

Energy Consumption Modeling
in Wireless Sensor Networked Smart Homes

by

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Thesis submitted to the
Faculty of Graduate and Postgraduate Studies
In partial fulfillment of the requirements
For Master's degree in
Electrical and Computer Engineering

School of Electrical Engineering & Computer Science
Faculty of Engineering
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Acknowledgements

Foremost, I would like to express my sincere thank to my supervisor, Prof. Hussein T. Mouftah, his patience, encouragement, and immense knowledge were my key inspiration throughout my master study. I am truly thankful for his selfless dedication to both my personal and academic development. I cannot think of a better supervisor to have.

Many thanks to Dr. Irfan S. Al-Anbagi for the guidance and support, his extensive knowledge in this field has always pushed me to achieve more in my study.

Special thanks to my best lab mate Naouar Yaagoubi for her help and many jokes we laughed together.

Finally, I want to thank my parents for their love and understanding through everything and always embrace me as who I am all the time.

Abstract

Smart home automation is the dwelling bridge of smart grid technology, as it integrates the modern home appliances power consumption information over communication networks in the smart grid system. Among all the appliances, Heating, Ventilation and Cooling (HVAC) systems is one of the most primary concerns. Since a great amount of power consumption is contributed by these HVAC systems. Traditionally, HVAC systems run at a fixed schedule without automatic monitoring and control systems, which causes load variation, fluctuations in the electricity demand and inefficient utility operation. In this thesis, we propose a Finite State Machine (FSM) system to model the air condition working status to acquire the relationship between temperature changing and cooling/heating duration. Finally, we introduce the Zigbee communication protocol into the model, the performance analysis of the impact of end-to-end delay over HVAC systems is presented.

I am dedicating this thesis to my beloved parents.

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List of Acronyms

AMI Advanced Metering Infrastructure

AMR Automated Metering Reading

ANN Artificial Neural Network

ASHRAE American Society of Heating, Refrigerating and Air-Conditioning Engineers

CCHP Cooling, Heating and Power

D&R Demand and Response

EM Engineering Methods

EMU Energy Management Unit

FFD Full Function Device

FSM Finite State Machine

GHG Green House Gas

HEM Home Energy Management

HVAC Heating, Ventilation and Air Conditioning

ICT Information and Communications Technologies

PHEV Plug-in Hybrid Electrical Vehicle

PLC Power Line Communication

PUC Personal Universal Controller

RFD Reduced Function Device

SHGC Solar Heat Gain Co-efficient

SM Statistical Methods

TOU Time-of-Use

Wi-Fi Wireless Fidelity

WSN Wireless Sensor Network

List of Symbols

- Q_t transmission load
- T_o indoor temporary temperature
- T_i indoor temporary temperature
- U heat transfer constant
- S air-conditioned area
- Q_{inf} Infiltration load
- q_v air flow rate
- c_p real time heat of air
- ρ air density
- h heights of a single story building
- V volume of the entire building
- W_o current atmosphere humidity
- W_{ro} indoor humidity
- Q_s solar load
- A_w area of total windows in the building
- E irradiance of solar beam
- $S(t)$ Solar Heat Gain Co-efficient function (SHGC)
- Q_{int} internal load
- G_{int} total light wattage
- $F(t)$ lighting use factor
- E HVAC system power consumption

E_{loss} energy loss

E_{init} HVAC systems power consumption at initial temperature

E_{setting} HVAC systems power consumption at setting temperature

Chapter 1

Introduction

1.1 Background

Smart grid technologies and the up-to-date electrical power grids are currently undergoing fast pacing innovation, making the effort to develop a newly styled power grid system to deal with the higher requirement of power consumption in the near future. The great convenient features of smart grid help improving the performance of energy utilization in terms of different applications, such as real time supervision of power distribution, individual smart home monitoring and the load management of energy consumption.

Smart grid integrated Information and Communication Technologies (ICTs) in its operation that work on the behavior of all the power suppliers and consumers, aiming at improving the efficiency, importance, reliability, security, economics and sustainability of the entire power system. Right now an exigent set of circumstances in traditional power grid still need to be solved. In fact, the most basic factor that triggers the development of smart grid is the Green House Gas (GHG) emission issue, rather than the well known coal burning approach of power generation, an alternative trending solution provides a better way of reducing the GHG pollution, some renewable energy resources such as sunlight, wind, ocean tide and nuclear

power gives a cleaner and safer environment, however it is estimated that more than half of the energy generated is wasted along the way of its generation and transmission due to the electricity natural physical feature [LUI10]. Therefore, this fact has been proving the inefficiency of operation over the traditional power grid, more accurate measurement needs to be taken to minus the gap between the power suppliers and consumers in order to avoid the possible energy waste.

As the current popular trend in smart grid, wireless sensor networks provides the intelligent sensors carrying the electricity information collected that can automatically build up the networks itself and communicate through the wireless channels, thus making it more flexibility and more possibility to scale. And without the higher cost of installation and maintenance of the physically attached sensor nodes, WSNs also offers the much cheaper way of deployment [MEL11]. In addition, however, as most of the sensors are deployed in an unmanned area, weather condition, electrical faults and other unexpected ambient situation can lead to the failure of sensors which may cause the whole area uncovered [HAB10], as a result, the restoration and back up scheme is also necessary to keep the network work well.

One of the heated studied applications over smart grid system is smart home, which is elaborated as a comprehensive system, deployed by a vast scope of technology such as wireless communication, intelligent computing and the real physical wiring to integrate all the indoor sub-systems. [CHJ09] These sub-systems control the home appliances and devices such as lightings, air conditioners, furnace, stove and washing machine. Through this manner, residents in both residential and

commercial buildings are able to simplify and unify the management within the living area, as well as offering the data and information interaction between different appliances. Smart home at the same time provides a more convenient, secured and power efficient environment, especially for seniors and people who need special help.

Home automation as one important technique of smart home system can be created through a great range of methods. System can take advantages from basic remote control to built-in computer controllers, which are connected to a small area of networks. With the increasing demand of multi-functional home appliances, interaction and communication between these devices become more vital than ever before, higher level of computing algorithm needs to be studied to reduce the burden of energy usage. For example, HVAC systems (Heating, ventilation and air conditioning) requires not only manual operation in terms of humidity and temperature, but also a more accurate comfort level to create a better indoor environment, and saving the energy bill in addition. Consequently, home automation indirectly has become an efficient approach to control the energy utilization and rendering the surveillance of home appliances to be better understood.

Space heating and cooling accounts for more than half of the entire residential energy consumption, researches carried out recently shows that there is an estimation of 48% of energy consumption in U.S. homes [USE09]. Therefore, HVAC contributes the most in energy consumption in residential and commercial buildings, necessary research on all perspectives of HVAC systems should be studied in order

to possibly rendering energy savings, as well as to improve humidity and temperature comfort level in the buildings.

Researchers all over the world are still dedicating to innovate the newer generation of wireless sensor network in smart grid which targets at the different sections of power system, and newer approaches will continuous its impetus to the efficiency, utilization and multi-functional of power grid.

1.2 Motivation

The increasing demand of energy need and the dwindling oil reserves are the two main factors bringing about the fast rising hydro price and the rigorous social debate regarding the green energy evolution. The global worsen climate and the fast growing population over the last century have been contributing to the greater desire of more energy utilization as well. It has been proven that for example, there is an annual increase of 2.5% power demand during the last two decades according to the U.S. Department of Energy report [USE09], and the residential power need is forecasted to rise by 24% in the coming-up 30 years according to the recent Annual Energy Outlook report of the U.S. Information Administration [USE09], and this number does not only apply to U.S., the global power demand is also on the increasing trend ever since. While such higher demand is stimulating the economics and bringing a lot of working opportunities, the negative sequences also caused controversy considering the declining fuels and the continuous emitted GHG

polluting the global atmosphere. In addition, the increasing power demand is putting unprecedented burden on the existed power system infrastructure, which had already been facing the same questions for years. Therefore, with the minor innovation and re-construction of the current power facilities, how to scientifically and intelligently distribute and utilize the power has become a popular topic today and also is facing lots of challenges.

According to [USE09], the number of housing units in U.S. was increasing on a fixed linear speed over the last 30 years, however, the total residential energy consumption was not on the same trend but on the contrary, has downsized at a stable rate. This would largely attribute to the improved energy efficiency that compensates the growing number of residential units. Among all the attempts of how to utilize the energy more efficiently, HVAC system accounts for most of the endeavor [YAH10]. Nevertheless, there is still a large margin to be filled for higher energy utilization inside the HVAC system.

1.3 Contributions

This thesis mainly focused on analysis of power consumption of HVAC system and other electrical appliances in residential and commercial buildings in smart grid.

The contribution of the thesis can be categorized into two parts. Firstly, we investigated the behavior of the power consumption of HVAC systems in a typical single family house of around 2000 square feet in Ottawa, Ontario all around the

year at different temperature set points, in addition, we did the analysis of optimizing the temperature gradients of HVAC systems to maximize the energy efficiency. Secondly, we introduced Zigbee wireless communication protocol into the model of a typical commercial office building; we allow each and every room to be equipped with an air conditioner, and these air conditioners are attached and controlled by the sensor nodes, which could not only enable the working status of the machines, but also collect the information to be transferred within the system. By doing this, we looked into how the end-to-end delay in Zigbee communication system would impact the power consumption of HVAC system.

We have proposed a Finite State Machine (FSM) system to model the air conditioner working status using Ptolemy software, and for the specific power consumption by HVAC systems, we used Matlab to train the real time data into our model and acquire the accurate power consumption data. Finally, we used OPNET to model the Zigbee communication in the model, in order to study the impact of end-to-end delay over power consumption of HVAC systems.

1.4 Thesis Outline

The rest of the thesis is organized as follows. Chapter 2 gives a literature review regarding the previous content of smart grid, smart home and different approaches to optimize the power consumption in HVAC systems. Then in Chapter 3 we present our model of residential and commercial buildings, and introduce the thermal

functions into the model; in addition, we present the integration of Zigbee and the HVAC systems. This is followed by Chapter 4, which we are presenting the simulation results and giving out the performance analysis. The whole thesis is concluded in Chapter 5 where we are introducing some future research works as well.

1.5 Related Publications

W. Xie, I. Al-Anbagi and H. T. Mouftah, "Finite State Machine Performance Analysis of Power Consumption in Residential and Commercial Buildings", in the IEEE International Conference on Smart Energy Grid Engineering (SEGE'14), 11-13 August, 2014, Oshawa, ON, Canada.

W. Xie, I. Al-Anbagi and H. T. Mouftah, "Impact of End-to-End Delay in Zigbee-based Communication Systems on Power Consumption in Smart Homes", Proceedings of the 6th Annual WiSense Workshop, University of Ottawa, Aug. 2014.

Chapter 2

Literature Review

2.1 Introduction

Proper measurement needs to be taken on renovating the existing power grid system into the next generation of smart grid due to the problems of global increasing power demand and the air pollution brought by fuel burning. Smart grid targets to co-operate the advanced ICT into power grid and thus initiate the operation over the grid. Smart grid is considered as the new solution for the connection of sensors, which could collect information and possibly analyze the data to be shared within the auto-build or pre-defined network. Therefore, a great group of applications have been studied over the past decades, such as environmental monitoring, energy management in smart home and communities [MAG10]. Smart grid has drawn an unprecedented attention in the last few years [QIU11]. Current power system has been criticized as of incapability to take on the burden for daily increasing demand, for example, unsound quality of monitoring over the aged power grid would be able to cause the serious blackouts and large financial losses, the concurrent imbalance between the growing demands and lack of enough power supplied is being enlarged continuously in the future, appropriate maintenance over the power grid system is urgently necessary [MEL11]. Finally, power system also needs to be protected from being hacked by malicious attacks and misbehavior, a

more comprehensive multi-function system has to be applied to create the real safe power grid environment.

In addition, in order to comprehend the concept of smart grid and how it is achieving energy savings, we have to understand the physical power infrastructure that backs up all of these cutting edge innovations, as well as at what point does the savings come from. That is the exploration of power utilization in the residential and commercial buildings, the particular methods to configure and manage the electrical devices, and the renewable power resources along with the energy storage mechanism.

This chapter is outlined into two parts. First part presents the overview of the literature on smart grid and different applications along with their technical points. From fundamental wireless sensor network techniques to specific approaches taken in the studies are surveyed in this part. The second part is all about detailed smart home technology, especially the research on HVAC systems. Therefore, this chapter is listed as follows. Section 2.2 briefly introduces the importance of smart grid and its basic architecture. In Section 2.3, the survey of technical design of smart home is given here. Section 2.4 describes the studies of HVAC systems and the its detailed energy consumption.

2.2 An Introduction to the Smart Grid

At the beginning of this century, two major electricity blackouts hit the North America which caused sever financial losses of almost 10 billions U.S. dollars and impacted about 55 millions of customers, this event aroused the discussions over the reliability of the traditional power grid and urges the system to be renovated.

The increasing power plants and the mounting up renewable resources are giving more pressure on the current power system in terms of power load shifting and GHG emission. And a basic diagram illustrated the power generation is give as Figure 2.1. Some latest techniques integrated into the old power system and the requirement of customers nowadays demand to get involved in this process also give promote the upgrading of the power grid system.

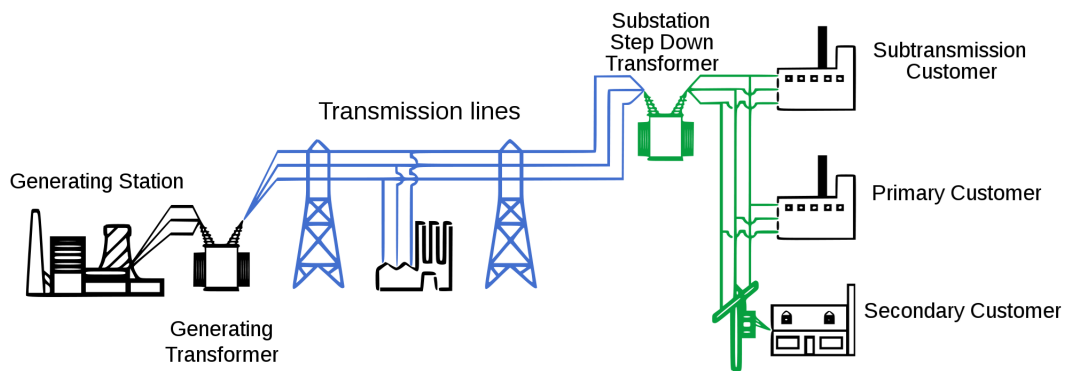


Figure 2.1 A basic power generation diagram¹

Re-building the whole power grid system can be expensive, however, either power supplier or customers would benefit a lot in terms of avoiding power transmission, in another word, power generation and consumption can be implemented at the same location, rendering the power supplier to produce more

¹ Author: US Department of Energy, under GNU Licence

electricity according to the local need dynamically and avoid the transmission waste. Moreover, prominent innovation of energy conservation has been proposed for a while and the according research is still undergoing, hence more infrastructure of power grid needs to be developed in order to lift up the whole system into a new era.

Smart grid is a highly integrated power grid based on the physical grid [MIL12] as shown in Figure. 2.2. Smart grid is defined as “*an electric network that can intelligently integrate the actions of all users connected to it: generators, consumers and those that do both, in order to efficiently deliver sustainable, economic and secure electricity supplies*”.²

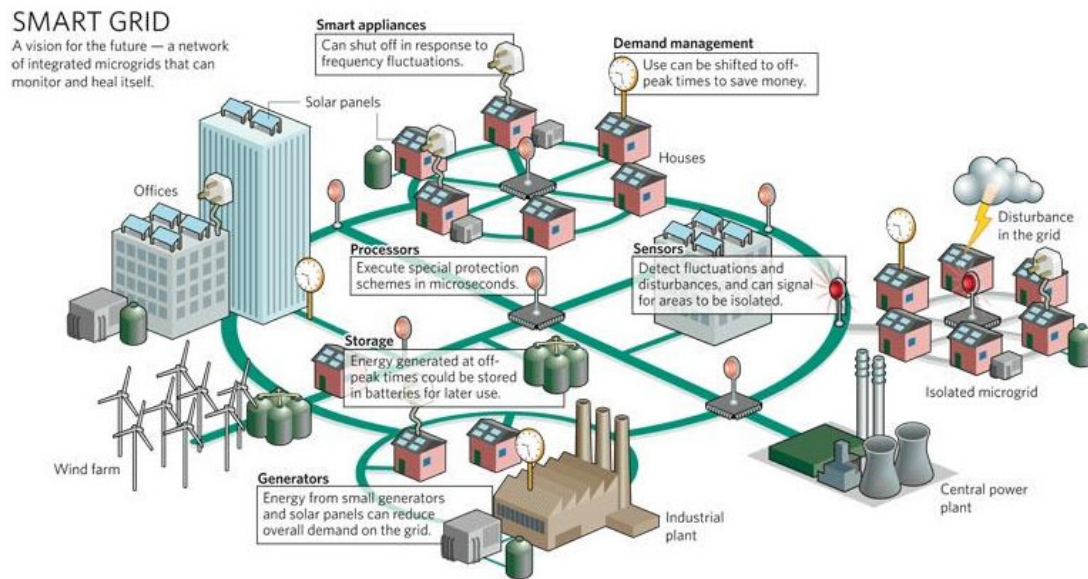


Figure 2.2 Smart grid conceptual scheme³

² By European Technology Platform Smart Grid (ETPSG) definition

³ By Schneider & Electric company

As the extension of the existed power grid, it cooperated the renewable energy generation as power plants into the system, combining the intellectual sensors detecting the ambient information and sending these data to the analysis center for the proceeded steps, eventually feedback into the system.

From the perspective of information sharing, the process of information and data is implemented by the communication infrastructure that builds up the connection in the grid. Plus, a controlling scheme is also a must taking responsibility of making sure the interoperability of communication into the power grid works effectively and efficiently [COS12].

To conclude the main features of smart grid, [MCD10] defined that it should posses the following capabilities:

- Power efficiency: with the simplified power system and transmission losses to improve the performance of load control, peak load shifting along with the governmental policies for power reservation;
- Operational efficiency: enhance the power generation efficiency, communication infrastructure optimization, improve the remote monitoring ability, power facilities utilization and reduce the labor maintenance;
- Customer satisfaction: to consolidate the original state of customers' operation level and improve the customers' self-service ability;

- GHG emission control: based on the load management to reduce the amount of power needed and to fully utilize the renewable energy as well as the improvement of the energy conservation, therefore enable the reduction of GHG emission.

There are two main challenges that needs to be solved when a concrete smart grid system is being built: first is the interoperability between different power grid infrastructures and the communication systems working on various protocols, and the second is the scalability with lots of different power supply organizations and the consumer environment where hundreds of appliances and cutting edge techniques will be applied. Therefore, it is crucial to address these two challenges to further implement the merging of both electrical and communication system into one unified model. Smart grid system with correctly designed communication mechanism will benefit its precise and efficiency energy consumption; in addition, a complete smart grid system should also be functioned as information collector such as the amount of power produced, transmitted, wasted, stored and consumed, as well as the performance of its distribution into the communication part. [CHE10]

We are now taking an overview of the smart grid architecture in terms of the internal components before the review of smart grid communication architecture. In the smart grid system, several energy resources plants with its intermittent nature are all associated into the electrical system as a complete entirety. As mentioned before, traditional renewable energy resources such as sunlight, wind and tide will be producing extra energy to supplement the shortage of the mainstream power generation method such as fuel and nuclear power, that is to say, the surplus will be

flowing back to the backbone of power system when the extra energy generated by the renewable power plants exceeds the real needs. [WAN11]

Under the guarantee of additional small-distributed energy resources, multi-direction energy transmission can be realized in the power grid dynamically. As in Figure 2.3 the smart grid architecture is built up, several devices with different functionalities are included in order to achieve better management upon the system. And these devices are A. Service provider, B. Market, C. Operation, D. Bulk generation, E. Transmission, F. Distribution and G. Customers, blue arrows are electrical flows and red dot arrows represent communications. Meanwhile, communication infrastructures among different devices are responsible for coordinating the diversified power bases throughout the whole system. The reference smart grid framework proposed in NIST⁴ usually includes customers, markets, service providers, management, bulk generation, transmission and distribution as well as communication devices.

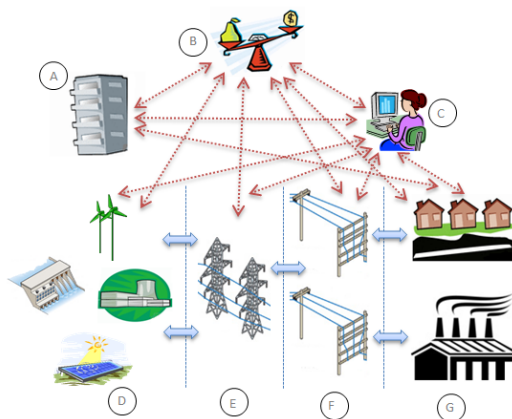


Figure 2.3 General Smart grid architecture

⁴ By National Institute of Standards and Technology

After taking a review on the traditional smart grid architecture, the smart grid can be concluded as the system possessing the ability of the following key points [CHE09]: (1) information transmission over the various agents; (2) data acquisition and analysis at the fast pace; (3) always adapting to the industrial changes; (4) scalability to more devices and various types of power systems while keep its reliability and security.

Finally, we are discussing the communication architecture [GAO12], which can be seen in Figure 2.4 as a conceptual system. The entire system is built up in a distributed approach as the smart grid system itself. The architecture just presents the layered elements what contributes to the communication system but does not provide the information about the specific techniques applied inside. So here we are going to provide a case study for smart grid communication system.

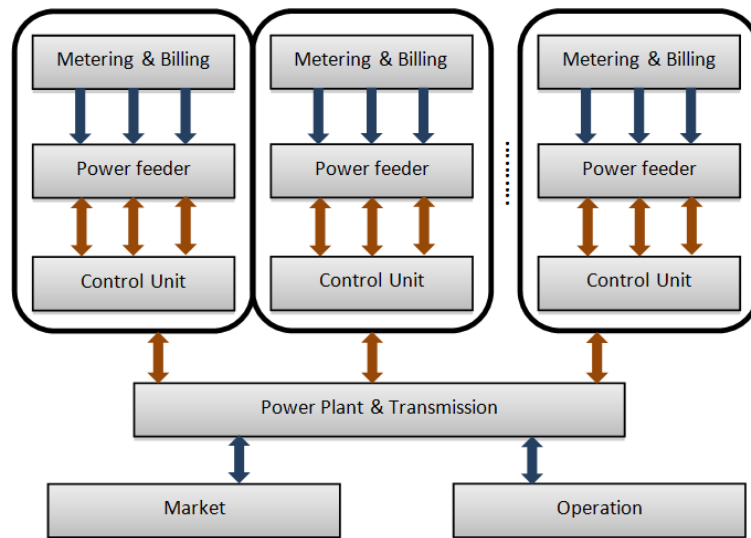


Figure 2.4 General Smart grid communication architecture

Different communication techniques can be employed into smart grid networks and both wired and wireless communication which establishes the connection between power generator plants and the consumers are deployed largely for supporting massive amount of applications such as demand response and distribution. [MED10] The coverage area of the networks varies depending on different system requirements and therefore diversified wireless communication techniques such as cellular, radio frequency, 802.11 and the Zigbee that was adopted in our projects can be applied inside of the smart grid communication systems.

In [PAP14] the author introduced a smart grid architecture of sensor platforms based on a hierarchical structure, it is distributional platform which reduces the possible environmental impact on the energy distribution and transmission side, resulted from the reason that wireless sensor network possesses the disadvantages of easily out-of-energy sensors, surrounding interferences and shadow fading.

Erol-Kantarci and Mouftah [MEL10] presented a mechanism called Appliance Coordination (ACORD) which deploys in-home Wireless Sensor Network (WSN) in order to improve the efficiency of energy consumption at the house-range level. Time-Of-Use (TOU) rates and Energy Management Units (EMU) are also introduced in this scheme to make it more reliable. TOU rates make the customers get billed in a flexible way and the rates varies at different time period. EMU can coordinate the requirements from customers and make rapid changes to the way of using power to get further less billed. The challenges, however, still exists in the difficulty to change people's choice on energy usage; secondly, energy waste for power oscillation when

load changes does exist and is unpredictable; and lastly, the potential communication interference might impact the data transmission when different home appliances are trying to communicate.

Authors in [BIS09] stated that power monitoring is incurring more attention due to the power quality requirements. And they present a complete scattered power supervision architecture, which focuses more on voltage monitoring based on the self-organizing wireless sensor networks. In this project, every sensor node has the ability to analyze the performance and take rapid actions based on the data collected locally or transmitted from other sensor nodes.

Authors in [SCH12] presented a method called mosaic for merging the existed, different kinds of simulation models into the smart grid simulation. It provides the capability of system monitoring, specification of scenarios and the simulation model establishment and a prototype has been validated over the approach proposed. However, the simulation model is carried under a hierarchical structure which is impossible in real life, additionally, the data communication between nodes in the smart grid relies on the power transmission first which makes it constrained under the requirement that communication should be among all nodes and power resources.

Communication system eventually has to be scalable for the potential use in the future and they should also provide the support for the access network that connects the backbone nodes to the attached extra nodes. Therefore in order to meet the previous requirements, our simulator will be using wireless sensor network along with

Zigbee communication protocol. Zigbee WSNs are of lower cost, energy consumption and the better performance in its scalability.

As mentioned previously, the study of smart grid can be penetrated into every aspect but some trending topics are currently drawing the public's attention in order to realize the power utilization improvement, and these fields are list as below:

- Delivery Optimization
- Demand Optimization
- Asset Optimization

And under each category, some more specific applications are included, for example, within the demand optimization scope, the idea of smart home automation, load management, operation of renewable energy and TOU billings are proposed, while smart metering is defined and carried out under asset optimization [COS12].

2.2.1 Demand and Response (D&R) optimization

By reconsidering the actual power demand and adjusting the load requirement especially during the peak hours afterwards can largely improve the performance of energy utilization both financially and efficiently. Demand and response as the vital method through which the energy usage control can be covering the whole area from physical grid to residential location is considered to be an effective way to enable the customers dynamical shifting of the power need based on their using habit.

To help realizing improving the performance of power utilization through the D&R method, a lot of according framework has been studied over the past decade.

[FAN10] proposed architecture for the distributed demand response and user adaptation in smart grid networks, as well as he applied the idea of congestion pricing in network traffic control and made the demonstration of how the billing data can affect the customer demand by leveraging the network load, therefore, it is the billing rate dominating the whole system to make the simulation and analysis.

Meanwhile, in [WAN10], end user preferences along with the idea of discomfort level are aggregated and managed to maximize both energy efficiency and user satisfaction. A distributed algorithm is also given to balance the power load and eventually optimized the results using selfish load balancing approach.

A similar study was carried out by [MOH10], in their research, Energy consumption scheduling devices are deployed into the smart meters within the local area where a one and only energy source is provided. Distributed algorithm is running automatically inside these devices to find the best solution to minimize the overall power consumption. Two-way communication between smart meters and the power grid via local area network was built to share the power usage data.

For the previous study, user preferences are taken into consideration right before the optimization can be done. Two-way communication between the users and the power providers is also required.

Overall, governments are still taking some measures to regulate the power market along with the infrastructure of communication to be re-designed and built in order to be interoperable with the physical power architecture.

2.2.2 Smart meter

A smart meter is an electronic device that reads and collects the real time power consumption data in a certain fixed time intervals and sends it back to the power utility company for supervision and billing purposes [MCK12]. This kind of device usually supports a bi-directional communication between the device itself and the monitor of the power system. Compared to Automated Metering Reading (AMR) services, smart meter offers an unbroken chain of functions such as quality control, dynamic billing query and unique customized user preferences. Integrating these features into the Advanced Metering Infrastructure (AMI), power providers and customers all can be benefitted with more diversified services and more accessible information.

Apart from the advantages that smart metering might bring to both side, it meanwhile offers a bunch of benefits to the customers on economical, social and even environmental protection level from their perspective. First, smart metering would help customers better manage their billing queries and make the predication and estimation for the future bills; secondly, smart metering at the same time is able to provide the better management over their power usage, pointedly, smart meter usually is commonly equipped outside every residential home so the customers can directly read their real time data, by doing so customers can adjust their power consumption in order to not only reduce tariff but also contributing to the GHG emission endeavor.

The authors in [KAR11] elaborated the generic survey on smart metering techniques and the specific role it should be playing in the smart grid architecture along with the analysis of implementing approaches, some of the potential feature that might be developed in the future was also discussed. Smart meters should serve both residential and commercial customers, therefore, the connection between meters and users gateway is of great importance here. Commonly, when people refer to smart meters, not only power consumption should be supported, some other utilities such as gas and water is also indispensable, thus, a multi-utilities smart meter that can provide all the comprehensive information regarding the different daily utilities is the future trending for the market. In addition, smart meters is better to be designed to be embedded system so that utility company can program on its platform to have all kinds of features implemented, and based on this point, a layered architecture should be built up inside of smart meters. Finally, the model consisted of physical power grid, utility company and the customers as end-users of smart meters are proposed at the end of the survey.

Some of the techniques that are necessary for smart meters are widely studied. [LUA09] proposed the wireless communication technologies design to implement the smart power meters. The Zigbee system is given and integrated into the smart meters to send the power consumption data to the end processor for the future analysis and the possible feedback. Similarly, [CAO08] proposed the remote wireless AMR system using Ethernet transmit data from the gateway set at the end-users to

the serve as the power utility company, wireless mesh network was deployed as the topology structure and the routing protocol is designed and verified as well.

2.2.3 Load control

Load Control is under study since 1990s, according to the [LIU11], it is the process of leveraging the supply of power with the load required from the end users by shifting or taking the direct control over the load rather than the power delivered as the fixed to the destined location. The whole idea can be implemented by the manual or automatic interference over the power utilities at any time, either software or hardware approach is applicable, for example, by the use of time clocks, or by the pre-programmed billing system to affect the user's power using habit. By taking load control, the demand of power at peak hours might be alleviated and continuous to reduce the total power consumption, as well as the cost of support and maintenance upon delivery of extra power amount. Conceptually, load control can be implemented using the following three types of control: direct control, local control and decentralized control [COS12].

2.2.4 Power demand prediction

There is the central monitor taking control of all the home appliances, this central monitor as we know for Home Energy Management (HEM) can provide various functions benefiting both customers and power utility companies, and one of the functions HEM can bring is the customer's energy consumption profiling [KHA13], and this information would help customers better schedule their power usage plan,

plus the power delivery burden would be largely reduced and maintenance cost is expected to be reduced too.

Lots of endeavors have been spared by hundreds of researchers on modeling the home power management through different approaches. [KAI11] gave a complete and comprehensive review on these modeling techniques upon the end-use power consumption in the residential area. The process of estimation of power usage made based on the modeling and simulation can deploy either top-down or bottom-up methods, for the previous approach, all the individual consumers as an entity in the certain residential area is treated as the energy sink and there is no gap between different power users; the latter bottom-up approach mainly concentrates on collecting customer's usage data and try to fit into the accumulated data model provided by utility companies. Under the scope of top-down method, it seems impossible to tell the difference between the users, that is to say, to decentralize the prediction upon individual customer, its results may only in favor of a certain area of community, and as it takes the raw collected data as a whole, the software design might be easier to implement. However, on the contrary, bottom-up technique seems have better performance in terms of customer's perspectives; data regarding each end user is collected individually in order to be extrapolated to represent the region based on the representative weight of the modeled sample [BON11]. Moreover, what makes bottom-up method stand out is that it consists of both statistics and engineering approaches. Statistical Methods (SM) largely depends on historical data and the regression analysis and to deploy this information to the specified end-user,

and the model can be deployed to predict the power consumption in the future. The Engineering Methods (EM) as its name explained already, is taking consideration of the empirical mathematical data model such as thermal characteristics of the house, power consumption of the specified appliances and the energy using habits of customers [FUM10].

The components of both top-down and bottom-up techniques for modeling power consumption in the residential home area are illustrated in Figure 2.5.

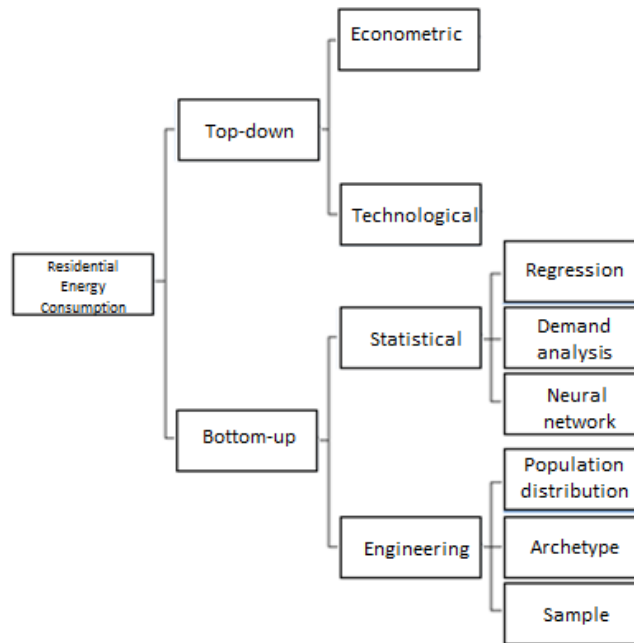


Figure 2.5 Top-down and bottom-up modeling techniques for estimating the regional or national residential energy consumption

Overall, energy consumption data aggregation is critical for the HEM, it provides not only the power usage prediction under the optimization scheme, and also some other services can be benefited too.

2.3 Review of smart home

Smart grid as presented in the previous content, integrates the communication and monitoring technology into the traditional power grid system in terms of power generation, delivery and distribution. These sections all targets to create the more effective and efficient power grid environment, one important application that cannot be ignored is the smart home, which usually contains a smart meters, smart appliances and smart HEM as previously introduced. Figure 2.6 shows the components of a typical smart home.



Figure 2.6 An example of Smart home automation

Smart home automation is the dwelling bridge of smart grid automation, which mainly concentrates on the residential home activities. Central monitor may take control over almost all the home appliances and secure the locks of the entrances, in

order to provide the living environment with better comfort, security and the most important is the power utilization efficiency.

A home automation system consists of various electrical appliances within a residential area. Local control is a critical issue for implementing home automation; it takes responsibility to change the ambient environment for different activities, and changes the working status of each device at home. All the devices can be connected to a local area network or they can build up the network automatically and eventually get communicated with a central monitor, which gives the permission to the customers either locally or remotely. By integrating the information technology and home automation, home appliances can work in an innovated method, creating a more convenient, power utilization efficient and secured living environment.

2.3.1 Communication architecture for smart home

It has become the prevalence to for smart home marketing in the recent years thanks to great changes taken place on the development of smartphone and wireless communication technology. Home communication network can be built up via different communication technologies such as wired Internet, wireless communication and Power Line Communication (PLC), and therefore, gateway between power grid and communication infrastructure has become an issue too.

Regarding to communication system in smart home, a wide range of selections as well as the communication devices are very important as they are responsible for the considerable data to be shared among power utility companies and customers, plus, these data should be secured and only accessible to restricted group of people only.

In [KOA03], authors designed and implemented the Bluetooth enabled energy meter, which sends the power consumption readings to the central processing unit wirelessly. Meanwhile, [HWA14] proposed the HEM system based on PLC, which takes usage of the existing power grid, network infrastructure, wireless communication devices and internet connection to implement the power consumption related data sharing. [HUC06] made a brief review over the development of PLC, he stated in the paper that all the electrical devices with the plug onto the wall are able to deploy the power line as their Internet service medium, however, there are still some open issues: 1) High frequency signals transmitted on the power line would cause higher interference due to the attenuation and noise to the data that needs to be sent; 2) Topology deployment largely depends on the already existed power line, modification or maintenance is hard to implement; 3) Different power lines would increase the possibility of more interference to the ambient lines; 4) The data acquired at one single node of the local network, pointedly, at a home appliances for example, are exposed to all the nodes in the connection and thus increase the risk of attacks. [LIP11] designed the smart home devices based on D/R scheme within the residential home, where the central control from the devices upon the billing rate takes charges over the whole area. Zigbee devices are deployed here enabling the interoperability between the home appliances and the interfaces throughout to the network.

After the issue of communicating with home appliances and the network infrastructure has been built up, an interface between the control and the network

over the appliances become a new issue to be solved. [NIC02] introduced such kind of generic interface covering a wide selection of appliances. In his paper, a self-programming interface was developed for Personal Universal Controller (PUC) that provided the complete appliance interface in only one device [COS12]. And based on the first transmission of data through the interface, the PUC can inquire and adapt to the scheme through the machine learning similar approach.

2.3.2 Management of renewable energy resources

Energy management is necessary in designing the architecture of smart grid. The initial and essence purpose of deploying smart grid is to shrink the energy consumption especially during peak times, thus to reduce the burden of entire power infrastructure. By dynamic allocating the power load into different slots of time rather than condensing in one could lend support to the purpose of achieving lower power usage, in addition, by applying time-based pricing notification toward residents could also done this [CHE09]. AMI and HEM are two main approaches to create such automatic power distributing system.

One of the promising research directions in smart home is to introduce the renewable energy resources into the environment, which could alleviate the sudden power outages [CHE09]. As is known, solar and wind are the most talked about methods of creating additional power, meanwhile, a Plug-in Hybrid Electrical Vehicle (PHEV) is the latest innovation whose battery could be plugged into the socket for power feeding [FER11]. Moreover, PHEV is able to offer the temporary energy storage function for residential use. [OVI14] has implemented a model

simulating the aggregation of renewable power resources with traditional residential power usage, and the PHEV has proven to not only reducing the energy bills but also shifting the high power demand off peak hours.

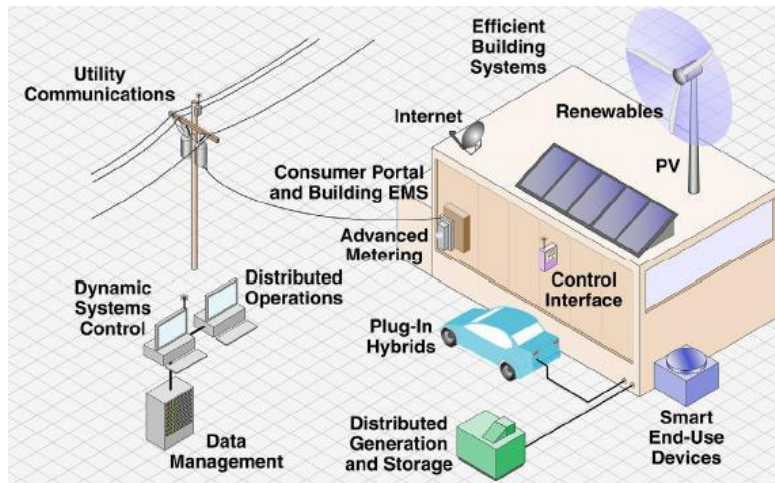


Figure 2.7 A typical residential energy resource system [CHE09]

A brief illustration of residential renewable energy resource system is given as Figure 2.7 shows. As can be seen, this ecosystem is able to take advantage of the energy generated by solar and wind for the purpose of home appliances usage, meanwhile, feeding power into the PHEV as the back up energy reservoir. The central controller administrates the energy management and coordination. System is able to take immediate reaction based on resident's choice of energy use, scheduling the utilization of energy for different appliances, making decisions on whether to use the renewable energy into the house. Residents could easily access and control the use of these devices and take actions remotely through web or mobile portals.

2.3.3 Power consumption in residential and commercial buildings

Based on the typical smart home model in Figure 2.7, sensors and control system need to be installed in the buildings. Any home appliances related with heating and cooling functions consumes much more energy than any other devices, such as HVAC system and water tank, which account for around 56% of the entire residential power consumption [PER08]. Authors in [WIL07] have discovered that there is significant power wasted on inappropriate operation manner on the appliances, for example, 24 hours switched-on air conditioners in unoccupied space, extra power usage to countervail the unbalanced temperature in different rooms due to the thermostat settings, and the possibility of appliances in off or standby mode.

Overall, the inappropriate operation on these appliances without HEM could lead to a great amount of power loss.

2.3.4 Smart operation of home appliances

Rather than simply turn on and turn off the appliances, the operation over the home appliances has to be smarter than before. Smart operation is proposed for home appliances and the renewable energy resources, and based on different characteristics of appliances; the authors in [CHE09] proposed the following approach. Each appliance can be operated in four modes: device registration, switching on and off, standby and auto-adjustment according to ambient environment.

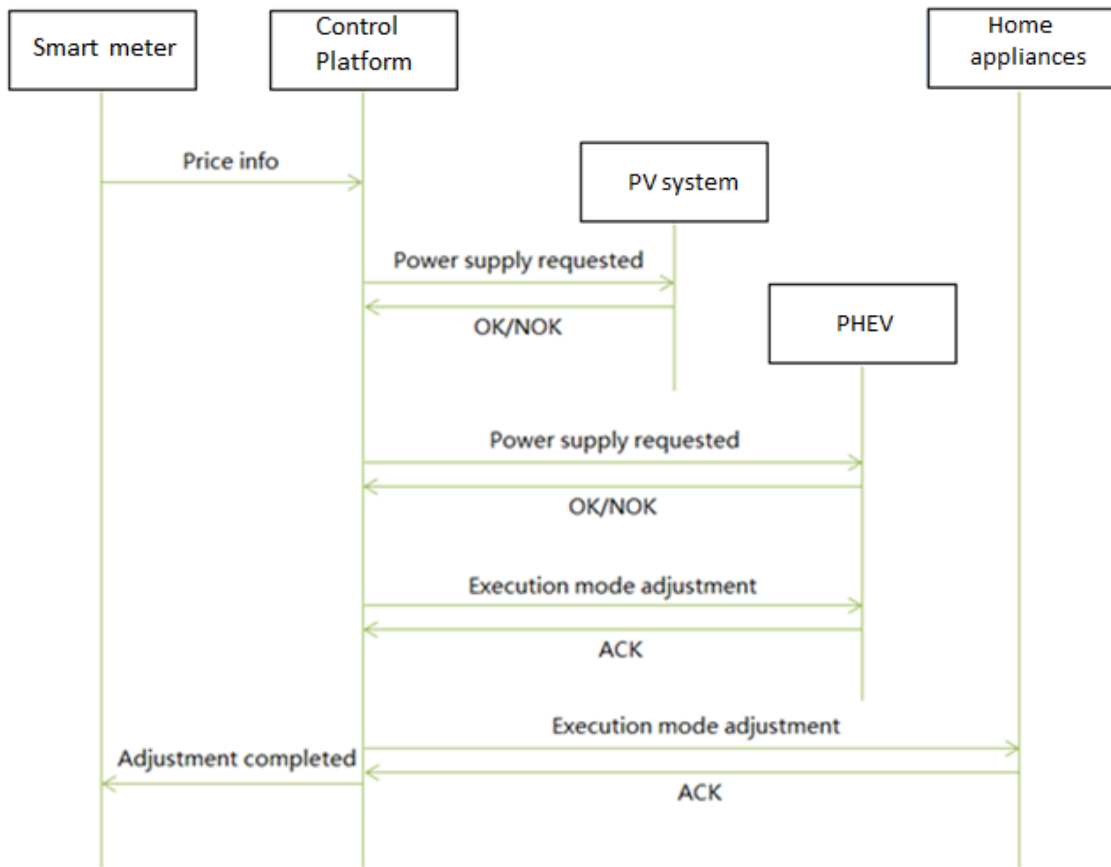


Figure 2.8 Adjustment of the execution mode based on price notification

As Figure 2.8 shows, the author takes dynamic billing mechanism into consideration. Firstly, the author assumes that current billing rate detected is higher than the other time. By reading the information from the smart meters, the central controller adjusts the energy supply resource and energy consumption. Controller first would have to send out power supply request, making sure there is enough energy reserved in the energy storage unit and feed all the power into the entire home. However, if there is no available power, the system sends out delay signals to all appliances, and then based on the user's preference, controller decides what appliances and at what time the certain appliance could be in use.

2.3.5 Smart home energy management system

In this section, we briefly investigate the related work on smart home energy management system.

Some researches showed the home network with efficient decision-making can achieve significant energy savings. Authors in [WAN09] proposed an intelligent agent-based middleware for context aware systems, which offered the users with multiple services in different environment securely, and finally, they applied the framework for a location-aware message system as the validation and application example.

Another example of smart aware home system is proposed in [DAS02], by acquiring the information from multi-camera tracking and audio sensors, the system is able to acknowledge the location of residents and based on which, making the right decisions. [HAN10] proposed a universal active sensor network-based control system in residents, which distributes the home daily tasks to the pre-defined component and activate the according home appliances with the smart sensors or actuators attached on.

2.4 Review of HVAC Systems

The Heating, Ventilation and Air conditioning (HVAC) system is an integration of infrastructures, devices and actuators that contribute to the indoor air exchanging, providing the thermal comfort and improve the air quality [NIX06]. Tones of

research on HVAC systems have been carried out since last century, and the devotion to improve the efficiency of the systems has never been stopped. HVAC systems relate very closely with power consumption and environmental problems and thus making it gathers a lot of attention. This section describes a survey on different techniques and approaches studied in various literatures.

2.4.1 Power consumption in HVAC systems

In recent years, there are numerous studies that discuss methods to optimize energy consumption in HVAC systems, current approaches mainly concentrate on innovating advanced power efficient appliances, applying renewable energy as the power supply, and investigating control strategies. In [LIN07] a feedback controller for air conditioners is proposed and the results show that the air conditioner is more efficiency by using this controller.

In [ZHA11], the authors have proposed an approach to independently control the temperature and humidity, attempting to reduce the energy consumption of air conditioner in an office building. In [MAZ09] and [HAS95], power efficient control methods have been presented to adjusting the speed pumps in the central air conditioner. In [ZAH93], authors have studied the power saving of air conditioner at the temperature of 23 oC and a model has been presented to predict the power consumption of air conditioners by studying the cooling load. Fuzzy control approach has been utilized onto multiple air conditioners to improve the power efficiency in [WAF09]. In [MOO11], the impact of power consumption of air

conditioner at different set temperature points has been tested in a single residential house in Miami, Florida, USA.

In [WAN06] and [ING03], thermostat strategy as a primary control method has been applied in the residential buildings. The results show that people's comfort level can be improved and significant power saving varies from 20% to 30%. In addition, apart from residential houses, commercial buildings, office buildings and the public architectures also can benefit from power savings by the deployment of thermostat.

Renewable energy such as solar has been studied through past years onto air conditioners, with which solar-assisted air conditioner is able to save significant amount of power annually [BEC81].

In [WAN13], the authors have presented an energy consumption calculation model for the estimation of energy consumption of air conditioners in a local data center in South Africa at different temperature set points, the results show that the root mean square between measured energy consumption data and the calculated data is 9%.

2.4.2 Thermal control in HVAC systems

Investigation over the thermal control and energy management in HVAC systems through out recent years mainly deployed optimization techniques, and most of them model the systems in nonlinear optimization way [SAM11].

Authors in [WAJ09] proposed a model of Cooling, Heating and Power (CCHP) to improve the efficiency of the system and alleviate the animal waste impact over the natural environment, they targets at the suburb area with multiple objective functions. A energy management strategy for residential electro-thermal micro-grid based on renewable energy resources was introduced in [PAS14], this strategy optimize the process in which power can be shifted to reduce the peaks and fluctuations, and lend the power in the storage system when needed, they have tested this strategy in a single family house with central HVAC systems, and the results showed this mechanism could reduce the positive and negative peak by 52% and 72% respectively. In [MAR14], authors proposed smart home task and energy resource utilization scheduling by using nonlinear programming function, which solves the problem of nonlinearities from the residential temperature limitation, and the results showed that the power consumption can be reduced while keeping the same comfort level for the residents.

Considering nowadays, HVAC systems should be smart enough to meet different thermal requirement among different residents in the same building, thus to formulate the problem of multi-room control over HVAC systems. Various studies have been carried out for the purpose of energy savings and peak load reduction [MOR94][BRA02][BRA03][FAR07]. [YAN14] introduced an approach on pre-cooling optimization to reduce the peak demand and energy cost. Authors in [CHA02] proposed the inverse model on HVAC systems in a multi-room building using short-term data for machine learning in order to let the system acquire the

optimal thermal settings. [MOS09] presented two optimal control strategies, the first one adjusts the fresh air flowing rate and air temperature while keeping the same level of air quality, and the second strategy adjusts the same conditions while keeping the same level of comfort. Both strategies are established on the power consumption cost but limited to the system and architecture constructional thermal properties. [HUA13] presented the Artificial neural networks (ANNs) modeling for thermal prediction in multi-room architecture.

2.4.3 Energy cost management in HVAC systems

The energy cost management of HVAC systems is receiving more attention during the last few decades. Authors in [HAD07] presented an auto-adjusting energy consumption threshold according to resident's preference based on a thermal model. [FON06] takes energy cost as a function into programming; this function contains the parameters that could directly control air condition systems. In [NOH11] authors takes consideration of dynamic billing into the simulation in addition to the energy saving optimization, while in [NGU12][AVC12], not only dynamic billing is included in the system, authors also includes residents comfort level as a very important factor. Authors in [NGU12] created the simulation model of home energy scheduling according to the general thermal dynamics, which is done by a look-up table. A two-stage cost HVAC systems load control strategy is created for residential buildings. In the first stage, the system finds out the relationship between electricity bills and thermal settings throughout the whole day with the pre-defined temperature-setting intervals, and in the second stage, system takes on the

mechanism of pre-cooling between random two consecutive time slots with different billing prices. The results showed that the proposed strategy could achieve energy saving while assuring comfort. In [JOR14], authors collected the comfort and thermal data at different rooms in a commercial building, by applying different sensor nodes within a WSN, and by doing so does the system offer a more precise factor for the system to make decisions and achieves higher level of comfort.

2.5 Summary

A wide range of survey was covered in this chapter from smart grid technology to one of its most important application, smart home, as well as some studies of HVAC systems. Lots of challenges still exist not only over the level of smart grid technology concept, but the whole world is still waiting for a delivery of a standard and regulated smart grid formats. Overall, power utility companies, customers and government shall all be participating in this process of increasing the performance of energy utilization and make a better performance for the next generation of power grid.

Chapter 3

System Analysis of HVAC Systems

3.1 Introduction

For power consumption in the residential building, HVAC system occupies a large portion of the total energy utilization. [MOO11] carried out an investigation over the components of annual energy consumption which can be seen from Figure 3.1, space heating and cooling (49%) is the biggest part of total power consumption for a typical single residential home, compared to the relatively smaller portion (10%) of water heating system, lighting (10%), computer and electronics (9%), refrigerator (8%), etc., accumulated to 51% of the entire area. Thus the better understanding of how HVAC system works would largely alleviate its impact over the energy consumption.

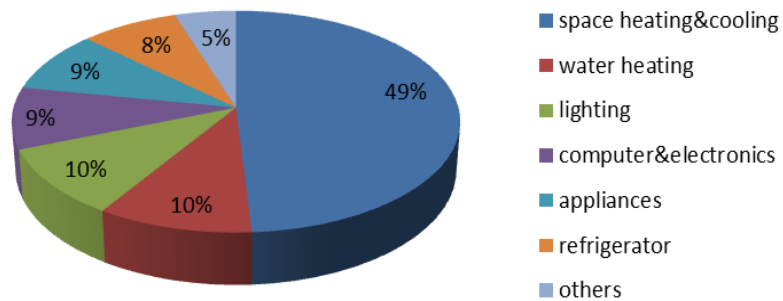


Figure 3.1 Components of energy consumption in percentage

Both commercial and residential HVAC systems provide the environment inside the buildings with “processed” air; the system also provides the relative comfort level for human in terms of the cleanliness, temperature, humidity and the flowing velocity of air. Air quality as the comprehensive index of healthy life greatly affects our living environment. The American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) has issued the standards which summarize air quality for indoor comfort conditions that are acceptable to 80% or more of a commercial building's occupants [4]. According to the standards, the temperature in the air conditioned area is suggested to range from 20 °C to 24 °C in winter and 22 °C to 24 °C during summer. Depending on the air flowing rate and the ambient temperature, indoor humidity is suggested to set around 50%.

In our research, we assume the models of single family home and commercial building to be presented in Sections 3.3 and 3.4 all belong to the category of smart homes.

The remainder of this chapter is outlined as follows. Section 3.2 introduces the residential home power consumption model, Section 3.3 introduces the power consumption model in commercial buildings, followed by Section 3.4, an Finite State Machine (FSM) based model is presented in this chapter, and finally in Section 3.5, wireless sensor networked HVAC system is presented here.

3.2 Residential home power consumption model

Power consumption of daily used home appliances was modeled in a typical North American single family house as Figure 3.2 shows the two story single home floor plan of around 250 square meters. Typical daily used home appliances included in house are central air conditioner, space heater, refrigerator, water heater, lighting, furnace, humidifier, television, electric oven, computer and other electronics, Table 3.1 is the suggested wattage of different appliances by Toronto Hydro [TORHY]. Here we do not consider non-daily-used appliances such as dishwasher, laundry and vacuum, etc. although they consume a certain amount of power. The residential house to be considered in our study has two story of the same height which means the humidity and air is evenly distributed throughout the entire house. We assume that there is no chimney and the heat storage impact can be ignored. Central air conditioner is installed in order to leverage the temperature to the settings; in addition to that, we assume the air conditioner is switched on 24 hours a day.



Figure 3.2 Floor plan for residential building suggested appliance wattage⁵

⁵ Floor plan by Monarch Group

Table 3.1 Home Appliances with Suggest Wattage [TORHY]

Appliances	Wattage
Air conditioner (2.5 tons)	3500
Space heater	800
Refrigerator	500
Water heater	3000
Lighting	1000
Television & Computer	400
Electric oven	1000

In order to calculate the cooling load for which air conditioner has to work to compensate, in order to keep the indoor temperature at a pre-set level, we present the model of cooling load for air conditioner in Figure 3.3. As we can see, cooling load usually consists four parts, which are transmission load, infiltration load, solar load and internal load [ASHRA]. These four parts will be explained later in this section.

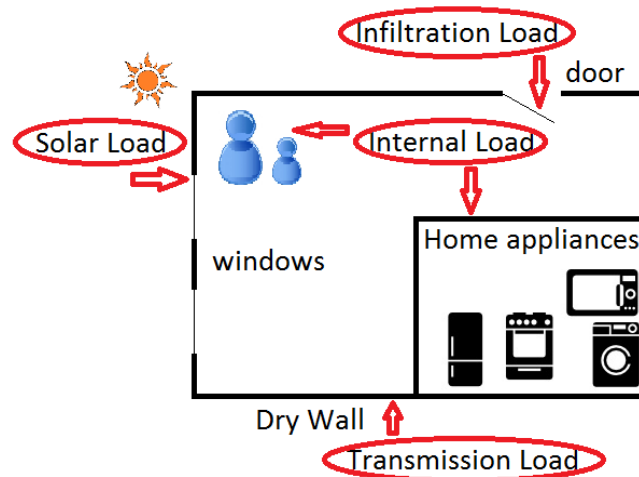


Figure 3.3 The components of cooling load

We apply the analytical model of [WAN13] into our scenario; total energy consumed by air conditioner at the set pointer is calculated as (1). In [WAN13], the authors have presented an effective thermal investigation and control approach on reducing the energy consumption by air conditioners, by adjusting the temperature set point. The results prove that every 1 °C increase of temperature is capable of saving approximate 9% of power consumption. There are some important parameters need to be explained here.

3.2.1 Transmission load

Transmission load is the heat-gain from the periphery of the building because of the temperature difference between indoor and outdoor. It can be calculated as (3.1) [ASHRA],

$$Q_t = US(T_o - T_i), \quad (3.1)$$

where Q_t is the transmission load in watt, T_o and T_i are the indoor and outdoor temperature respectively. U is the heat transfer constant in W/m²K, and S is the air-conditioned area in m².

3.2.2 Infiltration load

Infiltration load in the penetration of outside air into the building, which exists mainly because of the wind and negative pressure against the air. The infiltration load is calculated as (3.2) [DIA92],

$$Q_{inf} = q_v c_p \rho (T_o - T_i) + h q_v \rho \left((W_o - W_{ro}) \exp \left(-\frac{q_v}{V} t \right) \right), \quad (3.2)$$

where q_v is the air flow rate, c_p is the real time heat of air, ρ is the air density, T_o and T_i are the outdoor and indoor temperature, h represents the heights of a single story in the building, V is the volume of the entire building, W_o is the current atmosphere specific humidity and W_{r_o} is the indoor specific humidity, which can be largely impacted by air flow and temperature. It is proved that relatively dry air (humidity under 30%) would benefit the electricity to be more stable, thus avoiding the potential power surplus situation. However, humans are quite sensitive to the humidity [WAF08] due to the skin respiration mechanism; low humidity levels can increase the risk of bacteria invading into our body, leading to dry skin, irritated sinuses and throat, etc. Moreover, the same temperature environment with different humidity level would let us feel different about the actual temperature, according to American Environment Protection Agency; the ideal humidity level should be set between 40% - 50% [USEPA]. In our study, the energy consumed by the humidifier is assumed to be small and hence can be neglected; the air conditioner is also regarded to function as air exchanging thus causing the humidity fluctuation within the comfort range.

3.2.3 Solar load

The solar load is the temperature increase due to the solar radiation, windows is the main concern in architecture that transmit the radiation. Solar load can be calculated as (3.3) [ASHRA],

$$Q_s(t) = A_w S(t) E, \quad (3.3)$$

where A_w is the area of total windows in the building, E is the irradiance of solar beam, and $S(t)$ is the Solar Heat Gain Co-efficient function (SHGC) which can also be considered as overall energy performance of windows. Because the mix climate in Ottawa determines that heating is used more extensive annually than cooling, the windows with the SHGC vary between 0.3 and 0.4 are the best. In our model, we choose a deterministic value of SHGC as 0.35. The transmission load is defined as the heat gain results from the temperature difference of indoor and outdoor through the wall and windows.

3.2.4 Internal load

Internal load is the heat-gain due to the heat generated by the indoor lighting and other electric equipment, and lighting is the primary heat source, therefore internal load can be calculated as (3.4) [ASHRA],

$$Q_{int} = G_{int}F(t), \quad (3.4)$$

where G_{int} is the total light wattage, $F(t)$ is the lighting use factor which is set to be 1 when light is on and 0 when its off.

3.2.5 Power consumption calculation

Based on the previous analysis, the total load air conditioner needs to work on is the sum of the four parts of load as (3.5):

$$Q_{total} = Q_t + Q_{inf} + Q_s + Q_{int}, \quad (3.5)$$

And after further calculation, the power consumed by HVAC system can be interpreted as (3.6),

$$\begin{aligned}
E = \sum_{k=1}^N \frac{t_k - t_{k-1}}{2COP} & \left[4\sqrt{A} \left(b_0 \Delta T_1 + b_1 |\Delta T_1| \Delta T_1 + b_2 \Delta W \exp \left(-\frac{4b_3}{\sqrt{A}} - \frac{4b_4 |\Delta T_1|}{\sqrt{A}} \right) + \right. \right. \\
& b_5 |\Delta T_1| \Delta W \exp \left(-\frac{4b_3}{\sqrt{A}} - \frac{4b_4 |\Delta T_1|}{\sqrt{A}} \right) + b_6 \overline{S(t)} \left. \right) + b_7 A + G_{int} \overline{F(t)} + 4\sqrt{A} \left(b_0 \Delta T_2 + \right. \\
& b_1 |\Delta T_2| \Delta T_2 + b_2 \Delta W \exp \left(-\frac{4b_3}{\sqrt{A}} - \frac{4b_4 |\Delta T_2|}{\sqrt{A}} \right) + b_5 |\Delta T_2| \Delta W \exp \left(-\frac{4b_3}{\sqrt{A}} - \frac{4b_4 |\Delta T_2|}{\sqrt{A}} \right) + \\
& \left. \left. b_6 \overline{S(t)} \right) + b_7 A + G_{int} \overline{F(t)} \right], \tag{3.6}
\end{aligned}$$

where E is the total energy consumed by air conditioner at certain set temperature point. The time period $[t_k, t_{k-1}]$ is the duty cycle of measuring the total air conditioner power consumption, A represents the area of the building in m^2 to be calculated. b_0 to b_7 are the coefficients that has been simulated by existing data in [WAN13]. In equation (1), COP is the coefficient of performance of the air conditioner cooling capacity [ASHRA], which is proportional to the sum of ambient temperature and the temperature at the set point. Between certain period of time $[t_k, t_{k-1}]$, power consumption of air condition is calculated, in this paper, we choose the time range to be an hour so that the power consumption of air conditioner at the unit of time is easier to read. The energy consumption of HVAC system at the temperature point of, for example, 23 °C, can be calculated as E_{23} , and humidity is set accordingly as well. ΔT_1 and ΔT_2 in this example can be calculated by where $\Delta T_1 = T_o - 23 - \Delta$, $\Delta T_2 = T_o - 23 + \Delta$, where Δ represent the temperature interval to control the air conditioner to be switched on and off, for example, when the ambient temperature is 25 °C while 22 °C is the needed indoor temperature, air conditioner will be switched on when compressor detects the temperature $T = 22 + 1.5 = 23.5^\circ\text{C}$ while switched off at $T = 22 - 1.5 = 20.5^\circ\text{C}$.

Power consumption calculated in (3.6) is the integration of the above four kinds of load. We use equation (3.6) as the model to calculate the power consumption of central air conditioner, but for the other home appliances, deterministic power consumption is calculated by the time of running, we assume that the air conditioner and the refrigerator are running continuously 24 hours a day, electrical heater works 24 hours only in winter, lights are switched on 6 hours per day, television and computer are working 6 hours per day as well, water heater works different in different seasons, also depending on the frequency of using hot water, water heater could run for 20 minutes to an hour which summed up to around 3 hours a day in the winter, and in the summer, most of the time it is in the standby mode, thus 2 hours is the ideal time.

By using the model to calculate power consumption at different temperature set points, we can find out the energy savings by the difference between the two power consumption figures.

3.3 Commercial building power consumption model

Building structure and residing characters for commercial building are different from those of residential buildings. First, the power consumption peak hours are different, commercial building, taking shopping mall for example, opens from 9am to 9pm on weekdays, while at the same time, residential buildings are almost vacant of using power. Secondly, building material and its appliance patterns are different as

well. Lighting and air conditioners occupy almost 80% of the total power consumption of the commercial buildings [LAM03]. With a much powerful central air conditioner, different rooms are equipped with a sub-appliance, meaning there is only one compressor working while different thermal settings can be achieved at different locations. This giant system altogether serves a single big building to maintain the comfort level. Moreover, the internal load generated mainly by lightings should be proportional to the residential buildings in terms of the area.

In the last section, power consumption model on HVAC system has been well applied into the residential buildings, we may also taking the system and expand it to the volume of a commercial building, that is, a tall building with several small residential house inside, and by doing so can we apply the same power calculation model into commercial building too.

For a single unit of air conditioner, it is impossible to control the rate of the changing of temperature, however, with multiple units of sub-air-conditioner, the rate of heating or cooling becomes tangible.

We take a ten-story office building as research example in this thesis. As Figure 3.4 shows, each floor has four sections of area, and each area is equipped with five sub-air-conditioners with a micro-controller. For the simplicity of study, we also take the same parameters from the model of residential buildings and apply them here.

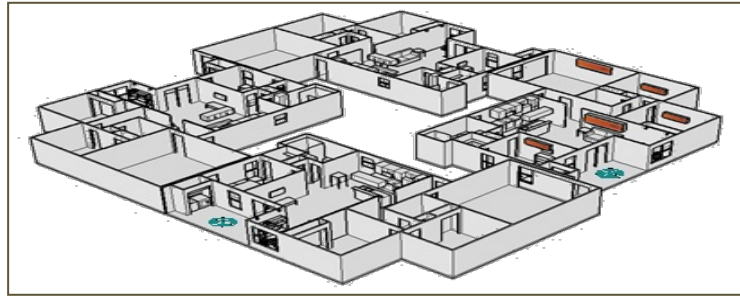


Figure 3.4 A single floor of a typical commercial building

What differs from residential building is the power consumption on electrical devices, rather than regular daily task needs to be done in the residential, commercial building operates in a different mode, and thus in the thesis, only HVAC system is under study here.

3.4 Finite State Machine based simulation model

Finite State Machine (FSM) is a mathematical model of computation used to design the computer program or system. It basically starts at the initial state at a given time and can take actions based on the input into this state, and then jumps into other state at the pre-defined time.

We developed a FSM based scenario to monitor the air conditioner working process using open source software Ptolemy [DAV03]. As Figure 3.5 shows, there are three states simulating the working status of HVAC system, initial, heating and cooling respectively. Initial state represents the standby mode of air conditioner, meaning it does not consume any power. Transitions between the heating and cooling state depend on the current temperature, it is of the same approach when we

calculate the power consumption of a single residential house. For example, we set the coolingpoint=25 °C and heatingpoint=22 °C, when the temperature as input starts at 23 °C, the air conditioner keeps heating up the air until it reaches the temperature of 25 °C then begins to cool down the air. There are four parameters here, which are cooling point, heating point, cooling rate and heating rate. The rate of how fast the air conditioner is controlling the air can be interpreted as the interval introduced in (3.6), and it is proportional with the number of sub-air-conditioners working at the same time. The FSM-based HVAC system simulation is carried out in the same environment of residential and commercial buildings.

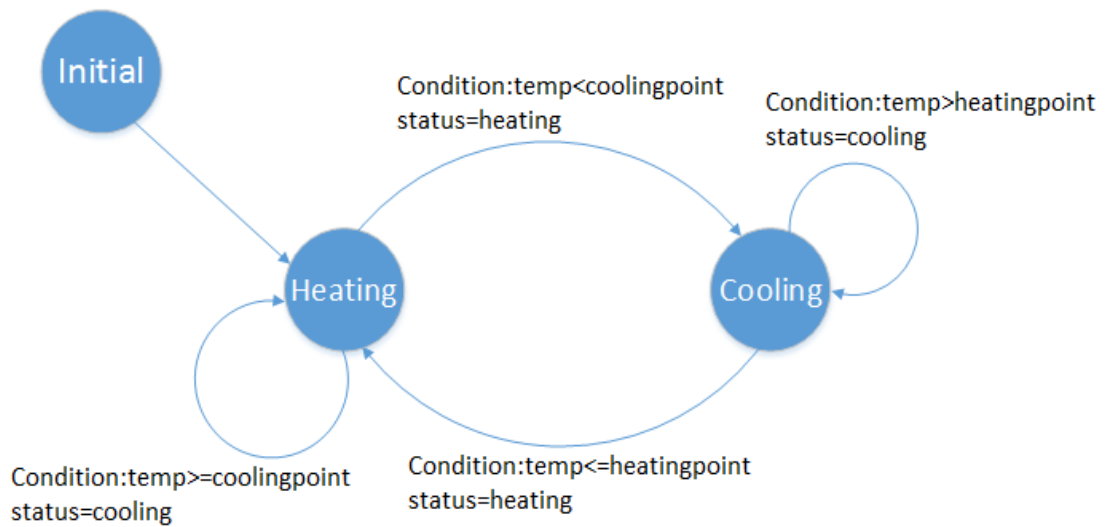


Figure 3.5 FSM-based air conditioner modeler

3.5 Zigbee-based smart HVAC systems

With the sensor nodes attached to each and every sub-air-conditioner, the HVAC system is able to collect the data and send out the command signal to configure the thermal settings for every unit.

Specifically, for the entire building there is one Full Function Device (FFD) node that coordinates the whole system, all the remaining sensor nodes are Reduced Function Device (RFD). Every floor has four sections, each installed with five sub-air-conditioners, and for every five sub-units, there is a router controls their working status. The network is established in a cluster tree manner. Vertically throughout the building, these RFDs are only allowed to transceiver the signal from the RFD close to it. Therefore, the network model on HVAC system can be illustrated as Figure 3.6. The red bolt line represents the command signal sending to every RFD, and the green thin line represents the data collected by different sub-air-conditioners at different locations.

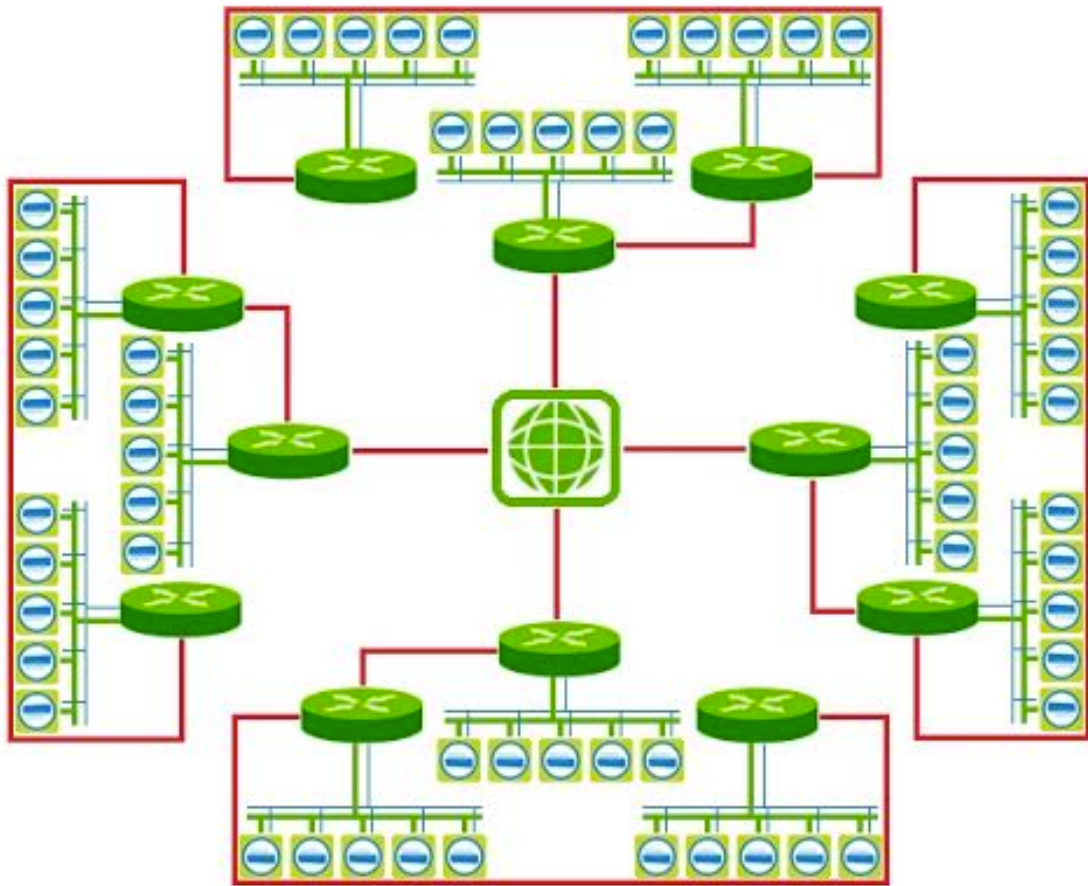


Figure 3.6 Framework of wireless sensor network for HVAC system

We use OPNET to model the wireless sensor network for controlling HVAC system. There are multiple of options in wireless networking for us to choose, for example, wireless network based on Wi-Fi, Bluetooth or Zigbee. Wi-Fi has been very popular in industry and residential home as well. Wi-Fi includes IEEE 802.11 a/b/g standards allowing users to access to Internet at a broadband speed via an access point or in an Ad-hoc mode [KPO14], it is known for its powerful signal penetration through obstacles and the long distance it can reach, however, installing Wi-Fi in the large architecture can be expensive and moreover, affecting human's

health due to its electromagnetic radiation, thus making us eliminating this choice. Bluetooth is not advised for long distance and long duration applications because of its power consumption constraints. Therefore, for small scale of devices which need long time running, far enough communication distance and limited power consumption, Zigbee stands out among the wireless communication technologies as a compromise of distance and power consumption. Table 3.2 summarizes the main differences that need to well fit into our model among the three protocols.

Table 3.2 Comparison between Wi-Fi, Bluetooth and Zigbee protocols

Standard	Wi-Fi	Bluetooth	Zigbee
IEEE Standard	802.11 a/b/g	802.15.1	802.15.4
Channel Bandwidth	2.4 GHz/5 GHz	2.4 GHz	868/915 MHz/2.4 GHz
Data Transfer Rate	54 Mb/s	1 Mb/s	250 kb/s
Power Consumption	15 - 20 dBm	0 - 10 dBm	-25 - 0 dBm
Max Cell Nodes	2007	8	65000
Security	32-bit CRC	16-bit CRC	16-bit CRC
Self-healing Ability	Medium	Low	High
Range	100 meters	10 meters	10 – 100 meters

Figure 3.7 is the overview of the simulation scheme. Every small group in the overview has ten individual sensor nodes representing sub-air-conditioners, each one

of them is installed at different height so to fill the requirement of vertical communication. Every center in four sections consists of ten routers surrounded by a group of sub-air-conditioners.

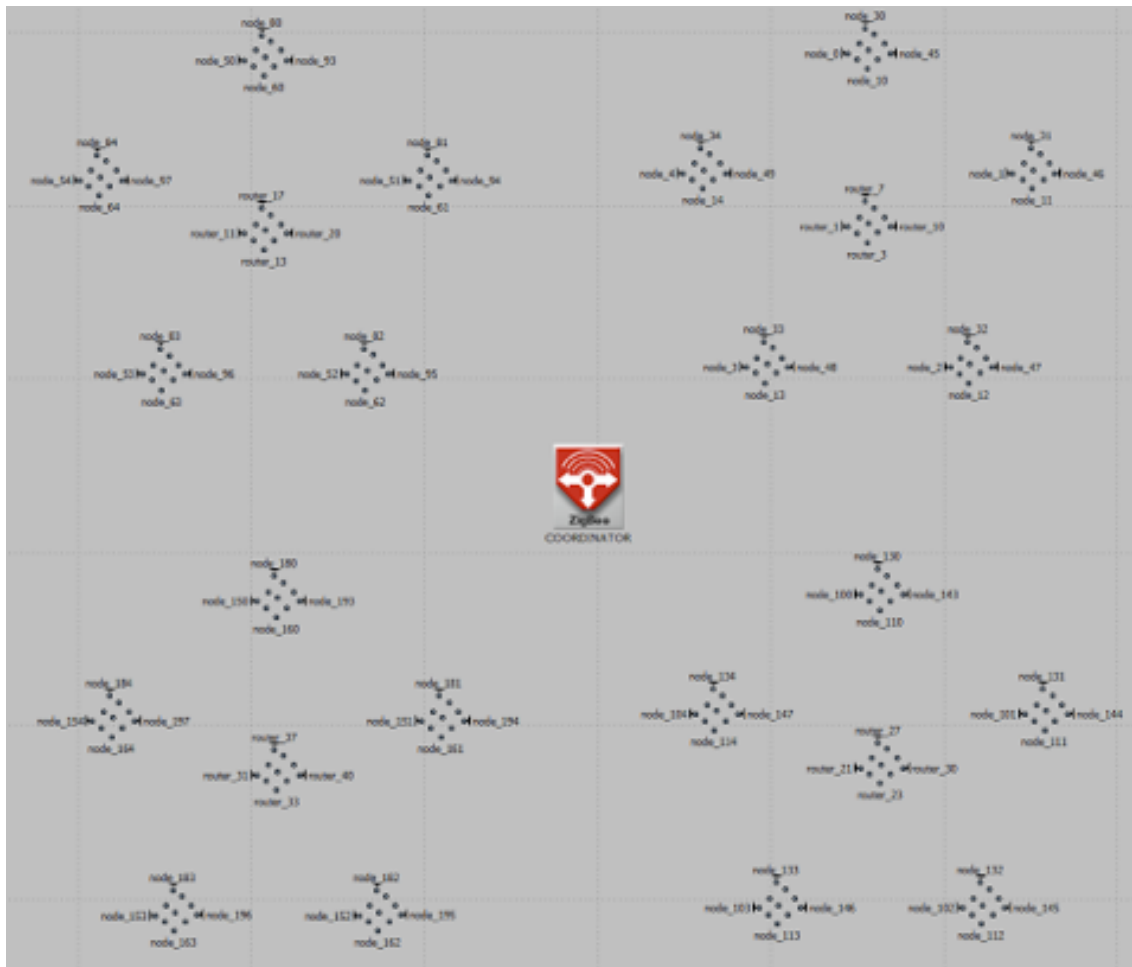


Figure 3.7 Zigbee-based communication system simulation in OPNET

By sending out signals from coordinator to routers then to the end devices, the coordinator in the middle is aggregating significant amount of information and thus making the end-to-end delay accountable in the entire system, especially those air conditioners with the longest distance.

3.6 Summary

This chapter presents the model of residential home and commercial buildings power consumption, we applied cooling load function into our model, and get the specific power consumption at different time of the day. A FSM based analysis model in designed to simulate the HVAC system working status, by setting the parameters we can acquire the relationship between the time that HVAC system needs to take to reach the configured temperature and the temperature itself. Finally, we introduce Zigbee into the system in order to study the impact to end-to-end delay over the HVAC system in terms of power consumption. The entire process can be concluded as Figure 3.8.

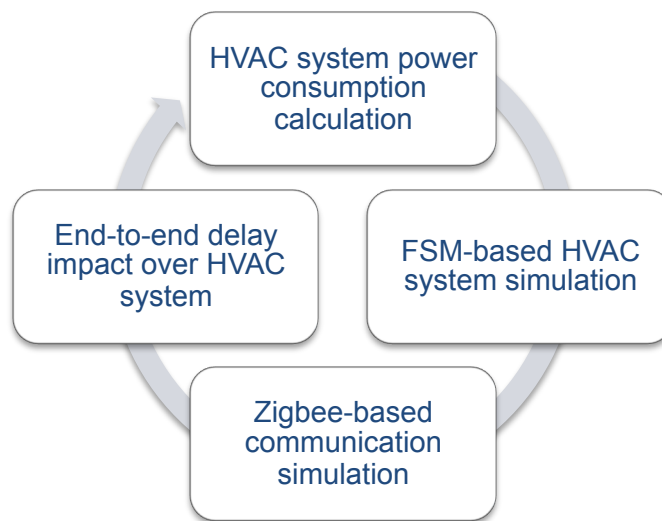


Figure 3.8 Simulation process of the thesis

Chapter 4

Performance Evaluation and Results

4.1 Introduction

In this chapter, we evaluate the performance of power consumption of HVAC systems in residential and commercial buildings based on the mathematical functions formulated in Chapter 3. As for Section 4.2, the power consumption of residential building is simulated and the results are shown here, as well as the performance analysis. In Section 4.3, the simulation result of end-to-end delay in Zigbee communication system is given, as well as its impact over the HVAC system. Finally, Section 4.4 summarizes this chapter.

4.2 Power consumption in residential home

Considered the model established in Chapter 3, we consider a single family home located in Ottawa as the example under our study. The floor area of the house is around 250 square meters as Figure 3.2 shows. The total lighting wattage is 3.56 kWh, the relative humidity is calculated accordingly. For a better understanding of how much power is consumed hourly, we set the time to be an hour for every calculation. We select a typical month in all four seasons that are January, April, July and October. Among which central air conditioner is only used in July and Electrical

heater is used in January, but for the other months, air conditioner is needed to work to modulate the temperature and the ventilation has to work to evacuate the humidity out. We assume the schedule for people to occupy the house is as follows, 7am – 8am is the wake up time, 8am – 5pm is the leave for work time, 5pm – 10pm is the return from work time and 10pm – 7am is the sleeping time. We also choose the most comfort level temperature at different sections of time according to Statistics Canada [STACA] that 22, 25, 22 and 24 °C are considered the optimal temperature in the previous four sections of the day. Yahoo weather provides the archived daily temperature of 2013 in Ottawa, Ontario [YAWEA], and we chose the average data for every hour throughout the whole day. In addition, for the other home appliances, we assume them to be turn on for an hour every day, but water heating for two hours in January. Figure 4.1 shows the power consumption under different temperatures of the day to maintain the comfort level at certain temperature points, we chose to show the results in these four months, and especially power consumption of HVAC system in July because according to last year archive, July has the highest average temperature.

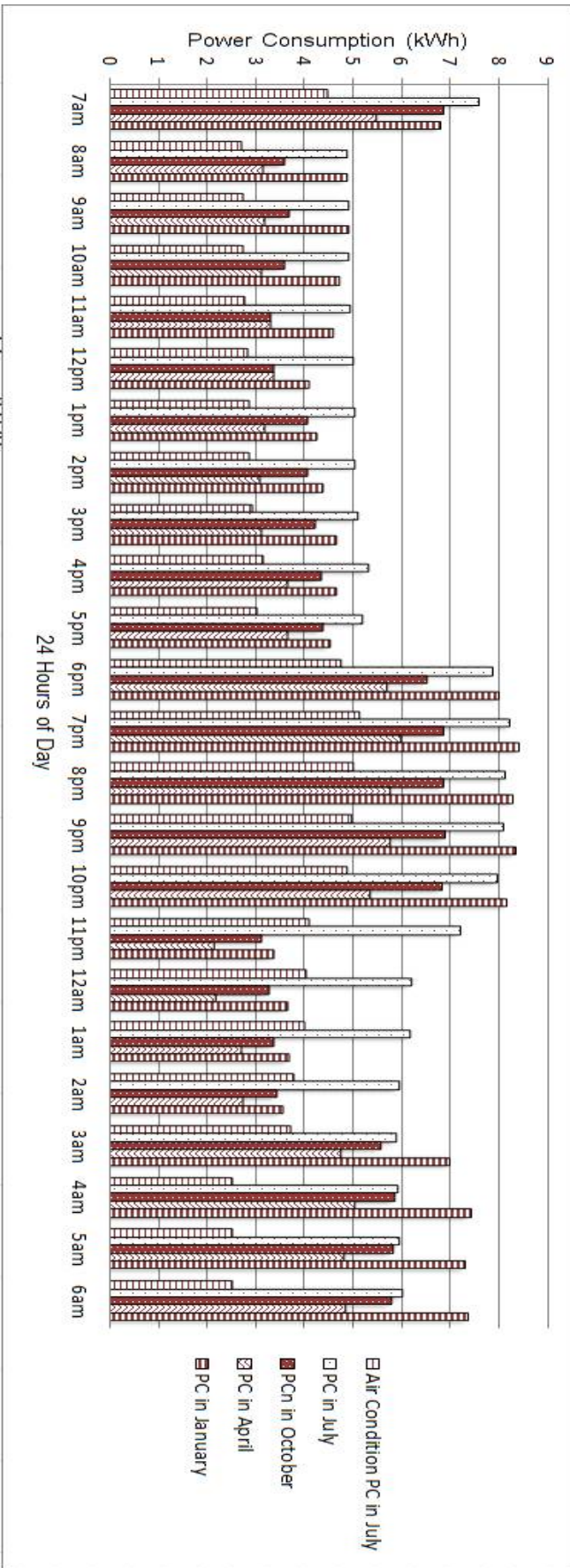


Figure 4.1 Daily power consumption in residential house at different months in 2013, Ottawa

As shown from Figure 4.1, air conditioner consumes the most power from 7am to 11am and from 6pm to 10pm, as people are more active during these two periods of time when the indoor temperature has to be set to 22 °C, which is relatively lower than other temperature settings. Additionally, we noticed that during 8am to 5pm at the temperature setting of 25 °C, the power consumption fluctuates around a stable value, which mainly is contributed by the difference of the indoor and outdoor temperature/humidity. From 11pm till 6am when 24 °C is the best temperature for sleeping, air condition does not have to take that much burden to keep the temperature low, therefore, consuming less power throughout the day. However, January is an exception as the ambient temperature keeps going down at night so the electric heater would have to consume more to maintain the temperature level. We also noticed that, even October and April share very similar ambient temperature, the power consumption of October is still relatively higher than that in April, that is due to the higher humidity level in October, which results from the fact that air conditioner usually consumes more power to cool down and dehumidifies the air leakage into the house.

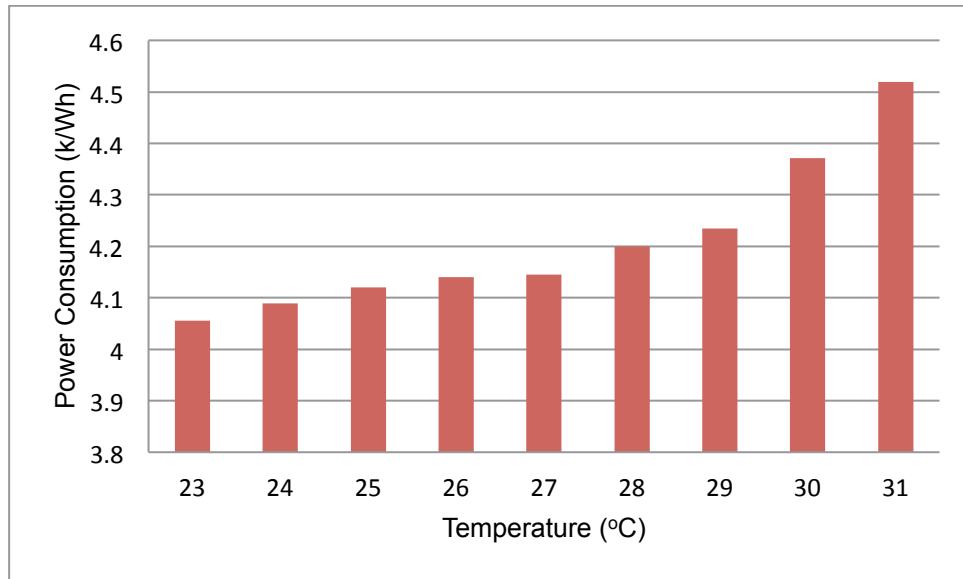


Figure 4.2 HVAC system power consumption at $T_0=22\text{ }^\circ\text{C}$

Since power consumption at selected temperature set point has been calculated, we may also apply this model into a single unit of air condition in the commercial building then the total HVAC system power consumption is relatively proportional to the number of running air conditions. Figure 4.2 shows that as the ambient temperature goes up, the energy HVAC system needs to maintain the indoor temperature at $22\text{ }^\circ\text{C}$ goes up accordingly, this is because of the HVAC system needs more power to compensate the higher cooling load caused by ambient temperature.

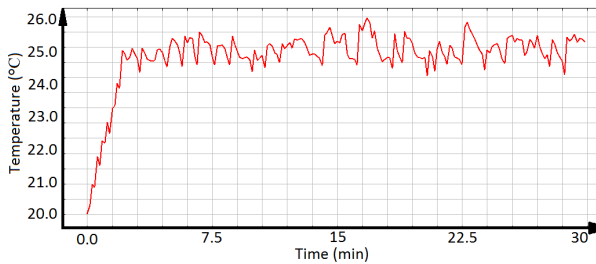
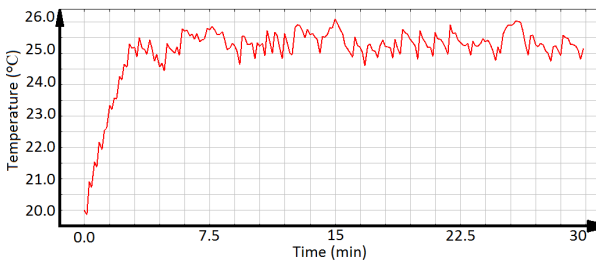
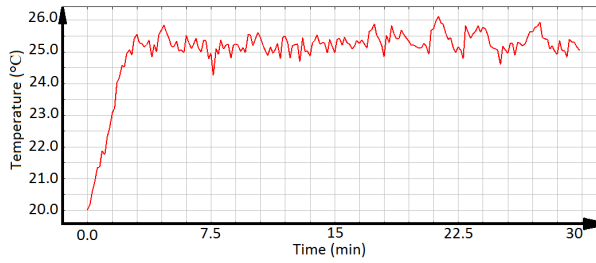
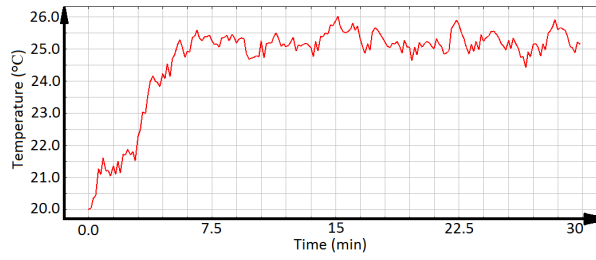
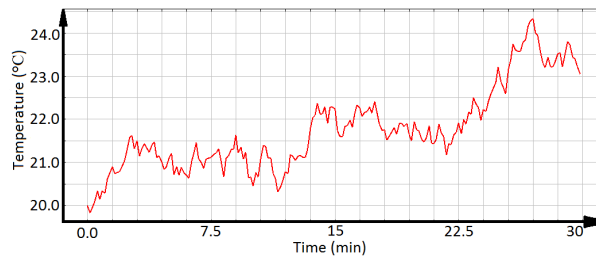


Figure 4.3 Initial Temp =20 °C, set point =24 °C with various heating rates

(0.1~1)

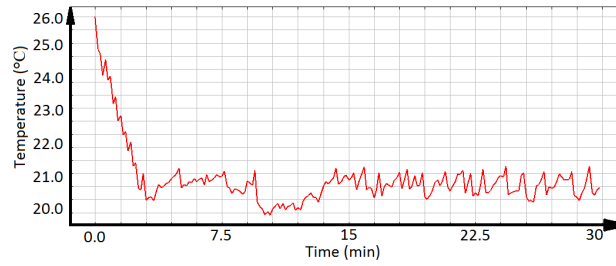
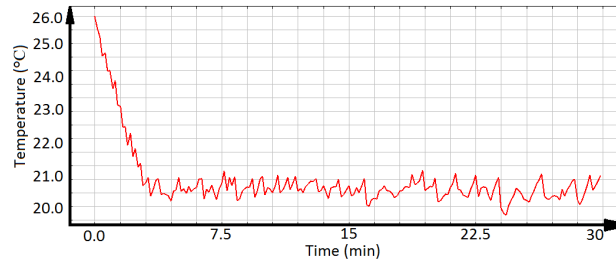
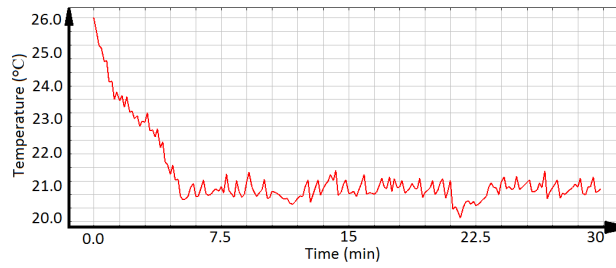
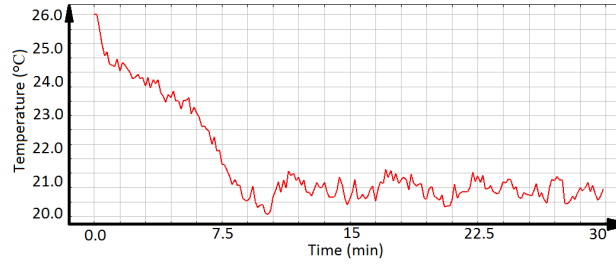
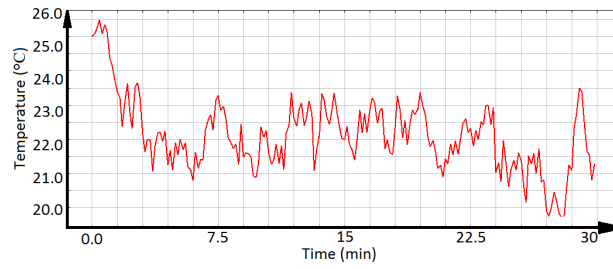


Figure 4.4 Initial Temp =26 °C, set point =20 °C with various cooling rates

(-1~-0.1)

Based on the model in Figure 4.3 and 4.4, we tried two scenarios, first one, the initial temperature is set to 20 °C, and the cooling point is 19 °C, we change the heating rate from 0.1 until 1 while cooling rate keeps the same; the second scenario is just the opposite, start at 26 °C, the cooling rate differs from 0.06 to 3 while heating rate keeps stable, these numbers here is just a quantified value representing the unit of working air conditioners. We assume the initial ambient temperature is 26 °C, and the setting temperature at people's need is 22 °C, the difference of power consumption at 26 °C and 22 °C is around 4.15 kWh from Figure 4.5, moreover, we can find out that the time that air conditioners need to lower the temperature is shrinking when the cooling rate keeps getting fast.

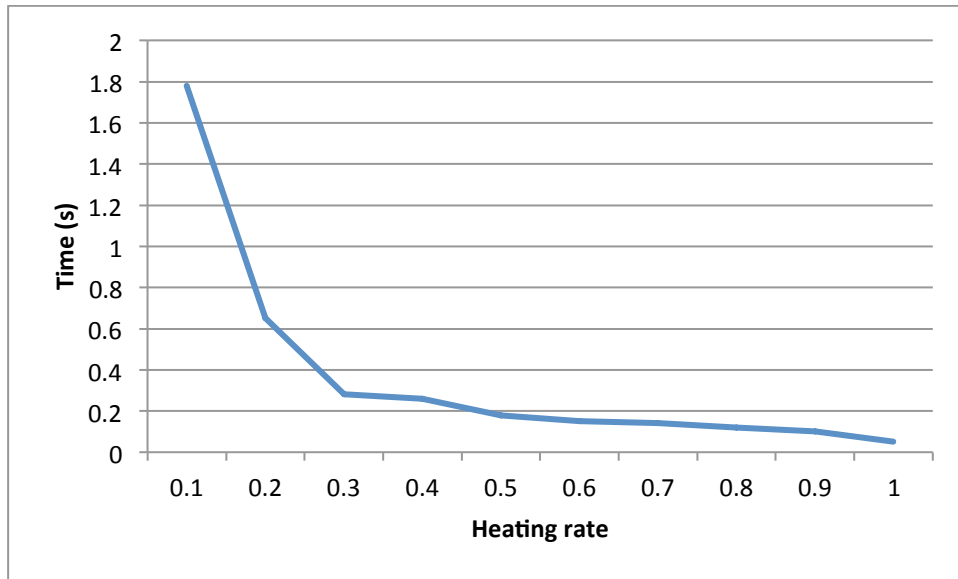


Fig 4.5 The heating rate versus air conditioner heating Time

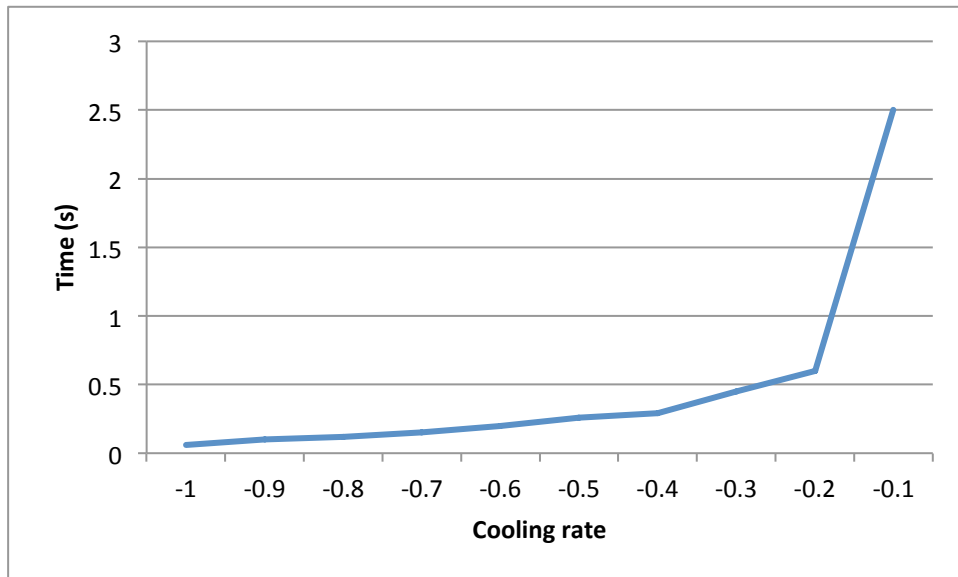


Fig 4.6 The cooling rate versus air conditioner cooling Time

However, from Figure 4.5 and 4.6, we can tell cooling/heating rate is infinitely close to 0 but rather no less than 0, the time the air conditioners need to take the temperature down tends to be infinite large. That is to say, the larger the rate is the short time the HVAC system needs to achieve the temperature set point. Finally,

consuming this amount (4.15 k/Wh) of power per unit of air condition takes more time than multiple air conditioners running at the same time, as the temperature can be lower down to the set point faster.

4.3 Zigbee-based communication system results

We established the Zigbee communication model and introduce the system to HVAC systems, so that every sub-air-conditioner could be remotely controlled, not only to set the temperature but also to achieve the optimal power savings.

We place the coordinator at the first floor of the building. It offers the service for local synchronization of the sensor nodes in its range, in this case, connects to all the routers. All the other nodes are placed onto the sub-air-conditioner as the RFD. The system deployed the cluster tree topology for better management within the HVAC system. Coordinator initialize the wireless network as the root, through routers to relay messages to the air conditioners, and sensor nodes can meanwhile collects the data either as pre-defined or according to resident's preference and send it over to the coordinator. The parameters used in this system are listed as follows:

Destination: 1) Coordinator connects to all the routers;

2) First router in all four sections connect to coordinator, the rest of the routers only connect to its previous ones respectively;

3) end-devices (sub-air-conditioners) are connected to the according

router

Packet Size: constant size packet of 2014 bytes

Packet inter-arrival time: constant with the index range from 0.05 to 10s

Height: we assume every floor is of 3.6 meters high and therefore every group of

devices are in an escalating order

Location: every group of device is of 20 meters spread apart

Start time: random passion distribution

Simulation time: 1 hour

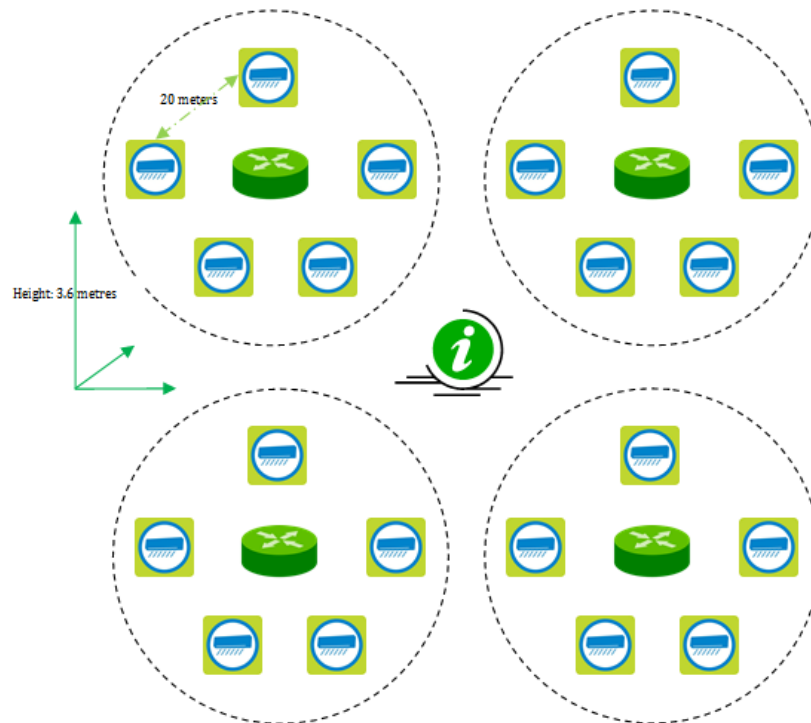


Fig 4.7 Physical dimension of the Zigbee-based communication system

End-to-end delay in this system detects the delay between the coordinator and the end devices by measuring the time interval when a message is queued for transmission at the physical layer until the last bit is received [MIH11].

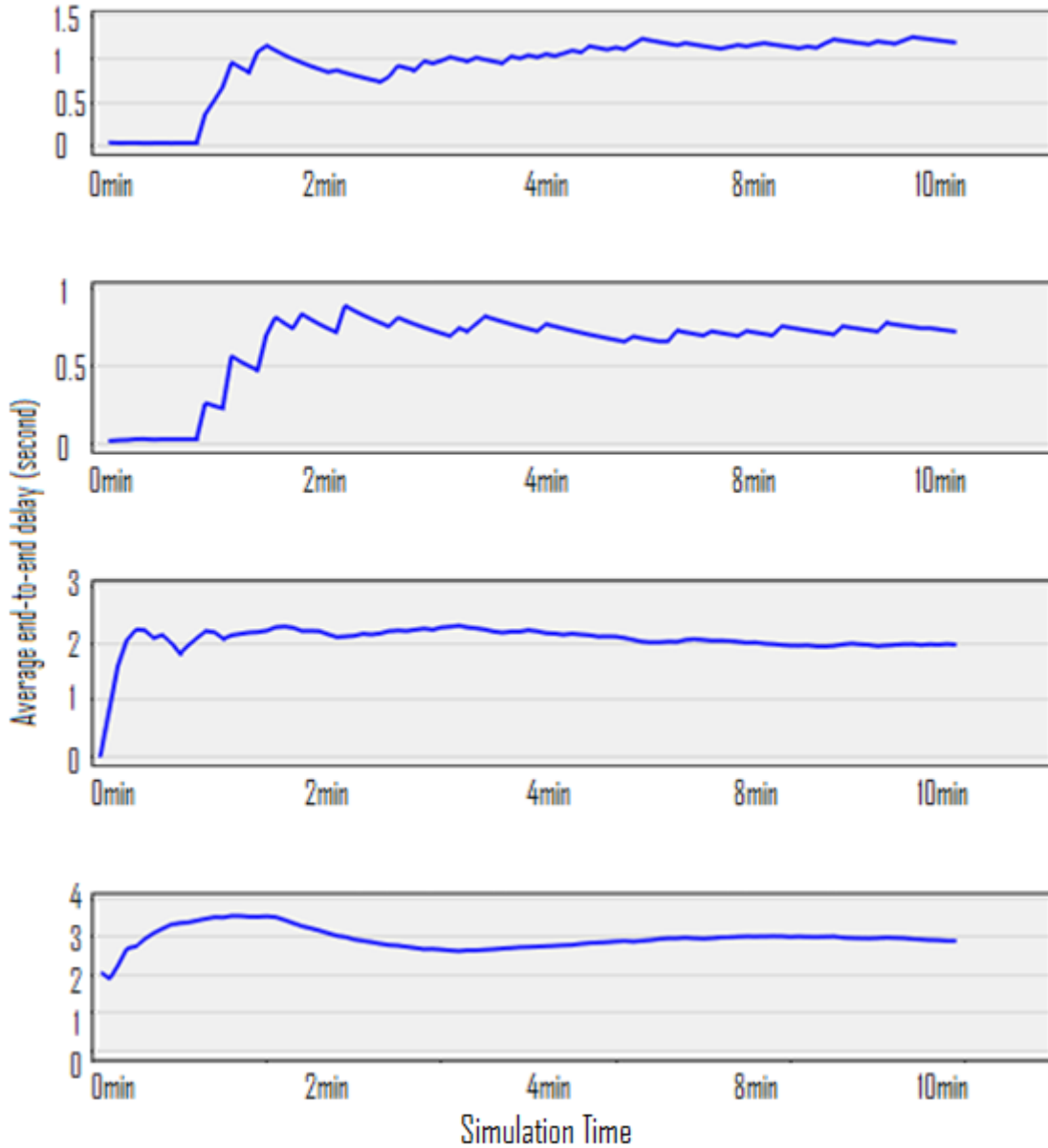


Fig 4.8 End-to-end delay in coordinator simulation results from OPNET

As can be seen from Figure 4.8, this is the end-to-end delay simulation results in coordinator in different scenarios, which are configured with different inter-arrival time (from top to bottom: 5s, 9s, 0.6s and 0.08s). We can clearly see the different between these plots, packet inter-arrival time specifies the times between successive packet generations, therefore, with the constant packet size and with fixed number of messages to be sent, the large the inter-arrival time is, the smaller the end-to-end delay is, because systems are allowed to have more time to buffer the packet in the queue.

The relationship between the packet inter-arrival time and the end-to-end delay can be seen from Figure 4.9. Figure 4.8 is the Average⁶ data results provided by OPNET, it also offers the function to average the results, and that's how we get the Fig 4.9. End-to-end delay gets reduced by increasing the inter-arrival time.

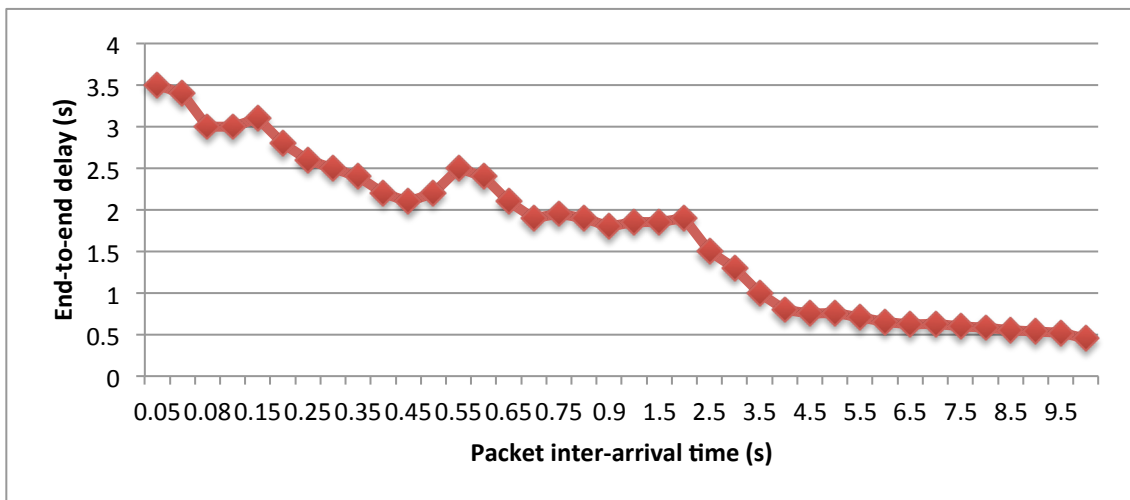


Fig 4.9 Packet inter-arrival time verses the end-to-end delay

⁶ Average filter plot the running sample mean of the raw results data

Taking into consideration of Fig 4.3 and 4.4, the HVAC system is time-sensitive, by introducing the Zigbee wireless communication mechanism into the system could bring power wasting or impact the comfort level, the HVAC system should have reached the temperature set point ahead of time if not for the delay brought by the WSN, the system would be waiting for the instructions to arrive, and within this period of time, the temperature is changing at every second and thus cause the unnecessary energy loss, or either the system just keeps in stand-by mode until the instruction comes, causing the HVAC system consume more energy to reach the target thermal settings. Because HVAC system works in a dynamic fluctuation process in terms of temperature changing, thus when every period of delay accumulated, the total impact is significant.

Such energy loss can be generalized as the (4.1) by using the model introduced in Chapter 3, since the temperature is not immediate changed due to the delay of time.

$$\begin{cases} E_{loss} = E_{init} + \Delta E' - E_{setting} \\ \Delta E' = \int_{t_0}^{t_{delay}} \Delta E \\ \Delta E = E_{init} - E_{setting} \end{cases} \quad (4.1)$$

Therefore within unit time, the system would be able to calculate the amount of energy lost that HVAC system has to compensate originally, it should be proportional to the time intervals, as we set 1 hour in Chapter 3.

Figure 4.10 presents a simple case of estimating the energy waste under the impact of end-to-end delay in the same model as Fig 3.2, it illustrates the relationship between delay and energy loss. The data of delay come from the OPNET simulation

results, we assume HVAC system keeps at the standby mode always in the Initial state of FSM until it receives the message, and the indoor temperature increases only due to transmission load (3.1), which is the heat gain from the periphery of the architecture.

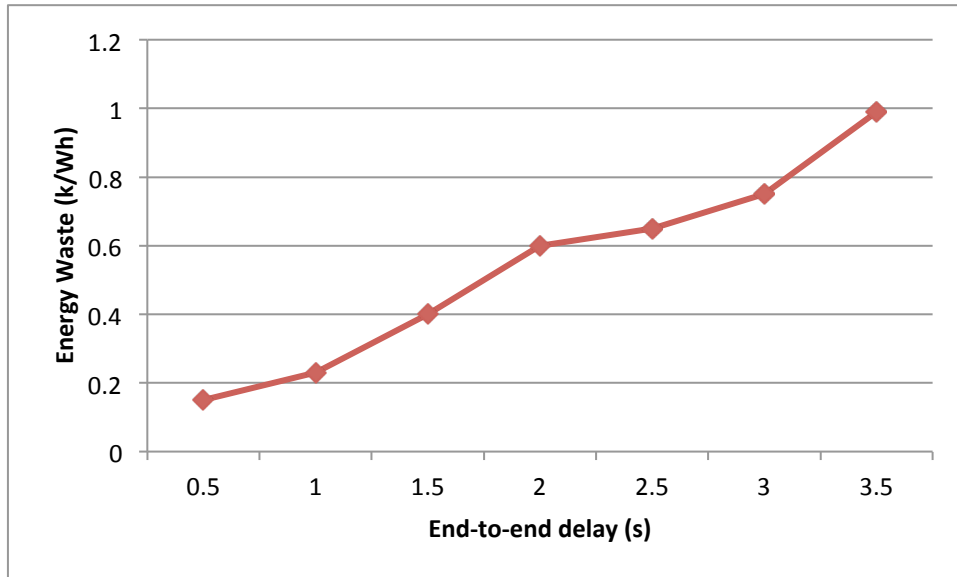


Fig 4.10 A simple case of estimation of the energy waste

4.4 Summary

This chapter presents the simulation results and performance analysis of the system. Based on the mathematical model into the residential and commercial buildings, the power consumption throughout the day especially for HVAC system has been given and analyzed. The simulation results of FSM based air conditioner and the end-to end delay of Zigbee communication system is given here too. Finally,

the impact of end-to-end delay over the power consumption of HVAC system is analyzed too.

Chapter 5

Conclusions and Future Work

5.1 Conclusions

This thesis has focused on power consumption of HVAC system, and gives performance analysis on the impact of end-to-end delay in Zigbee-based communication system on power consumption in smart home. In order to understand better of how this system works, we firstly investigated the wireless sensor networks and smart grid technology, and then a wide range of survey on smart home, as well as some studies of HVAC systems were presented. Great amount of challenges and weakness of the system still exist not only on smart grid technology concept, but the whole world is still waiting for the delivery of a standard and regulated smart grid formats.

HVAC system occupies an important part as an electrical appliance in both residential and commercial buildings, understanding its working behavior and applies it to the real environment would greatly enhance the performance of the entire power utilization. And therefore, we modeled the power consumption in the scenarios of both singled family home and commercial building, especially the power HVAC system consumes. A Mathematical model on power consumption of

HVAC system is introduced in our model to calculate the specific power consumption at different indoor temperature set points.

Moreover, an FSM based analysis model was established to simulate the HVAC system working status, by setting the parameters we can acquire the relationship between the time that HVAC system needs to penetrate the cooling load out and the temperature, and we give the initial effort of showing the relationship between the cooling/heating rate and the power consumptions. Finally, we introduce Zigbee-based communication system into the model in order to study the impact of end-to-end delay over the HVAC system in terms of power consumption. And the results prove that the delay does impact the power consumption of HVAC system, causing unnecessary energy waste and affect the comfort level.

5.2 Future work

The mathematical model we introduced into our system has the coefficient variant of the root mean square error of 9.7% between training data and the results, which could be improved and the model ignored the cooling load caused by evaporation could be studied more in the future.

The finite state machine used in the simulation model could be extended with more states such as system idle and system complete. As the real HVAC system works in a sophisticated way, more than just “heating” and “cooling” states, adding

more states into the model could considerably increase the practicality of the simulation results.

Typical North American residential and commercial buildings are the topic of this thesis, however, more types of architectures can be studied where different factors such as height, area, location, and other infrastructural parameters may be considered as well.

Zigbee communication protocol simulated in our system considers the physical and MAC layer, more application layer development could be carried out here. As well as the end-to-end delay affecting the power consumption of HVAC system could be enriched. How the end-to-end delay impacts the HVAC system may not only targets at the infiltration load section, but more ambient circumstances could be taken into consideration.

There is still a lot in Zigbee communication system to be exploited, apart from making effort to reduce end-to-end delay, how to securely transfer the message to end devices while collecting the according data, avoiding the malicious attack into the system could be discussed.

Great amount of research has been focused on incorporating power shifting and dynamic billing mechanism together; therefore, considering these may lead to reduce the burden of the power grid as well as the energy cost.

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Appendix A

Confidence Interval

In the engineering field, the correctness of simulation results is opened to be questionable for their validity, and therefore the Confidence Interval (CI) is introduced to testify the statistical accuracy. Generally, when the simulation is run under the same condition, that is, the same group of initial and environmental values and the same input, the results is still supposed to be different each time because of the statistical independency of each and every simulation. CI provides us with an estimated range of values which is likely to include the population parameter of interest. Here is the definition of CI: assume there exists an unknown parameter θ of a set of values X_1, X_2, \dots, X_n , for the given $0 < \alpha < 1$, if θ satisfies $P\{\theta_1 \leq \theta \leq \theta_2\} = 1 - \alpha$, we define the range $[\theta_1, \theta_2]$ is the confidence interval of θ when its confidence is $1 - \alpha$, θ_1 and θ_2 are the confidence lower bound and upper bound respectively. $1 - \alpha$ is called the confidence, and the selection of confidence is based on the requirement, for example, we choose 95% as the CI for the results in the thesis, which means the probability of the simulation results $P\{\theta_1 \leq \theta \leq \theta_2\} = 1 - \alpha$. Let us assume μ is the mathematical expectation and σ^2 is the variance, and X_1, X_2, \dots, X_n is the sample of set $X \sim N(\mu, \sigma^2)$, \bar{X} and S^2 are the sample average and sample variance, our job is to find the range based on the set of result values for the given α , it contains the expectation μ of X with probability $1 - \alpha$.

For the given variance σ^2 , the confidence interval of μ is calculated as below:

there is $X \sim N(\mu, \sigma^2)$, and $\bar{X} \sim N\left(\mu, \frac{\sigma^2}{n}\right)$,

$$E\bar{X} = \mu, D\bar{X} = \frac{\sigma^2}{n},$$

$$\text{random value } Z = \frac{\bar{X} - \mu}{\sqrt{\sigma^2/n}} \sim N(0,1),$$

$$\text{assume } P\left\{\left|\frac{\bar{X} - \mu}{\sqrt{\sigma^2/n}}\right| \leq \frac{z_{\alpha/3}}{3}\right\} = 1 - \alpha,$$

$$\text{then } P\left\{-\frac{z_{\alpha/3}}{3} \leq \frac{\bar{X} - \mu}{\sqrt{\sigma^2/n}} \leq \frac{z_{\alpha/3}}{3}\right\} = 1 - \alpha,$$

$$P\left\{-\frac{\sigma}{\sqrt{n}} \frac{z_{\alpha/3}}{3} \leq \frac{\bar{X} - \mu}{\sqrt{\sigma^2/n}} \leq \frac{\sigma}{\sqrt{n}} \frac{z_{\alpha/3}}{3}\right\} = 1 - \alpha,$$

$$P\left\{\bar{X} - \frac{\sigma}{\sqrt{n}} \frac{z_{\alpha/3}}{3} \leq \mu \leq \bar{X} + \frac{\sigma}{\sqrt{n}} \frac{z_{\alpha/3}}{3}\right\} = 1 - \alpha,$$

and here we acquire $\left[\bar{X} - \frac{\sigma}{\sqrt{n}} \frac{z_{\alpha/3}}{3} \leq \mu \leq \bar{X} + \frac{\sigma}{\sqrt{n}} \frac{z_{\alpha/3}}{3}\right]$, the confidence interval we need,

$\bar{X} - \frac{\sigma}{\sqrt{n}} \frac{z_{\alpha/3}}{3}$ is the confidence lower bound, and $\bar{X} + \frac{\sigma}{\sqrt{n}} \frac{z_{\alpha/3}}{3}$ the upper bound.

and the set of values should follow the normal distribution as Figure A.1.

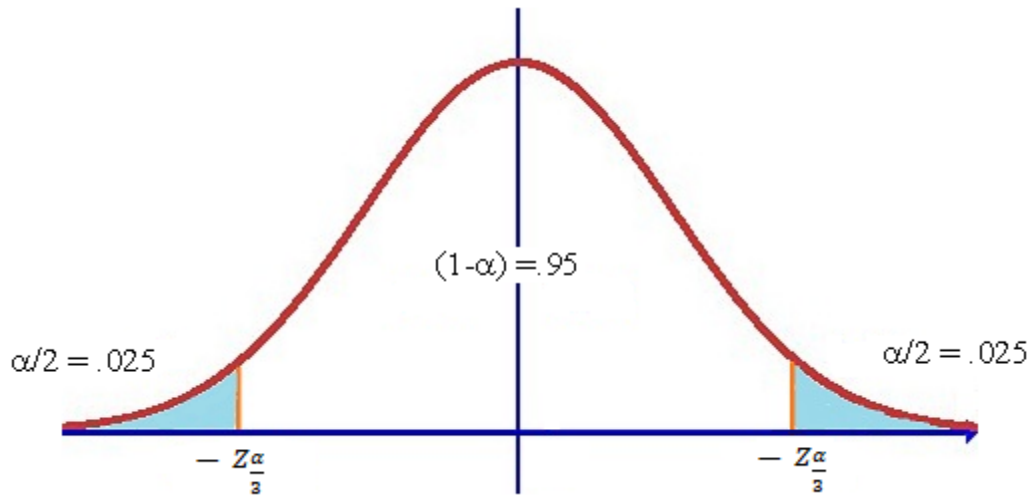


Figure A.1 Normal distribution

As we mentioned before, we choose 95% as the CI for simulation results, then the value of $Z_{\frac{\alpha}{2}}$ is $0.5 \times (1 - 0.95) = 0.025$. The CI obtained is referred to as the CI with probability $1 - \alpha$ confidence. In this thesis, 95% confidence interval is obtained.