mechanism for both individual-based and group-based voting schemes are proposed and their performances are evaluated via simulations. A more comprehensive study towards the dynamic voting schemes are expected to work in the future.

CHAPTER 5

CONCLUSION AND FUTURE WORK

Human spends 80% of their daily time in buildings nowadays. Not only the energy consumption has become a worldwide concern, but the quality of services delivered by building systems are also important, since these factors affect the productivity and healthiness of people.

Building management system (BMS) is commonly installed in buildings to date. The BMS acts as the spinal cord to control and monitor various systems of buildings, including the HVAC system, lighting system, lift and escalator etc. Hundreds to thousands of sensors of different types for various purposes are deployed in buildings and installed in the equipment, providing real-time information to ensure the well-being of the operation of systems. This information is important to indicate any abnormal operations of equipment, and at the same time identify energy saving opportunity.

Based on the collected data, different measures and control improvements can be carried out to enhance the human comfort. For instance, the room temperature sensors help identify the distribution of conditioned air in the zones of building under different setpoint temperatures, by which the occupancy information can help the facility management decide the loading of air-conditioning and lighting provision during non-office hours. As such, additional sensors are desirable for providing a finer view of building information. It is envisaged that more sensors can be installed in a building; however, the enormous costs for additional wiring and engineering work have hindered the deployment of additional sensors.

Thanks to the mature development of wireless sensor network and drastic reduction in the cost of smart sensors, tremendous amount of smart sensors development and installation have been witnessed in the domain of buildings in recent years. Notwithstanding, most of the prior work are on an *ad-hoc* or short-term basis, they sought to propose new architecture from the bottom layers, or design from scratch, e.g. the data formats, the communication mechanisms and network topologies. Unfortunately, the abovementioned work either requires the replacement of the entire system components, or take a long time to be adopted by the existing legacy system, which requires re-architecture and sustainable efforts to consolidate the new architecture into standard from industries.

In chapter 3, an innovative framework is proposed that can convert existing wired building management system into wireless without modification on the existing building protocols. The modular design of *asynchronous-response* framework supports the seamless connection between the wired controllers and the connected smart sensors. With the wireless control engine, it adjusts and selects the optimized transmission between the smart sensors that relayed from the corresponding controllers. The critical frame identifier, which controls data under wired connection, helps eliminate the useless frames. In addition, simulations are conducted to validate the design of fast-forward of frame transmission.

The proposed framework can be adopted incrementally to buildings with existing BMS. The adoption is also restorable since no replacement of hardware and changes are made to the existing controllers. The evaluations are performed through experiments, simulations and the success in real-world deployment have affirmed its design effectiveness.

The design has omitted the routing module; the routing module is important if the communication range is long and relays are needed. Since this thesis focuses on the main challenges of remaining the upper layer protocols unchanged, the routing module will be left for future work.

To the best of the author's knowledge, this is the first research work done in converting a wired BMS into wireless without changing the upper layer protocols. The valuable experience and the innovative design of asynchronous-response framework can be applied into other domains.

Aside from the lower layers, on-going researches on applications are greatly available. This is primarily driven by the huge energy consumption of buildings worldwide, where different proposals are raised to curb the trend of increasing energy consumption. Prior to that, human-centric studies are carried out to ensure the energy saving scheme does not affect the provision of qualitative services to the occupants in buildings.

Heating, ventilating and air-conditioning (HVAC) system occupies a major portion of the energy consumption of buildings. Hence, numerous efforts have been paid to seek for the possibilities to save energy while maintaining the occupants staying in a comfortable indoor environment. This thesis studies the thermal comfort of people in buildings, seeking to find out the optimized temperature to a group of people.

In Chapter 4, the modular design of occupant-participatory thermal comfort (OPTC) framework is presented that aims to connect the occupants' thermal preferences to the temperature settings of buildings. Smartphones are adopted as the intermediary to help collect occupants feedback. Considered the difference of thermal requirement among a group of people, and the dynamic change of thermal preferences of people from time to time, the temperature-comfort correlation (TCC) model is first developed to establish a correlation between the indoor and outdoor temperature with the comfort index of each individual occupant. The setpoint optimization module is developed based on the TCC model to compute the optimal setpoint temperature for a group of people. The event monitor module collects data from the existing environment (e.g., indoor and outdoor temperature) and occupants information to facilitate the setpoint optimization, while gradually training the TCC model. After setpoint optimization module makes an adjustment decision, the building controller module communicates with the BMS to change the setpoint of the specified area.

Simulation and comparison to different body mass index (BMI) ratios of people using classroom schedule are studied to evaluate the potential thermal comfort improvement of people. Real-world experiments are conducted in a university and a commercial office. The results show that an average of 63% and 33.8% thermal comfort improvement are observed respectively, while the proposed system is able to save 18% of energy consumption of the air-conditioning terminal units during the experiment. Lastly, the false vote problem of occupants is also studied, and a strategy-proof voting schemes for the thermal comfort vote is presented.

For the future work, the experiment of OPTC framework can be scaled up in the number of people and the difference of ambient conditions, and more studies of the temperature-comfort correlation can be carried out in each BMI category that target to improve the precision of models. For example, the alternative of Estimated Energy Requirement (EER) model can be adopted and compared to seek for a better reference of the heat generation model.

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