Design and Implementation of a Web-based Home Energy Management System for Demand Response Applications

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ABSTRACT

The objective of this work is to design and implement an architectural framework for a web-based demand management system that allows an electric utility to reduce system peak load by automatically managing end-use appliances based on homeowners' preferences. The proposed framework comprises the following components: human user interface, home energy management (HEM) algorithms, web services for demand response communications, selected ZigBee and smart energy profile features for appliance interface, and security aspects for a web-based HEM system.

The proposed web-based HEM system allows homeowners to be more aware about their electricity consumption by allowing visualization of their real-time and historical electricity consumption data. The HEM system enables customers to monitor and control their household appliances from anywhere with an Internet connection. It offers a user-friendly and attractive display panel for a homeowner to easily set his/her preferences and comfort settings.

An algorithm to autonomously control appliance operation is incorporated in the proposed web-based HEM system, which makes it possible for residential customers to participate in demand response programs. In this work, the algorithm is demonstrated to manage power-intensive appliances in a single home, keeping the total household load within a certain limit while satisfying preset comfort settings and user preferences. Furthermore, an extended version of the algorithm is demonstrated to manage power-intensive appliances for multiple homes within a neighborhood.

As one of the demand response (DR)-enabling technologies, the web services-based DR communication has been developed to enable households without smart meters or advanced metering infrastructure (AMI) to participate in a DR event via the HEM system. This implies that an electric utility can send a DR signal via a web services-enabled HEM system, and appropriate appliances can be controlled within each home based on homeowner preferences. The interoperability with other systems, such as utility systems, third-party Home Area Network (HAN) systems, etc., is also taken into account in the design of the proposed web services-based HEM system. That is, it is designed to allow interaction with authorized third-party systems by means of web services, which are collectively an interface for machine-to-machine interaction.

This work also designs and implements device organization and interface for end-use appliances utilizing ZigBee Device Profile and Smart Energy Profile. Development of the Home Area Network (HAN) of appliances and the HAN Coordinator has been performed using a ZigBee network. Analyses of security risks for a web-based HEM system and their mitigation strategies have been discussed as well.

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ACK	Acknowledgement
ACL	Access Control List
AES	Advanced Encryption Standard
AJAX	Asynchronous JavaScript and XML
AMI	Advanced Metering Infrastructure
ANFIS	Adaptive Neural Fuzzy Inference System
API	Application Programming/Programmer's Interface
APL	Application Layer
APS	Application Support Sub-layer
APSDE	Application Support Sub-layer (APS) Data Entity
APSME	Application Support Sub-layer (APS) Management Entity
ARL	Attribute Report Listener
ARM	Advanced RISC Machine
ASH	Auxiliary Security Header
CA	Certificate Authority
CBS	Cipher Block Chaining
CD	Clothes Dryer
CRUD	Create, Read, Update, Delete
CSMA/CA	Carrier Sense Multiple Access with Collision Avoidance
CVSS	Common Vulnerability Scoring System
DB	Database
DE	Data Entity
DEHEMS	Digital Environment Home Energy Management System
DoS	Denial-of-Service
DR	Demand Response
DRA	Demand Response Algorithm
DRAS	Demand Response Automation Server
DRLC	Demand Response/Load Control
DRRC	Demand Response Research Center
DSDM	Device and Service Discovery Module
DTD	Document Type Definition
EMM	Energy Monitoring and Management
EMP	Energy Management Panel
EMS	Energy Management System
ESI	Energy Service Interface
EUI	Energy Usage Information
EV	Electric Vehicle
FERC	Federal Energy Regulatory Commission

FFD	Full Functionality Device
GHEMS	Green Home Energy Management System
GUI	Graphical User Interface
HAN	Home Area Network
HCI	Human Computer Interaction
HEM	Home Energy Management
HEM IM	Home Energy Management (HEM) Information Model
HEM-WS	Home Energy Management (HEM) Web Server
HIG	HAN (Home Area Network) Internet Gateway
HMAC	Keyed-Hash Message Authentication Code
HTML	Hyper Text Markup Language
HTTP	Hyper Text Transfer Protocol
HTTPS	Hyper Text Transfer Protocol Secure
HVAC	Heating Ventilation Air Conditioning
IDS	Intrusion Detection System
IEEE	Institute of Electrical and Electronics Engineers
IP	Internet Protocol
IPHA	IP Host Application
IPS	Intrusion Prevention System
IPSec	Internet Protocol Security
IUI	Intelligent User Interface
JSON	JavaScript Object Notation
LBL	Lawrence Berkeley National Laboratory
M2M	Machine-to-machine
MAC	Media Access Control
MAC	Message Authentication Code
MC	Master Controller
ME	Management Entity
MHJ-DR	Multi-Home Joint Demand Response
MIC	Message Integrity Code
NAESB	North American Energy Standards Board
NAT	Network Address Translation
NHLE	Next Higher Layer Entity
NIST	National Institute of Standards and Technology
NL	Network Layer
NLDE	Network Layer Data Entity
NLME	Network Layer Management Entity
NLPDU	Network Layer Protocol Data Unit
NSA	National Security Agency

NWK	Network
OpenADR	Open Automated Demand Response
OS	Operating System
PAN	Personal Area Network
PAP10	Priority Action Plan 10
PCT	Programmable Communicating Thermostat
PDU	Protocol Data Unit
PHY	Physical Layer
PLC	Power Line Communication
PMD	Personal Mobile Device
RAM	Random Access Memory
REST	Representational State Transfer
RF	Radio Frequency
RFD	Reduced Functionality Device
RMI	Remote Method Invocation
S2B	Series 2B
SAGA	Sensor Actuator Gateway
SAP	Service Access Point
SCAN	Soil Climate Analysis Network
SE	Smart Energy
SEN	Smart Energy Network
SEP	Smart Energy Profile
SHA	Secure Hash Algorithm
SH-DR	Single-Home Demand Response
SHEMS	Smart Home Energy Management System
SOAP	Simple Object Access Protocol
SoC	System on a Chip
SSL	Secure Sockets Layer
TCP	Transmission Control Protocol
TED	The Energy Detective
TLS	Transport Layer Security
ToU	Time of Use
UI	User Interface
VT HEM	Virginia Tech Home Energy Management System
WH	Water Heater
XHTML	Extensible Hyper Text Markup Language
XML	Extensible Markup Language
ZAL	ZigBee Abstraction Layer
ZCD	ZigBee Xommand Dispatcher

ZCL	ZigBee Cluster Library
ZDO	ZigBee Device Object
ZDP	ZigBee Device Profile
ZED	ZigBee End Device
ZGD	ZigBee Gateway Device
ZHA	ZigBee Home Automation

Chapter 1
Introduction

1.1 Background

In the U.S., 20% of generation assets are used for 5% of the time during the peak demand, which illustrates the importance of peak load management or load shifting during peak hours. Engineers and researchers have been trying for decades to find suitable peak load shifting techniques. Over the years, Demand Response (DR) programs have been proven to be an effective approach in this regard, which bolsters the fact that awareness and management of electricity consumption can collectively have great impact. An automated Home Energy Management (HEM) system can offer seamless customer participation without sacrificing customer comfort. This way HEM could encourage more householders to participate in such programs and alleviate this problem of peak load situation.

To address this timely issue of alleviating peak load condition, this research identifies opportunities and challenges related to technologies and demonstrate the initiatives and solutions by a prototype implementation of a Home Energy Management (HEM) system with DR focus.

Today approximately 5.9 billion people use smart phones, of which approximately 334 million smart phones have been sold by Samsung and Apple – which are more capable and feature-rich. To achieve the full DR potential for residential customers, it is necessary to utilize these ubiquitous devices as well as develop user-centric applications to feed the growing interest and awareness among the individuals. This research has been engendered from this noble motivation where relevant technological issues have been identified and solved. Some of the solutions have been implemented and demonstrated and some have been recommended. Many of these concerns have been identified from the limitations of past implementations from other prototypes or products from both the academia and industry.

1.2 Objective

The objective of this work is to develop an intelligent web-based Home Energy Management (HEM) system that can enable automated demand response participation for residential customers, and illustrate relevant technological challenges and issues. The HEM system proposed and designed in this work is called *Virginia Tech Home Energy Management* (*VT HEM) System*. The primary focus of this work is on identifying functional and user interface requirements, relevant technologies, system architectures, implementation techniques, wireless and cyber security, interoperability, efficiency, and associated application models.

To achieve the above objective, the following specific tasks are performed:

- To develop an intelligent web-based user interface—accessible from desktop as well as PMD (Personal Mobile Device) computers including smart phones—for monitoring and feedback of energy consumption and control of appliances, either locally or remotely.
- To develop intelligent DR algorithms to tackle a number of challenges regarding home energy management.
- To develop web services based machine-to-machine interface to promote interoperability and circumvent communication problems.
- To implement device organization and interface for end-use appliances based on standardized ZigBee application profiles and communication protocols.
- To implement Internet and wireless communication security measures; and conduct analyses of security risks of wireless communication and ZigBee security features.

1.3 Contributions

The first and foremost contribution is the development of a web-based feedback and control system for homeowners, which has been conducted as an experimental and interdisciplinary endeavor by intimate collaboration with power and electrical engineers and researchers. Their expertise and practical experiences have been instrumental in shaping the application-level features, requirements and user interfaces for the web-based HEM system. The collaboration has been a real eye opener where the efficacy of reasonable compromise between simplicity and exquisite interface has been demonstrated. Therefore, this work can be used as a reference for functional requirements and User Interface (UI) design research for this domain. The building blocks of the UI have been inspired not only by prior industry and research projects—in some of which large-scale user evaluation has been conducted—on feedback and control systems but also by applications from other domains as well.

Second, an extension of a single-home DR algorithm has been designed and incorporated within the proposed web services-based system, allowing DR to be performed for multiple households in a neighborhood. This provides better optimization—in managing overall appliance operation—than that would be possible by managing appliance operation of a single home. The proposed algorithm shows its effectiveness to mitigate the demand compensation phenomenon—an undesirable increase in electrical demand after a DR event ends. In addition, it also demonstrates the ability to avoid the transformer overloading problem, when implemented in a group of homes served by the same distribution transformer.

Third, a web services-based communication framework for Demand Response signaling and Application Programmer's Interface (API) to the HEM system has been developed, which offers opportunities for the development of innovative applications. The HEM system proposed in this work is in its propitious position to circumvent communication challenges—via an alternative mechanism employing web services—between an electric utility and residential customers. That is, web services-based interface makes it possible for an electric utility to offer residential customers to participate in a DR program in an area without an Advanced Metering Infrastructure (AMI). This will serve as an enabling technology for automated end-use demand response.

Fourth, device organization and interface for end-use appliances have been implemented based on the ZigBee application framework and the Smart Energy Profile (SEP). These devices have the device and service discovery features developed by implementing clusters from ZigBee Device Profile, SEP and ZigBee cluster library.

Fifth, some of the potential vulnerabilities of the ZigBee standard and proposed best practices to resolve these vulnerabilities have been discussed in this work. Potential security concerns are identified and proper security measures have been implemented.

Chapter 2
Literature Review

2.1 Feedback and Energy Monitoring

Dr. Sarah Darby of Environment Change Institute at the Oxford University investigates the effect of feedback on user behaviors in an interesting manner in [1]. There she focuses more on the result in raising interest in users rather than on technological nitty-gritty. The work presented by her has taken into consideration the earlier work in several fields, which address the efficacy of feedback systems and heightened awareness. She has mentioned about the finding in the 1970s that it has been established that feedbacks have proven impact and her publication explores if this applies to householders for the specific purpose of energy saving or reducing waste of this valuable resource. According to her, for sustained demand reduction both instantaneous direct feedback and indirect feedback in the form of accurate billing is necessary. This 2006 study finds that direct feedback can result in 10-15% saving and indirect feedback has the potential of 0-10% saving. The study also classifies the value of comparison in energy consumption into normative and historical. Normative feedback is the comparison of data or findings regarding the consumption of a householder with that of other similar households. Historic feedback is the comparison of energy consumption data or facts with that from a past time period for the same user. Between the two above feedback techniques, it has been found that historical feedback is more effective more easily accepted by householders. Feedback with energy consumption information promotes actions from householders. For decades researchers have realized the potential of feedback. But it was not possible in the earlier decades to provide the user with direct feedback. It had been observed that over a quarter of the consumers used to painstakingly check meters—although those meters used to be installed in out of sight places—regularly in 1980 and these householders who happened to be have higher level of awareness tended to be more likely to install energy efficiency measures. The potential saving with motivated customers were found to be in the region of 10%-20% in the advice program run by the West Lothian District council [1] where the participants used report meter reading over few weeks by making a phone call. This scheme found to be very encouraging. In the publication of Dr. Darby [1], many other similar results have been reported from extensive efforts to promote energy conserving behaviors among the clients. Many of these have been conducted when computing and Internet was not as ubiquitous as today. Reviews of many other encouraging results have been published in [1].

In a study conducted in Japan, as described in [2], the total energy consumption was reduced by 12%. This study had been conducted in Japan in 2001-2002. User friendly HEM system has been utilized to make it convenient for the users.

The researchers of [3] have developed a proactive energy management system that takes into consideration the interaction with smart grid. They have built G-HEMS (Green Home Energy

Management System) in a prior project. Now they are building an EMM (Energy Monitoring and Management) system to manage the energy of buildings. It is also known as BEMS or Building Energy Management System. The authors' objective was to propose architecture for the EMM system.

The Digital Environment Home Energy Management System (DEHEMS) [40-6] is a wide-scale energy monitoring system. The development is performed in three cycles. After initial research a monitoring and control system has been developed as the first cycle and users are involved. This team has set up living laboratories with hundreds of real households. Data from those households are collected, and their interaction with the system is analyzed to find useful features that contribute in energy saving. Based on extensive feedback collected by discussion sessions, questionnaires, etc., and upon analyzing their motivation subsequent cycles are conducted. For example, in Cycle 1, individual appliances monitoring was not available and wired connections had been used. But upon receiving the reactions of the users—which revealed their inconveniences—the researchers had implemented ZigBee mesh network based wireless communications, and individual appliance monitoring. Some of the users had expressed concerns about privacy, location of the server where their usage data has been stored, etc. Also concerns about remaining connected to the Internet for 24 hours have been expressed by users who used to be in the habit of accessing the Internet on demand basis. DEHEMS offers both local display and web based monitoring options, and found that more computer and web savvy householders preferred web based monitoring, which enables them to monitor and control appliances remotely. This entitled them with a sense of empowerment. On the other hand some other users preferred the local in-home display. Users gave requirements for features for appliance and gas monitoring, attractive user interface with personalized energy saving tips, etc. This system heavily depends on sensors. DEHEMS provides real-time consumption, historical consumption, cost saving, cost saving, average consumption, comparison against similar household among other DEHEMS participants, context-aware personalized tips and alerts, etc. From the extensive user study by DEHEMS project, one important and often overlooked issue has been revealed. This is the fact that many appliances lack a button to turn the device off and some of the appliances, which do contain such a button, have the off button placed at inconvenient or inaccessible positions. This single issue contributes a great deal in unnecessarily leaving appliances in the standby mode, which is a significant contributor in the 39% waste of total energy supplied to the residences. This helps realize how important it is for users to be offered a convenient remote controlling mechanism, which can be used to identify which appliance is responsible for energy consumption in its standby state and turn it off as needed.

Wattson [7] is a state of the art energy monitoring system which uses ambient light to glow and alert the householders about energy consumption. It is easy to integrate with an inverter where in home electricity generation is available, e.g., from photovoltaic solar panels. In such generation option, it glows green when more power is generated than consumed. When more is consumed the display light becomes purple and during high consumption period it glows red. This way it helps users to conserve energy by providing continuous feedback. It can store historical consumption data of up to 28 days. It can run as a standalone device, and it can also be accessed from the Personal Computer (PC) using custom software.

AlertMe [8] is a UK based company who offers a suite of commercial products including autonomous management of appliances to offer the user with comfort and convenience. AlertMe SmartEnergy [9] offers second by second energy monitoring. In-Home Display, web based display and smart phone applications are available for monitoring second by second data. AlertMe SmartHeating [10] enables the user to monitor, program and control heating and cooling of space and water. Hot water and space heating becomes 80% of load sometimes and being able to control the appliances related to these two activities have the potential for saving energy or preventing loss. Inefficient and unnecessary heating/cooling contributes greatly to the 39% waste of energy supplied to residences as mentioned in [11]. AlertMe SmartData [12] has the ability to learn from collected data about the habits of the users and based on this knowledge it is able to offer the user more features for maximum comfort and convenience. SmartData determines energy consumption by individual appliances by means of profiling. It has the ability to detect which appliances are operating inefficiently. In other words, AlertMe products discussed above offer a wide range of comfort and convenient features.

Plogg Network Controller [13] is a commercial product which is a smart meter and plug providing real-time and accurate energy reading. It communicates using wireless technologies. It sits right at the source of power as a smart plug and it can be controlled remotely. Although it is not a Home Energy Management system, it can be used by an HEM system. In VT HEM, smart plugs have been used, which have played similar role as Plogg meters. Plogg meters can be controlled by sending wireless signals, and it has the potential of being used in a DR program where some other HEM systems or the utility would be able to control the operation of an appliance.

WattBot [14] is a research project to design energy monitoring and feedback system that would promote energy conservation. It offered iPhone and iPod touch applications which displayed energy consumption data from different appliances to get the users motivated by means of awareness and visualizing the consumption of electrical energy. The authors describe their user interface in their report. It had bar charts which were proportionately long with energy consumption amount. They conducted evaluation of their User Interface design by presenting their product to real users and capturing their reactions. The users had given feedback that they wanted more information such as energy consumption of the previous days, weeks or months, which was not available at WattBot at that time. In their Future Development Section, they have emphasized on developing web based remote access to such energy consumption visualization interface. They had also mentioned about their plan of collecting usage history at appliance level. All these features are available in HEM system developed in this work.

The Energy Detective (TED) [15] offers a family of hardware and software products for the measurement and monitoring of energy consumption. They have put up a demo website which we have used as another source of inspiration for user interface and visualization design. It offers live dashboard, history, graphing and load profile sections.

The HEM system proposed in [16] emphasizes on user interaction interface. It is called and Energy Management System (EMS) which contains an Energy Management Panel (EMP). EMP combines two approaches: The resident is able to analyze the energy flows in his household and to configure the integrated EMS. On the EMP, it can be shown how much energy has been consumed within the last 24 hours. The plot can be zoomed so that the user can get an accurate value at a certain time period. The plot displays negative values to indicate energy flow to the grid. A price signal is also shown on the EMP. An Energy Information System for apartments has been proposed in [17], considering electricity generation capabilities of the homes. This system is related to a project in Europe. Verizon has developed a home energy management solution as well [18].

Google PowerMeter [19] was an endeavor by the philanthropic arm of Google Inc. It had been deployed for the electricity customers of San Diego Gas and Electric and received encouraging reviews. This service had been retired on September 16, 2011. In the service information page Google is optimistic about the future of this nascent field of energy monitoring and feedback.

There have been many other endeavors in the energy monitoring fields which had gained great reputation at the short term but later were discontinued or failed. The failures did not necessarily stemmed from the lack of features or any other technical limitations, but can be attributed to not addressing users' interests. Also it has been speculated that it had been too early for those programs since majority of the population were not aware of the existence of such energy management programs [20]. It may take years for users to start using such HEM systems as part of their normal life style. For these reasons, emphasis of this work is given on implementation of only proven features which would add real value. Even if a feature sounds very interesting and sophisticated, from engineering perspective it needs to have reasonable effect to be incorporated within an HEM. The design philosophy of making the prevalent and high impact features better and reliable has been followed in developing VT HEM.

The HEM system developed in this work implements many of the features from the above systems but purposefully excludes some less important features to prevent it from appearing too complicated to a user. Many of the projects discussed above do not offer homeowners any controlling ability—their users can only monitor appliance operation and have rich sets of visualization features. Those devices employ sensors but no actuators. Most of those do not offer intelligent autonomous management and control of the appliances which would be able to help homeowners to automatically control energy usage. On the other hand, the proposed VT HEM is a sensor-actuator system with intelligent autonomous controlling option employing many of the rich visualization techniques with intelligent interfaces.

2.2 Overview of DR and HEM

With the emergence of the smart grid, Demand Response (DR) has become a new possibility. DR is an approach to allow end-use demand management, where an electric utility company—according to prior agreements—sends price or demand response signals to residential/commercial customers. Federal Energy Regulatory Commission (FERC) defines demand response as: "Changes in electric usage by demand side resources from their normal consumption patterns in response to changes in the price of electricity over time, or to incentive payments designed to induce lower electricity use at times of high wholesale market prices or when system reliability is jeopardized."

DR requests or signals can be sent using Power Line Communication (PLC) or Radio Frequency (RF) communication to customer premises through smart meters. Based on this signal, customers may choose to manage their energy usage and turn ON/OFF selected appliances based on their specific preferences. An HEM system can help a customer to respond to such DR events.

Fig. 2.1 illustrates the overall concept of the proposed HEM system that can be used to allow automated DR applications (i.e., managing or scheduling appliance operation) within a residential house. There are basically two categories for DR, pricing-based and incentive-based. In pricing-based DR schemes, per unit electricity price varies based on time of day. Usually during high demand periods, electricity is charged at a higher rate. In incentive-based DR schemes, participating users receive a pre-agreed incentive—usually monetary—for allowing an electric utility to manage their electrical consumption.

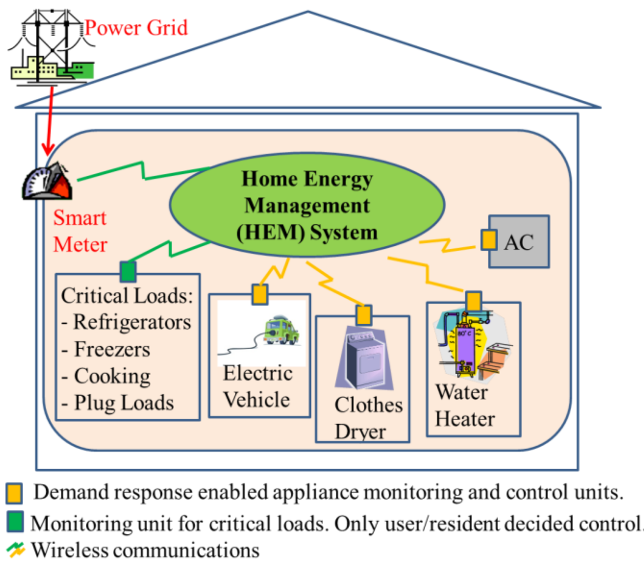


Fig. 2.1. Conceptual architecture of the Home Energy Management (HEM) system.

Here some of the earlier DR-capable HEM systems are discussed. Authors in [21] describe a high level overview of HEM. Interconnections among various sub-systems are given. It is claimed to be an optimized system. The system utilizes weather data, DR signals and user preferences to perform the control operation. The authors discuss two energy saving techniques, namely active and passive. The control of the appliances by the HEM is called active energy management, and improving insulation, heat loss, etc., is called passive energy saving.

Green Home Energy Management System [22] or GHEMS emphasizes heavily on determining comparative efficiency of an appliance. An appliance is compared to other appliance of the same kind. It has individual appliance based real-time active power consumption, and also hourly, daily, monthly accumulated energy consumption information. This system can detect the active or standby state of appliances and can provide feedback to the user. In this work, a design and implementation of an electrical outlet has been demonstrated. It has the capability of connecting with a device called ZigBee controller. It is of great convenience that the measuring and controlling circuitry remains encapsulated from the residents.

Smart Home Energy Management System (SHEMS) has been shown to have potential for future efficiency measures in the work published in [23]. A MATLAB/Simulink model has been used to conduct analysis of various aspects of HEMS. Authors of SHEMS [23] have defined HEM system in terms of its four major functionalities: ‘informative’, ‘automated’, ‘advanced’ and ‘integrated’. The ‘informative’ HEM system offers useful visualization of information—by means of graphical elements or charts—regarding energy consumption at households. The ‘automated’ HEM system allows the customer to set their preferences, and priorities regarding the operation of the appliances and local generations. Advanced HEM system includes both ‘informative’ and ‘automated’ functionalities. The ‘advanced’ HEM system offers the ability of being controlled either locally or by third parties. The ‘integrated’ HEMS include all functions offered by the ‘advanced’ HEMS along with the ability to forecast loads and local generation. The work in [23] presents the potentials of energy saving by means of a Smart Home Energy Management system or SHEMS. Besides controlling, SHEMS plays one of the key roles in Demand Response programs. Taking advantage of distributed micro-generation at residences is also achievable through an advanced SHEMS. Using simulated data, case studies have been shown. The first case study shows that, SHEMS based feedback and control reduced the energy cost of 40 Euro over a 5 months period. The second and third case studies show that based on the feed-in tariff for the generated electricity, the customer can has to pay 14 Euro, and receives 174 Euro of feed-in income from the utility respectively. This not only saves energy expenses of the householders, but also helps peak-load reduction for the utility. Some potential barriers of widespread deployment of SHEMS have mentioned in this paper. High cost of SHEMS is one of those. Another important reason is the fear of cyber-attacks and privacy breach. Successful pilot projects have been mentioned in this paper. Some of these pilots have been fully implemented later.

An aggregated decision making system based on neural-fuzzy learning of user energy consumption has been proposed in [24]. Utility can forecast load, and design ToU (Time of Use) electricity pricing program accordingly, and also can control individual appliances. When a user goes to turn on a device, it shows how a rescheduling would result in decreased energy cost, given such opportunity exist at that scenario. Message can be shown either on the Master Controller (MC) or on the Appliance display. They formulate the automatic management of the operations of the appliances as an instance of scheduling problem. Some other similar algorithms have been mentioned in this work as well. The network is zero-configuration, i.e., the user doesn’t have to do anything at all. In [24], the prediction is made by means of Adaptive Neural Fuzzy Inference System (ANFIS). For predicting, it needs to be trained. Electricity usage data from real homes had been used to collect the necessary training data. Times of switching appliances ON/OFF for the previous two days, and other information such as the day of week, weather condition, room temperature, etc., are used as parameters for the prediction task of ANFIS. It is not evident what load profile data and aggregation methods have been utilized in [24].

Physical characteristics based residential load model has been developed in [25]. Support for Demand Response can be enabled for these models. In that work, the Demand Response strategy and load profiles have been simulated in MATLAB. The Demand Response algorithm is described in more details in [26]. Hardware implementation of an HEM system has been proposed in [27]. It has Graphical User Interface (GUI) for the user to provide input. The GUI can be used to configure and test the HEM system. Their concept is to implement the HEMS in an embedded system. However the demonstration has been performed in a Laptop with ZigBee communication module. In the work in [27], data collection is purely command based, i.e., the HEM system sends a command to the controller of the appliance, and the controller sends electrical consumption data back to the HEMS. Therefore, for each appliance, transmission of at least two messages is necessary.

The work proposed in [28] extends the earlier work published in [25]. In this publication, the authors proposed DR in the context of households under a distribution transformer, as opposed to the previous work considering only a single house. The main goal here is to prevent a distribution transformer from overloading. With the advent of electric vehicles, it has become likely that more than one household served by the same distribution transformer can have electric vehicles, which might be charged at the same time after getting back from work. In such scenarios, the overloading of the distribution transformer can be significant. If a transformer is overloaded at 130% or more, lifetime of the transformer can be significantly shortened. Another solution to prevent overloading is to upgrade a distribution transformer to a higher rating. But this would be prohibitively expensive. Therefore, an automated HEM system, capable of controlling total household load within a certain load limit, seems as an obvious choice. The work proposed in [28], deals with this issue without assuming a demand limit signal from the utility company. Instead they rely on a signal from a distribution transformer. The authors assume that, this signal will contain the demand limit information for individual households. Based on this limit, the respective corresponding HEM systems in the households under that transformer would reschedule the operation of their respective controllable loads. The algorithm used here does not implement any different strategy than that of [25]. Same algorithm has been applied for three residences independently by applying individual load limits so that the total load does not overload the transformer. In simulation, an individual load limit for each household has been performed in a straightforward manner. All households get same load limit which is determined with the consideration that the total load does not surpass the transformer capacity significantly.

In this work it has been demonstrated that an online or web-based HEM system can offer practical solutions to the challenges of transferring transformer signal and performing joint load controlling of multiple homes.

2.3 Web Services

Interoperability issues of the HEM system have been approached by many researchers. In [29], authors present a home gateway that offers interoperability among various devices at the service level. The proposed gateway comes with an ability to apply an energy management strategy. In [30], authors have described a home energy monitoring system using sensor networks. Its accuracy and energy saving efficiency have been evaluated. Authors in [31] offer a RESTful interface of a building management system. Challenges of interoperability, integration, overhead, and bandwidth limitation of a wireless sensor network) are discussed. In [32], authors present a thorough evaluation of applications of machine-to-machine (M2M) communications and discuss their open research issues. The work in [33] offers a network architecture for HEM. Authors in [34] offer a service-oriented system to enable delivery of energy management services by other providers who are interested to develop innovative applications. They also offer an algorithm that makes use of aggregated user information to yield more efficient energy saving strategy. The system in [35] offers a generic energy consumption model with the support for per user and per appliance energy consumption measurement. Authors in [36] present the development of a system to achieve energy efficiency and to manage alternate power generation for buildings. Authors also propose a new information model for describing devices and power consumption or generation. Sensor-Actuator Gateway Agent (SAGA) [37] is another system offering easy configuration and grouping of devices using a web interface. It has been deployed in three homes in the Pittsburg area for the data collection purpose for several years. The Green Button [38] initiative is an approach to standardize the framework by utilizing a common information model, which is NAESB (North American Energy Standards Board) PAP10 (Priority Action Plan 10) [39]. Green Button relies heavily on the web where all data are uploaded on a centralized server and it depends on utility companies to make it available to their respective users.

From the discussion above, despite having many proposals of HEM architectures developed in the past, and many new are on the way, very few have dealt with the challenge of making these systems interoperable. If all available systems use as many different information models, or utilize different types of communication protocols, it would not encourage others to build innovative applications and solutions.

2.4 Security

The work published in [40] shows that performing encrypted communication adds significant processing and communication overhead. It results in decrease of information possible to be transmitted within a frame as well. This reduction can be up to 33.8% Therefore, communication overhead increases for the exchange of same number of frames. In addition to these two overheads, it might be necessary to send more frames as securing the frames require additional header ASH (Auxiliary Security Header) and MIC (Message Integrity Check). Since these take extra space, sometimes the data which need to be transported might not fit in a single frame because of this overhead. This will require the device to transmit more frames.

The authors of [40] have shown that the energy expenditure caused by securing frames is: 393.54 μJ per frame. IEEE 802.15.4 wireless protocol offers eight different modes of security which ranges from no security at all to various combinations of authentication and confidentiality (encryption) of various MIC (Message Integrity Code) size. These various capabilities are offered to accommodate a wide range of requirements of potential applications. Some applications do not use security at all, and some require high security. For example, ZigBee home network applications usually require standard security, but some ZigBee industrial applications require high security.

In [41] the author has implemented security functionalities to prevent reply attack which is usually performed by an adversary by recording an encrypted frame when a legitimate frame is transmitted, and later playing it back. Since the recipient of the frame receives the same data, it might have no way to detect that this frame is in fact transmitted by some illegitimate sender. To prevent that, a sequence number is added to the frame on every frame transmitted by the sender. Therefore, if the recipient gets a frame and upon decryption it finds that the frame is tagged with a frame number it has already processed, the receiving node can determine that this frame is a stale one, and discards it without any further processing.

The authors of [40] and [41] have identified three specific overheads that increase the memory (RAM) requirement of the node with implementing security features.

The authors of [42] have published a lightweight security framework called TinySec to secure the link layer of wireless sensor networks. Implementation of security options for most wireless communication protocols, including IEEE 802.15.4 are very resource consuming. TinySec finds a balance among security, packet overhead, and resource requirements.

In the research published in [43], the authors have mentioned some security flaws of IEEE 802.15.4. Two major concerns expressed in that paper are regarding key establishment and insecure ACK (acknowledge) messages. Another criticism in that paper is that an unauthenticated node would be able to send messages to other nodes. In addition to that, the authors of [43] have also commented about the lack of completeness of the IEEE 802.15.4 in case of a Reduced Functionality Device (RFD), which may remain asleep when it needs to respond to participate in message exchange for security features. The authors of [43] have also expressed concerns about the maintaining the ACL (Access Control List) state after power off.

The authors [44] mentions about the device AVR RZ Raven USB Stick, which can be used to perform various attacks including sniffing to ZigBee traffic. Two of such devices can be used to inject illegitimate packets into the network as well as impersonate as the Coordinator device of the wireless PAN (Personal Area Network). Efforts required for such attacks are surprisingly low, since the devices can be bought only for $40, and free software implementation to conduct this attack is available as well.

National Vulnerability Database maintained by NIST [45] lists the vulnerability of the ZigBee related implementation of Wireshark—a mature and widely used tool for analyzing, monitoring network packets and their relevant measurements. It has a ZCL (ZigBee Cluster Library) dissector program for analyzing ZigBee application, and it has been diagnosed with a vulnerability that allows remote attackers to launch Denial-of-Service (DoS) attacks using a crafted ZCL packet, related to attribute discovery. The Access Complexity metric of the CVSS (Common Vulnerability Scoring System) score is “Low,” meaning that it is usually always exploitable, without any specialized conditions or extenuating circumstances [46, 47]. Although this is not a weakness of ZigBee standard, it emphasizes the fact that while implementing various clusters and services, extreme caution should be exercised. Information available at [48] summarizes the reason by saying that it fails to handle certain types of packets. The vulnerability is mentioned in [49] as “Failure to Handle Exceptional Conditions.”

2.4 Research Gap

2.4.1 Appliance Level Feedback and Remote Control Technologies

In Section 2.1 a number of relevant research and/or commercial endeavors, aimed at developing effective home energy management solutions, have been discussed. Many of these are only feedback and monitoring applications with focus on the visualization of energy consumption data. Some of the projects have been developed on both monitoring and control. Most of the prior work on monitoring and feedback systems does not offer the service at an individual appliance level. Web-based remote monitoring, and especially controlling of appliances over the Internet with high reliability is rare as well. It has been observed that there is a lack of energy monitoring and/or appliance controlling systems that have the ability to combine user's comfort preferences and lifestyle needs with along with DR participation.

Selected prior published work lacks details of user interface or schematic of other system components. Quantitative evaluation of the responsiveness of the user interfaces has not been conducted in most work.

Selected previous work is to perform simulation within a single platform, such as an interpreter of a simulation language like MATLAB/Simulink. Contributions of these work are useful, but experience of practical implementation using real-world technologies as a truly distributed system is important as well.

2.4.2 Demand Response/Load Control Strategies

Only a few earlier publications have addressed the issue of DR thoroughly. Some deal with price signals and show to the user the real-time price of electricity. But it has been found that price-based DR, e.g., time-of-use or real-time pricing schemes, are not effective in motivating homeowners in conserving energy. The more effective programs—as found from the decades of experience—are pre-agreed incentive based DR programs.

Selected prior work has formulated the energy management algorithm abstractly and those do not focus on practical integration of the algorithm within a real HEM system, as demonstrated in this thesis. In addition to that, constraints and preferences in those solutions are quite abstract and often do not match/cannot be mapped to real world situations properly. Although some of the proposed rescheduling solutions take into consideration the controllability of the loads, based on user demands, most do not handle the priority among the loads.

Demand response or load control schemes have been proposed or demonstrated to avoid undesirable side effects of DR, such as demand restrike. Practical algorithms to solve these problems are not available in the literature.

Not many prior DR algorithms have been evaluated quantitatively. No suitable metrics have been proposed to compare performances of algorithms. Neither their side effects have been explained in the light of such metrics.

No prior works have been found that combine preferences of different users from different households and their corresponding comfort settings to perform appliance level load control for DR, in a fair manner.

2.4.3 Web Services and Communication Requirements

A co-design of HEM system and its web services interface is necessary for being useful in the real world. There are communication barriers to solve important problems regarding coordinating the energy use among households and conducting DR signaling. Most of the current approaches depend on AMI network or Power Line Communication (PLC). The messaging is proprietary as well. Web services are an appropriate fit to solve such issues. But it has been observed that there is considerable lack of available experiments conducted in this regard.

For an example, transferring an overload signal from a distribution transformer to the HEM systems at the houses has been identified as a requirement for several prior work. First, it can help avoid the overloading of the transformer. It can also help coordinating the charging of electric vehicles. Coordination among multiple appliances from different households can yield much better results. Communication mechanisms or alternative system design to offer more elegant solution in this regard has not been demonstrated. Monitoring of the transformer load by the utility, or sending of DR-related signals can be performed as well, by means of web services. Unfortunately no prior work on web services has solved these real life issues.

It has been envisioned that, upon the maturity of HEM systems and the smart grid, there would be new marketplaces for services and energies, and it would be essential to be able to offer opportunities for new innovative applications to interact with the HEM system in a secure and reliable manner. So far this progress has happened in quite an ad hoc manner, without considering application designers and developers. Selected prior work offers web services for retrieving Energy Usage Information (EUI) based on NAESB PAP10. But it depends on the utility to upload this information on the server. No prior work has demonstrated such services where householders can participate with/without the involvement of utility.

In some cases, vendors of individual appliances provide both WiFi and ZigBee chips, and offer web services-based interfaces to control appliances. Such an interface makes device integration easy for that particular device. One problem with such features is that, there can be as many such different web services interfaces as there are devices. This makes it impractical for the developer to implement numerous vendor specific web services. Such a collection of appliances will have a collection of different APIs (Application Programming Interface) and it will be difficult to implement bunch of different web services for even a single home. Another problem with traditional HEM systems is that, each of those has a different energy usage information (EUI) model. This creates barriers when interfacing with other systems.

2.4.4 ZigBee Application or Smart Energy Profile based Device Organization and Interface for End-use Appliances

Many of the energy monitoring researchers of home energy management systems use some form of wireless networking but they do not dig into details of this important aspect. Also it has been found that most prior work do not go above the Network Layer communication. ZigBee Device Profile (ZDP), Smart Energy Profile (SEP), ZigBee Home Automation (ZHA), etc. offer constituents for building a truly smart ecosystem of devices—with ZigBee based system organization and interface for end-use appliances—from HEM point of view.

Selected prior work, describing their system as ZigBee-based, only utilizes ZigBee mesh networking for the communication purpose. ZigBee mesh networking is a low-level Network Layer service which is application agnostic; more specifically ZigBee mesh networking has nothing to do with HEM system or Demand Response (DR). There is a significant lack of published experiences of developing HEM systems and implementing DR-based on ZigBee Application and Smart Energy Profile (SEP).

Selected prior commercial product implemented the communication and generic electric appliances' logic within the electric outlet. This would be inconvenient to plug in an appliance at a fixed outlet. Considering that this research advocates and implements the coupling of appliance behavior with the appliance itself not with any outlet.

2.4.5 Security Requirements and Implementation

Security requirements of an HEM system depend on its system architecture and its dependency on wireless and Internet communications. Selected prior work has considered security issues of wireless networking technologies, especially for IEEE 802.15.4.

Over the decades, security issues of Internet communications have been covered in numerous research endeavors. However, there is considerable lack of previous work on the security of an HEM system from a system point of view.

Security aspects of an HEM system are heavily dependent on the design of the distributed system as well as on technologies used to implement different subsystems. Even chips used to implement various components are important factors, since resource constraints severely extenuate the ability to implement security measures. Considering these, it appears that an investigation of HEM system and associated security measures should be conducted as a co-design process. For prior work on HEM systems, it is rare to find such approaches.

Chapter 3
Objective

The main objective of this thesis is to bring into daylight the challenges and issues of building an intelligent web-based and highly distributed home energy management system. The following tasks have been accomplished to fulfill this objective:

- **To develop an intelligent web-based user interface—accessible from desktop as well as PMD (Personal Mobile Device) computers including smart phones—for monitoring and feedback of energy consumption and control of appliances, either locally or remotely.**

  The User Interface (UI) dynamically adapts itself based on inputs from a user. The UI has been designed and developed using visual and input elements based on components which have been found to be useful from practical user evaluations conducted by prior studies in feedback and control systems.

  Interface showing live states of appliances as well as for controlling appliances have been designed.

  Intuitive and easy to use interface for assigning priorities of controllable appliances have been developed as well.

  Joint visualization and input interface for managing comfort settings related to individual appliances and relevant operational preferences have been shown for each type of appliance. The input interface has been designed thoughtfully so that a user does not have to type anything or worry about input formats. Some of the input interfaces dynamically adapt based on input values for other elements.

  Visualization of live power consumption for individual appliances is shown, along with long-term energy consumption history over several time periods.

  Quantitative measurements, regarding the responsiveness of the user interface, have been shown as well.

- **To develop intelligent DR algorithms to tackle a number of challenges regarding home energy management.**

  First, an algorithm to perform load control of appliances in a single household has been implemented and incorporated within the HEM system. In this writing it has been referred to as a Single-Home Demand Response (SH-DR) algorithm.

  Second, the SH-DR algorithm has been extended to a new algorithm capable of performing joint appliance-level load control among multiple households at the same time. This algorithm is called Multi-Home Joint Demand Response (MHJ-DR) algorithm. The algorithm computes decisions, taking into consideration the preferences and comfort settings of the users of the individual households.

  Third, it has been demonstrated thorough case studies that the MHJ-DR algorithm is more resilient to the demand compensation effect, which is an undesirable side effect of performing demand response.

  Fourth, if households are served by the same distributed transformer, the transformer overloading can be mitigated by using this algorithm. It can tackle the transformer overloading problem when each household starts charging their electric vehicles at the same time.

  Fifth, the algorithms have been validated by simulation using physical characteristics based models of homes, water tanks, and appliances developed in [25]. A number of prior work published in [28], [26] and [27] have used the same load models.

- **To develop web services based machine-to-machine interface to promote interoperability and circumvent communication problems.**

  Web services have been developed for communication and message/data exchange between the utility system and the VT HEM system, making it possible to implement DR programs even when an AMI (Advanced Metering Infrastructure) Network or Smart Energy Network (SEN) is not present.

  Communication and functional features necessary to enable automated end-user/residential DR management for multiple homes have been implemented based on web services. A utility system (computer) can interact with the VT HEM systems of a group of households under designated distribution transformers. Upon doing that, monitoring of a transformer's load and setting its limit becomes possible using the implemented web services.

Services have been designed and developed for accommodating future interaction and data exchange requirements for other third party systems as well. These services would promote innovation and facilitate development of unforeseen future applications either by the utility or other independent organizations. In this regard, web services-based retrieval of the electricity consumption data in the proposed VT HEM Information Model (VT HEM IM) has been implemented. VT HEM IM has been developed based on Energy Usage Information (EUI) model standardized by NAESB (North American Energy Standards Board) PAP10 (Priority Action Plan 10).

Web services have been developed not only for the utility systems and potential third party systems but also for other system components of the VT HEM system itself. Web services have been developed and employed to transfer data—necessary for visualizations—between the HEM Web Server (HEM WS) and the client devices, e.g., a PMD, to render the highly dynamic web page containing the Intelligent User Interface. In addition to the transfer of visualization data, information about user actions on appliances is submitted from client devices to the server.

Web services have been developed for Home Internet Gateway (HIG)—residing at homes and bridging the wireless Home Area Network (HAN) and the HEM-WS—to retrieve the actions of their corresponding residents and decisions of the Intelligent Demand Response algorithm. By these services, loose coupling (independence) between the HEM-WS and HIG is achieved. Now HEM systems—developed by other academics or companies—can be hooked with the web server to extend themselves to the Internet realm.

- **To implement device organization and interface for end-use appliances based on standardized ZigBee application profiles and communication protocols.**

The device organization has been implemented in an Application Processor and a Network Communication Processor/chip. Each of the end-appliance devices has been equipped with an IEEE 802.15.4-2003 radio controlled by a communication chip with implementation of ZigBee mesh networking.

Each end-use appliance is coupled with a microcontroller with the implementation of the following components according to the standardized ZigBee device organization and profiles: ZigBee Network Layer Entity (NLE); and Application Support (APS) sub-layer has been implemented as well including APS Data Entity (APSDE) and APS Management Entity (APSME). In APSME, support for binding between services and devices have been implemented.

On top of the APS, the following clusters from ZigBee Device Profile (ZDP) and ZigBee Cluster Library (ZCL) have been implemented:

- Active Endpoint Request/Response clusters.
- Simple Descriptor Request/Response clusters.
- Match Descriptor Request/Response clusters.
- Analog Input (Basic) cluster.
- Attribute Reporting Cluster including Configure Attribute Reporting Command, Configure Attribute Reporting Response, and Report Attribute Command.

The above clusters are used to perform Device and Service Discovery functions and reporting of power measurements.

- **To implement Internet and wireless communication security measures; and conduct analyses of security risks of wireless communication and ZigBee security features.**

Measures to secure all communications that go over the public Internet and that happen over the private wireless HAN have been implemented. Certificate-based client authentication, TLS (Transport Layer Security)-based encrypted communication and safeguarding of the HEM-WS using server Access Control List (ACL) and Intrusion Detection System (IDS) have been implemented. 128-bit Advanced Encryption Standard (AES) has been used to encrypt wireless communication.

User authentication and authorization for the HEM-WS have been implemented in VT HEM system. A sophisticated group-, role- and permission-based access control authorization system has been used. Monitoring and searching of user activities have been implemented as well, using which system administrators can identify malicious users and take immediate action on them.

Functionalities of the device organization and interface for end-use appliances have been done carefully so that no implementation vulnerability is introduced. Rigorous bound checking has been implemented from top to the bottom layer—of the implementation in application processor—to thwart buffer overflow attacks. Custom memory management has been implemented instead of employing the dynamic memory allocation libraries offered by the C language, for its unreliability and susceptibility of exploitation or buffer overrun in case of low resource microcontrollers.

Many of the concerns mentioned in prior work—most of which are about the IEEE 802.15.4 point-to-point wireless communications—have been assuaged by choosing appropriate devices with higher layers of the ZigBee stack and by implementing security at the higher layers.

Chapter 4

Architectural and Behavioral Design of the VT Home Energy Management System

This chapter offers the technical implementation details of the Home Energy Management (HEM) system developed in this work. It is a highly distributed system and there are many sub systems or devices which interact among each other to accomplish the objective of the system. Depiction of these internal subsystems and their interfaces are called architectural design. In addition to this design, another endeavor has been made at describing the system by dividing the overall system into smaller functional components to perform a specific function. This approach is expected to offer further clarification to the reader.

4.1 Architectural Design

The VT HEM is a distributed system with many components. It is a web-based Home Energy Management (HEM) system, which offers access from any place with an Internet connection. The VT HEM system Web Server (HEMS-WS) is one of the most important and versatile systems. It resides on the public Internet and stores selected information for displaying to users. Whenever the HEM-WS receives a user request it renders a webpage—containing the user interface—to the client device the user is using. It also captures user actions on the interface. The information shown to the user is submitted from his/her residence using web services. The appliance-level power consumption data are retrieved by a wireless communication network within a home, called Home Area Network (HAN). A HAN coordinator receives the appliance-level power consumption data and sends them via a gateway to the HEM-WS residing on an Internet server. The gateway system is called HAN Internet Gateway (HIG) in this thesis.

The HIG communicates with the HEM-WS to submit the power consumption status of appliances, as well as to retrieve information about user actions on appliances. Upon retrieval of this information, HIG uses services of the HAN coordinator to send appropriate commands to specific appliances using HAN formed on a wireless communication channel. Upon receipt of a command, an associated appliance takes an appropriate action to change its status.

The proposed system also allows an electric utility to send a DR control signal to the HEM-WS using web services over the public Internet. The overall system architectural design of the VT HEM is shown in Fig. 4.1.

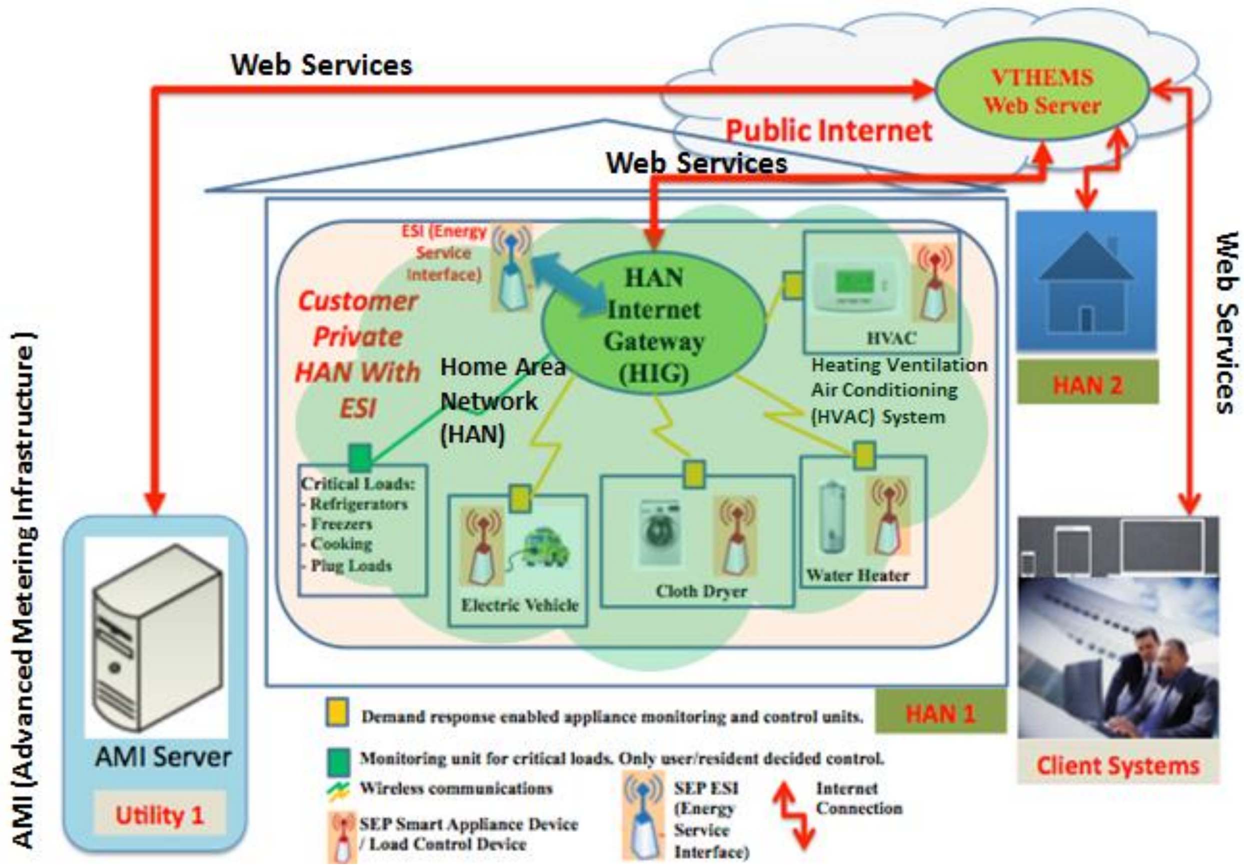


Fig. 4.1: System architecture of the VT HEM system.

Selected features of the proposed VT HEM to be highlighted include:

- An intelligent web-based User Interface (UI) has been developed as part of the HEM-WS.
- To enable wireless networking between the coordinator and an individual appliance, a chipset with implementation of ZigBee mesh networking protocol has been used.
- On top of the networking protocol, some functionalities based on ZigBee Device Profile (ZDP) [50] and Smart Energy Profile (SEP) [51] have been implemented at the coordinator and at each appliance. This topic is discussed in details in Chapter 9.
- In the prototype implementation of the HEM system presented in this work, the HIG and the HAN coordinator are implemented within a single desktop computer.

The device organization and interface for end-use appliances are implemented within a MSP430F247 microcontroller, which controls the operation of the appliances.

4.2 Behavioral Design

The user interface is rendered by the centralized sever to users' devices, such as smart phones or tablets, to allow accessing the webpage. Services offered by the API is contacted at the centralized HEM-WS sever.

As shown in Fig. 4.2 (the portion with green background), functional components of the system are arranged in two tiers:

1) ZigBee Abstraction Layer (ZAL)
2) HEM-WS

The ZAL and database (DB) behaviors are implemented on the machine that hosts HIG and the HAN coordinator. The DB tier is implemented as an internal supporting layer. For this reason DB layer has not been given much emphasis here. The HEM-WS is implemented on a web server.

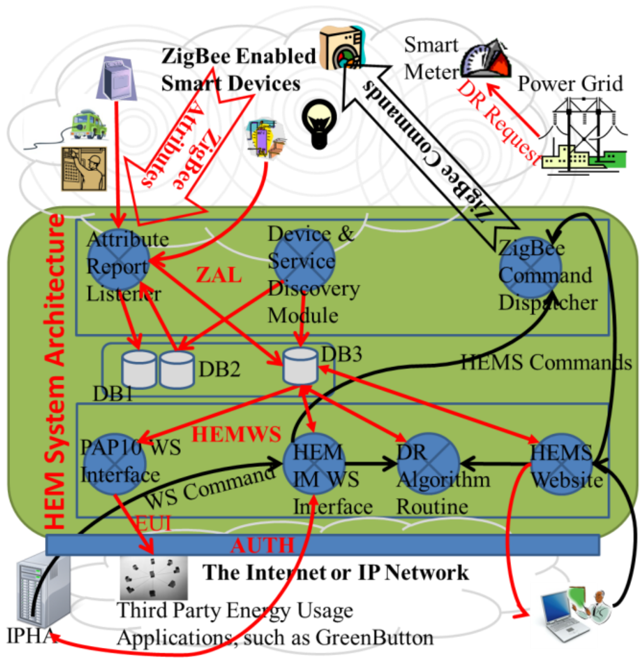


Fig. 4.2: Functional units of the VT HEM.

4.2.1 ZAL (ZigBee Abstraction Layer)

ZAL is responsible for interacting with the ZigBee-enabled devices. This tier has three modules:

- ZigBee Command Dispatcher (ZCD)

A brief overview of the organization of the ZigBee devices is offered in the Subsection 9.3 (ZigBee Device Organization). The implementation of the HAN Coordinator and device organization and interface for end-use appliances are based on ZigBee Device Profile (ZDP), for the elements shown as ZigBee enabled Smart Devices in Fig. 4.2. In this work ZigBee has been chosen as the preferred technology because of its wide acceptance and comprehensive nature. ZigBee protocols and standards have been defined by ZigBee Alliance, which is a conglomeration of all major technology companies who have track record of pioneering new standards. ZigBee Alliance consists with many other leading organizations and standards bodies to keep its standards, and products compatible.

- Attribute Report Listener (ARL)

The ARL periodically receives values of various attributes, which are sent by ZigBee devices. The sensor device has been implemented on each appliance. The sensor device provides the value of an analog quantity. It implements the cluster "Analog Input (Basic)." This is a standard cluster published in the ZigBee Cluster Library (ZCL). Implementation of this functionality is covered in more details in Chapter 9.

- Device and Service Discovery Module (DSDM)

The DSDM is responsible for discovering devices and services on those devices. It stores discovery information in database DB2 from where this information is submitted to the web server. It also processes the endpoint service descriptions, and maps these devices and services with the household appliances. Appliances identified will be stored in HEM Information Model or HEM IM (simple information model designed in this work) format upon submission to the HEM-WS. The HEM IM is discussed more elaborately in the Information Models Standard Subsection 7.4. The ARL uses this information to store measurement sample for a particular appliance. Implementation of this module is covered in more details in Chapter 9.

4.2.2 HEM Web Services (HEM-WS) Layer

Above the ZAL, the proposed design offers the web services layer. This layer renders the web site which is the primary human user interface. HEM-WS offers web services-based machine-to-machine interface as well so that utility systems or other authorized third party systems can interact with the HEM system. Chapter 5 covers the Human User Interface in details.

The intelligent autonomous control of the appliances is determined by the unit shown as "DR Algorithm Routine" in Fig. 4.2. More details on algorithm can be found in Chapter 6.

The web services layer contains another component that allows external utility systems and authorized third party systems to interact with the VT HEM system. Another service offered by this layer is used by the internal subsystems such as the HIG and the Intelligent User Interface. More details are available in Chapter 7.

4.3 Implementation Technologies

Various technologies have been utilized to implement the VT HEM system presented in this work. These technologies are widely used by numerous commercial and non-commercial systems. For security additional protocols and systems have been used as well. Chapter 10 covers more details about security technologies employed in VT HEM system.

4.3.1 HEM Web Server (HEM-WS)

Although in the discussion here and in prototype implementation the HEM-WS, is shown one sub-system, in real life, it would be natural to further divide it into smaller parts. These could be done for load balancing and redundancy. The components are designed in such a manner so that redundancy and load balancing can be done without changing the implementation at all. In Fig. 4.3, various components of the HEM Web Server (HEM-WS) have been shown along with various technologies used.

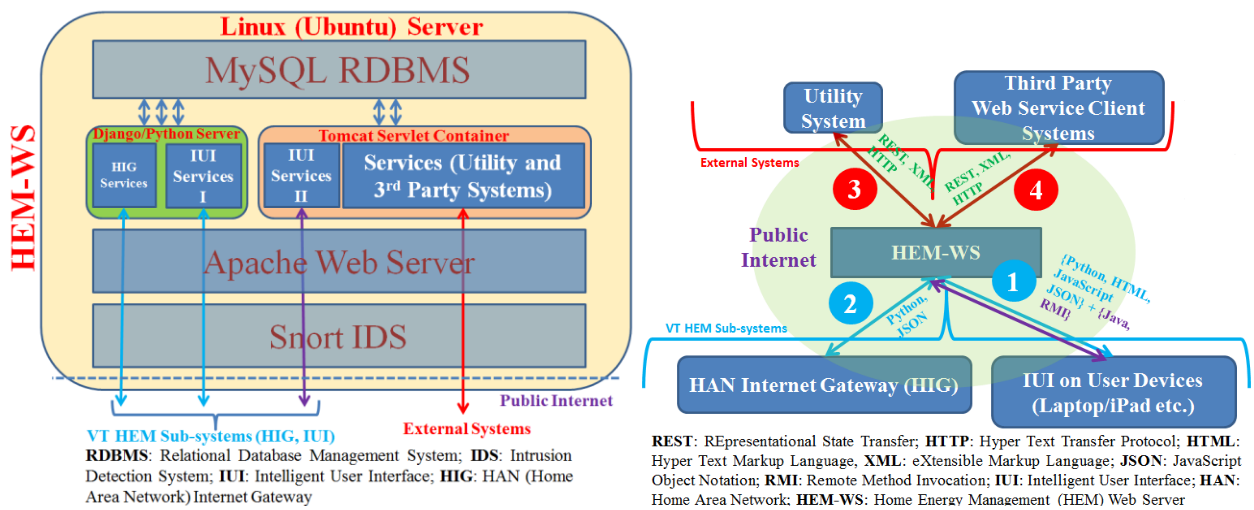


Fig. 4.3: Architecture and technologies of HEM Web Server (HEM-WS).

4.3.2 HAN Internet Gateway (HIG)

The HAN (Home Area Network) Internet Gateway, HIG, has several sub systems as well. HAN Coordinator has been implemented using Java. ZigBee PAN (Personal Area Network) Coordinator device has been used for HAN Coordinator. Some logical devices—standardized in the Smart Energy Profile (SEP)—related to Demand Response. Metering and Time of Use (ToU) Pricing has been implemented on the same machine. Java has been used to implement these sub-subsystems.

4.3.3 Device Organization and Interface for End-use Appliances

Device organization and interface for end-use appliances have been developed by implementing clusters of ZigBee Device Profile and Smart Energy Profile (SEP). ZigBee Device Object (ZDO) has been implemented according to the ZigBee Device Organization described in Chapter 9. Device—organized according to ZigBee system architecture and interfaces for end-use appliances—implement the SEP defined Load Control Device as well.

These functionalities have been implemented in MSP430F247 microcontroller from Texas Instruments (TI). C programming language has been used to implement these functionalities within this microcontroller. For ZigBee mesh networking XBee PRO Series 2 module has been used. ZigBee mesh networking employs IEEE 802.15.4-2003 for wireless point to point communication.

Chapter 5

Design and Implementation of VT HEM User Interface

From the discussion on effectiveness of feedback mechanism it is evident that User Interface (UI) of an HEM system plays one of the most important roles in assisting and engaging users to actively manage energy usage. Here UI refers to all active and passive display elements visible on the screen. Therefore, in this discussion all information visualization and feedback are considered a part of the UI. In addition to visual elements, dynamic behaviors of input or output elements are also discussed in this chapter. In the rest of this chapter, various characteristics of the web-based user interface of the VT HEM system are described.

5.1 Introduction

An intelligent user interface relieves a user from actively thinking while interacting with the VT HEM. Visualizations are graphs and real-time energy consumption data. Input values about the preference settings—which are shown back to the user—are considered a part of the visualization as well. Based on user's inputs, for some of the input elements, the behavior of other input/output elements may change dynamically to render a more convenient experience for the user. For example, selecting the start time of a preferred time window causes the set of available end time options to change. In the rest of this chapter, these techniques are discussed in more details. UI is primarily employed for two main purposes. First, the UI shows the user information; and second, the UI takes input from the user. It is what will interact with the user. Therefore, one of the major focuses of this work is designing a user-friendly and intuitive user interface. From the review of prior work, it is evident that without the active participation from users it would not be implement conservation of electricity. For the time being, the UI is available as a website, which can be accessed from any computer, ranging from a desktop computer to a handheld smart phone. Since VT HEM is web-based and runs on a central server, native applications for various computing devices, such as phones and tablets, can be developed for the user.

In the website design of the proposed HEM system, only the useful input and feedback elements—which are found to be important for DR applications—are implemented and discussed. These inputs are related to user preferences and comfort settings, such as room temperature set point, vehicle charging time, etc. Some other important inputs accepted by the VT HEM UI are priority order of controllable loads or appliances, hot water temperature, maximum allowed room temperature, visualization options, etc. The number of required input elements has been kept low purposefully so that the user does not get overwhelmed with too many technical details. These inputs influence decisions of the demand response algorithm at every step or time interval. The input elements are carefully designed so that the user does not have to type any text at all. These necessary UI elements have been organized on the web page under separate tabs: Live Dashboard and Graphing, DR Simulation, and Settings. See four tabs at the top section of Fig. 5.1.

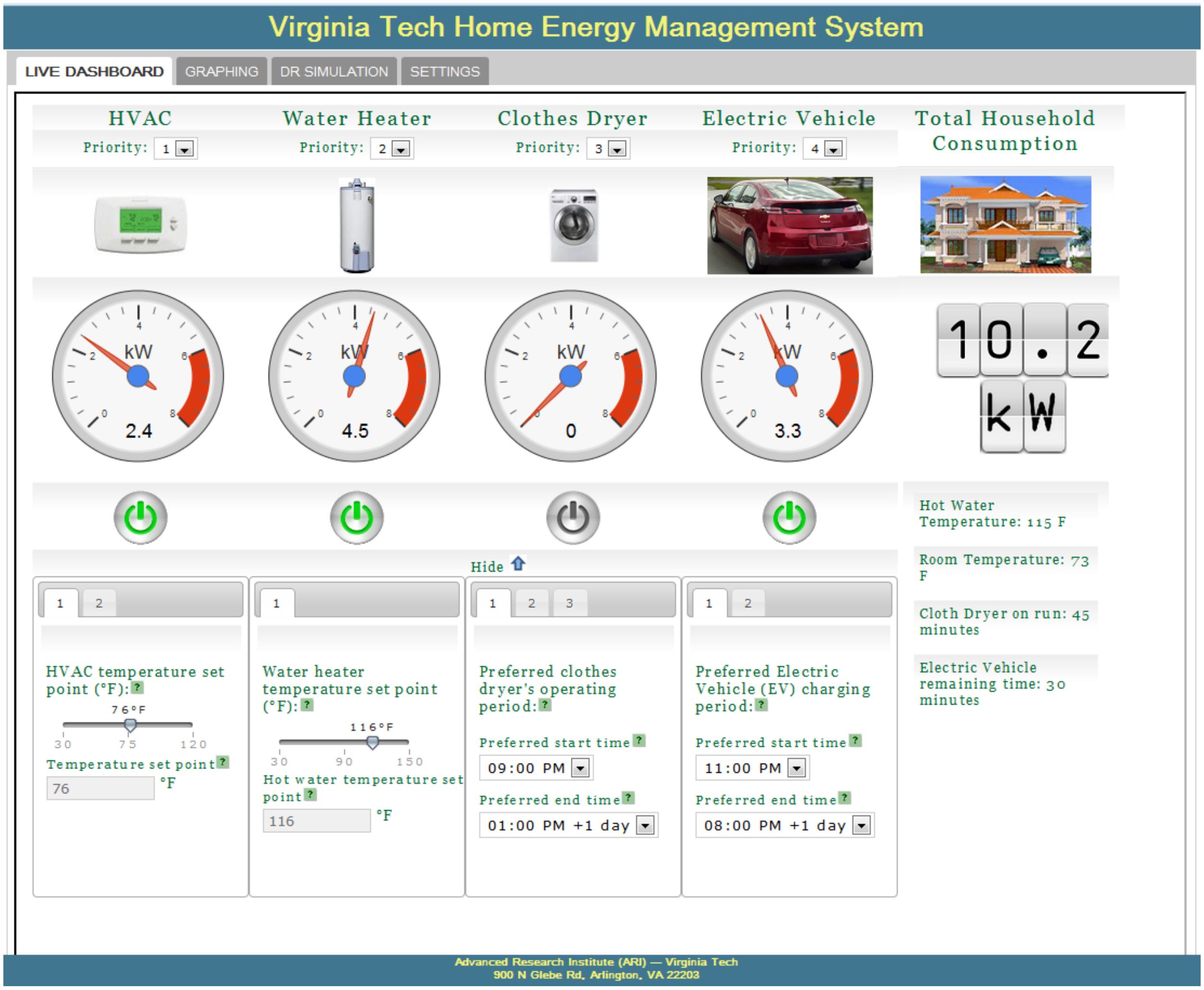


Fig. 5.1: The dashboard of the online VT HEM.

5.2 Tab 1 - Live Dashboard

The UI contains a section called Live Dashboard (See Fig. 5.1) where the instantaneous power consumption information is displayed. The purpose of the Live Dashboard Section is to present the user with a display that presents instantaneous power consumption information of monitored appliances and the total household in a readily recognizable and familiar manner.

Human Computer Interaction (HCI) researchers have been using the unconscious human behaviors—also known as thoughtless acts—to design interaction systems [52]. This philosophy has been carefully implemented within the HEM system developed in this research. Interface metaphor is another user interface design philosophy which has been used in this work. Interface metaphor suggests design visuals and other interaction to trigger the knowledge or experience of a user from other domains. The purpose is to let the user instantaneously understand how to interact with the user interface. For example: One of the earliest interface metaphors is the design of the icons of the file system folders (directories) to organize files. The folder resembles a real-life folder used to manage papers. Such design practices have been proven to be widely successful in every domain.

5.2.1 Displaying Real-time Load for Appliances

The instantaneous power consumption (kW) is displayed for an individual appliance using an analog meter, which resembles a clock face or car speedometer-type gauge. This helps the user to grow a sense of immediate recognition of the states of these appliances.

The gauge employed here is from the Google Visualization API (Application Programmer's Interface). This API offers the ability to define colored regions on the clock face. Red zones have been defined for high power consumption values. The hand or the rotating pointer of the gauge can be animated so that it gradually reaches the designated value at a moment. The pointer can change immediately as well. In this work, the animated option has been utilized, so that the user can notice the change in value. This would give the user a more realistic experience and better understanding. The user can also identify this behavior with real life mechanical analog devices.

The unit of the value displayed is also possible to be displayed. Kilowatt (kW) has been used as the default unit of the live power consumption by appliances. For smaller loads the implemented UI is able to decide dynamically if it would chose Watt or kW unit. In cases when Watt is used, only integer value is shown. In cases of kilowatt, one digit after the decimal is shown. All these are carefully designed by means of feedback from other researchers and domain experts. The automatic switching can be disabled so that only a consistent unit is shown everywhere on the user interface. This is the default setting, meaning the dynamic switching of units is disabled by default.

5.2.2 Pictures of the Appliances

To make it possible to identify the appliances immediately—without reading the text or just from scanning—pictures of real appliances are shown above the gauge dial displaying live power consumption data. The rightmost column of the dashboard shows a picture of a house, implying the display of whole-house power consumption data (elaborated below).

5.2.3 Total Household Load

The number shown below that picture of the house is the total household load or the power being consumed at that instant. Since total power consumption is important during a demand response event, the default display has been built using a scorecard like digital display. From experiences gained by other researchers in the field of power consumption data visualization and feedback, it is expected that design choices regarding the visualization of live data would have immediate effect on the user.

5.2.4 Current Operating Condition

In the right-most column several other measurement values are also shown under the total household load. These are the hot water temperature in the water heater tank, the room temperature, duration for which the clothes dryer’s heating coil is ON. The remaining time of charging of electric vehicle has been show there as well.

5.2.5 Control Interface for Appliances

Power buttons of controllable appliances shown in the HEM system have been placed below corresponding gauge dials. This enables the user to act upon a device effortlessly. When a device is turned ON and consuming energy, its power button is filled with green color. As soon as it is clicked, the device is turned OFF. At OFF state, the corresponding power button is painted with ash color. The color schemes are chosen to resemble that of the power button of computers, which used to emit green light when off, and no light when off. Such coloring scheme and shape of the buttons would let the brain of the user identify with everyday life habits of or past experiences and would help him/her to immediately recognize its function without conscious thinking.

5.2.6 Appliance Priority Order

Each of the controllable appliances has a priority order, which can be set by the user. From Fig. 5.1, it can be observed that there are numbers just above the picture of each appliance following the label “Priority.” Here, there are four controllable appliances. Therefore, there are four priority levels numbered from 1 to 4. The lower the number the higher the priority is. From the dropdown box, the user can choose the priority level of each appliance.

In Fig. 5.2, the UI to change overall priorities of the controllable loads is shown. When the user selects a priority level for a load, the priority levels of other loads will change accordingly. If the priority of a load is made higher, i.e., if a lower number is chosen for the priority value from the UI, the priorities of other loads, which had higher number (i.e., lower priority) than the old priority of the appliance, remain unchanged. The priorities of the loads, which had higher priority than the newly chosen priority of the appliance under discussion, also remain unchanged. All other priority levels of the loads, whose priorities were higher than the old priority and same or lower than the new priority, are reduced by one level. The function below shows the priority adjustment policy.

Let priority levels are $P_{i,t}$ before adjustment and $P_{i,t+1}$ after adjustment for any of the controllable loads indicated by $i = 1, 2, \dots, 4$. Let us change the priority of controllable load

$i = K$. Let the priority level of this load has changed from $P_{K,t}$ to $P_{K,t+1}$. The formula to change the priority level of other loads is given below:

$$P_{i,t+1} = \begin{cases} P_{i,t}, & P_{i,t} \leq P_{K,t+1} \ or \ P_{i,t} \geq P_{K,t} \\ P_{i,t} + 1, & P_{K,t+1} \leq P_{i,t} < P_{K,t} \ and \ P_{K,t+1} < P_{K,t} \\ P_{i,t} - 1, & P_{K,t} < P_{i,t} \leq P_{K,t+1} \ and \ P_{K,t+1} > P_{K,t} \end{cases} \tag{5.1}$$

In the above function, the lower the value of priority level, P_i, the higher priority the load has.

Fig. 5.2: Changing priority for controllable loads.

For example, if the original priority level of all appliances is as shown in Fig. 5.2, after the user increases electric vehicle (EV) charging priority level from 3 to 1—which is the highest priority—the adjusted priority level of the HVAC would be 2 or the second highest, and the priority level of water heater (WH) would become 3. This is demonstrated in Fig. 5.3. This means that charging of EV would be preferred over "room temperature set point violation," which is directly related to the operation of the HVAC—given both of these appliances has only these violations. In case of multiple violations, the DR algorithm reassigns priorities giving the appliance with higher violation score higher priority.

Fig. 5.3: Adjusted priority levels of appliances.

5.2.6 User Preferences and Comfort Settings

All controllable loads have some related user preferences. Now, the user interface elements shown below each of the appliances and their relationships with those appliances are discussed in this subsection.

5.2.6.1 HVAC Temperature Set Point Preference

First comes the discussion about user preferences settings related to HVAC. Fig. 5.4 shows the two HVAC preference settings forms. The first one can be used to fix the temperature set point of the HVAC.

The single valued slider can be used to select a value between 30°F and 120°F. The text box below the single valued slider reflects the temperature chosen by the user. Such an interface relieves the user from worrying about input format and unit. The user no longer has to think about the unit or worry about wasting time for putting invalid input. It also prevents the user from entering a malformed input value; therefore, it doesn't require the ability to show an error page upon submission of a form, which is common in today's most form submissions. This is the temperature at which the room temperature would be maintained.

The VT HEM in various manners can use input temperature. First when the DR event takes place, the DR algorithm may chose not to keep the HAVC on. In a hot summer day this would result in an increase in indoor temperature. When the room temperature goes over the set point temperature—set by the user—plus the tolerable band of temperature—which is maintained internally and not asked for to the user—the violation occurs. In case of other appliances having higher priority, and possibility of violation, the DR algorithm might keep the HVAC off and let the violation occur. Even if the DR algorithm allows the violation of the preference to occur in certain situation, it remains aware of the violation and keeps it into consideration in the next step. Without the knowledge of the user's preference of the set point temperature, the DR algorithm might let the room temperature grow indefinitely causing serious discomfort to the user. A sophisticated DR algorithm can ignore minor violation and respond back at larger violation. To keep such options possible it has been decided to offer the user input interface for this preference setting. In the Chapter 6, the implemented DR algorithm is discussed in details.

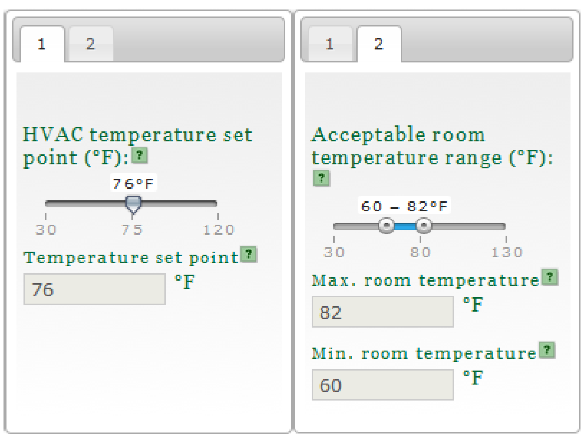


Fig. 5.4: User preferences related to HVAC (Heating, Ventilation and Air Conditioning).

5.2.6.2 HVAC Preference: Acceptable Room Temperature Range

This second setting is called acceptable room temperature range. The right hand side image of fig 5.4 shows the interface, which the user can use to set this temperature range. Unlike the first setting, “HVAC temperature set point,” this second option require the user to choose two values for a range of temperature—from lowest allowed to the highest allowed.

This setting becomes relevant when the first user preference regarding room temperature has been violated during a DR event. This is the temperature range the HEM system should consider as the maximum allowed violation of the first preference. In the Fig. 5.4, the range is shown to be between 60^{o}F and 82^{o}F.

There are two text fields below the doubly slider, which immediately show what values the user has chosen using the slider. The doubly slider allows a minimum temperature of 30^{o}F for the minimum acceptable temperature, and a maximum temperature of 130^{o}F for the maximum allowed room temperature. This renders it unnecessary for the user to think about valid input format or temperature unit, thus reduces cognitive load on the user. The user interface leaves no option for the user to get surprised, and everything happens according to the intuition of the user. The minimum allowed room temperature can never be greater than the maximum allowed temperature. This demonstrates the importance of using appropriate input fields according to the characteristics of input values. As with the previous input, this also renders some error handling unnecessary, especially involving the user.

For example, if the user were given just two text fields to input the numbers, then sometimes the users would input malformed values or inconsistent values, such as a minimum temperature which is greater than the maximum temperature. Even if the users have no malicious intent, handling for such exceptional cases would have been mandatory where there are uncontrolled inputs. To provide the user feedback about such an inconsistent feedback, the form would have to be displayed again, but now with error messages under the fields where wrong inputs have been entered. This not only causes the server processing overhead and network communication overhear but also frustrates the user in case of inadvertent wrong input. To avoid all these overheads altogether, such controlled input fields have been employed.

The tiny green question mark icons beside each green text labels on the comfort settings are discusses in the Subsection 5.2.3 on “Help Texts.” The detailed discussion of these features is deferred to keep the focus on comfort setting and preferences.

5.2.6.3 Water Heater Preference: Hot Water Set Point Temperature

Below the user preference related to water heater (WH), is discussed. This is the appliance that continuously work in the background to maintain the temperature of hot water supply. Like the HVAC, a water heater also has a set point temperature for hot water and a tolerance band of deviation from that set point. The water heater tries to keep the temperature inside the tank at the set point temperature. More detailed discussion on this topic is presented in the water heater modeling Subsection in Chapter 6. The user interface to set the water heater temperature set point is a single valued slider, which lets the user choose any temperature from 30^{o}F to 150^{o}F. The value selected by the user is shown in the text field under the slider. The text field is kept disable and work as an assurance of the value selected using the slider.

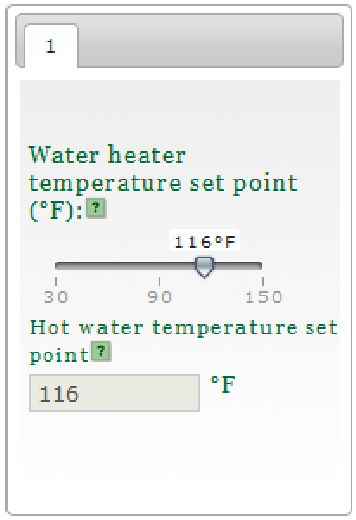


Fig. 5.5: User interface for setting the preference for water heater temperature set point.

5.2.6.4 Electric Vehicle Preference: Preferred Charging Time

Below user preferences related to the electric vehicle (EV) are discussed. There are two available user preferences settings in the VT HEM, regarding EV charging. In Fig. 5.6, the interfaces are shown.

The preferred EV charging period is the time period or time window—which may span two consecutive calendar days—within which the user wants to charge the electric vehicle. The algorithm keeps into consideration the preferred end time, and if the remaining charging time is more than the difference between current time and preferred end time, charging tasks priority is increased.

When the user plugs in an EV, the EV moves to the “ready for charging” state, but the charging might not start immediately. When the HEM allows the current flow into the battery, the vehicle is considered to move into the “charging” state. At the charging state, a timer is started within the HEM system to keep track of time spent in the active charging state. Depending on if a DR event is ongoing or not, and also based on user preferences and status of other power-intensive appliances, the charging of the electricity may be stopped by the HEM system. When this happens, it moves back to the “ready for charging” state again, and the timer is stopped.

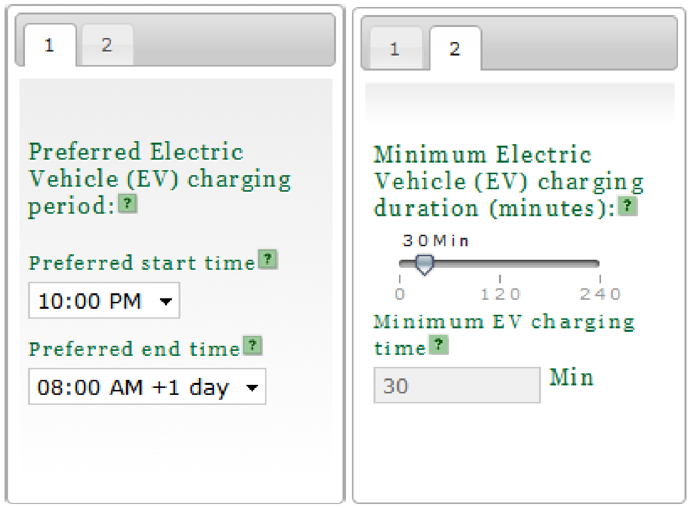


Fig. 5.6: Interface for setting user preferences regarding EV charging. The left image shows the preferred charging time, and the image at right shows the interface for choosing minimum charging duration.

The time period window for charging can be selected using two drop down lists. The first list lets the user select the starting time of the time window within which the vehicle is expected to perform charging. The second dropdown list offers the interface to input the end time of the window. The options available within end time dropdown list are not fixed—they are dynamically generated after the user selects the start time.

5.2.6.5 Electric Vehicle Preference: Minimum Electric Vehicle Charging Time

“Minimum electric vehicle charging time” is another user preference option. See the image on the right hand side of Fig. 5.6. A singly slider has been provided to choose the time and it has a default value of 30 minutes. This preference indicates that when the charging of an electric vehicle has been started, it is not desirable to stop charging after a very short period of time. This is because within that short time period the progress of the charging job would not be significant, and the charging job will have to be performed again sometime later. This will cause to perform charging state to switch frequently, which could have been done in one go. Although it is not expected to have any significant impact on the quality of battery life, this preference setting has been offered for demonstration purpose of the VT HEM.

5.2.6.6 Clothes Dryer Preference: Preferred Operating Period

The user preferences related to clothes dryer are discussed. There are three preferences settings.

The first one is the “Preferred clothes dryer’s operating period.” This is the time window within which the user wants to have the clothes dryer finish the drying job. This is shown in the left image in Fig. 5.7. This time window can act as the user requirement when the user wants the drying job to complete. An important feature of the VT HEM is that when the Demand Response (DR) algorithm makes the decisions, at every step it shows the estimate of the remaining job. This live appliance status update and additional visualizations are shown in Section 5.4.

5.2.6.7 Clothes Dryer Preference: Minimum Heating Coil ON Duration

The second setting is “Minimum heating coil on duration.” This setting becomes relevant when the HEM system tries to find an appliance for suspending its normal operation if that results in reducing the total load at that moment. A clothes dryer has two parts: motor and heating coils. The motor causes the revolution of the clothes within the clothes dryer. The heating coils are heated up to a high temperature and heat wet clothes. The heater consumes much more electric power than the motor. If the electricity supply to heating coils is turned off, heat loss occurs and the drying job takes longer time to complete. To keep the electric load within the load limit, the HEM system might cut off electricity supply from the heating coil. This is performed only because the clothes dryer is considered as a controllable load with high DR potential. If the heating coil is allowed to be at the ON state for a short duration before switching it OFF, it would not be able to accumulate sufficient heat and upon switching OFF this heating coil the insignificant heat would be a complete waste of energy in unusable form. Therefore, the preference “Minimum heating coil on duration” has been included. The HEM system’s DR algorithm takes this into consideration and may restrain itself from switching OFF the heating coil if it finds that the coil has been at the ON state only for a short duration.

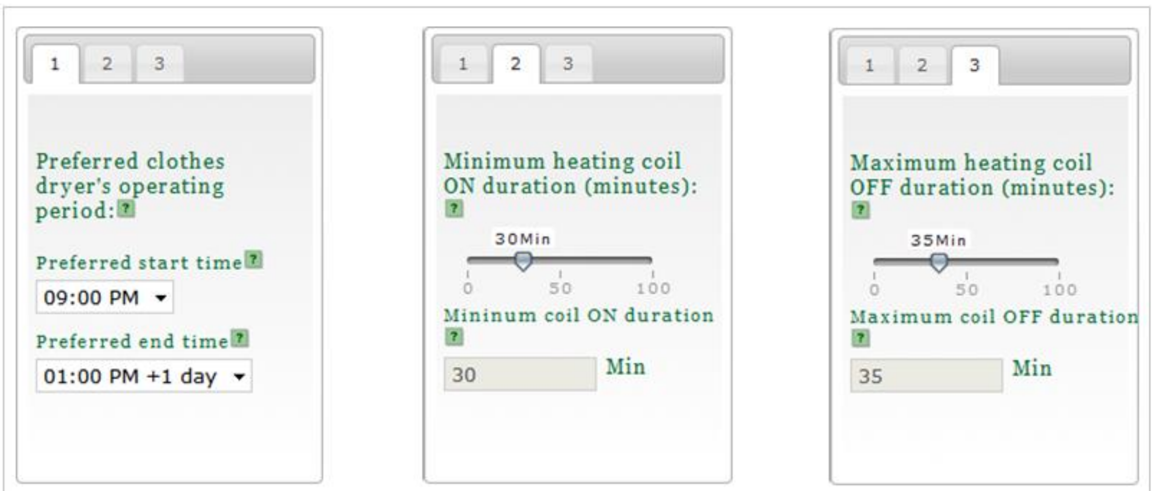


Fig. 5.7: UI for user preference settings regarding the clothes dryer.

5.2.6.8 Clothes Dryer Preference: Maximum Heating Coil OFF Duration

The third user preference related to clothes dryer is the “Maximum heating coil OFF time.” This is relevant when the HEM system turns heating coils OFF to keep the load level within demand limit. This parameter is present to avoid excessive heat loss when the clothes dryer’s heating coils are kept off for too long. The default value is 30 minutes.

5.2.7 Intelligent Input UI for Preferred Time Period

The rationale behind choosing drop-down list based input mechanism for time period selection is discussed in this section. Limitations of doubly slider are discussed as well. The start time can be any hour within a day, so there are always 24 possible inputs, and this set is fixed. The end time options starts with the hour next to the hour selected as start time. According to current setting, it contains eleven more subsequent hours making the total number of selectable options as twelve. Therefore, if the user chooses 10:00 AM as the start hour, the options for end hour start from 11:00 AM, and goes up to 10:00 PM. This is evident from Fig. 5.8.

The image shows that when the set of potential end hours containing twelve hours from the start hour goes spans more than one day, the hours are shown with the annotation "+1 day." This feature is offered to keep the user from worrying about entering invalid input values. The user gets assurance that the system has indeed recognized that his preferred time is spanning two days. Without such demonstration, the user would worry if the system would have understood what his/her true intention is. From above discussion it is evident that the user is not allowed to select an end hour which is beyond 12 hours of the start time.

However, the opposite is not true, meaning after the selection of the end hour, if the user wishes to change the time window or just wishes to change the start hour, he can choose any time before the end time from the first day. This is permitted because if the start hour is forced to remain within 12 hours of the end hour, the user would not be able to move the window to earlier values. This is shown in the left hand side image in Fig. 5.9. From that image it can be observed the options for the start hour remains regular, so the user can set the start hour at any value. Let the start hour is changed to 8:00 AM. In this case the end hour options start at 09:00 AM, but it does not stop at 8:00 PM with twelve hours option. Instead it runs up to the current value of end hour. In this scenario the options set for end hour has more than twelve hours to accommodate the window size bigger than 12 hours, which was made by the changing of start hour after selecting the end hour.

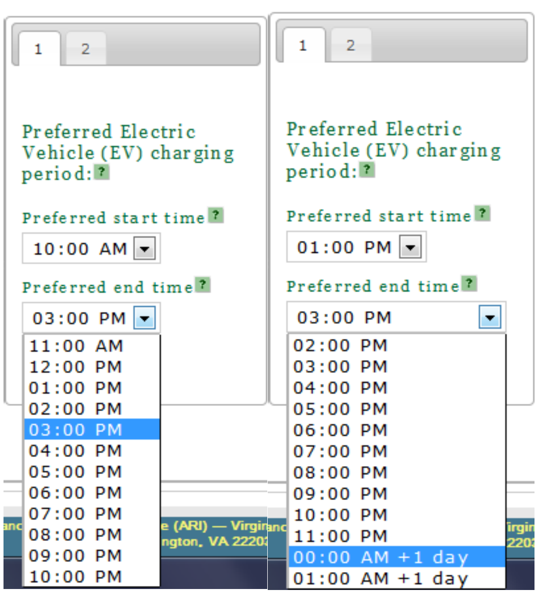


Fig. 5.8: Computed available options for the end time, based on the start time.

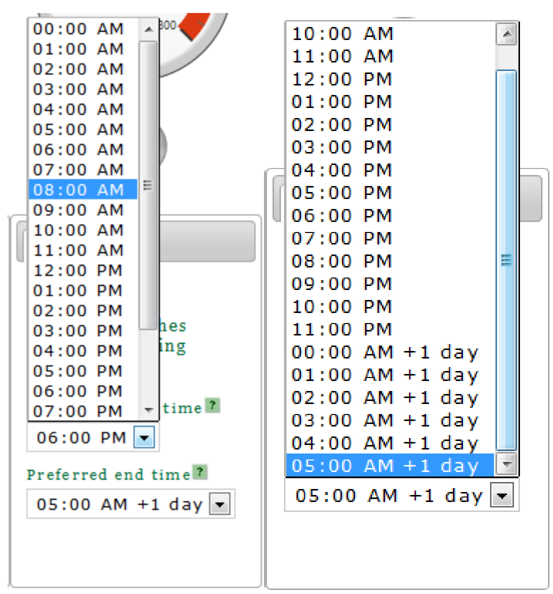


Fig. 5.9: Available options for start hour after selecting the end hour (left). The available options for end hours (right).

Next we demonstrate another intelligent feature of this dropdown list based time window selection. This intelligent behavior is demonstrated by showing an example behavior using Fig. 5.10. When a time range selection already exists and when the range spans two different days, the end time falls in the next day and it is annotated using +1 day. In such scenario, if the user decides to change the time window starting from any hour which is earlier than the of end hour in the sense of hour of day, i.e., earlier hour, the end hour is changed from the next day to the current day. For example, earlier the user had set the preferred start hour at 07:00 PM and the end hour at 05:00 AM of the next day. Such a range indicates that the load can be operated between 07:00 PM in the evening and 05:00 AM in the next day morning. Now if the user changes the start hour from 07:00 PM to an earlier hour of the day which is earlier than 05:00 AM, e.g., 02:00 AM, in such case the end hour automatically changes from "05:00 AM +1 day" to "05:00 AM." The selection of 02:00 AM as the start hour tells the UI of the VT HEM system that the new preferred time window of operation starts at 02:00 AM, but the end hour still remains at 05:00 AM. Since, such a range can be accommodated within a single day, there is no need to go to the next day. Based on this rationale, VT HEM automatically updates the end time of the preferred operational hour for the corresponding appliance or load. It also changes the available options as shown in the right-most image in the Fig. 5.10.

Please notice the condition here: the start hour must be earlier than the end hour taking into consideration as hour of day only. In the example scenario, since the end time had been 05:00 AM (next day), and new start time was 02:00 AM, the condition had been met. If the user had chosen 06:00 AM as the start hour, it would not be possible, since in that scenario the user has said that his preferred hour range is between 06:00 AM to the 05:00 AM of the next day.

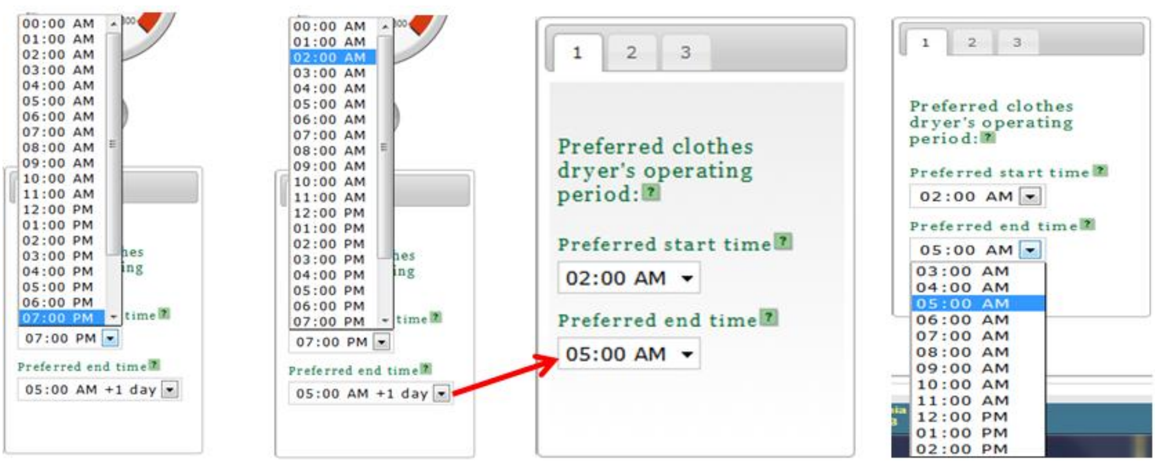


Fig. 5.10: Intelligent adjustment of the end hour when start hour is earlier.

If the end time is 05:00 AM next morning and the user changes the start time at 05:00 AM on the current day, VT HEM UI would handle such critical input gracefully without failing or resulting error condition. This case is demonstrated in Fig. 5.11.

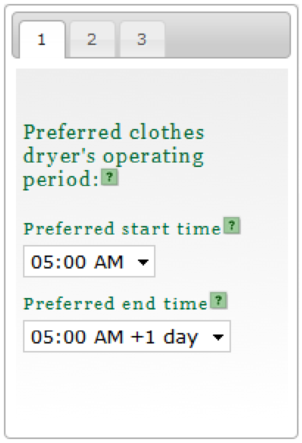


Fig. 5.11: Selecting 24 hour range.

The next intelligent behavior described is about choosing the date range as well. When the time window remains within same day the hour of day for the start time is always smaller than the hour of day for the end time. Now if the user changes the start time to a new hour of day which is larger than that of the end time, the end time is automatically considered to be in the next day, and makes this window span two days now. For example, let the current preference for charging the electric vehicle is between 01:00 PM and 08:00 PM. Now the start time is changed to 11:00 PM which has resulted in a larger hour of day (23:00 hours) than that of the end time (20:00 hours). In this situation, the UI automatically annotates the end time with +1 day, which works as an assurance for the user that the input in changing in start hour has been graciously handled without resulting in any inconsistency. It is really a decision deemed to reduce user confusion, but not the only method handling such input.

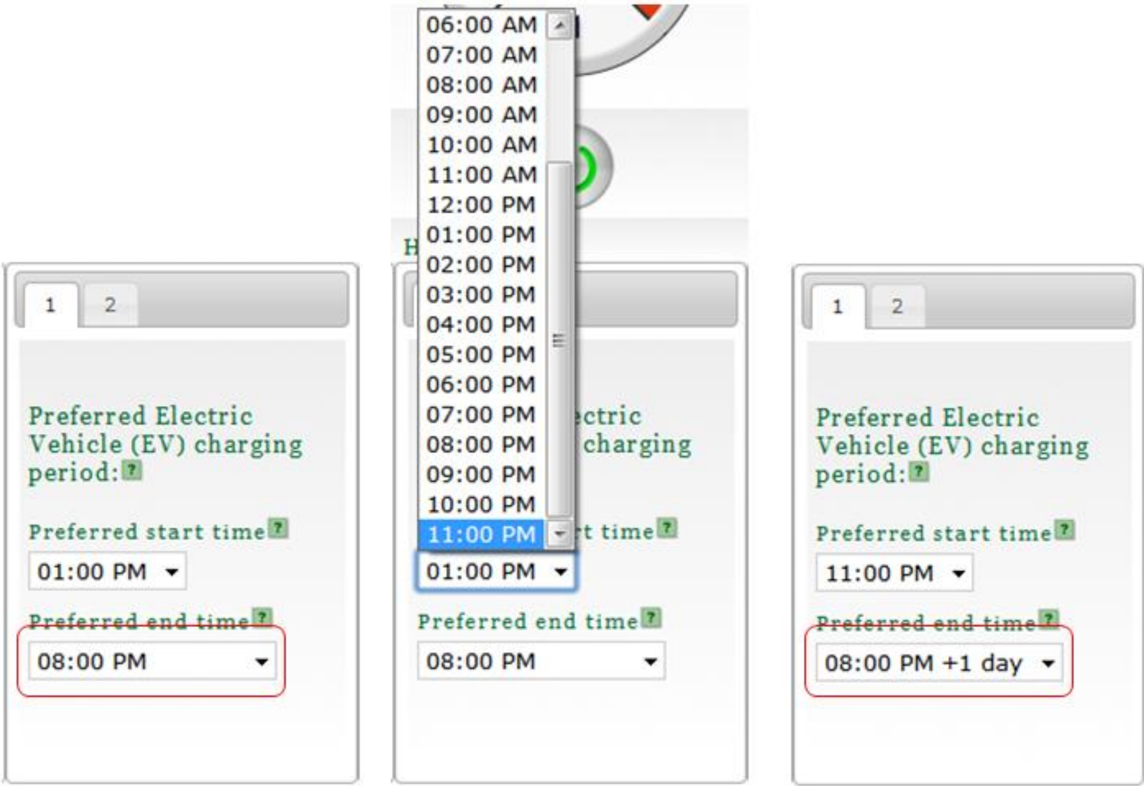


Fig. 5.12: UI responses in a scenario where the user changes the start time to an hour which is later than that of the end time.

5.2.3 Help Texts

Another useful feature implemented in this user interface is the explanation of all texts where user inputs are expected. For the first HVAC preference form, there are two text labels in green color. The top one is the title of the preference section which read: HVAC temperature set point (^{o}F). Beside this text—like all other labels shown on all preference forms—there is a question symbol. This symbol represents help message. Numerous applications that are used on a daily basis use such question mark icons to indicate help or suggestion. Therefore, the question mark icon shown here would require no explanation for the user to readily determine its purpose. If the user drags the mouse over the question mark, there would be a message explaining the corresponding label. In Fig. 5.13, this is demonstrated.

In this example, the HVAC related preference “acceptable room temperature range (°F)” is shown. In that preference there are three text elements. The second one is the label of the input shown as “Max. room temperature.” This label has a more user friendly explanation accessible using the little question mark shown beside the label. If the user places the mouse cursor on that question mark, the more elaborate description pops up. In Fig.5.13, we can see that the text: “Maximum tolerable room temperature (°F)” is shown as the popup text. On the right hand side image in Fig. 5.13, we show another displaying method implementation for similar descriptions.

If the user clicks the little question mark, instead of just putting the mouse pointer on it, the description would be shown within the preference form just above the title of the form. In this example, the question mark beside the label "Min. room temperature" has been clicked. As a result, the description "Minimum tolerable room temperature (°F)" is shown in the empty space right above the title of the form. In Fig. 5.13, the raw snapshot has been annotated with red rectangular area to highlight the help texts. In the latter case, the text displayed is evanescent. The text disappears and the space becomes empty again. The duration of the text is three seconds, which have been found to be reasonable for reading that information.

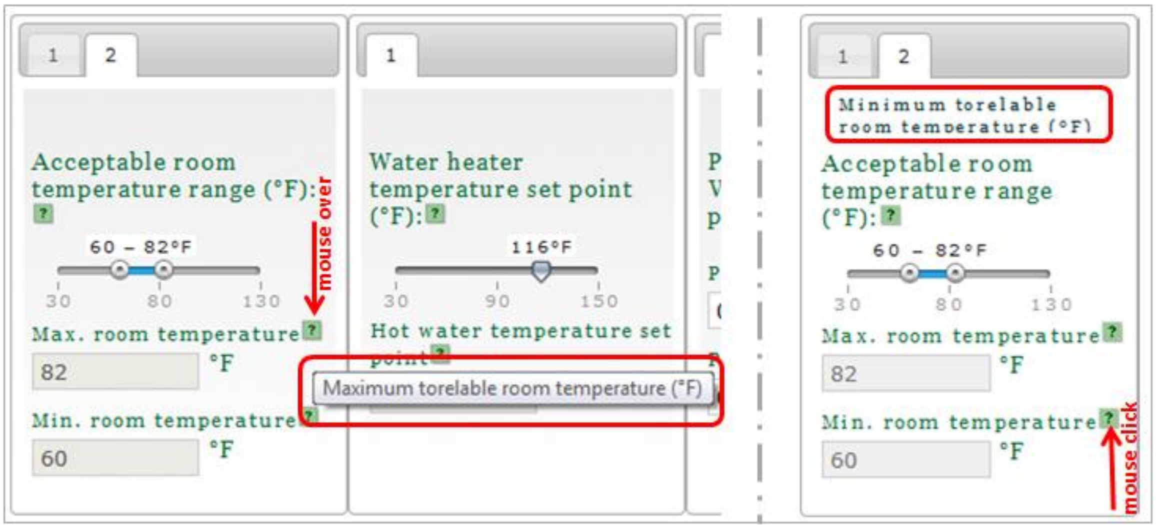


Fig. 5.13: User friendly description of the text shown on the preference setting. On the left image, the popup display on mouse over event is shown. On the right hand side image, the help text is shown on the event of mouse click.

5.2.4 Limitations of the Doubly Slider

In this subsection, the limitation of using a doubly slider in taking inputs for a date time range is discussed. Using a doubly slider is usually very convenient for choosing a range. A doubly slider has innate characteristics of positioning the one knob to the left to the other knob, and it perfectly fits with the user intuition that the left one is smaller/earlier than the right hand side knob, in the context of selecting a time window.

Initial implementation of preferred time range input was done using a doubly slider, in which the left extreme was set to be 00:00 hours or mid night and right most extreme was set at 23:59 hours. It was found to be very convenient for choosing a time range which fits within a single day. However, in cases where the preferred time window spans more than one single day, it was found to be impossible with the doubly slider to make the selection using those earliest and the last permissible values.

As an example there was no way to choose a time frame between 08:00 PM and 08:00 AM next day. When the earliest permissible time was changed to 10:00 AM and the last permissible time was changed to the next day 10:00 AM, the above case of selecting 08:00 PM to 08:00 AM was selectable. However, in such scenarios become impossible to input such as 11:00 PM to 11:00 AM next morning. In other words it was found that no matter how the options were shifted within 24 hour period permissible time ranges, there would be many ranges which would not be able to be satisfied, when the preferred period of operation spans multiple days. A simple solution to this problem would be to make the permissible range between the earliest hour and the last hour cover a period of 48 hours. But from the user feedback from lab researchers, it was found to be confusing. Instead the dropdown list approach was preferred to the 48 hour long doubly slider. This lead to the dropdown lists based implementation of the user input interface for the time period selection.

5.3 Tab 2 – Graphing: Power/Energy Consumption Feedback

The VT HEM maintains and displays both real-time energy consumption data and historical data. Many case studies have found that most users feel interested to reduce energy consumption when provided with comparison between his past usage and recent usage. In places where the summer and winter temperature varies greatly, energy usage data of the same month from the previous year can also provide the user with better understanding of the consumption information.

The VT HEM UI has a section called GRAPHING which offers a plethora of options. The purpose of this section is to show the user his/her historical power and energy consumption data. By default it shows raw or live appliance power consumption data. The time window it supports is 10 minutes wide—from the current moment to 10 minutes in the past. Fig. 5.14 illustrates instantaneous power consumption of four lighting loads connecting to the VT HEM. These values are derived in the Demo mode; therefore the values found in the plots in 5.14 are from the real measurements of lights used in the lab environment.

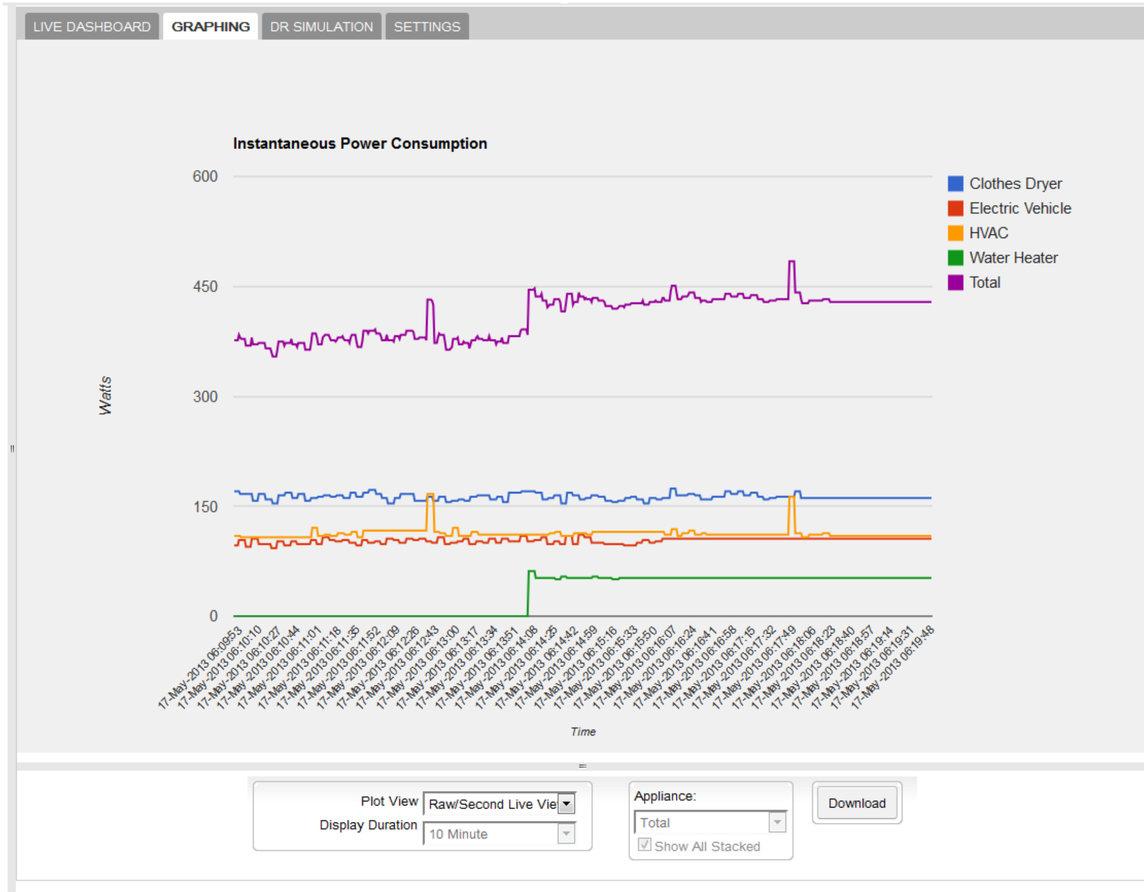


Fig. 5.14: Real-time power consumption of appliances.

The control panel at the bottom of the GRAPHING Section can be used to choose other data visualizations available. The plot has some interactive capabilities. The user can hide the plots selectively. This enables the user to reduce the information available in the plot, and helps him to focus on any specific appliance. From Fig. 5.15, it can be seen that there are several different options for viewing live and average load levels as well as historical energy consumption information. In Fig. 5.16, the plot view option allows a selection between viewing live/average power consumption data or historical energy consumption data.

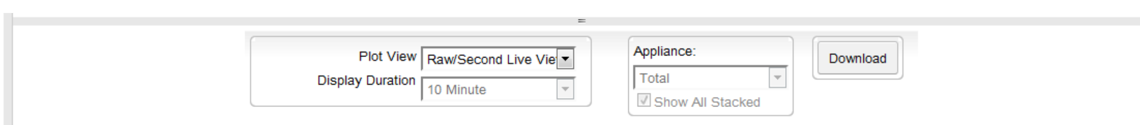


Fig. 5.15: The control panel for the data visualization options (GRAPHING).

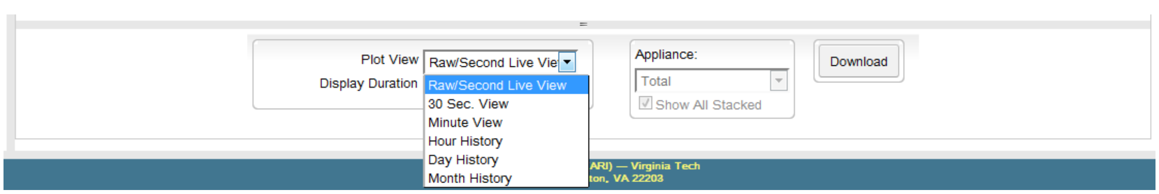


Fig. 5.16: The control panel for the data visualization options (GRAPHING).

In Fig. 5.16, selection of Raw/Live view, 30 second view and Minute view options shows power consumption visualization in Watts or kW. Selection of hour history, day history and month history options shows historical energy consumption in kWh. The raw or live view shows the data for every second. The VT HEM do not collect data from each of the appliances at every second. Instead it collects data at a slower—yet as fast as possible—rate and not at any fixed rate. But in brief the principal reason is VT HEM is not dependent on the absolute timestamp of when a measurement is taken. Another reason is in case of fixed rate, even though the coordinator sends the requests at fixed intervals, there is higher likelihood of collisions and exact time cannot be guaranteed anyway by any reasonably precise measurement system. Hence the VT HEM system is developed in such a way that it will not depend on the sample timestamps to become same. Instead it is robust enough so that it can handle various samples from same or various appliances at various times.

In the Raw/Second Live view VT HEMS show the data to the user in a way as if measurements were taken at every second. To accomplish this, VT HEM supports two mechanisms. One is interpolation by taking average on the time intervals on the visualization plot, and the other is assuming same value for all time intervals until a new sample is received. It is assumed that upon the reception of a new sample, an abrupt discrete change happens. The second approach is more natural for the application here since it resembles the characteristics of discrete signals. Therefore, all measurements and visualizations in this work are done using that approach.

The display duration control is disabled for the Raw/Second Live View. This is because only 10 minutes of raw/live data record is shown and no bigger time range is offered for this live view. This is because for a longer time window, there would be too many data points and because of resource limitations of PMD (Personal Mobile Device) computers, the browser may freeze and crash. This would impact the user experience and the users would consider it painful to use the system on a regular basis. Considering the responsiveness of the system, currently only up to 10 minutes of live data can be seen. For each moment 60 data points are shown in this plot view option. Therefore, for 10 minutes there would be 600 data points. Based on the client the VT HEM system could perform the interpolation on the server and send the 600 data points to the client or the server can just send the measured samples, in which case the client would generate the internal data points by performing calculations. The former increases the load on the network and latter increases the burden for the client. In present day’s context, networks are capable of streaming rich multimedia contents such as graphics and videos. Comparing to those, the data points are not a big burden in reality. Also the routers don’t have to allocate any special resources for such traffic. It can only be an issue when there is congestion, but again its contribution to the congestion would be much little than that of multimedia applications. Considering all these VT HEM by default performs complete data generation on the server side. This relieves the clients from doing interpolation. Such reduction in processing load results in better user experience, while viewing from PMD (Personal Mobile Device) computers.

The user can choose 30 second averages of power consumption from current moment to the 1 hour past in time. Unlike the live view, this option supports flexible display duration. In this case average load over 30 second periods are taken into consideration. In this view, for every minute there would be only two data points. This allows us to extend the range for much longer display duration than the live view. A comparable duration would be 600 data points from 300 minutes or 5 hours. However, VT HEM limits the view up to one hour only. This is because a comparable view is available as the minute-view option to see an average load for every 60 seconds average period for up to 4 hours. For this reason, to keep the UI as less cumbersome as possible we chose not to offer 30 second average beyond past 1 hour. Also from the visual inspection perspective 30-second average and 1-minute average would not appear much different.

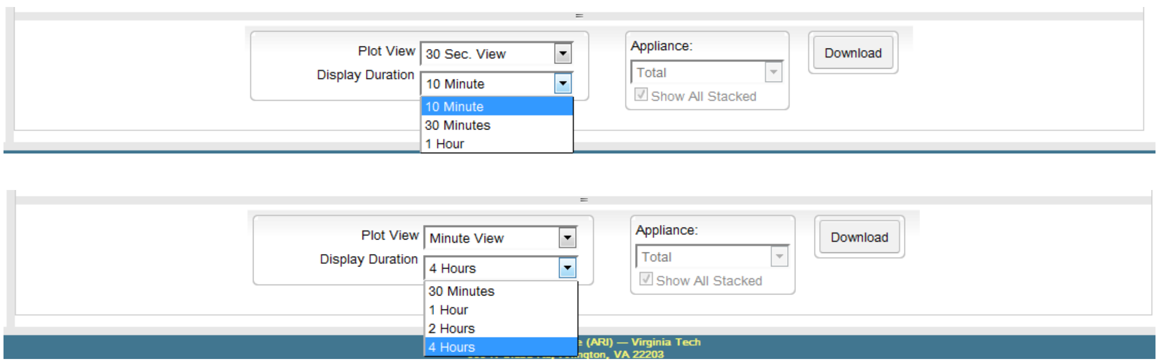


Fig. 5.17: Available display duration events for 30 second average load data (top) and 1 min average load data (bottom).

The minute view supports time window size of up to 4 hours. These dynamic adaptive time window lengths are chosen to provide the user with a fast rendering page. For example, if raw or live values of energy consumption are shown for 1 hour, there would be 3,600 data points for every single appliance or total load of the house. This would result in freezing and/or crashing of the browser, especially for handheld devices such as smart phone. 1-minute average load data beyond four hours or live load data beyond 10 minute appear to be non-intuitive for users.

Load charts shown in Fig. 5.18 are interactive and if necessary can be used to selectively disable plots of appliances.

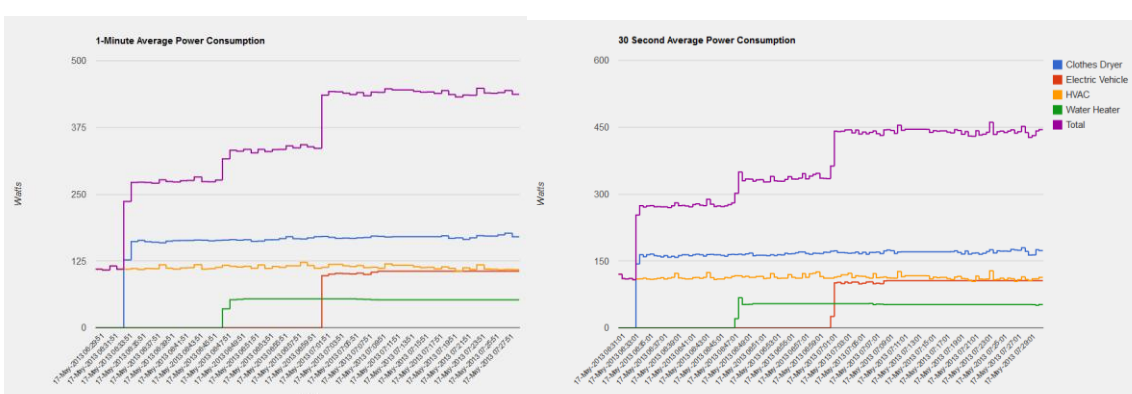


Fig. 5.18: Visualization for average power consumption 1 min average (left) and 30 second average (right).

For all three of these power consumption views, VT HEM does not offer any use of the "appliance field" next to the plot view options. The appliance field is used to select the plot of a particular appliance, which is not applicable for the live or average power level plots, where plots of all appliances are shown.

For other options with longer time aggregation periods, total energy consumption history in kWh is shown, instead of power. By default total consumption of energy is shown in disaggregated by appliance using stacked bar charts. See Fig. 5.19.

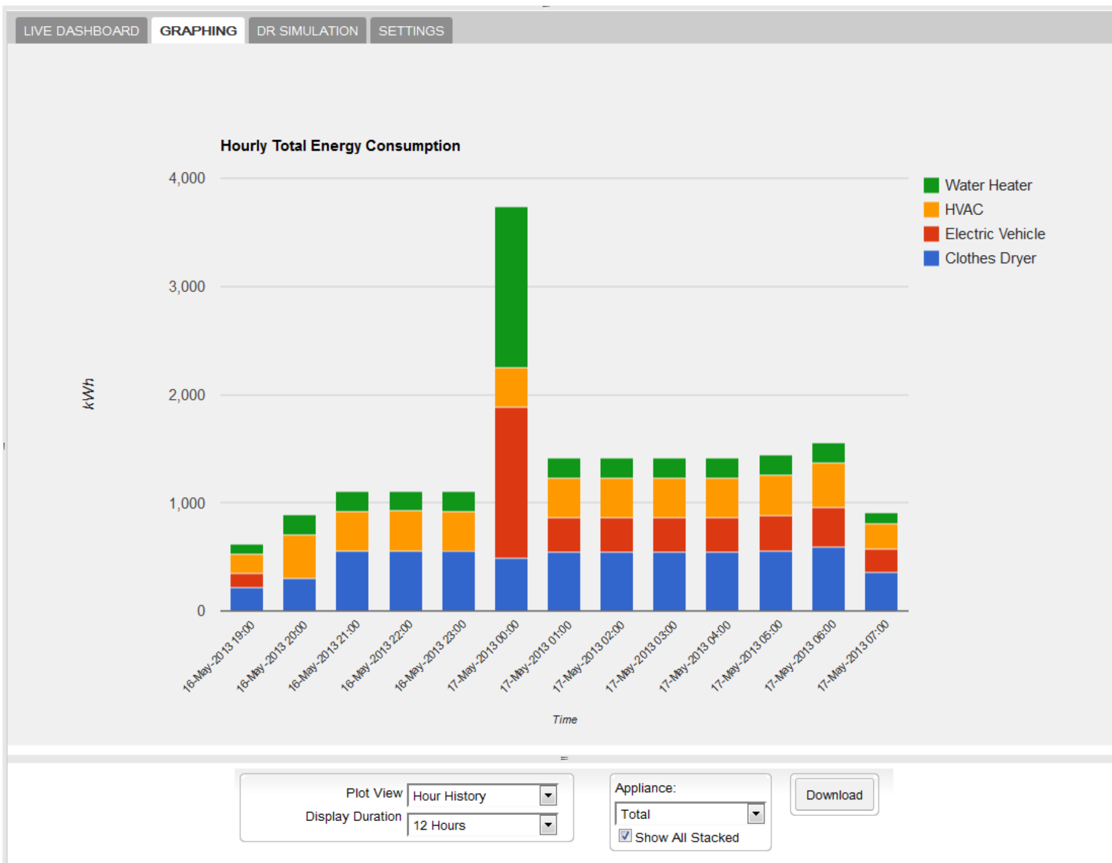


Fig. 5.19: Hourly energy consumption history of up to 12 hours.

The total heights of the bar charts show the total energy consumption and individual contributions can be identified from colored regions. By unchecking the 'Show All Stacked' option, it is possible to view total energy consumption without the displaying the contribution from individual appliances. By this, the user will not only be informed about his consumption history, but also be able to have a quick glance of how each individual appliance is contributing to the cost. Serious emphasis has been placed on accurate and frequent billing data, along with other information about usage in an understandable manner. These charts serve that purpose. In Fig. 5.19 hourly energy consumption data has been shown. At the bottom of Fig. 5.19, it can be observed that the appliance dropdown list gets enabled. By default total energy consumption is selected. Under the dropdown list there is an option to show the total energy consumption as stacked charts of individual contributor appliances. This option is by default kept selected. In case of hourly energy consumption history user can see up to 24 hours period. The energy consumed at the current hour is also shown, which could be significantly low at the early minutes of an hour, but almost of regular value when the hour is about to complete.

For daily consumption report the user can see historical records of 1 week and one month. In case of one week, total energy consumption of last seven days is shown, along with the consumption of the current day. The consumption of the current day can be much lower or almost same as the consumption of other days based on the time of the day. In the morning the consumption for the current day would be little but at night the consumption for the day would reach at the level of typical value of total energy consumed. Seeing these progressive energy consumption levels, the user can get active in keeping the total consumption lower than that of the previous day. Such encouragement would result in saving in residential energy. For the 'Day History' plot view, display duration of one month can be chosen, in which case daily consumptions for the last 30 days are shown. This is shown in Fig. 5.20.

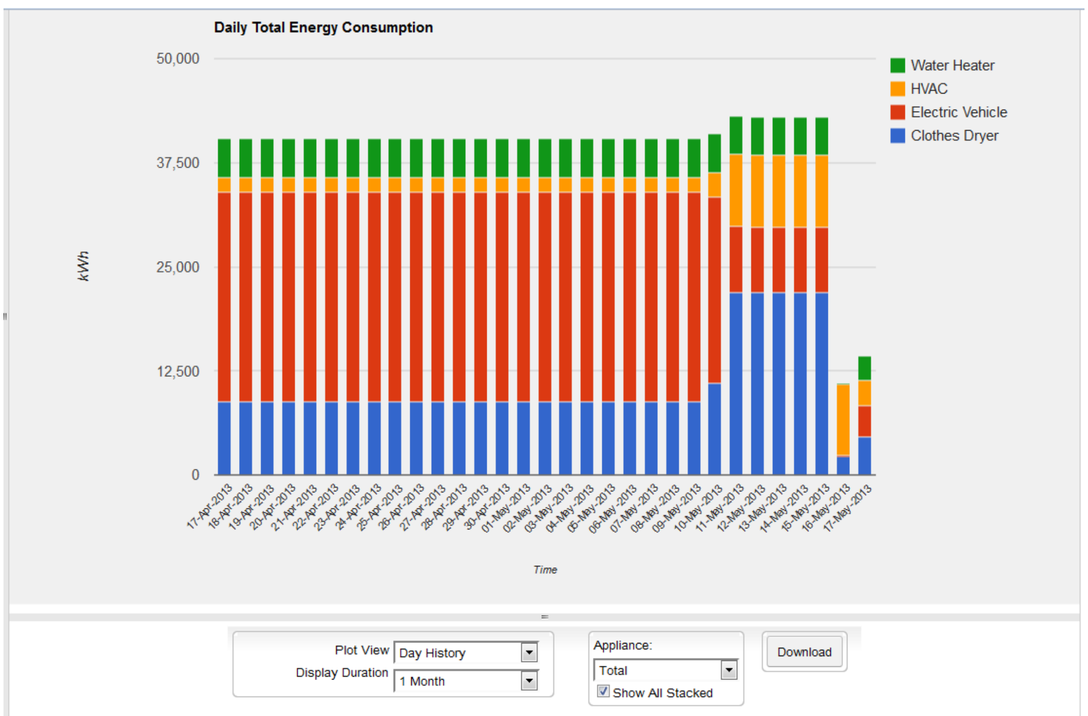


Fig. 5.20: Total daily energy consumption history for 1 month.

There is another option, aggregation option, which shows graphically the monthly energy consumption. In this view total historical energy consumption for full calendar months are shown. For the current month, energy consumed up to that point is shown. For this reason, the last column can or bar chart can be much shorter for if the time of using the VT HEM is an early month day. On the other hand for any day at the end of the month the energy consumption would be comparable to all other columns representing earlier months. This would help the user to track his progress in energy consumption and he can control to keep the energy consumption lower for the current month. There are two time period options available for the ‘Month History’ view. The default selection is the one-year time period for which the chart would contain energy consumption history for previous 12 months plus the current month progress. Another time period option is the two-year history. In this option, monthly energy consumption history would be shown for the last 24 calendar months plus the energy consumption for the current month. Like the hourly and daily energy consumption reports, the default option is to show the total household consumption by all appliances. The user can choose any appliance, to see how much it has consumed alone. If the user invests in purchasing a new appliance, which is supposed to be more energy efficient, the user can find the reflection from this report. The chart for that appliance will be smaller after the energy efficient appliance has been installed. Also from the energy consumption from the HVAC can give important indication about the insulation of the residence.

All three of these power consumption rates and total historical consumptions shown graphically can be immediately download and saved as spreadsheet files. Daily energy consumption history is another option for the convenient tracking of energy usage in households. In Fig. 5.20, total daily energy consumption history for 1-month period is shown. Daily energy consumption for a week period is also available.

Next the monthly energy consumption history is discussed. In Fig. 5.21 individual energy consumption history is shown. In this case the appliance is water heater. From Fig. 5.21, it can be seen that the option under the appliance dropdown list is disabled. The option is applicable in the case of total energy consumption history. Therefore, when any individual appliance is selected this option is disabled by the VT HEM UI. Such intelligent behaviors are performed to restrict the user from providing invalid combination of choices as input. This also reduces the cognitive load of the user. The ability to track energy expenditure based on individual appliances results in more encouraged participation from the users. Fig. 5.21 shows monthly energy consumption history for 1 year. The display duration dropdown list also offers 2 years option, meaning monthly energy consumption history can be seen up to 2 years.

In case of all of the above energy consumption options, the data visualized can be downloaded in a spreadsheet. In Fig. 5.22 Raw/Live View data is downloaded in a file named *Raw-Second_Live_View-10_Minute.xls*. Fig. 5.23 shows the downloading of daily energy consumption history for a 1-week time period. The file name in this case is Day_History-1_Week.xls.

Fig. 5.21: Monthly energy consumption history for 1 year for individual appliance (water heater).

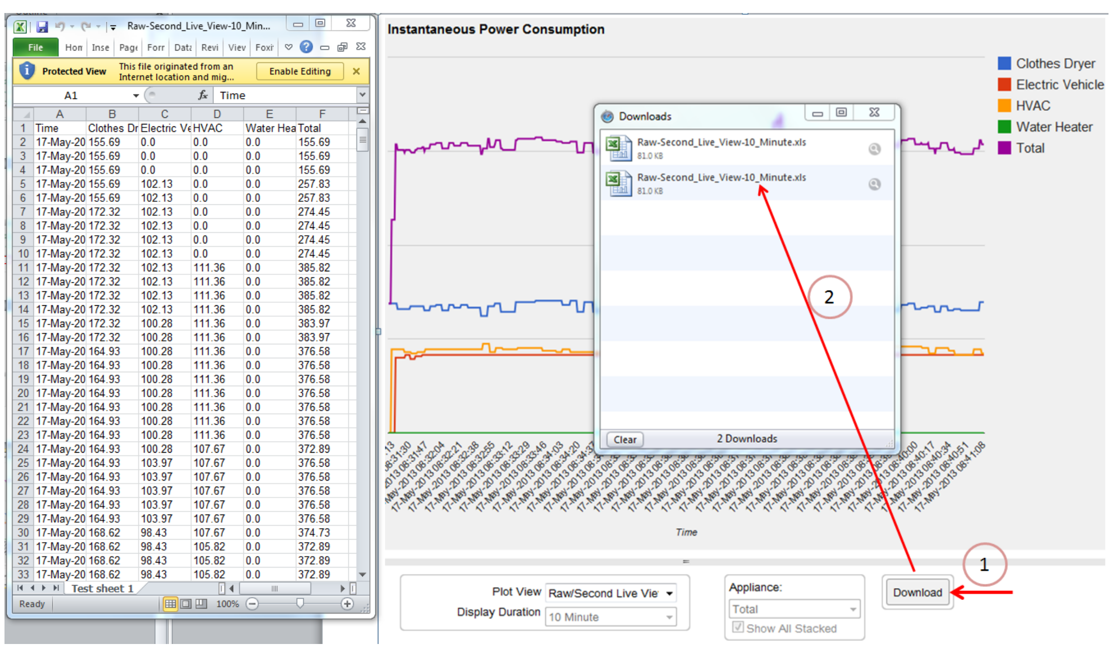


Fig. 5.22: Downloading of raw/live data.

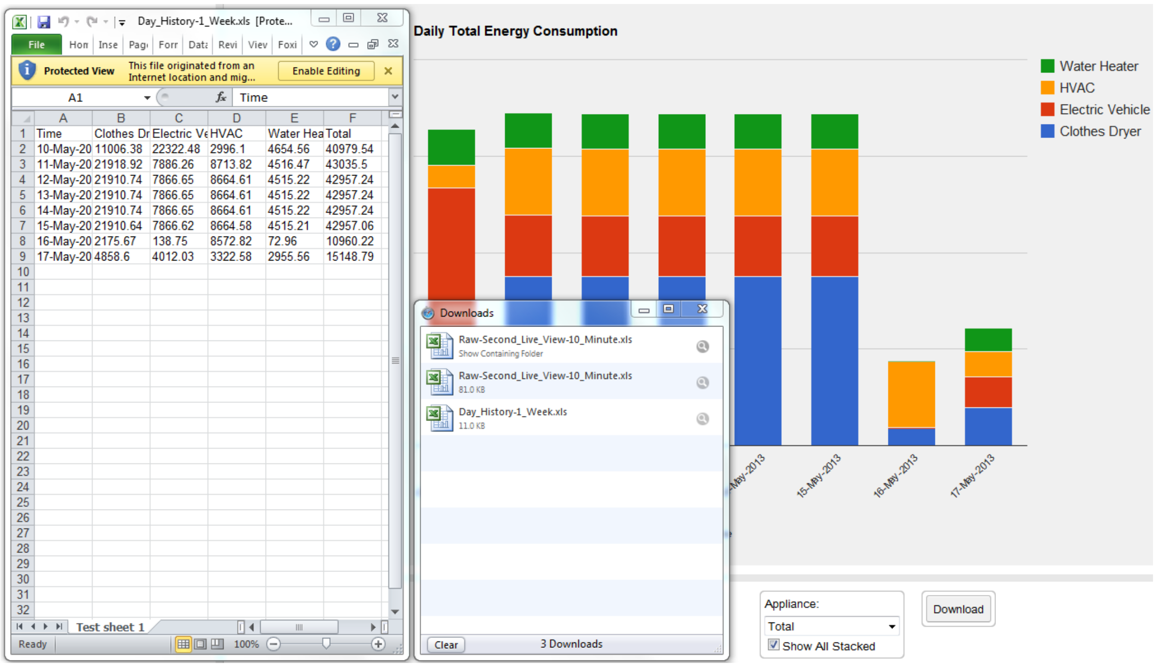


Fig. 5.23: Downloading daily energy consumption history for 1 week.

5.3.1 Time Period Alignment

Unlike power consumption views, in all visualizations of download options where energy consumption history is shown, the intervals are aligned. For example, in case of Raw/Live view, data points for every second from the present are included as long as it falls within the display duration. If it is 08:56:43 AM, the data points shown are between 10 minutes in the past and current moment. In case of the 30-second average, the last (rightmost) interval shown would be between 08:56:13 and 08:56:43, the previous interval would be between 08:55:43 and 08:56:13, etc. Therefore, there is no alignment of time interval.

On the other hand, when it comes to the energy consumption history, time intervals are aligned based on the plot view. If the plot view is ‘Hour History’, time intervals shown on the plot are aligned with every hour boundary except for the last interval, which includes the time of request. If the time of request is 08:56:43, the last or rightmost interval would be 08:00:00 – 08:56:43. This interval doesn’t completely align with the hour boundary on the right. This is last interval contains the time of request (often current time). Therefore, the last interval which contains current time is a fraction of the intervals relevant to the ‘Plot View’ option. All other intervals are full-length time chunks. The interval which is to the left of current interval would be 07:00:00 – 08:00:00. The one at the left would be 06:00:00-07:00:00.

In this work, this is “aligning of the time intervals” according to the plot view option. The last interval shows the energy consumption for the part that had been elapsed. If the plot view is one month, then all intervals are regular months from the past, and the their corresponding energy consumption value accounts for the whole month. But for the last interval, i.e., for the current month the energy consumption data shown only accounts for the time elapsed. So, if only 10 days have passed in a month, the last value in the monthly energy consumption history would reflect the consumption of 10 days only. All consumption data for previous months reflect energy consumption for whole months. In Fig. 5.24 this has been demonstrated. The data shown is about total energy consumption history of 12 hours. All hours are aligned with regular hour boundaries of that day and the previous day—since the 12 hour went back to the previous day. For the last time interval the time interval accounts for only 15 minutes, since the time of request of the chart shown in 5.24 was 09:15 AM.

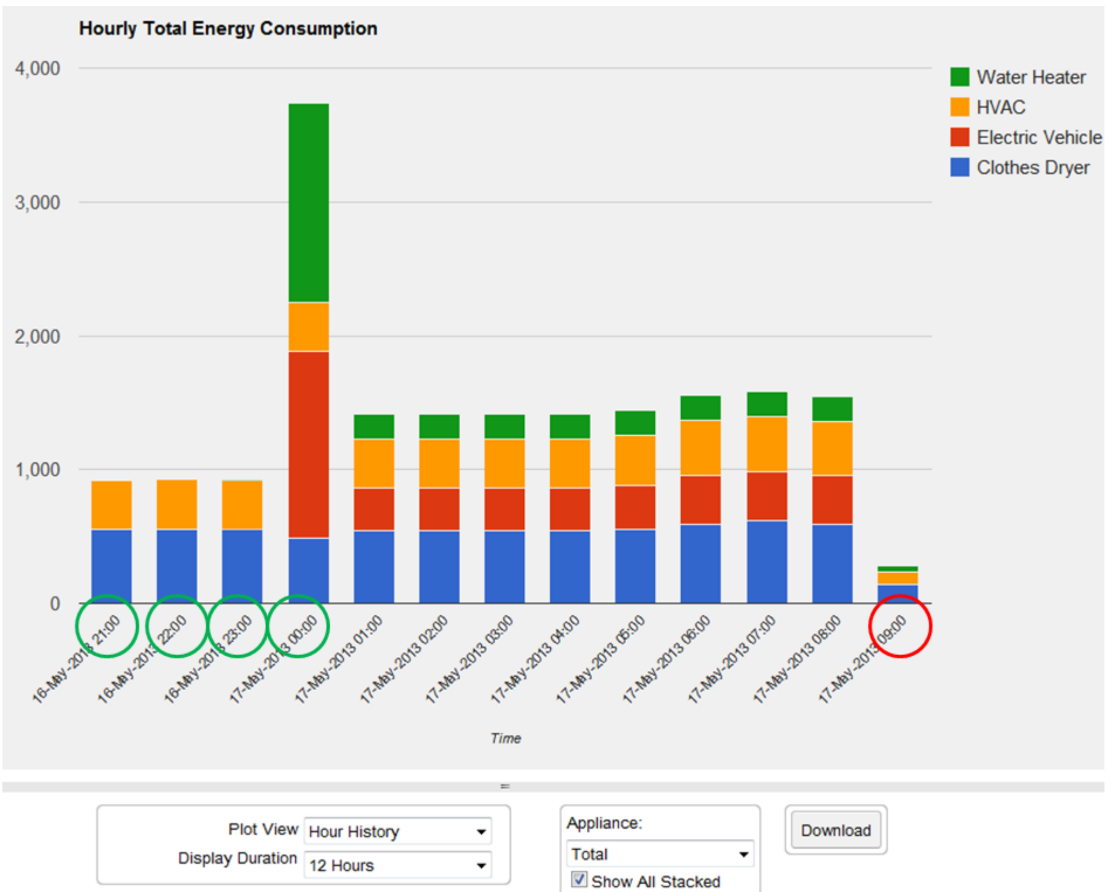


Fig. 5.24: Daily energy consumption data illustrating alignment of time intervals. The intervals with green circle account for the full hour. The last circle which is red accounts for just 15 minutes, as this is the elapsed time for the current hour.

In all these plots—power consumption or energy consumption history—a constant color scheme has been used. This means in all plots each appliance has a fixed color. In the current color scheme in the VT HEM UI, green corresponds to 'water heater', orange corresponds to 'HVAC', blue corresponds to 'clothes dryer', red corresponds to 'electric vehicle', and, when applicable, magenta corresponds to the total energy consumption.

All plots are interactive. If the user places a mouse pointer on a plot, the reading at that point is displayed. For example, in the Fig. 5.27, when the mouse pointer is placed upon a plot, the data is shown.

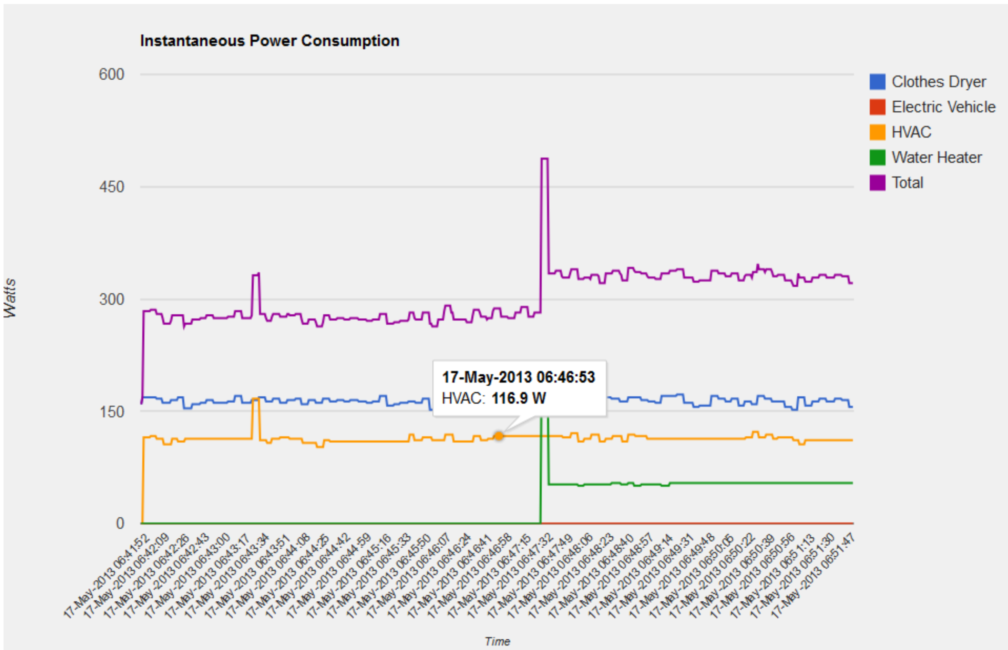


Fig. 5.25: Showing plot data point on mouse over event.

Next how the plot can be hidden by the user is demonstrated. If the user clicks on the entry for a particular appliance on the legend, the corresponding plot gets highlighted and it becomes hidden. Fig. 5.26 shows that upon clicking on a plot, it gets highlighted and on the next update of the chart it banishes.

Intelligence in the GRAPHING has been incorporated so that when the user is viewing another section of the HEM, the plot data capturing is halted. Usually data is collected every 15 seconds from server. But as soon as the user starts to view another tab, the data collection stops. This is to reduce unnecessary computational load on the client device being used to browse. It also reduces load on the server.

Since the server will be interacting with many client devices being used by users from multiple homes, unnecessary computation of the plot data points would not only cause processing burden on the server, but also would overwhelm the network of the server. The impact on the server bandwidth would be much higher than those on individual client networks. Although the server would have much faster network and higher bandwidth, it would still be a problem for thousands of households. Network bandwidth is an expensive resource and for scaling up to hundreds of thousands of clients, the server the application should be designed so that unnecessary burdens are not there. In such cases little measures can add up to great numbers.

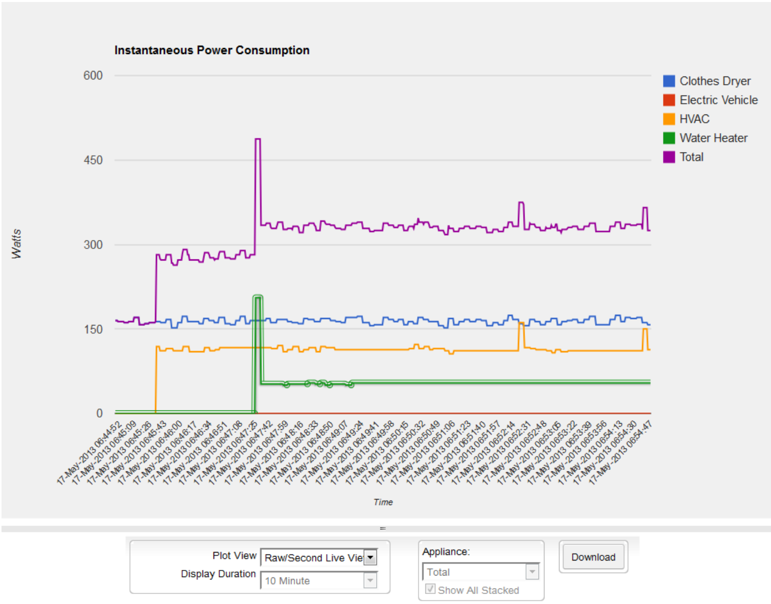
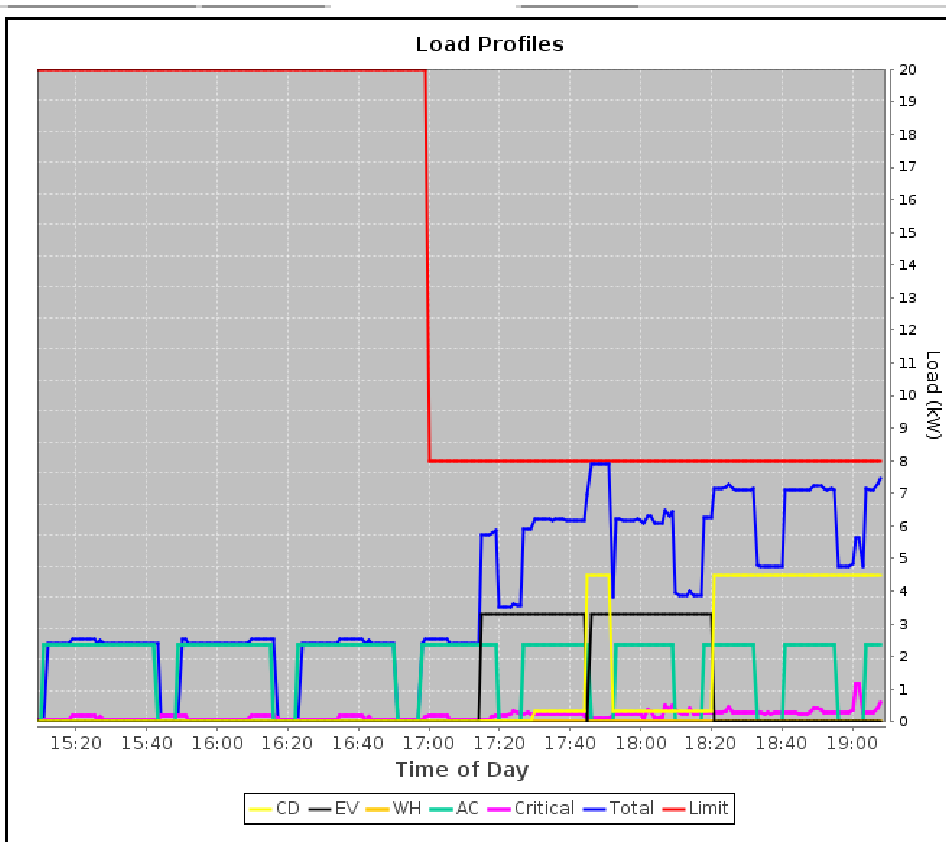


Fig. 5.26: Hiding a plot for appliance load.

5.4 Tab 3 – Operation of Demand Response Algorithm and Live Operating Condition

In Fig. 5.27 the autonomous control of appliance operation and the live update of the status are shown side-by-side. The live status and operating condition shown are displayed at the bottom picture of the Fig. 5.27. From showing the interested visitors our lab this visualizations have been found to be very useful. Appliance status and current operating conditions as shown in Fig. 5.27 also help to validate the algorithm. This can be done checking the completion of the electric vehicle charging and clothes drying tasks as well as room temperature and hot water temperature can be matched against the corresponding set points.



Appliance Status

Air Conditioner (AC)	ON
Water Heater (WH)	OFF
Clothes Dryer (CD)	ON
Electric Vehicle (EV)	OFF

Current Operating Condition

Room Temp	77.1 °F	Set Point	76 °F ± 2 °F
Water Temp	116 °F	Set Point	112 °F – 120 °F
CD Remaining Time	6 min	Total CD runtime	60 min
EV Remaining Time	19 min	Total EV runtime	120 min

Fig. 5.27: Status of various tasks under the control of the DR algorithm.

The top picture shows the state of the appliances under the influence of the Demand Response Algorithm (DRA), when a Demand Response event is going on. The picture at the bottom shows the live status of the appliances and also the Operating Conditions at that moment.

The user interface of VT HEM also remembers the interactions of the user. It collects which tabs the user visit and in which order. Later it might be possible to understand the users intents. When the user loads a page, this is used to show user the tab he left opened last time.

5.5 Tab 4 – Settings

This section of the UI has been included to experiment with the Demand Response algorithm. It is intended to keep disabled for the real householders.

5.6 Responsiveness of the UI

In this subsection, findings about the responsiveness of the VT HEM UI are presented. The VT HEM is a distributed system and the display employs some heavy graphics and animation. Multiple requests are made at the background after the user enters the web server address into the address bar commands to load the page. Upon loading of the main page, which renders the tabbed panels, two additional requests are sent to the server for loading the 'Live Dashboard' and to load the 'DR Simulation' Tab (which shows the Load Profile and live appliance status update). Upon loading of these pages, preference forms in the dashboard are loaded using separate requests in the background. This is because if all these requests are made initially at the same time, the initial waiting time would be higher. To alleviate the situation, only main sections of the UI page are loaded, and gradually other smaller parts are loaded by background requests. Also the dashboard page keeps sending requests continuously to the server for updated status of the appliances so that any change can be immediately shown to the user. All these operations not only involve network delay but also adds to the processing burden on the user agent running on the client devices. For this reason careful tradeoff need to be made so that the user experiences acceptable behavior from the UI in terms of responsiveness and freshness of data.

Time needed to render the page has been measured to find the justification quantitatively.

5.7 Experimental Setup

To perform the measurements of delay, the Web Console developer tool that is available with the Mozilla Firefox Web Browser has been used. The Web Console tool shows all HTTP (Hyper Text Transfer Protocol) requests being sent to the client and reports back as soon as any response is received. From this report it can be learnt how much delay the user would experience.

VT HEM has several components: the web server, the coordinator, and end devices, and the client computer. Specifications of the various components are given below:

5.7.1 The Web Server

The Web Server used in this experiment is a desktop version of the Ubuntu Linux Operating System (OS) being simulated as a guest operating system using Oracle Virtual Box software. The guest operating system is running within a Windows 7 Desktop Version host operating system. The host operating system was running on a physical machine with 4 GB memory (RAM) and hundreds of gigabytes of free disk space available within the primary partition, and from which the disk space of the virtual guest OS is running as the web server. The Windows host OS is a relatively new installation and it has been made sure that all unnecessary processes have been uninstalled so that the Virtual Box process emulating the Guest OS does not have to compete for resources. Since the host OS is a desktop version it could be optimized for either best appearance or best performance. The host OS has been optimized for best performance. With all these measures the windows OS is expected to render a performance level close to a server edition, since even the Windows Server editions come with graphical user interfaces.

The Virtual Ubuntu Server is the guest OS with which the HEM server environment has been installed. It also contains the database server. The guest OS is allocated 2 GB of memory (RAM). The virtual box allows a dynamic disk option or a static disk size option. In case of the dynamic disk size option the disk space of the guest OS is allocated from the host OS as on demand basis. Therefore, there is no question of running out of disk space, albeit it is expected to respond slowly because of it runtime allocation nature. In case of static disk option, the total disk space of the guest OS is predefined. Static disk option and the total available space was 18 GB, and 83% of it had already been occupied. Such constrained environment is used to make sure that the measurement does not result from perfect situation. This would give us a better understanding of the practical production environment.

Within the guest operating system, six server processes have been used. One of the processes is responsible for rendering the 'Live Dashboard' static files regarding the style, graphics, and JavaScript libraries—needed for the interaction with the user and background loading of other components—of the live dashboard. Another server process serves the web service, which is continuously used to retrieve the live status of the appliances. This web service is available at the URL *^smarthomes/house/<house_id>/power-status*. The status of the appliances is requested by the client—web browser—, when it interpret the JavaScript accompanying the 'Live Dashboard'. This web service is also used by the coordinator, which uses the response to learn about what appliance should it turn on or off by sending wireless command. Another server process accepts the status information submitted by the coordinator. The fourth server process renders the main user interface that encapsulates the dashboard, graphing section, settings and the demand response algorithm section. Apache 2 web server is used in from of these servers and all requests passes through it. Apache 2 uses as the proxy and reverse proxy servers, which sits between the client and four the application server processes just described. The database server used is the MySQL server. MySQL serves all four the application server processes. Therefore it is a critical component and it need to be very efficient. In real life production environment the database server is usually run on a dedicated machine. In case of high load, clustering is also performed where many instances of the database server run and the load is balanced among them.

The client is a Mac Book Pro computer with 4 GB memory and using Mozilla Firefox to perform the test.

The server and client use two different networks to get connected to the Internet. In this test the Server is in the Virginia Tech network and the client is connected through a Comcast connection.

5.7.2 Rendering of the Demand Response Algorithm page

In this scenario the DR algorithm page is requested at an interval of 2000 milliseconds, i.e., the load profile page is requested every 2 seconds. The URL at which the request is sent is: ^hems-vtech/vtechhemsui/lpc. The result is shown in Fig. 5.28.

```
17:26:19.663    GET http://8.30.77.140/hems-vtech/vtechhemsui/lpc [HTTP/1.1 200 OK 348ms]
17:26:21.665    GET http://8.30.77.140/hems-vtech/vtechhemsui/lpc [HTTP/1.1 200 OK 391ms]
17:26:21.668    GET http://8.30.77.140/smarthomes/house/2/power-status/ [HTTP/1.1 200 OK 100ms]
17:26:23.668    GET http://8.30.77.140/hems-vtech/vtechhemsui/lpc [HTTP/1.1 200 OK 292ms]
17:26:25.675    GET http://8.30.77.140/hems-vtech/vtechhemsui/lpc [HTTP/1.1 200 OK 420ms]
17:26:25.679    GET http://8.30.77.140/smarthomes/house/2/power-status/ [HTTP/1.1 200 OK 89ms]
17:26:28.930    GET http://8.30.77.140/hems-vtech/vtechhemsui/lpc [HTTP/1.1 200 OK 509ms]
17:26:30.318    GET http://8.30.77.140/hems-vtech/vtechhemsui/lpc [HTTP/1.1 200 OK 338ms]
17:26:30.922    GET http://8.30.77.140/smarthomes/house/2/power-status/ [HTTP/1.1 200 OK 101ms]
17:26:32.009    GET http://8.30.77.140/hems-vtech/vtechhemsui/lpc [HTTP/1.1 200 OK 267ms]
17:26:33.910    GET http://8.30.77.140/hems-vtech/vtechhemsui/lpc [HTTP/1.1 200 OK 315ms]
17:26:33.920    GET http://8.30.77.140/smarthomes/house/2/power-status/ [HTTP/1.1 200 OK 87ms]
17:26:35.909    GET http://8.30.77.140/hems-vtech/vtechhemsui/lpc [HTTP/1.1 200 OK 1217ms]
```

Fig. 5.28: Result of the experiment to determine the responsiveness of the UI. Here the time required for the updating of the DRA operation is shown.

The requests for the updated state of the load profile graph have sent every 2 seconds but the browser deviates a little. For example, 2 subsequent requests are sent at 17:26:23.668 and 17:26:25.675 with a gap of 2007 milliseconds. Here it can be observed that the browser process has not frozen and working fine. The 7-millisecond delay is negligible. Now the time elapsed between the sending of the requests and receiving the responses has been analyzed. The data shown above is collected to evaluate the responsiveness of the load profile chart service which renders the DR algorithm simulation chart along with the appliance status and current operational condition chart as shown in Fig. 5.27. The average of the delays is 455 milliseconds. In one of these measurements one sample—1217 ms—appears to be noisy data which is not representative of average case. If this is ignored, the average becomes 360 ms.

Chapter 6
Implementation of HEM Algorithms

Intelligent Demand Response (DR) algorithms have been implemented as part of the proposed web-based HEM system. One is based on the concepts covered in [011-ARI, 013, 015]. The other is a new algorithm, devised in this thesis, which improves the result of the first one and extends the capability of the first one to perform joint Demand Response (DR) on multiple homes. These algorithms can influence the appliance operation in a household so that the agreement with the utility is honored while maintaining homeowners’ preferences as much as possible. The implementation of these algorithms has been validated using critical inputs. The HEM system uses the algorithms to deal with four controllable or non-disruptive appliances, including heating ventilation air conditioner (HVAC), water heater (WH), clothes dryer (CD) and electric vehicle (EV). These controllable loads are power-intensive devices, where HVAC and WH can consume around 80% of total residential energy consumption. Unguided usage of HVAC and WH are also to be blamed for large share in the 39% waste of energy supplied to the residences.

This chapter discusses, in Section 6.1 - behavioral and load models of controllable appliances; in Sections 6.2 and 6.3 - DR algorithms for a single home, along with case studies; and Sections 6.4 and 6.5 - DR algorithms for multiple homes, along with case studies.

6.1 Appliance Behavioral and Load Models

The web-based HEM system can measure indoor temperature (°F) and hot water temperature (°F) using temperature sensors. This information is used in decision making during a DR event. For a simulation purpose, operational models and load profiles of four power-intensive controllable appliances and the model of the physical system or the environment, which those appliances affect, are employed in this work. Load profiles and their corresponding physical models of the target systems for HVAC, water heater (WH), clothes dryer (CD) and electric vehicle (EV) are discussed below. After that the Critical load (uncontrollable or disruptive loads) profile has been discussed system. Finally, the total household load is discussed.

6.1.1 HVAC Behavioral and Load Model

The HVAC model developed in this thesis follows the model presented in [25]. Brief description of the model is presented in this subsection.

The space heating/cooling model is closely related to the load model of the HVAC and they have been discussed together here. The operation of the HVAC is divided in discrete time steps of equal duration. The ON or OFF decision is made at the beginning of a step. For the duration of the discrete step, the state of the appliance remains unchanged. The power consumed at a step, i, is:

$$p_{AC,i} = w_{AC,i} \times P_{AC} \tag{6.1}$$

In the above equation P_{AC} is the rated power of the HAVC system and $w_{AC,i}$ is the status of the unit at the discrete time slot i. In this model w_{AC} can have the value of 0 or 1. An HVAC unit has a set point temperature T_s (°F) and the unit tries to maintain the temperature of the space at that value. During summer the HVAC performs as the space cooler and it switches itself to ON state ($w_{AC} = 1$) when the space temperature is higher than the set point temperature. Upon cooling of the space, when the temperature falls below the set point the unit switches itself OFF ($w_{AC} = 0$). In a typical hot summer day, if the HVAC is in ON condition, room temperature decreases. When the temperature reaches below the set point, HVAC turns itself OFF. Therefore, the temperature begins to rise. When temperature reaches above the set point, the HVAC is again turned ON, and it remains ON until the room temperature becomes lower than the set point. Based on this operating principle, HVAC will continuously cycle between the states ON and OFF to maintain this temperature.

In a practical HVAC system, there is a tolerable band of temperature (ΔT_{hvac}) above and below the set point, and the switching from one state to another (e.g., ON to OFF) occurs only when the room temperature and the set point temperature differs by more than the tolerance band, i.e., when $T_i \leq T_S - \Delta T_{hvac}\ or\ T_i \geq T_S + \Delta T_{hvac}$. In other words, the switching of the value of w_{Ac} used in equation (6.1) occurs when the temperature of the inside of a house deviates from the set point temperature, T_s, by more than ΔT_{hvac}. The HVAC has an internal thermostat type function which operates in reference to the set point. A user can set the set point temperature (T_s). The HVAC continuously try to maintain the room temperature at that set point temperature (T_s). For example, let $T_s = 76$°F and ΔT = 2°F. The HVAC operates while room temperature T_i is greater than 78°F or less than 74°F based on if the unit is cooling or heating respectively.

The value of $w_{AC,i}$ is determined using the relationship below:

$$W_{AC,i} = \begin{cases} 0, & T_i < T_s - \Delta T_{hvac} \\ 1, & T_i > T_s + \Delta T_{hvac} \\ w_{AC,i-1}, & T_s - \Delta T_{hvac} \leq T_i \leq T_s + \Delta T_{hvac} \end{cases} \tag{6.2}$$

The above equation is a modification of the one presented in [25] for space cooling. For space heating similar equation is used as presented below:

$$w_{AC,i} = \begin{cases} 0, & T_i > T_s - \Delta T_{hvac} \\ 1, & T_i < T_s + \Delta T_{hvac} \\ w_{AC,i-1}, & T_s - \Delta T_{hvac} \leq T_i \leq T_s + \Delta T_{hvac} \end{cases} \tag{6.3}$$

For the detail of how the room temperature T_i at a time step i is determined—which is a function of room temperature T_{i-1} at previous step $i - 1$, and other parameters—the reader is requested to see equation (4) in [25]. In this implementation the HVAC unit has the rated power of 2.352 kVA.

In Fig. 6.1, the room temperature maintained by the HVAC is shown using plot for a hot summer day, when the unit is performing space cooling. The orange curve represents the indoor temperature. The blue time series data represents the outdoor temperature of a typical summer day. The downward change of the room temperature indicates the HVAC unit's state of being ON. The upwards change in the orange curve indicate the state of being OFF. The ON cycles are the rectangular green blocks in this image. It can be observed that, the higher the outdoor temperature is the longer is the duration for which the HVAC remains in ON state.

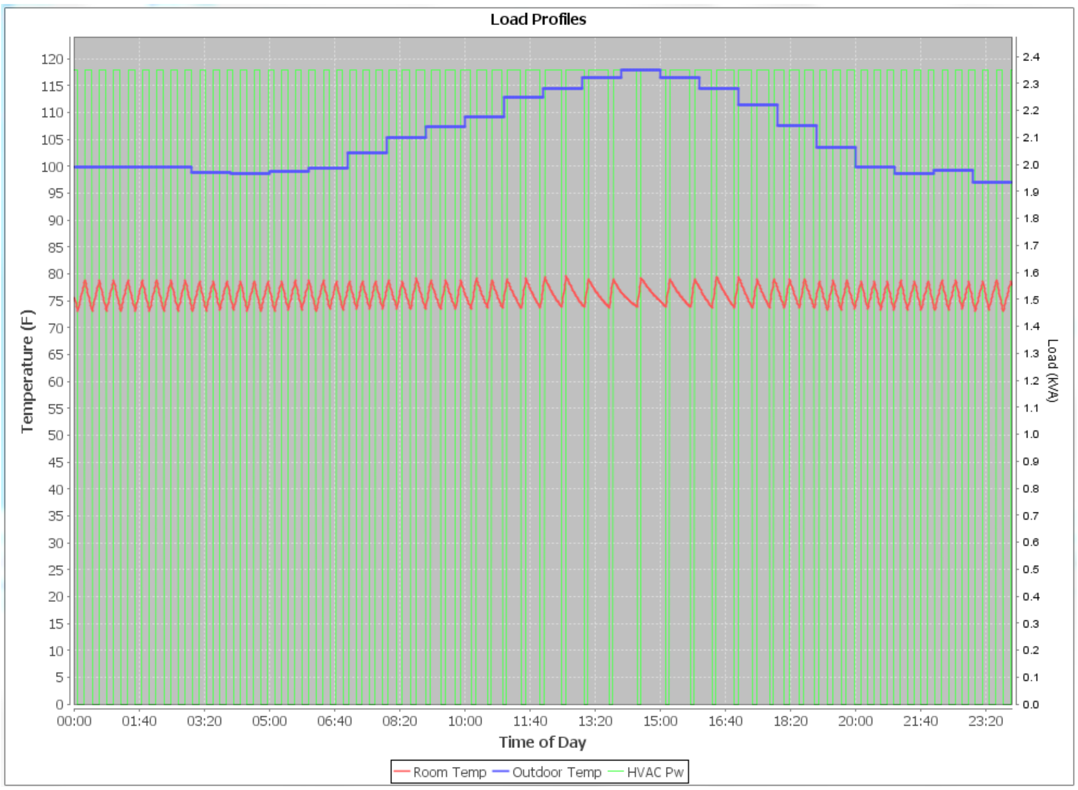


Fig. 6.1: HVAC load profile along with outdoor temperature, indoor temperature and HVAC load.

From Fig. 6.1 it can be observed that between 13:00 and 18:00, the difference between the outdoor temperature and the HVAC set point temperature is high, which causes the ON state of the HVAC to last longer. As the outdoor temperature falls, the HVAC ON cycles get shorter. The ON or OFF states shown here results from the autonomous switching decisions of the HVAC itself. The HVAC model used in this plot has the rated power of 2.352 kVA. The vertical axis to the right shows the HVAC load (P_{hvac}), which is either 0 or 2.352 kVA according to the equation (6.1).

When the HVAC is turned OFF, the room temperature is supposed to follow the outdoor temperature, and when it is turned ON, the room temperature should follow the set point temperature. This behavior has been demonstrated to assure that the space heating/cooling model behaves in a realistic fashion.

In Fig. 6.1, no influence from any external system, such as an HEM system, is present. These HVAC cycles are decided by the HVAC itself. Using the web interface the user can manually turn the AC ON or OFF. The HEM algorithm can also control the operations. In Fig. 6.2, controlling of an HVAC system, by means of an external signal from the HEM system, is demonstrated. Usually the HEM system interferes with this otherwise regular pattern of room temperature under the influence of the HVAC alone. As a result the room temperature pattern cannot be maintained close to the user preferred set point temperature when HVAC cannot operate to bring the indoor temperature down and gradually the indoor temperature begins to follow the outdoor temperature.

Fig. 6.2: HVAC is suspended by external signal between 17:30 and 22:00.

This becomes necessary when there is a DR event at which the user is participating and the event requires the user to curtail electricity demand so that it remains under a certain demand limit. In such cases, the HVAC's ON/OFF decision might have to be overridden by the HEM system. If the HEM system decides to override the decision of the HAVC, and decides to keep the HVAC in OFF state, the indoor temperature could rise to a much higher value. HEM system will embrace such situation when there are other user preferences with higher priority and which had used up the allowed quota of load limit. The HVAC unit itself cannot make such a sophisticated decision.

In addition to the set point temperature, the VT HEM implemented in this work however offers another comfort setting for the user, which, is related to the HVAC operation and room temperature as well. These settings are called “Maximum allowed room temperature” and “Minimum allowed room temperature.” These work as temperatures which the HEM system should not violate.

6.1.2 Water Heater (WH) Behavioral and Load Model

The water heater model has been implemented according the physical-based model published in [25]. According to the equation (7) in [25], electrical power consumed by the WH at a discrete time step, i, is:

$$p_{WH,i} = w_{WH,i} \times P_{WH} \times \eta_{WH} \times c_{WH} \tag{6.4}$$

where

P_{WH}	rated power of the water heater (kW);
η_{WH}	efficiency factor;
$w_{WH,i}$	status of the WH at the time slot i, 0 = OFF, 1 = ON;
c_{WH}	DR control signal for WH, 0 = OFF, 1 = ON;

P_{WH} is the rated power of the electric water heater (WH) which is considered to be 4.5 kW. In this thesis, a value of 1.0 has been used for the efficiency factor, η_{WH}.

w_{WH} is the WH status based on if heating of the water is necessary or not. In the context VT HEM, the quantity C_{WH} represents control signal from the HEM system. From this equation it is evident that the HEM system has the ability to suspend the operation of the WH by setting 0 as the value of C_{WH}.

Whenever a water draw event takes place the hot water is delivered through the outlet and the cold water is drawn from the inlet. The newly drawn water usually has different temperature than the outlet temperature supplied to the user. The operation of the WH is more critical in the winter, when the soil temperature is very low, and so is that of the newly drawn water. When cold water mixes with the existing hot water within the tank the overall temperature drops. This drop can be slow or drastic, based the proportion of the hot and cold water within the tank. If the new temperature is too low it cannot be used and this cold water must be heated up to the hot water set point temperature, $T_{WH,s}$, which is set by the user.

Like the HVAC system, the WH supports an acceptable temperature deviation, ΔT_{WH}, as well. If the temperature of the water within the tank falls below $T_{WH,s} - \Delta T_{WH}$, the water heater turns heating ON ($w_{WH,i} = 1$). When the temperature of the water reaches over the hot water set point temperature, ΔT_{WH}, the WH turns itself OFF ($w_{WH,i} = 0$). This behavior can be expressed using the following equation:

$$w_{WH,s} = \begin{cases} 0, & T_{outlet,i} > T_{WH,s} \\ 1, & T_{outlet,i} < T_{WH,s} - \Delta T_{WH} \\ w_{WH,s-1}, & T_{WH,s} - \Delta T_{WH} \leq T_{outlet,i} \leq T_{WH,s} \end{cases} \tag{6.5}$$

WH cycles between ON or OFF states autonomously based on the temperature of the water inside tank and the set point. Water has high heat capacity and the hot water tanks usually have good insulation, which prevents heat loss and water temperature is retained at the set point for a long period if no hot water is drawn. If the water outflow rate is high, the drop in temperature of the hot water falls drastically. In such a situation, the WH is turned ON, and the water inside the tank is heated.

In Fig. 6.3, the autonomous operation of the WH model has been shown. The orange curve shows the temperature of the hot water, T_{outlet}. The hot water temperature set point, $T_{WH,s}$, is 120°F (green horizontal line) and the acceptable deviation temperature, ΔT_{WH} is 10°F. The ash-colored spikes are the demand for hot water. The heights of the spikes are proportional to the hot water demand coming at that moment. The cyan curve shows hot water temperature in the tank. The water heater has a maximum flow rate, therefore, based on which the demand is served. The higher the total demand of water is, the higher the water outflow rate until it reaches the maximum flow rate. The largest decline in the hot water temperature is resulted in when the hot water is drawn at maximum rate. From this plot a water draw event can be observed before 19:46 hours. Immediately after the spike, the cyan curve goes downward indicating the fall in hot water temperature. As soon as the temperature goes to 109.948°F, which is below 110°F ($T_{WH,s} - \Delta T_{WH}$) at 19:53 hours, the water heater switches itself ON, immediately at 19:54. This is evident from the maroon rectangular lines. After this the hot water temperature reduces at a slower rate until 19:57 when the water draw event fully stops. After that temperature starts to increase until it reaches the hot water set point temperature, $T_{WH,s}$ at 20:33 hours. At 20:18 a small water draw event occurs causing the hot water temperature to go downwards for just one step.

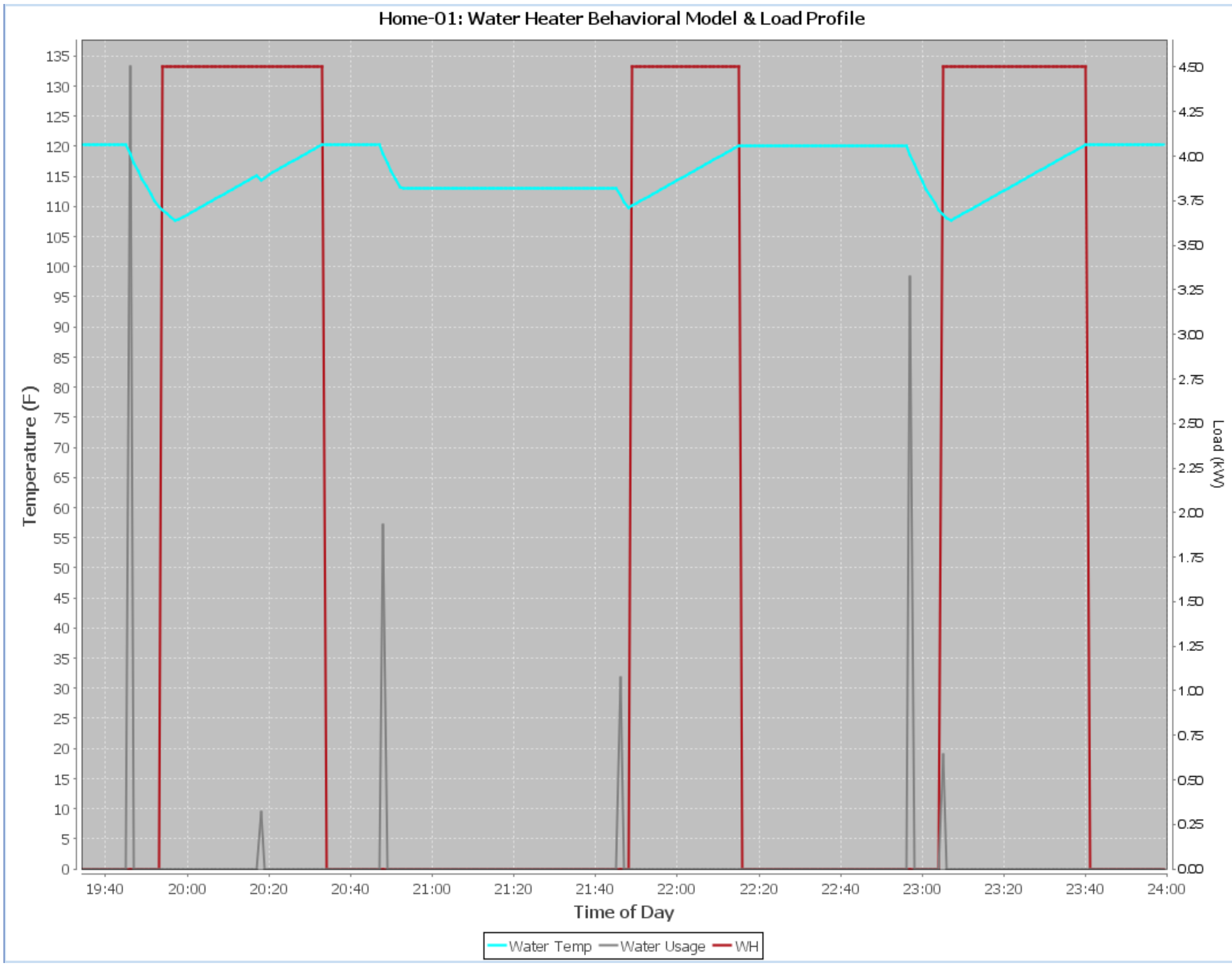


Fig. 6.3: Water heater behavioral model and load profile with hot water temperature.

This is the default behavior of the WH when there is no interference from any external system. The HEM system can override the decision of the WH about switching to OFF state, i.e., the HEM system can suspend or resume the operation of the WH. Such a control is necessary when the WH is needed to remain OFF because the user has a higher priority load to run during a DR event. To maintain the total household load below the demand limit, the HEM can analyze load priorities and other user preference conditions, and make an informed decision.

Below the realistic behavior of the developed water heater model has been demonstrated for a scenario when the operation of the WH is suspended by an external control signal. The scenario is exactly same as the previous scenario, where a large hot water demand event arrives and goes on until 19:57. Like the previous case, at 19:54 the water heater turns itself ON. While the hot water temperature rising, suddenly at 20:10, the water heater's operation is suspended by an HEM signal. Upon receipt of the suspend signal, further warming of the hot water temperature ceases. Subsequent water draw events lower the temperature further, but the water heater is not able to run. Following the water draw event at 23:05, the hot water temperature goes even lower at 97.15°F. At 23:30 the water heater's operation is resumed. The water heater starts to heat the water immediately. As a result the hot water temperature begins to rise (as shown by the cyan curve).

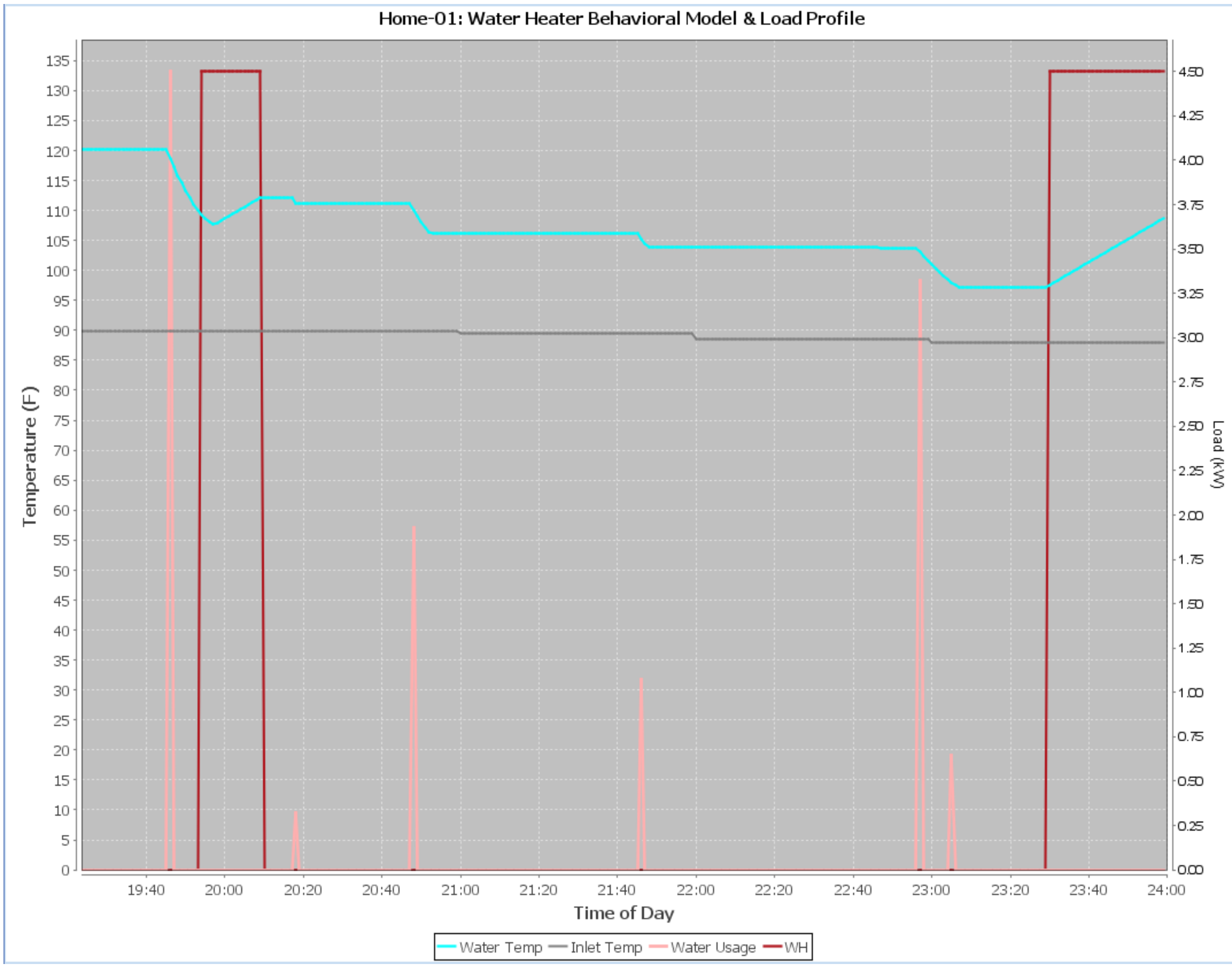


Fig. 6.4: Water heater operation suspended by DR control signal.

For the WH load model, the work conducted in [25] has been utilized. According to [25], the water heater load profile depends on the temperature profile, water heater characteristics, and hot water usage. The soil of ground temperature is same as the inlet water temperature as discussed earlier. The temperature is obtained from the Soil Climate Analysis Network (SCAN) [53]. The hot water temperature set point is also an import factor in water heating load profile according to the water heating model from [25] used in this work. The average range of hot water temperature set point is derived to be between 110°F and 120°F [25]. For hourly hot water usage, [25] uses California's Hourly Water Heating Calculations.

6.1.3 Clothes Dryer (CD) Behavioral and Load Model

A cloth dryer has a motor and a heating coil. The model used, for the clothes dryer, in this work can control heating coils OFF while the motor part rotates without heat. The motor part consumes power in the range of few hundreds of watts whereas heating coils consume power in the range of kilowatts. The power consumed by these two components represents the total load of the clothes dryer. The following equation can be used to express the clothes dryer power consumption at time interval, n:

$$P_{CD,n} = w_{motor,n} \times P_{motor} + w_{coil,n} \times P_{coil} \tag{6.6}$$

where

w_{motor}	state of the motor of the clothes dryer at time step n, 0 or 1;
P_{motor}	rated power of the motor (kW)
w_{coil}	state of the heating coil of the clothes dryer at time step n, 0 or 1 and $w_{coil} \leq w_{motor}$;
P_{coil}	rated power of the heating coil (kW);

In this work, it is assumed that $P_{motor} = 300$ W, and $P_{coil} = 4.2\ kW$.

A clothes drying task size is represented by a duration, CT_{max}, for which heating coils should remain ON in total. The task is considered completed when the total heating coil on time, CT_n, reaches that certain value. As soon as a homeowner loads the CD with a laundry load and presses the start button, it would start the motor and heating coils, and remain in that state as long as the drying task is not completed, i.e., $CT_n < CT_{max}$. This relationship can be expressed as follows:

$$w_{coil,n} = \begin{cases} 0, & CT_{CD,n} \geq CT_{CD,max} \\ 1, & CT_{CD,n} < CT_{CD,max} \end{cases} \tag{6.7}$$

In the above equation, $CT_{CD,n}$, stands for Cumulative Time spent at the state with heating coils ON, which is state 3 shown in Fig. 6.5 below. The HEM system can interfere with the above operational strategy by suspending the operation of the clothes dryer, in which case its heating coils are turned OFF, even if the above condition, $CT_{CD,n} \geq CT_{CD,max}$, does not hold. This can happen during a DR event when other appliances of higher priority use up the available load limit. In Fig. 6.5, this is shown using a diagram.

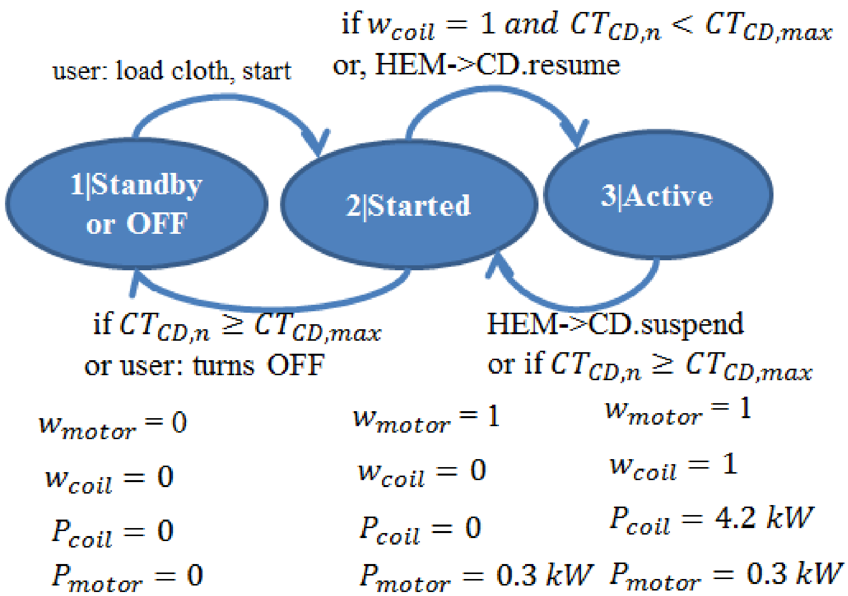


Fig. 6.5: Clothes dryer states of operation and corresponding transitions.

As long as heating coils are left on, the job progresses towards completion. When the heating coil is turned off, no progress is made. An example scenario of the clothes dryer load profile is illustrated in Fig. 6.6.

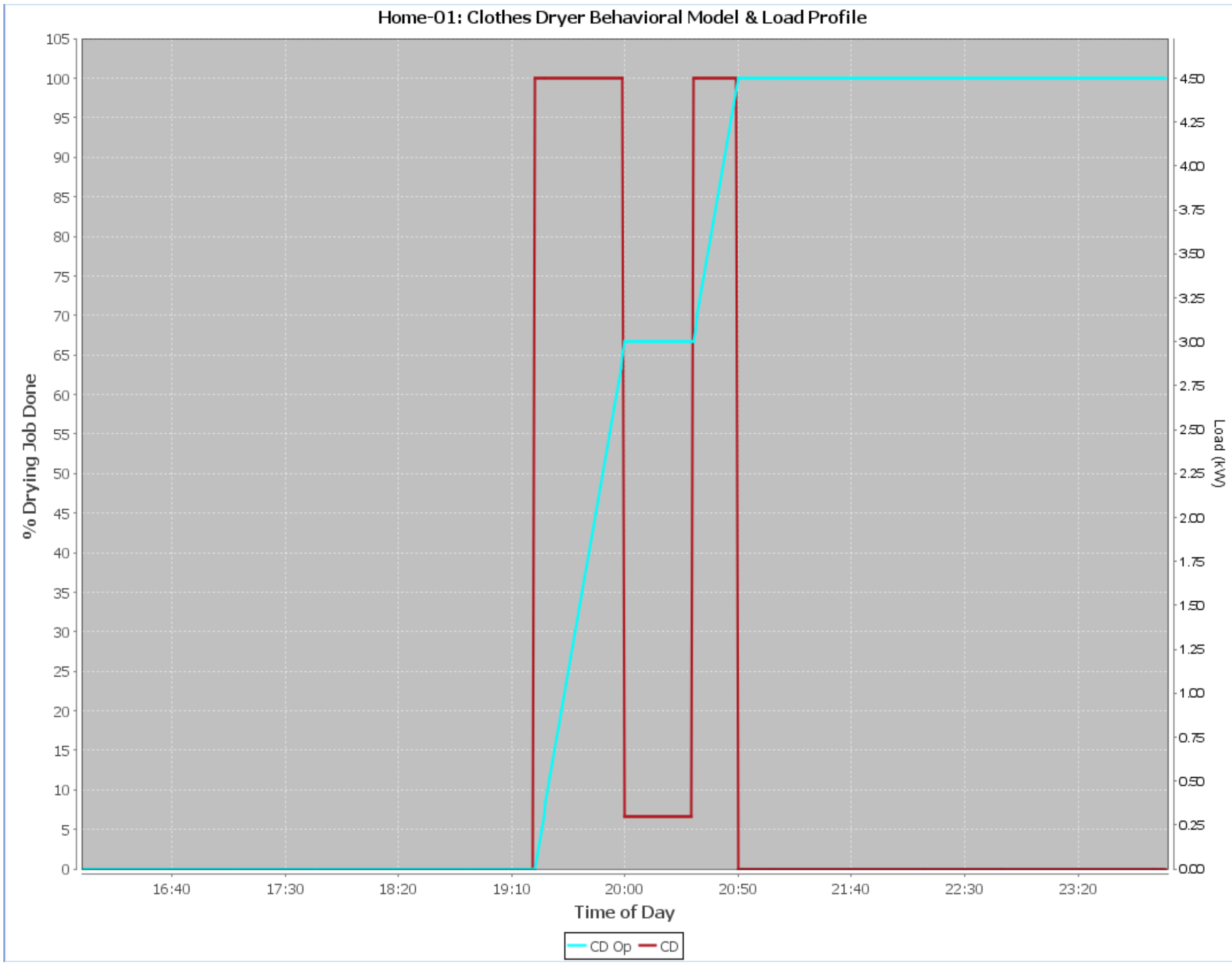


Fig. 6.6: Clothes dryer load profile.

In this example scenario, user starts the drying job at 19:20 by loading clothes and pressing a start button. For illustration purpose, let an external signal causes heating coils to turn OFF at 20:00. The total drying job is requires the heating coil to remain ON for at least 60 minutes, i.e., $CT_{CD,max} = 60\ min$. The job has completed 66.67% at this time. Upon receipt of the signal, only the motor keeps running which causes the consumption of 0.3 kW of power. At 20:30 heating coil is switched ON and drying job starts progressing after that point. This time, the drying job progresses towards completion. At 20:50 the job is 100% complete and the clothes dryer turns both the heating coil and the motor OFF, which is the typical behavior of existing clothes dryers.

6.1.4 Electric Vehicle (EV) Behavioral and Load Model

The EV load model and its charging characteristics implemented in the developed HEM system is described here. Like the model for the clothes dryer, the EV charging job is also considered to be progressing towards completion linearly as long as the charging state is maintained. Power consumed by the EV charging at time step n is given by the following equation:

$$p_{EV,n} = w_{EV,n} \times P_{EV} \tag{6.8}$$

where

$w_{EV,n}$ electric vehicle charging state at time interval n, 0 or 1;

P_{EV} rated power for the charging of the electric vehicle (kW)

This work uses $P_{EV} = 3.3\ kW$, as the rated power of the EV charging operation.

The charging of the EV battery is assumed to be of certain duration. The total time, $CT_{EV,n}$, at charging state (state 3 in Fig. 6.7), $w_{EV} = 1$, must exceed the total time required, $CT_{EV,max}$, for full charge. This can be expressed using the following function:

$$w_{EV,n} = \begin{cases} 0, & CT_{EV,n} \geq CT_{EV,max} \\ 1, & CT_{EV,n} < CT_{EV,max} \end{cases} \tag{6.9}$$

Fig. 6.7 below shows the states of EV charging and their corresponding triggering actions or conditions.

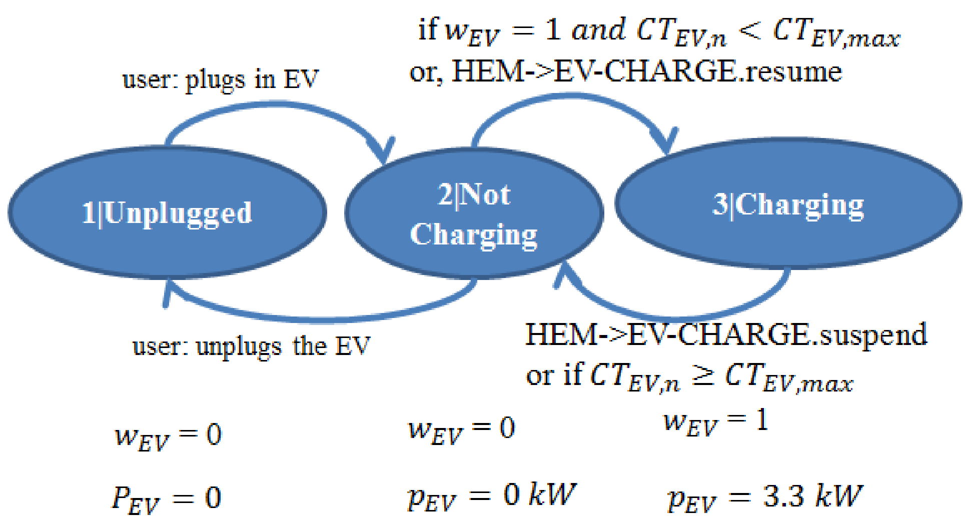


Fig. 6.7: EV charging states of operation and corresponding transitions.

The HEM system can interrupt this state by suspending charging action. This can occur when the HEM system decides to defer EV charging at a particular time interval. This can happen when higher priority appliances use up the available load limit during a DR event. For illustration purpose Fig. DR-5 shows how such an interrupt signal would cause charging progress to halt; and resume when the charging state is reinstated.

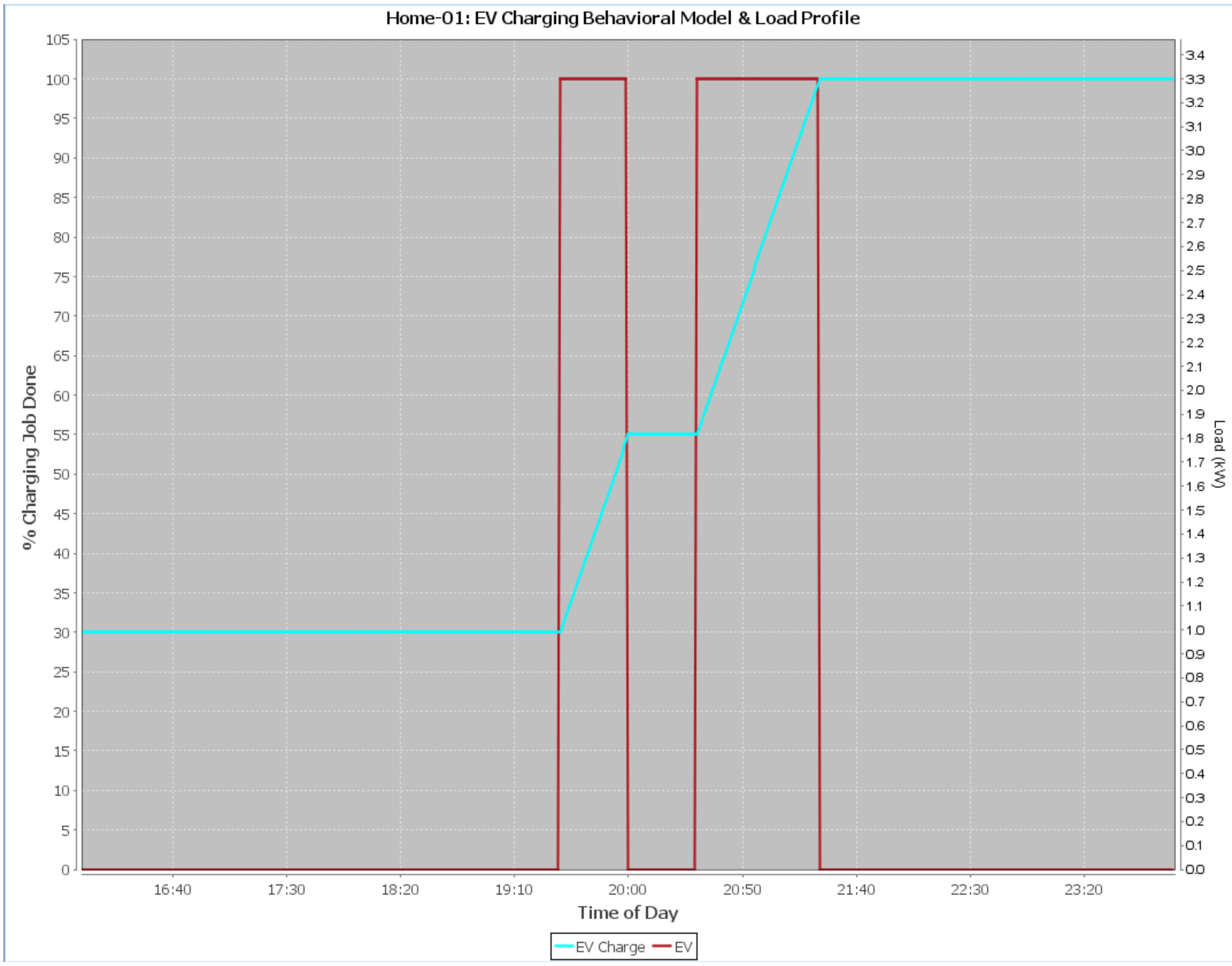


Fig. 6.8: EV charging job in two steps under the influence of DR algorithm. The second charging phase begins as soon as the DR event ends.

At 19:30 the EV is plugged in with residual charge of 30%. Support for this option has been included in the model implemented in this work to reflect the fact that, when the EV is plugged in, it doesn't necessarily mean the battery has been emptied out. In most cases the battery will have residual energy stored. Initially EV is not suspended and charging job begins immediately to progress towards completion. At 20:00, charging stop signal is received from HEM, which results in the halting of charging process when 55% has been charged only. Therefore, the load at that time becomes 0. At 20:30 the charging state is reinstated again and the charging job start progressing and completes at 21:24 at which point the charging state is turned off. The total charging time of the electric vehicle used here is 120 minutes, i.e., $CT_{EV,max} = 120\ min.$ Since it had residual charge of 30%, only $0.7 * 120 = 84\ minutes$ of charging has been required to complete the charging task. Without the interruption it would have completed at 20:54. Because of the interruption starting at 20:00, which lasted for 30 minutes, actual completion time of charging is shifted to 21:54 hours. This behavior of turning off the charging state is included to reflect the behavior of practical batteries. For this to become possible, no external signal by another system is necessary.

6.1.5 Critical Loads

For considering the power consumed by all other appliances—which are considered as critical loads—within a house real total load data for every minute on a hot summer day has been recorded. From the total measured load, selected power-intensive loads have been filtered out. The resulting representative of critical loads has been plotted in Fig. 6.9.

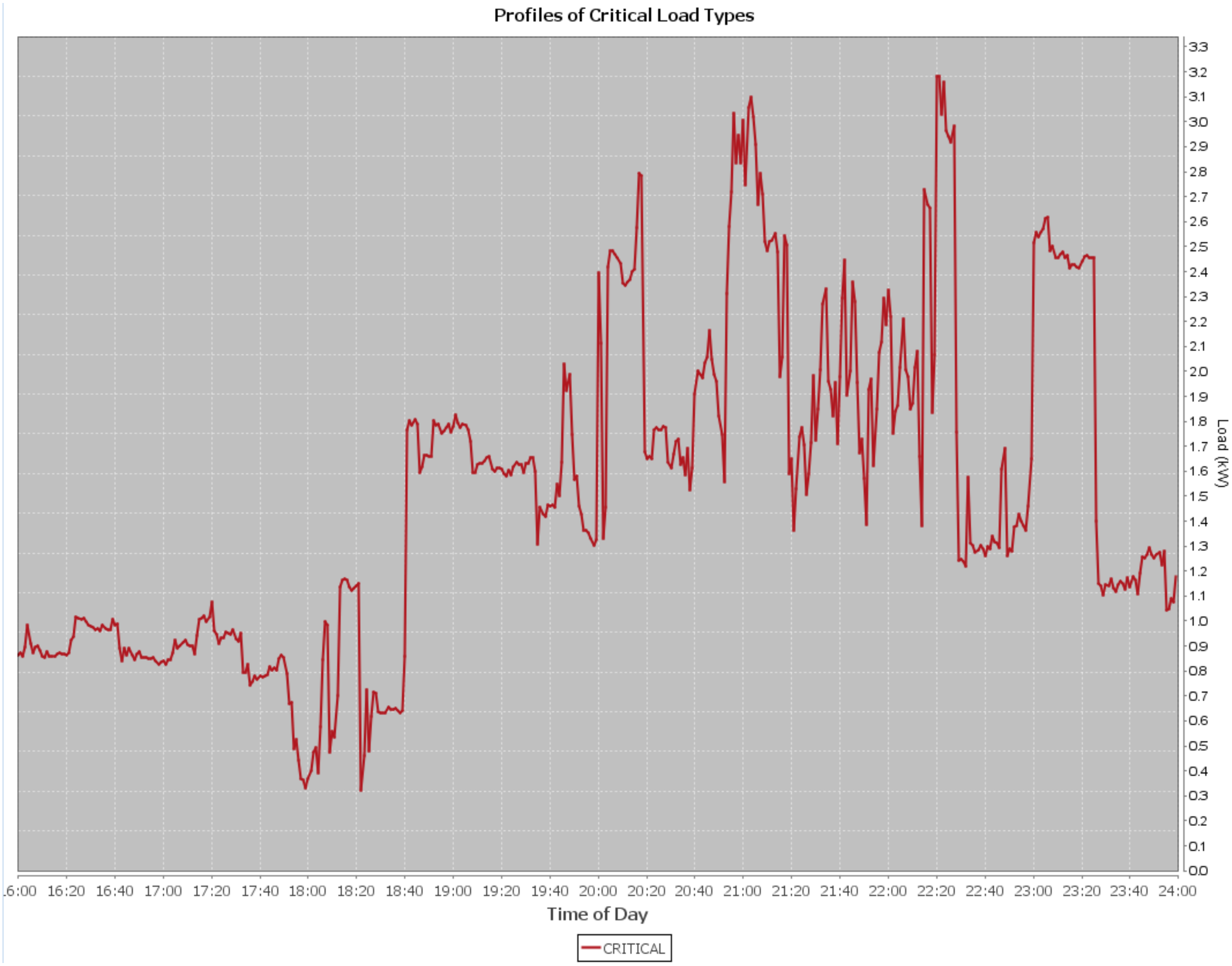


Fig. 6.9: Critical load profile of an average household for a day in August.

6.1.6 Total Household Load

Total household load is calculated for every discrete time interval i, by taking the summation of the critical load profile (shown in Subsection 6.1.5) and load profiles of all controllable loads (shown in Subsections 6.1.1-6.1.4).

Fig. 6.10 illustrates an example of the total household load profile (in magenta), along with load profiles of all other power intensive appliances and critical loads for a typical summer day in

August. The clothes dryer task is scheduled at 19:20. The electric vehicle is plugged in at 19:30 hours.

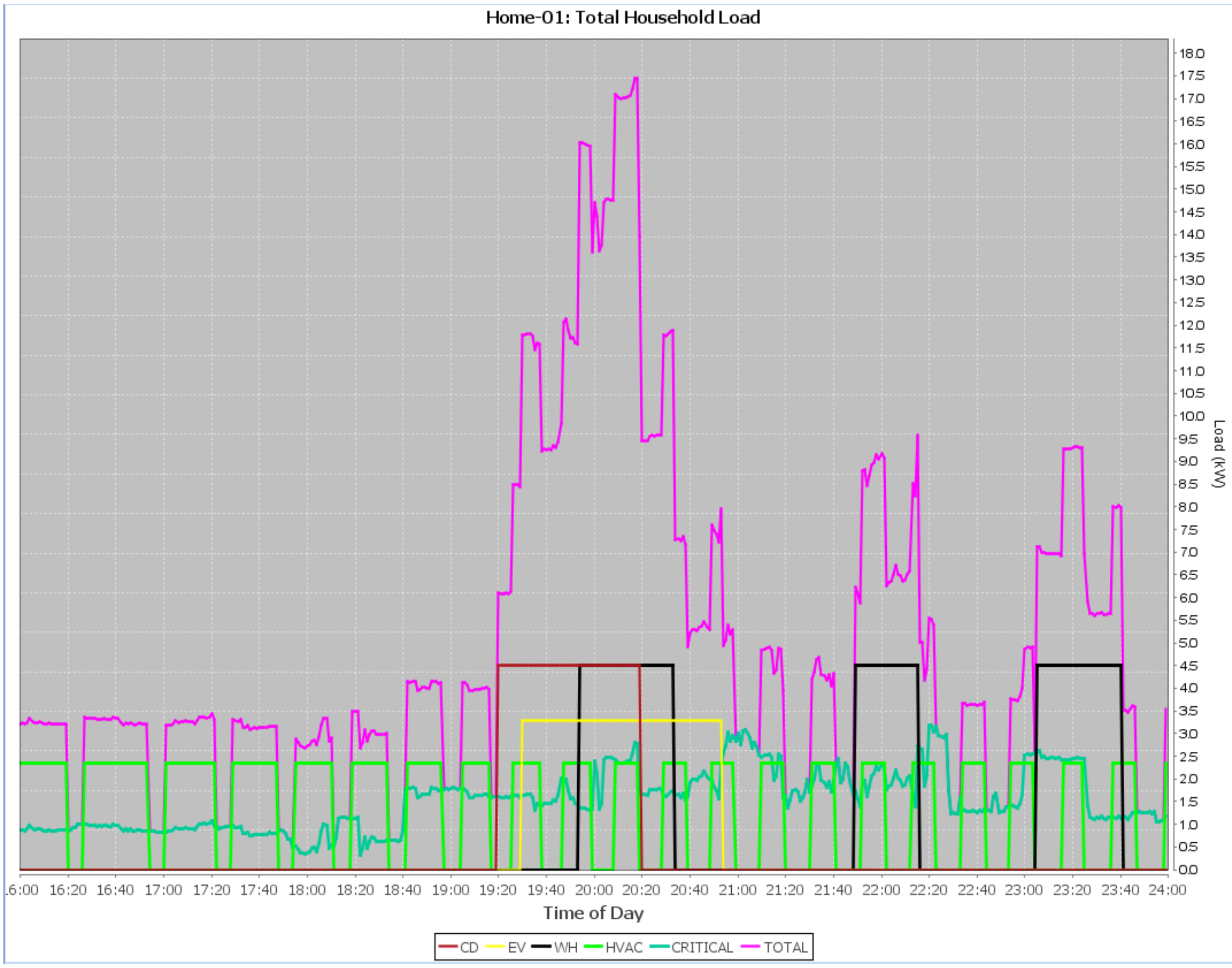


Fig. 6.10: Critical load profile of an average household for a typical day (afternoon to midnight) in August.

6.2 Single-Home Demand Response Algorithm

DR algorithms for appliance-level management in a single home have been developed based on the prior work published in [011, 013, 015]. The implementation of the algorithms in the proposed HEM system is described below in a high-level language.

6.2.1 Steps of the Single Home DR Algorithm

1. The list of controllable appliances is taken according to the priority order set by the user.

2. The appliance order is changed by applying re-prioritizing operation (Section 6.2.1).

3. A sum CURRENT_TOTAL_LOAD is initialized with the value of the critical load for the current time step. Since critical loads are beyond the control of this algorithm, critical loads are considered first.

4. If the clothes dryer's motor is running, its rated power for the motor is added to the sum CURRENT_TOTAL_LOAD as well. If the clothes dryer is in its "2|Started" state (Fig. 6.5), it will not change until the task is finished. So, it is considered before all other controllable appliances

5. For each of the controllable appliances (in the new priority) either of the following steps are performed:

    a. If the appliance is currently suspended and eligible (explained in Section 6.2.3) for operation, a check is performed to ensure that the condition would not be violated: CURRENT_TOTAL_LOAD + Appliance Rated Power ≤ Demand Limit. If the violation would not occur the autonomous operation of the appliance is resumed and its rated power (P_{coil} for clothes dryer) is added to the CURRENT_TOTAL_LOAD.

    b. If the appliance is not currently suspended and operating fully at the rated power, the appliance is suspended if the CURRENT_TOTAL_LOAD ≥ Demand Limit.

6.2.2 Re-prioritizing operation

This operation is performed taking into account comfort settings and schedule preferences set by a user whereas the initial priority order reflects the overall priority. For example: A user can set the priority of the clothes dryer to be higher than that of the electric vehicle charging. Let at 17:20 hours the electric vehicle is plugged in and the clothes dryer is loaded and started as well. Also assume that because of load limit constraint both of these appliances cannot run simultaneously. For higher priority the clothes dryer would allow to operate until 18:00 hours. But if there is a preference setting indicating that electric vehicle charging operation is expected to complete by a certain time such as 20:00 hours, the priority of the electric vehicle will go higher at 18:00 hours, if it 2 hours is necessary for the completion of the charging.

To implement the strategy to reprioritize the controllable appliances looming preference and comfort setting violations are taken into consideration. All the violation penalty scores are considered to promote one appliance over another. If the penalty scores are same for two different appliances, initial priority order remains in effect between those two appliances. Additional details about HEM algorithms can be found in [26].

6.2.3 Eligibility of an Appliance

An appliance is considered eligible for resuming by the Demand Response algorithm if it has unfinished job and it is able to continue if no longer kept suspended.

The HVAC system and the water heater are always considered eligible here, meaning if not suspended, these appliances may operate based on their autonomous decision depending on the indoor temperature or hot water temperature respectively.

The clothes dryer is considered eligible if it is in state 2 (Started) as shown in Fig. 6.5. It means the clothe dryer has unfinished drying job and it has been already loaded and started (and the motor is rotating, too).

An electric vehicle charging operation is eligible if it has already been plugged in and the charging job has not been completed yet.

6.2.4 Experimental Verification of the Algorithm

The algorithms have been tested for stringent scenarios and they have been found to not fail any test case. Extremely detailed simulation trace has been generated to and both programmatically and manual verification has been performed to and no violation has been found.

In Fig. 6.11 below the simulation trace for the Single Home Demand Response algorithm has been shown. Each line of the trace begins with the time step. Next it prints the demand limit and the decisions of the algorithms about the controllable appliances. If the Demand Response algorithm suspends the autonomous operation of an appliance, it is printed as well. The line ends with a breakdown of the power consumed by each controllable appliance and the critical load at that time interval, and the total household load at that time interval. For manual observation, this total household load can be matched against the load limit printed at the beginning of the line. To assist to detect violation, the comparison between total load and the load limit is performed programmatically and a message is printed in case of violation. For example, at time interval 17:40 hours, the critical load is 0.238 kW, the clothes drying load is 0.3 kW, the electric vehicle load is 3.3 kW, and the HVAC load is 2.352 kW, totaling 6.187 kW.

Several case studies have also been discussed in the subsequent sections. The results would validate the proposed implementation of the HEM algorithm.

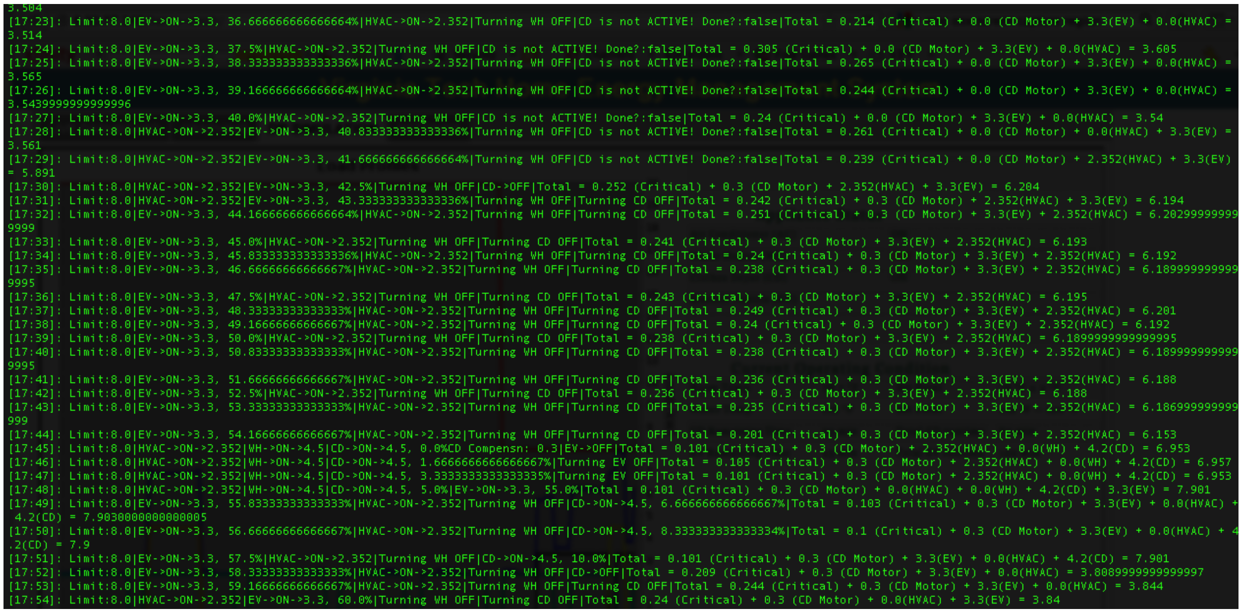


Fig. 6.11: Simulation trace for the correctness of the DRA.

6.3 Case Studies for the Single Home Demand Response Algorithm

Two case studies have been presented in this Section to evaluate the Single Home Demand Response algorithm. In each of the case studies the conditions under which the algorithm is tested is described. Along with this information, the result of the algorithm has been described as well. Finally the performance of the algorithm is evaluated by comparing outcomes with preference and comfort settings.

a) Case Study SH-1

Various operational and comfort preferences and initial priority order of appliances for this case study is presented in Table 6.1. In this table appliances are shown according to their initial priority order. The result of applying the Single-Home Demand Response algorithm is shown with a shaded background to allow easy comparison with the requirements. In this case study, the demand limit for the DR event has been considered to be 8 kW between 17:00 to 22:00 hours.

TABLE 6.1: PREFERENCES AND COMFORT SETTINGS AND OUTCOME OF THE SH-DR ALGORITHM

Settings & Results (Shaded)	**SH DR**	**No Algorithm**
HVAC		
Rated Power	2.352 kW	
Acceptable room temperature range	60-85°F	
HVAC set point temperature	76°F	

Acceptable tolerance band	2°F	
Maximum indoor temperature during DR event	87.88°F	79.41°F
Overall maximum indoor temperature	87.88°F	79.43°F
Water Heater		
Rated Power	4.5 kW	
Hot water set point temperature	120°F	
Acceptable tolerance band	10°F	
Minimum hot water temperature during DR event	107.63°F	107.63°F
Overall minimum hot water temperature	107.63°F	107.63°F
EV Charging		
Rated Power	3.3 kW	
Preferred EV charging time	18:00-22:00	
100% charging time	120 min	
EV residual charge	30%	
EV charging start time	19:30	
EV charging completion time	22:14	20:54
Clothes Dryer		
Rated Power of the Motor	0.3 kW	
Rated Power of the Heating Coil	4.2 kW	
Required drying time	60 min	
Preferred clothes drying time	18:00 - 22:00	
Clothes Drying start time	19:30	
Clothes Drying completion time	23:00	20:30

From TABLE 6.1 it can be found that the initial priority order of the appliances is: HVAC, water heater, electric vehicle charging, and clothes drying load. The maximum room temperature reached is 87.88°F which is a slight violation of acceptable temperature range 60-85°F resulting from deferring of HVAC operation for maintaining load limit. The minimum hot water temperature reaches to 107.63°F during the DR event whose difference with the hot water set point temperature (120°F) is slightly bigger than the allowed deviation of (10°F). From the behavioral model presented in 6.1.2 this condition trigger the switching ON of the water heater. So, the temperature of the hot water increases back to the set point temperature level (120°F). The load levels of the appliances and the operating conditions, and critical load, total household load, etc.,—without any control and with control of Demand Response algorithm—are shown in Fig. 6.12 and Fig. 6.13 below respectively.

Fig. 6.12: Plots of appliance load profiles for Case Study SH-1 without DR.

From Fig. 6.12 it is clearly evident that without any Demand Response algorithm, the total load does not remain without any limit. Each of the appliances starts operation at full capacity immediately when necessary. In the Fig. 6.13 shown below, it is shown how the operations of various appliances had to be deferred to keep the total load under the imposed demand limit. Since, the autonomous and necessary operations of the appliances are deferred, it is not unexpected to see some violation in preferences and comfort settings.

For example, because of low priority the clothes dryer does not have a chance turn the heating coil ON until the end of Demand Response event. The electric vehicle is charged but it cannot complete within the preferred time range. Therefore, as soon as the Demand Response event ends and the stringent load limit is removed, these two appliances compensate for their inability to run earlier. This results in the sharp spike in demand following immediately the Demand Response event. This is called Demand Compensation.

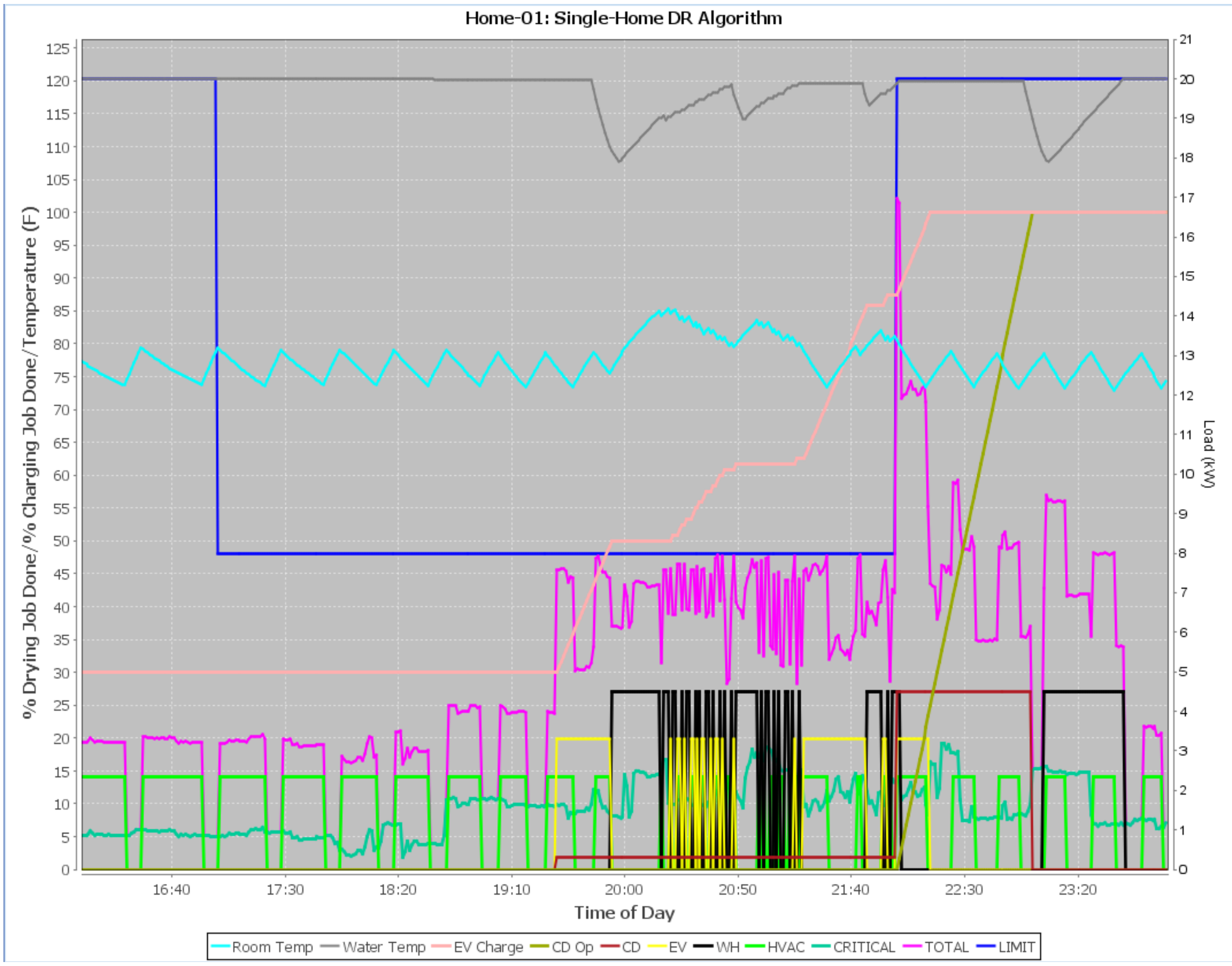


Fig. 6.13: Plots of appliance load profiles for Case Study SH-1 with DR.

During the DR event period, the total household load has never surpassed the demand limit. This can be verified from the plot shown in the Fig. 6.13 by manual inspection. The horizontal blue line between 17:00 and 22:00 hours indicates the demand limit during the DR event.

b) Case Study SH-2

In this case study a different scenario is given. Here the acceptable room temperature has been changed to 60-80°F. This would result in a more stringent scenario than the previous case study. The clothes drying job is started at 19:20 and electric vehicle charging has been started at 19:00 in this case study so that there is less overlap with the electric vehicle charging operation. This would allow the operations to be more distributed and the utilization of available limit during the Demand Response event would increase. Another change is in the priority order of the appliances. The clothes dryer is given higher priority than the electric vehicle in this case study. In table 6.2 these preferences and comfort settings are shown along with other related input. The results achieved by the Single-Home Demand Response algorithm and without any algorithms have been displayed as well.

TABLE 6.2: PREFERENCES AND COMFORT SETTINGS AND RESULTS OF THE SH-DR ALGORITHM

Settings & Results (Shaded)	SH DR	No Algorithm
HVAC		
Rated Power	2.352 kW	2.352 kW
Acceptable room temperature range	60-80°F	60-80°F
HVAC set point temperature	76°F	76°F
Acceptable tolerance band	2°F	2°F
Maximum indoor temperature during DR event	89.91°F	79.40°F
Overall maximum indoor temperature	89.91°F	79.43°F
Water Heater		
Rated Power	4.5 kW	4.5 kW
Hot water set point temperature	120°F	120°F
Acceptable tolerance band	10°F	10°F
Minimum hot water temperature during DR event	107.63°F	107.63°F
Overall minimum hot water temperature	106.13°F	107.63°F
Clothes Dryer		
Rated Power of the Motor	0.3 kW	0.3 kW
Rated Power of the Heating Coil	4.2 kW	4.2 kW
Preferred clothes drying time	18:00 - 21:00	18:00 - 21:00
Clothes Drying start time	19:20	19:20
Clothes Drying completion time	22:13	20:20
EV Charging		
Rated Power	3.3 kW	3.3 kW
Preferred EV charging time	18:00-22:00	18:00-22:00
EV residual charge	30%	30%
EV charging start time	19:00	19:00
EV charging completion time	22:22	20:24

From the above table it is found that the indoor temperature of the household reaches to maximum 89.91°F. From Fig. 6.14 shown below, it is easy to notice that without any control of the appliances the demand limit is violated to a great extent. The total load reaches at 17.5 kW during the Demand Response event when there is no control.

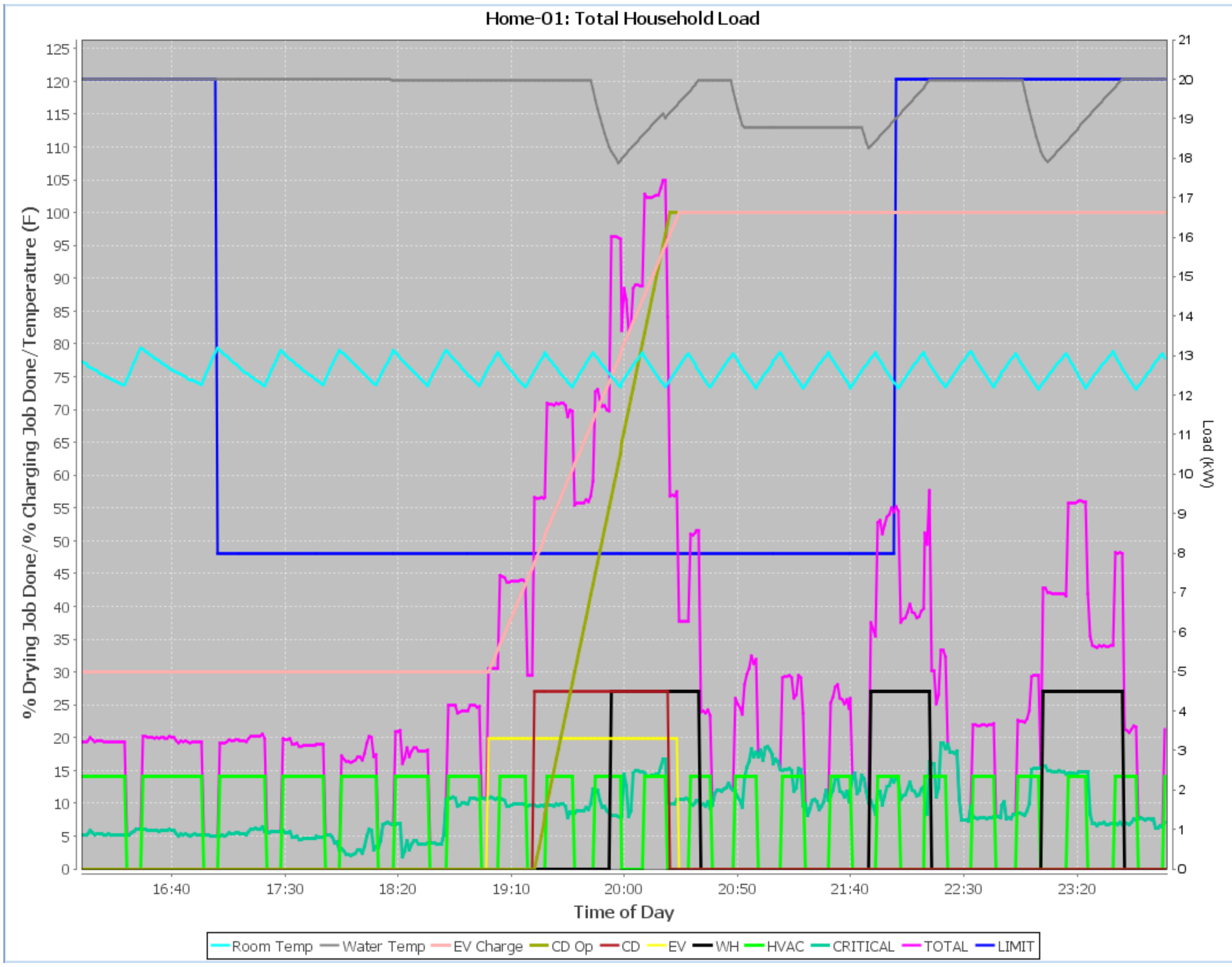


Fig. 6.14: Plots of appliance load profiles for Case Study SH-2 without any DR algorithm.

In the Fig. 6.15 below, the total household has been kept under the demand limit. This resulted in a violation in the room temperature requirements. Another effect can be observed here. Immediately after the Demand Response event the Demand Compensation occurs. Because of the lower limit available during the demand response event comfort setting violation occurs. When the demand limit is lifted, load compensation to make up for the earlier violation begins. For example, because of temperature rise to a higher degree beyond comfort level, the HVAC starts immediately along with the clothes dryer and EV charging load. This is observed from Fig. 6.15 below, just after the 22:00 mark. Without any Demand Response participation there would be no need for such compensation as evident from Fig. 6.14.

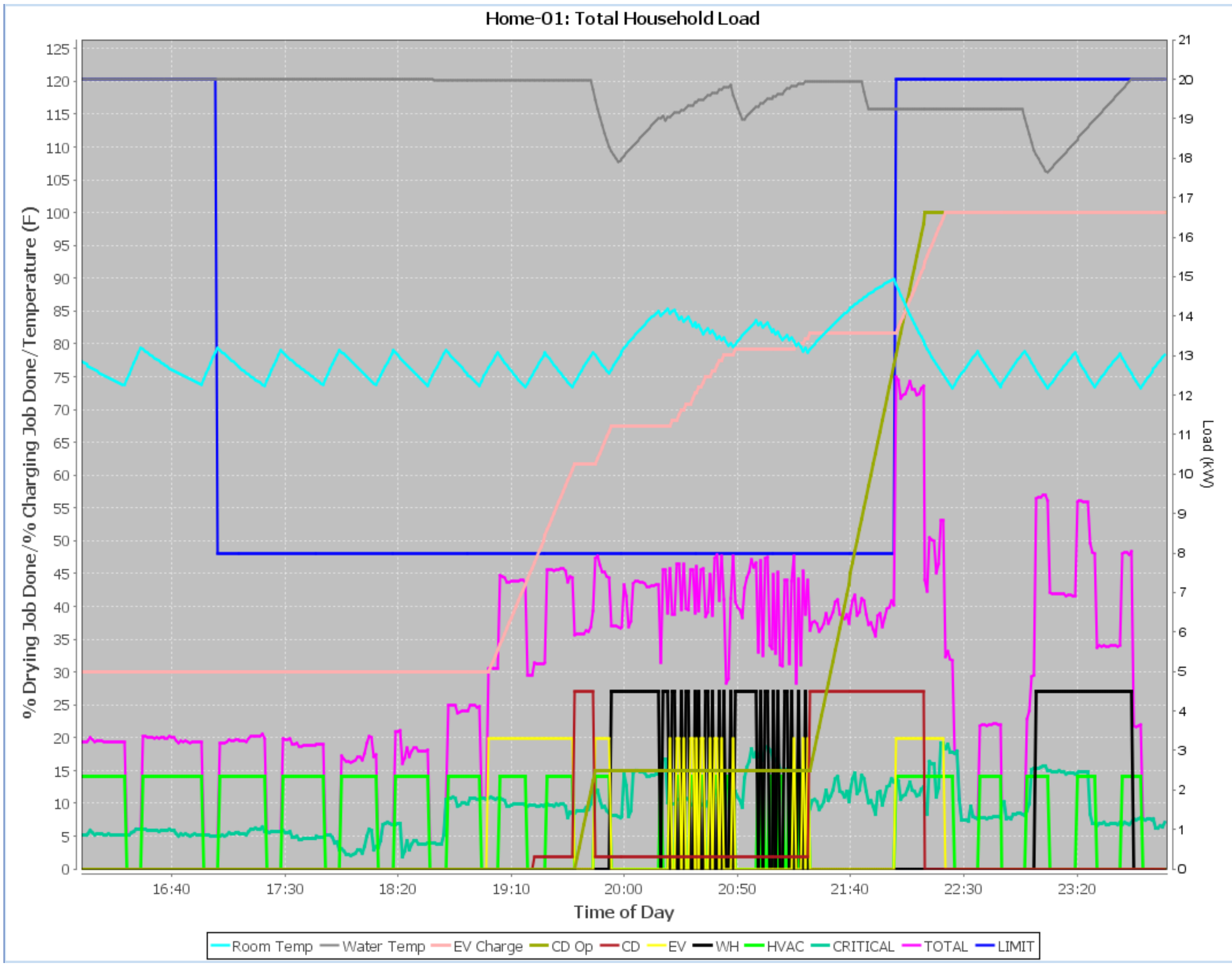


Fig. 6.15: Plots of appliance load profiles for Case Study SH-2 under the control of Single-Home DR algorithm.

In this case study, the total household load has never surpassed the imposed demand limit, which would not be the case in the absence of any Demand Response algorithm. This verifies the 100% correctness of the algorithm.

Between 21:22 and 21:59 and some other intervals, as shown in the Fig. 6.15, the electric vehicle is not able to be charged. In other words during those periods its operation has not been resumed in spite of its being eligible. This is because the clothes dryer has higher priority during those time intervals and resuming the charging of electric vehicle would cause transcending of the demand limit.

From the simulation trace of time step at 21:51 hours, it is found that 2.114 kW of available demand limit has been left unused. Although the electric vehicle charging was been “eligible” for being resumed at that time interval, it was not possible because that operation would have increased total power consumption by3.3 kW.

In Table 6.3 the simulation trace data at 21:51 hours has been shown.

TABLE 6.3: POWER CONSUMED BY THE APPLIANCES FROM SIMULATION TRACE

Simulation Trace Data at 21:51 Hours	
Appliance	**Load (kW)**
Critical Load	1.386
Clothes Dryer Motor	0.3
Clothes Dryer Heating Coil	4.2
Total	5.886
Rated Power for Charging of EV	3.3
Demand Limit	8
Unused	**2.114**
Total if heating coil turned ON	9.186

The observation of this inability to schedule appliances even when significant portion of the demand limit available engendered the idea of designing a Multi-Home Joint Appliance Level Demand Response algorithm that would combine such unused portions from multiple homes to have enough capacity to operate more appliances. Had there been two households with the same setup the unused capacity of 2.114 kW from two homes could have been combined to 4.228 kW. This would allow the HEM system to perform the charging of electric vehicle for one of those two households. And this extra facility can be rotated between different households for fairness.

6.4 Multi-Home Joint Demand Response Algorithm

Multi-Home Joint Demand Response (DR) algorithm has been developed to improve the result of its single home counterpart. Like the Single Home algorithm, it works at the appliance level. Unlike the single home demand limit a Multi-home Demand Limit (MHJ-DL) is applied on a group of households participating in Joint Demand Response/Load Control program. A natural grouping would be the case where the participants are served by a single distribution transformer. But this is not any absolute requirement. Groups can be formed between houses which are not in the same neighborhood. The implementation of the algorithm is described in high level language.

6.4.1 Steps of the Multi-Home Joint DRLC Algorithm

1. The lists of the appliances for each of the participating homes are taken in the priority orders entered by the users of the respective households.

2. Re-prioritization operation is performed for each of the homes independently according as done in the Single Home DRLC algorithm described in Subsection 6.4.2.

3. A sum, $TotalLoad_i$, is initialized with 0. The purpose of it is to keep track of the total load—at time interval i—from the appliances already allowed to run.

4. For each of the households, h, participating as a group of households (H) in Joint Demand Response/Load Control scheme, the following operation is performed: Critical load for that house, $CriticalLoad_h$, and the power consumed by the Clothes Dryer motor is added to the sum used to track total allocation of available limit. The following pseudocode is used to express this operation. If the motor of the clothes dryer for house h is ON at the time interval i, $w_{h,motor,i} = 1$. Otherwise, $w_{h,motor,i} = 0$.

$$TotalLoad_i \leftarrow TotalLoad_i + CriticalLoad_{h,i} + w_{h,motor,i} P_{h,motor}$$

5. Let the re-prioritized lists of the appliances for the households are denoted by RA_h, where $h = 1, 2, 3, \ldots N$. For each of the "re-prioritized" lists, RA_h, the eligible appliances are chosen one by one according to the priority with their corresponding list and either considered for suspension or resuming. Unless all of the appliances from the lists from other houses have been already considered, only a single appliance would be considered from a single house.

5.1.WHILE ($TotalLoad_i \leq MHDL_i$) do:

5.1.1. For h ←1 to N do:

5.1.1.1.

For each household, a thread, T_h, is spawned. All the threads race for reserving the load necessary to schedule the highest priority appliance, from RA_h, for the household at that iteration. Mutually exclusive access to, $TotalLoad_i$, has been ensured so that only one thread can compare and increment it as atomic operation. Upon incrementing, the thread is then put into sleep, so that other threads get the opportunity to reserve load, by incrementing $TotalLoad_i$, for their respective appliances.

5.1.1.1. If EMPTY (RA_h) do:

Exit/Complete thread, T_h;

5.1.1.2. ELSE do:

a. Try to gain exclusive lock to $TotalLoad_i$. If failed, T_h, would be blocked.

b. ELSE do:

c. $App \leftarrow REMOVE\_FIRST(RA_h)$

d. If $TotalLoad_i \leq MHDL_i$ do:

If App is suspended but is eligible for resuming and if $TotalLoad_i + RatedPower(App) \leq MHDL_i$ then resume the autonomous operation of the appliance referred to by App by invoking RESUME(App).

e. Else if App is eligible for running and not already suspended, invoke SUSPEND(App).
f. Notify other threads blocked for exclusive access to $TotalLoad_i$
g. Put the thread, T_h, to sleep to give other threads chance.

5.1.2. Wait for all the threads to complete/exit.

The operation REMOVE_FIRST (RA_h) removes and returns the first element (appliance) from the list ordered according to the revised priority. When all the appliances from a list, RA_h, have already been removed, the list is considered empty, and the operation EMPTY(RA_h) would return FALSE. If an appliance is referred to using, App, the invocation of $RatedPower(App)$ returns the rated power for that appliance. The effects of invoking $RESUME(App)$ and $SUSPEND(App)$ are self-explanatory.

6.5 Case Studies for the Multi-Home Joint Demand Response Algorithm

In this section, three case studies have been presented. The first two case studies are included to serve as a comparative evaluation of between the Single-Home Demand Response algorithm, and the Multi-Home Joint Demand Response algorithm. Demonstrating the resilience of the latter algorithm against Demand Compensation is another purpose of these case studies. Third case study demonstrates how the Multi-Home Joint Demand Response algorithm alleviates the transformer overloading problem. In each of these case studies the Multi-Home Joint Demand Response algorithm has been applied to a group of three homes. In the case studies regarding the Single-Home Demand Response algorithms presented in Section 6.4, a load limit 8 kW had been applied. For consistency and convenience of comparison, same 8 kW load limit has been considered per household. The objective of the Multi-Home Joint Demand Response scheme is to keep the total load from a group of houses under a certain limit. For that reason total 24 kW of demand limit has been imposed jointly for the three homes.

6.5.1 Case Study MH-1

To demonstrate the resilience of the algorithm against the worst case scenario, the clothes dryer and electric vehicle at each home are scheduled at the same time to operate. In the next case study it has been shown that the algorithm performs better if the scenario is relaxed. To illustrate the potential improvement achieved from the Multi-Home Joint Demand Response algorithm, first the totally unmanaged situation has been shown. It can help us to realize the difference the algorithm makes.

In Fig. 6.16, the total load for the three households peak to 28.746 kW at 22:15 hours.

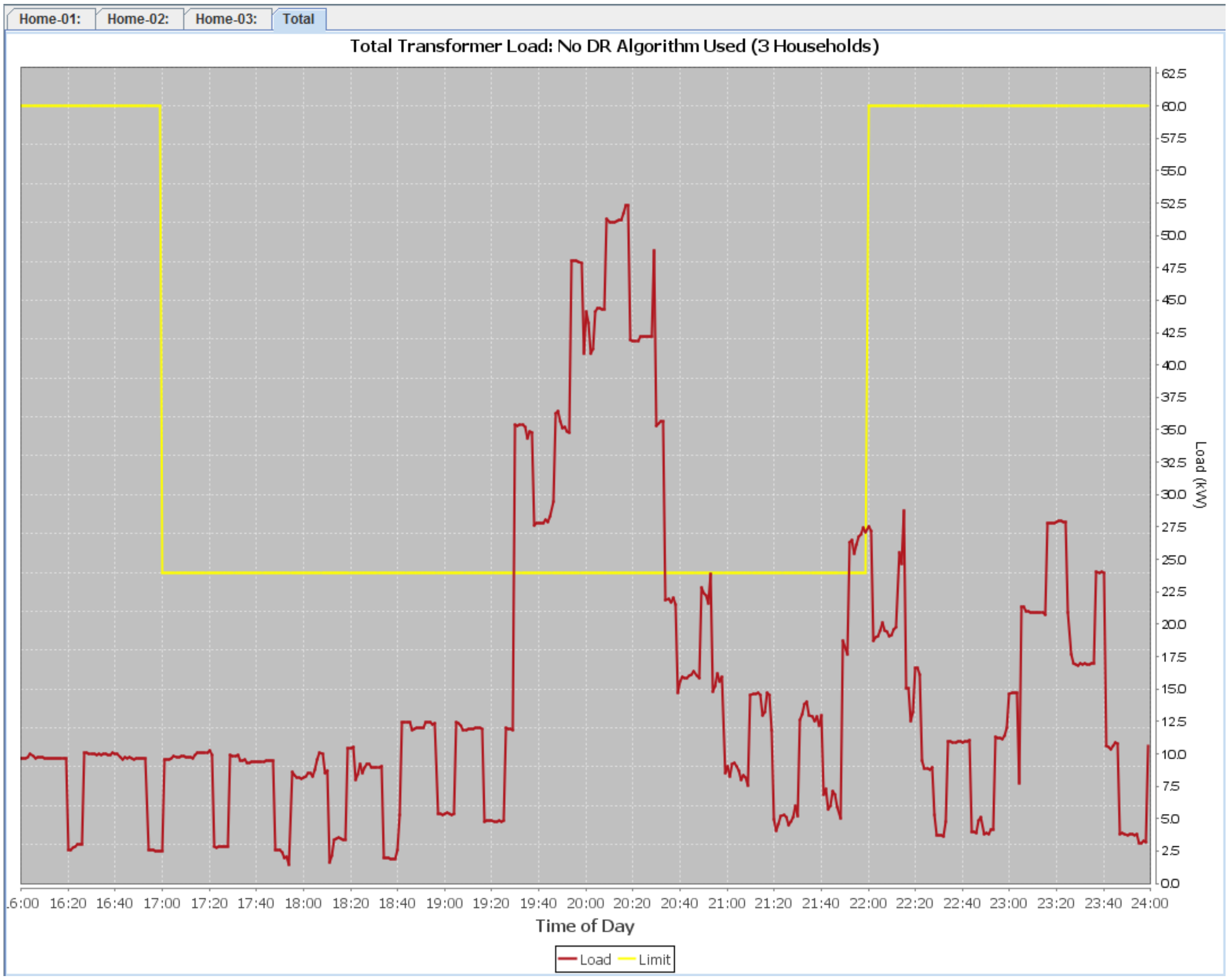


Fig. 6.16: Time series of total load consumed by three households.

Next the total load from three households under the control of Multi-Home Joint Demand Response algorithm has been shown in Fig. 6.17. In this Demand Response scheme a total limit of 24 kW has been imposed upon for the group of three homes. It can be observed that the Demand Response algorithm has successfully kept the total demand under the load limit of 24 kW. To show that the user preferences and comfort settings have been maintained Table 6.4 has been provided, in which the maximum room temperature, hot water temperature, completion time of charging of electric vehicle, and completion time of the clothes dryer operation has been shown for all the three houses. For the sake of comparison, the results for the single home algorithm have been added as well.

After the demand response event the Demand Compensation can be observed. This is not unexpected, since during the Demand Response event, the autonomous operations of the appliances are suppressed. The peak demand after the Demand Response event is 41.034 kW, which is 12.288 kW ($41.034\ kW - 28.746\ kW$) higher than the uncontrolled case. However, the severity of Demand Compensation in this case is much lower comparing to that observe when the Single-Home Demand Response algorithm is used.

Fig. 6.17: Time series of total load consumed by three households utilizing Multi-Home Joint Demand Response algorithm.

In Fig. 6.18 the total load from three households has been shown. In this case the Single-Home Demand Response algorithm has been applied independently for each of the three households with 8 kW load limit. Therefore, the total load from three houses are limited under 24 kW during the Demand Response event. After the Demand Response period is over, the spike in demand is observed and this is more severe than that of the Multi-Home Joint Demand Response algorithm. The peak demand after the Demand Response period is 50.934 kW. In this case, the compensation is $50.934 - 28.746 = 22.188\ kW$. Therefore, in this scenario the Demand Compensation for Multi-Home Joint Demand Response algorithm is approximately 55% than that of the Single-Home algorithm.

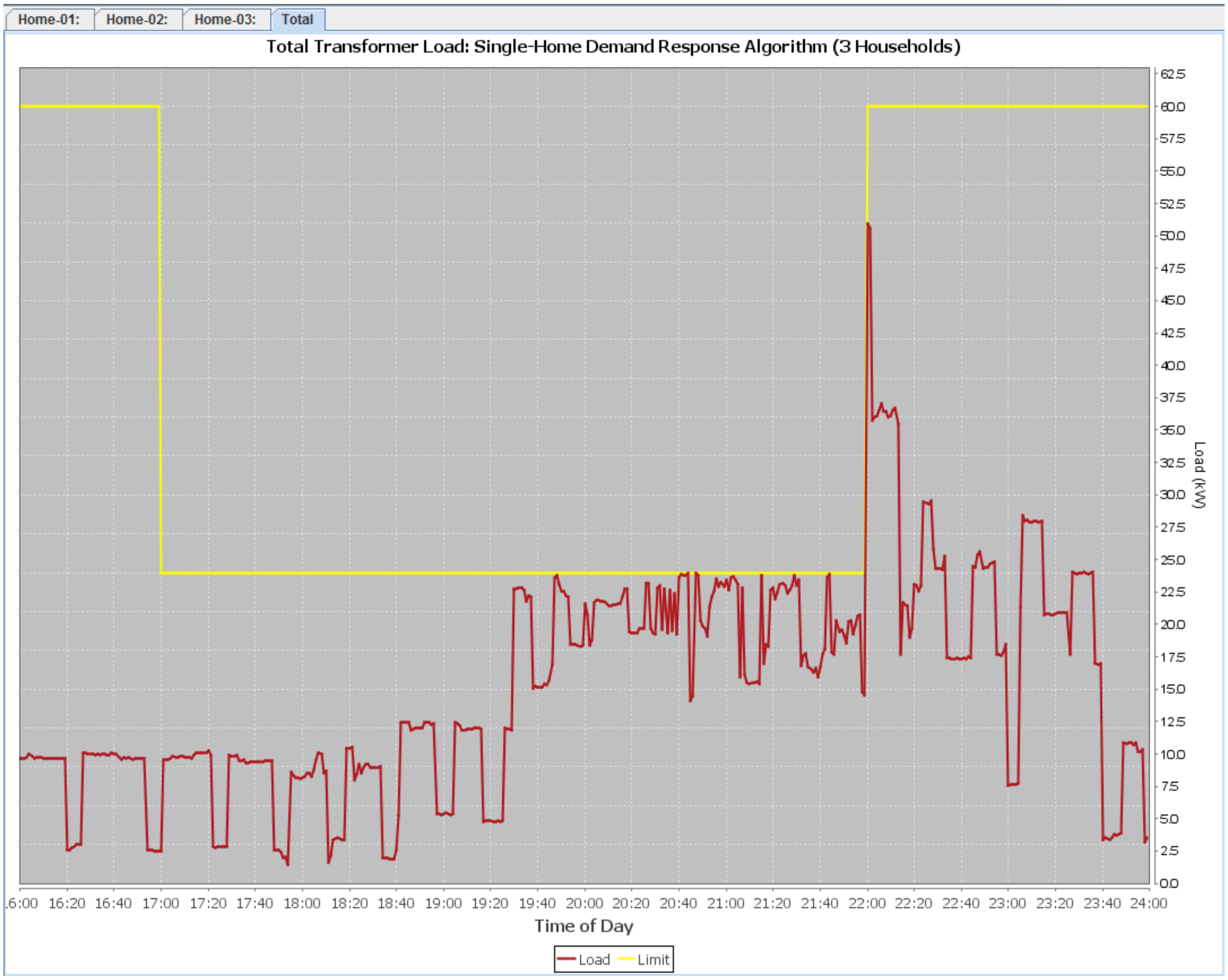


Fig. 6.18: Time series of total load consumed by three households utilizing Single-Home Joint Demand Response algorithm.

From Table 6.4, it is evident that the Multi-Home Joint Demand Response algorithm yields better result than the Single-Home algorithm in maintaining the operating conditions.

The maximum room temperatures maintained for three houses have been found to be much better than the Single-Home algorithm. The set point temperature is 76°F with tolerance of 2°F. And the maximum allowed temperature is 85°F. In case of the Single-Home algorithm, the temperature reaches to 87.88°F during the Demand Response period, as the HVAC system's operation had to be suspended to maintain the total load within 8 kW demand limit. If Single-Home algorithm is used, all of those three households would experience the similar violation in comfort setting other things remaining same. On the other hand the room temperatures that were possible to be maintained by the Multi-Home Joint Demand Response algorithm are found to be: 84.427°F, 82.998°F and 85.795°F. In other words, for the two of the households, the room temperatures have always remained within the allowed range. For one of the households it slightly went above that range.

TABLE 6.4: COMPARISON OF RESULTS OF MULTI-HOME JOINT DR ALGORITHM WITH THAT OF THE SINGLE-HOME DR ALGORITHM

Settings & Results (Shaded)	SH DR	No Algorithm	Multi-Home Joint DR		
			Home-1	Home-2	Home-3
HVAC					
Rated Power	2.352 kW				
Acceptable room temperature range	60-85°F				
HVAC set point temperature	76°F				
Acceptable tolerance band	2°F				
Maximum indoor temperature during DR event	87.88°F	79.41°F	84.427°F	82.998°F	85.795°F
Overall maximum indoor temperature	87.88°F	79.43°F	84.427°F	82.998°F	85.795°F
Water Heater					
Rated Power	4.5 kW				
Hot water set point temperature	120°F				
Acceptable tolerance band	10°F				
Minimum hot water temperature during DR event	107.63°F	107.63°F	107.643	107.643	107.643
Overall minimum hot water temperature	107.63°F	107.63°F	107.643	107.643	107.643
EV Charging					
Rated Power	3.3 kW				
Preferred EV charging time	18:00-22:00				
100% charging time	120 min				
EV residual charge	30%				
EV charging start time	19:30				
EV charging completion time	22:14	20:54	21:37	21:39	21:31
Clothes Dryer					
Rated Power of the Motor	0.3 kW				
Rated Power of the Heating Coil	4.2 kW				
Required drying time	60 min				
Preferred clothes drying time	18:00 - 22:00				
Clothes Drying start time	19:30				
Clothes Drying completion time	23:00	20:30	22:32	22:35	22:24
Energy consumed during DR	23.607 kWh	27.675 kWh	**25.543 kWh**		
Post-DR event peak demand	50.934 kW	28.746 kW	**41.034 kW**		

Significant improvement in performance can be observed in case of the charging of electric vehicle. The Single-Home algorithm is able to complete the charging operation at 22:14 hours where the user preference of ending time is 22:00 hours. Under similar conditions, the Multi-Home algorithm is able to complete charging at: 21:37, 21:39 and 21:31 hours. So, on average the Multi-Home Joint Demand Response algorithm finishes the charging of the electric vehicles 38.33 minutes earlier.

Another significant improvement in performance can be observed in case of the operation of the clothes dryer. The Single-Home algorithm is able to complete the drying task at 23:00 hours where the user preference of ending time is 22:00 hours. Under similar conditions, the Multi-Home algorithm is able to complete drying at: 22:32, 22:35 and 22:24 hours. So, on average the Multi-Home Joint Demand Response algorithm finishes the operations of the clothes dryers 29.67 minutes earlier.

The superior results achieved by the Multi-Home Joint Demand Response algorithm can be explained from the observation that it has the ability to operate more appliances than what the Single-Algorithm is capable of. Such a scenario has been shown at the end of the case study SH-2 in Subsection 6.5.b. The Single-Home algorithm is able to consume 23.607 kWh of energy while maintaining the total power consumption within 8 kW for each of the households individually during the Demand Response event. The average energy consumed at three households under the control of the Multi-Home Joint DR algorithm is 25.543 kWh which is approximately 8% higher than that of the Single-Home algorithm in this scenario.

6.5.2 Case Study MH-2

This case study has been created by making the room temperature preference more stringent than the previous case study. The maximum allowed temperature has been changed from 85°F to 80°F in this case study. The priority order between the electric vehicle and the clothes dryer has been switched. In the previous case study the initial priority of the electric vehicle charging was higher than the drying operation. In this case study, the drying job has been given higher initial priority than the electric vehicle charging operation. In the previous case study the charging of the electric vehicle and the clothes drying task are started at the same time. In this case study this has been relaxed by starting the operations of these two appliances at different times. The electric vehicle charging is scheduled at 19:00 hours, whereas the clothes dryer task is started at 19:20 hours. In brief the operations of the electric vehicle and the clothes dryer have been shifted towards left, i.e., much earlier than the Demand Response event completion time (22:00 hours). This leftward shift causes the Demand Compensation effect to disappear for the Single-Home Demand Response algorithm.

To illustrate the potential improvement achieved from the Multi-Home Joint Demand Response algorithm, first the totally unmanaged situation has been shown. It can help us to realize the difference the algorithm makes.

In Fig. 6.19, the total load for three homes peaks to 28.746 kW at 22:15 hours.

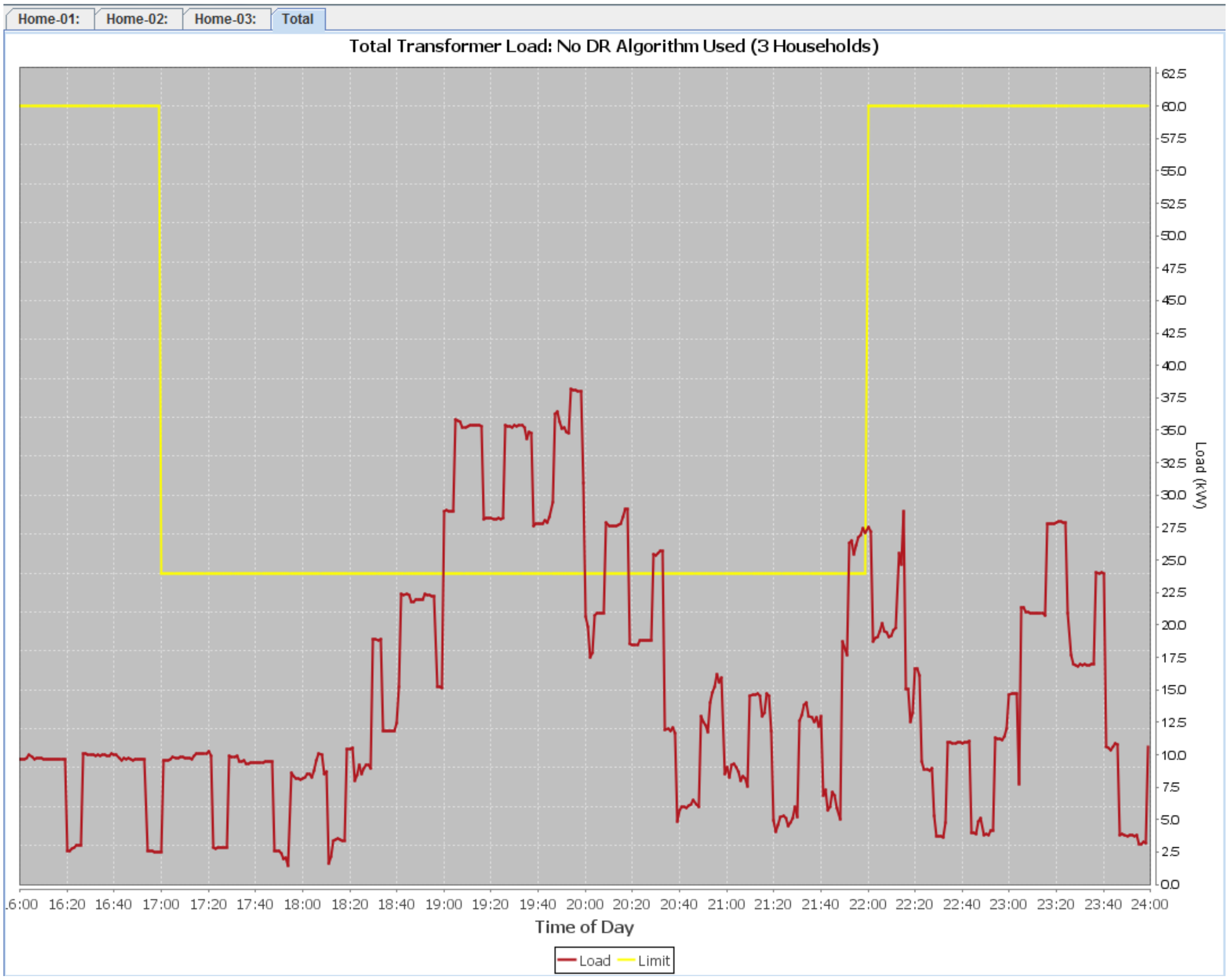


Fig. 6.19: Time series of total load consumed by three households.

Next the total load from three households under the control of Multi-Home Joint Demand Response algorithm has been shown in Fig. 6.20. In this Demand Response scheme a total limit of 24 kW has been imposed upon for the group of three homes. It can be observed that the Demand Response algorithm has successfully kept the total demand under the load limit of 24 kW. To show that the user preferences and comfort settings have been maintained Table 6.5 has been provided, in which the maximum room temperature, hot water temperature, completion time of charging of electric vehicle, and completion time of the clothes dryer operation has been shown for all the three houses. For the sake of comparison, the results for the single home algorithm have been added as well.

After the demand response event no Demand Compensation has been observed in this case. This is due to the leftward shift in the scheduling of the clothes dryer and electric vehicle charging. This causes any compensation to disappear within the Demand Response period.

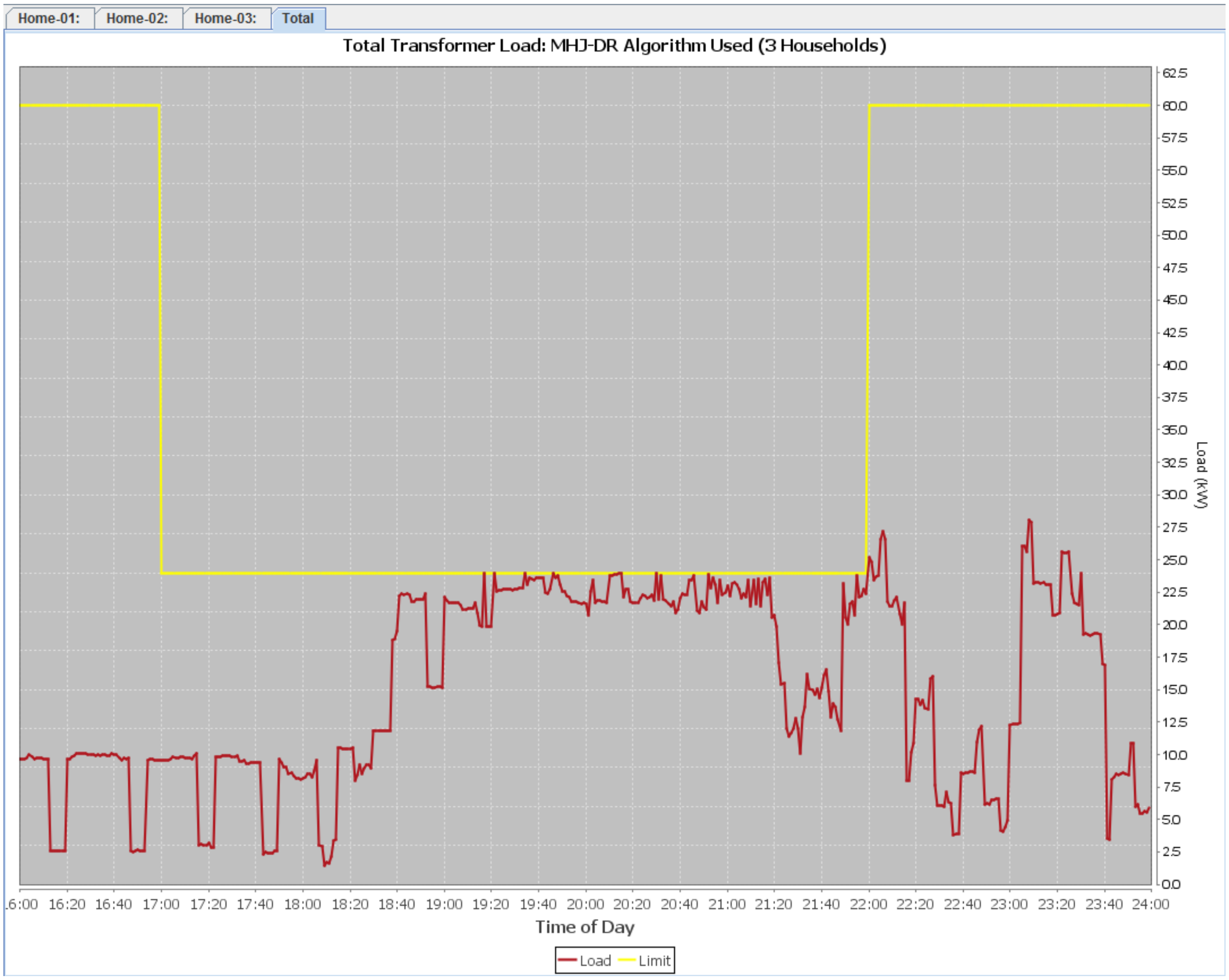


Fig. 6.20: Time series of total load consumed by three households utilizing Multi-Home Joint Demand Response algorithm.

In Fig. 6.21 the total load from three households has been shown. In this case the Single-Home Demand Response algorithm has been applied independently for each of the three households with 8 kW load limit. Therefore, the total load from three houses are limited under 24 kW during the Demand Response event. In this scenario, which is less stringent than the previous case study, no Demand Compensation has been observed. This can happen when the schedule is not very congested. However, a lower demand limit, say 7 kW per household, would bring the Demand compensation back for the same schedule and the MHJ-DR algorithm would show more resilience than the Single-Home algorithm.

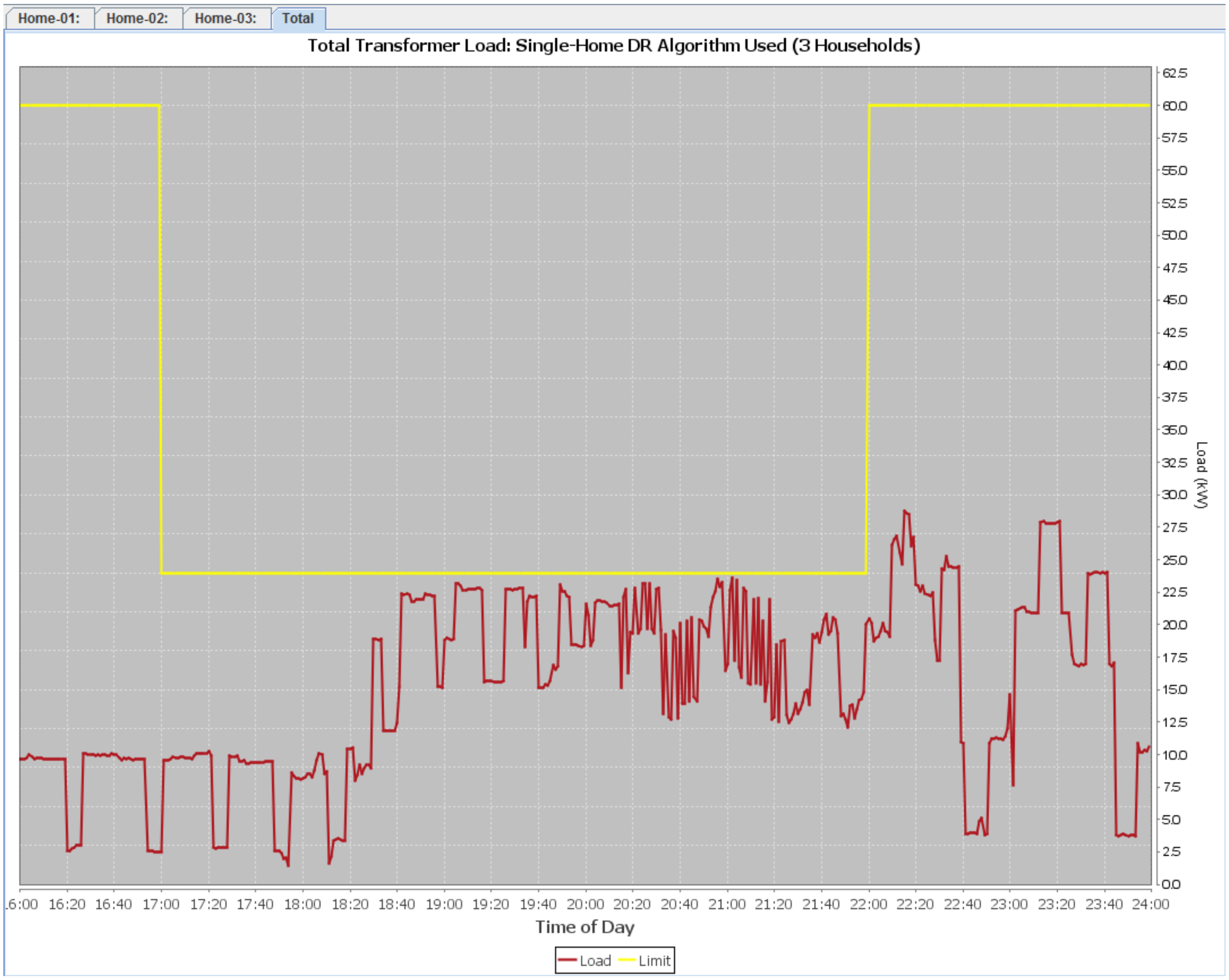


Fig. 6.21: Time series of total load consumed by three households utilizing Single-Home Demand Response algorithm.

From Table 6.5, it is evident that the Multi-Home Joint Demand Response algorithm yields better result than the Single-Home algorithm in maintaining the operating conditions.

The maximum room temperatures maintained for three houses have been found to be much better than the Single-Home algorithm. The set point temperature is 76°F with tolerance of 2°F. And the maximum allowed temperature is 80°F. In case of the Single-Home algorithm, the temperature reaches to 85.317°F during the Demand Response period, as the HVAC system's operation had to be suspended to maintain the total load under 8 kW demand limit. If Single-Home algorithm is used, all of those three households would experience the similar violation in comfort setting other things remaining same. On the other hand the room temperatures that were possible to be maintained by the Multi-Home Joint Demand Response algorithm are found to be: 82.282°F, 81.208°F and 84.709°F. Therefore, for each of the households, the violation in room temperature is always lower than that for the Single-Home algorithm case.

TABLE 6.5: COMPARISON OF RESULTS OF MULTI-HOME JOINT DR ALGORITHM WITH THAT OF SINGLE-HOME DR ALGORITHM

Settings & Results (Shaded)	SH DR	No Algorithm	Multi-Home Joint DR		
			Home-1	Home-2	Home-3
HVAC					
Rated Power	2.352 kW				
Acceptable room temperature range	60-80°F				
HVAC set point temperature	76°F				
Acceptable tolerance band	2°F				
Maximum indoor temperature during DR event	85.317°F	79.41°F	82.282°F	81.208°F	84.709°F
Overall maximum indoor temperature	85.317°F	79.43°F	82.282°F	81.208°F	84.709°F
Water Heater					
Rated Power	4.5 kW				
Hot water set point temperature	120°F				
Acceptable tolerance band	10°F				
Minimum hot water temperature during DR event	107.629°F	107.63°F	107.643	107.643	107.643
Overall minimum hot water temperature	106.136°F	107.63°F	107.643	107.643	107.643
Clothes Dryer					
Rated Power of the Motor	0.3 kW				
Rated Power of the Heating Coil	4.2 kW				
Required drying time	60 min				
Preferred clothes drying time	18:00 - 22:00				
Clothes Drying start time	19:00				
Clothes Drying completion time	22:39	20:00	21:14	21:34	21:31
EV Charging					
Rated Power	3.3 kW				
Preferred EV charging time	18:00-22:00				
100% charging time	120 min				
EV residual charge	30%				
EV charging start time	18:30				
EV charging completion time	20:32	19:54	21:17	21:29	21:28
Energy consumed during DR (Transformer average)	25.639 kWh	27.675 kWh	**27.818 kWh**		
Post-DR event peak load (Transformer)	28.746 kW	28.746 kW	**27.534 kW**		

Significant improvement in performance can be observed in case of the operation of the clothes dryer. The Single-Home algorithm is not able to complete the drying task until 22:39 hours, where the user preference of ending time is 22:00 hours. Under similar conditions, the Multi-

Home algorithm is able to complete drying at: 21:14, 21:34 and 21:31 hours. So, on average the Multi-Home Joint Demand Response algorithm finishes the operations of the clothes dryers 72.67 minutes earlier. This is a huge improvement per household. This is significant because of another reason: in case of the Single-Home algorithm the user preference has not been satisfied.

Now the result yielded in terms of the performance in charging of electric vehicle. The Single-Home algorithm is able to complete the charging operation at 20:32 hours where the user preference of ending time is 22:00 hours. Under similar conditions, the Multi-Home algorithm is able to complete charging at: 21:17, 21:29 and 21:28 hours. Although the Multi-Home Joint DR algorithm finishes later, it cannot be attributed as a weakness of the MHJ-DR algorithm, since the completion times of charging of the vehicles are well within the preferred end time 22:00 hours.

The Single-Home algorithm is able to consume 25.639 kWh of energy while maintaining the total power consumption within 8 kW for each of the households individually during the Demand Response event. The average energy consumed at three households under the control of the Multi-Home Joint DR algorithm is 27.793 kWh which is approximately 8.4% higher than that of the Single-Home algorithm in this scenario. This matches with the expectation that MHJ-DR algorithm is able to run more appliances than the Single-Home algorithm. This is slightly higher than the case when no algorithm is used, which is 27.675 kWh. This can be because of several reasons. For example, if the water heater is interrupted and it operates in later hours, it would consume more electricity to reach the set-point temperature. Another example is when the clothes dryer is interrupted, its motor is still ON and consumes about 300 watts of power throughout interruption period(s).

6.5.3 Case Study MH-3

This case study is intended to demonstrate the application of the Multi-Home Demand Response algorithm in alleviating the transformer overload problem. To solve the problem the total demand limit for all the households served by a single distribution transformer needs to be within the capacity of the transformer. Although transformers can tolerate little overload for short duration, but it can result in reduced operational life of the transformer.

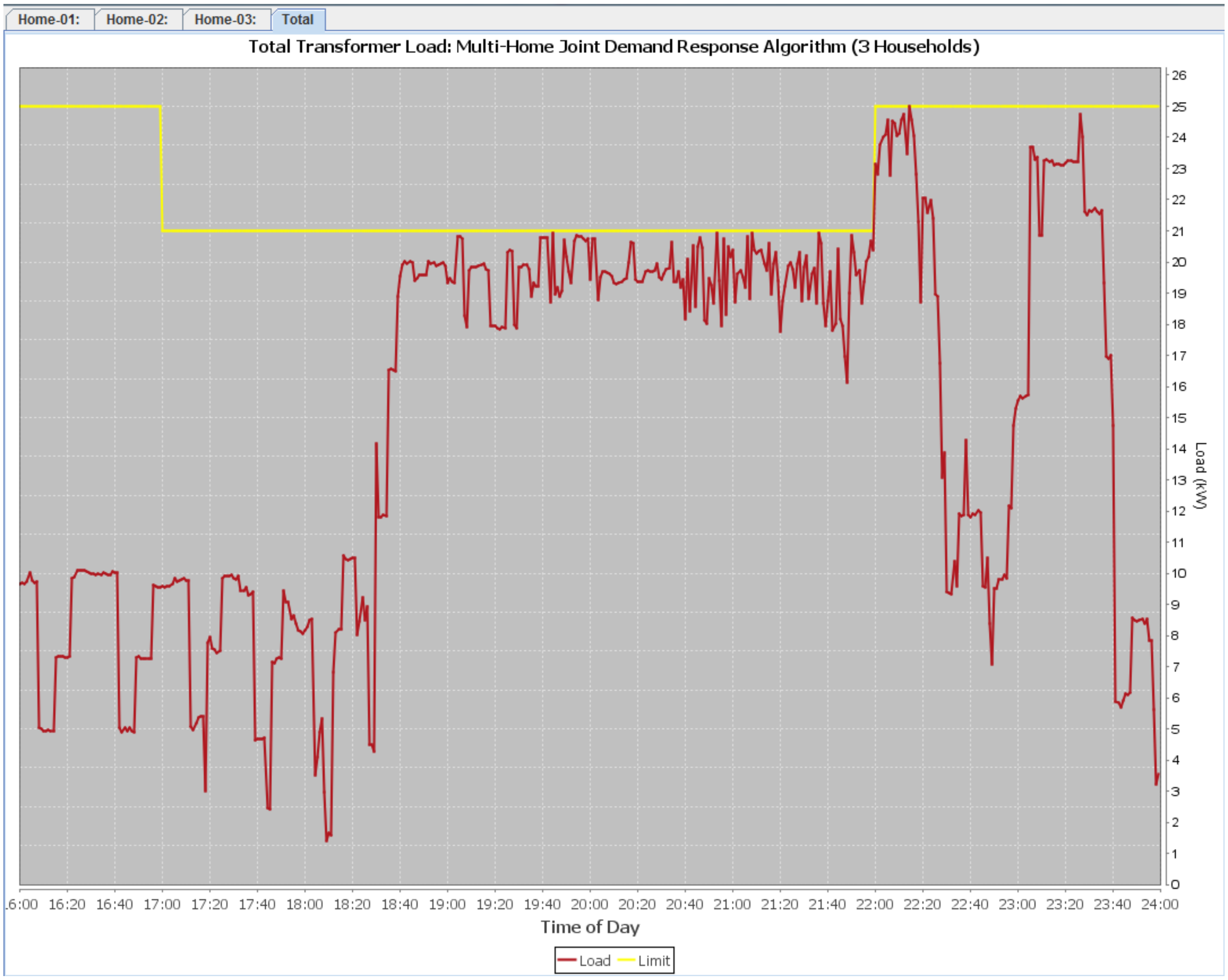


Fig. 6.22: Preventing the overloading of a 25 kVA distribution transformer using MHJ-DR.

Next from Fig. 6.23 it can be observed what would happen in case of the Single-Home algorithm is applied independently. In short, by the virtue of the communication framework designed and developed in this work, it is possible to solve the transformer overloading problem. Either Single-Home or Multi-Home Joint DR algorithm can be used to prevent transformer overloading; however, the SH-DR would cause greater violations of user preferences.

In this case study all the settings are same as the prior case study except Demand Response load limit, which has been changed to 7 kW per household. This increase in restriction results in the failure of the SH-DR algorithm. Charging completes only 94.16% and drying completes only 83.33% by midnight which is two hours after the user preferred completion time. This is because when the transformer capacity has been applied as load limit, after the Demand Response event, the SH-DR algorithm does not have the room for Demand Compensation. On the other hand in case of MHJ-DR algorithm, the completion times of charging of the electric vehicles for the three households are: 21:34, 21:06 and 21:10. The drying tasks are completed at: 22:46, 22:29 and 22:39. MHJ-DR algorithm is more resilient to the Demand Compensation effect, by virtue of which it is able to able to yield satisfactory result even when transformer capacity is brought into the equation. This allows a utility to offer higher user satisfaction without requiring the upgrade of the transformer.

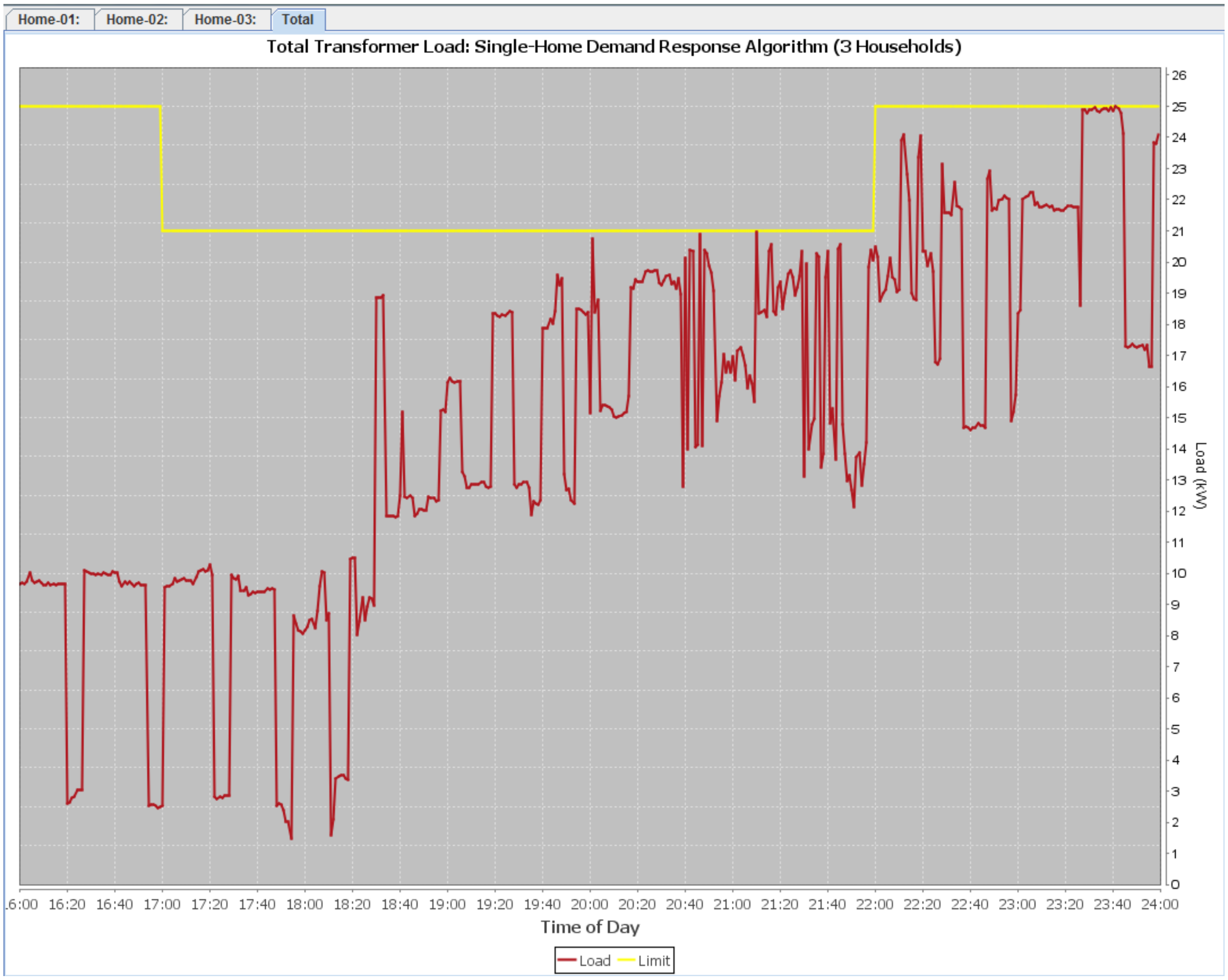


Fig. 6.23: Preventing the overloading of a 25 kVA distribution transformer using SH-DR.

The superiority of the MHJ-DR algorithm over the SH-DR algorithm would be more prominent in case of higher capacity transformers such as the ones with capacity of 37.5 kVA, 50 kVA, or 75 kVA, where there are more households being served by the same distribution transformer.

6.6 Conclusion

In this chapter it has been demonstrated that using Demand Response (DR) algorithms it is possible to alleviate the peak load problem. A Single-Home DR (SH-DR) algorithm has been implemented and validated using realistic models of the appliances. The behavior of the HVAC system has been modeled how its operation impacts the indoor temperature has been explained and a realistic model has been implemented. The same is performed for the water heater unit. The clothes drying load model and clothes drying task have been explained.

A new algorithm, Multi-Home Joint Demand Response algorithm has been designed and implemented. MHJ-DR algorithm is able to perform Joint Appliance Level Demand Response. It has been demonstrated that the new algorithm greatly expands the capabilities of the SH-DR algorithm. First, the MHJ-DR algorithm is found to be more resilient to the demand compensation effect. Second, it is possible to alleviate the distribution transformer overloading problem. Using the MHJ-DR algorithm, it is possible to serve more households, even with electric vehicles, that would not be otherwise possible. This would help to avoid the need for installing new higher capacity transformers. The more households can be grouped (e.g., in a situation where there is a higher capacity distribution transformer) the higher efficiency can be achieved using MHJ-DR algorithm. This confidence stems from the fact that the MHJ-DR algorithm has been proven to be very robust and resilient to extremely stringent test scenarios.

Chapter 7
Web Services

VT HEM demonstrates the design and development of web services-based communication infrastructure and data model for reliable, repeatable and low-cost interoperable signaling. Web services for HEM are essential for enabling machine-to-machine interaction, using which the utility and other third party systems can offer innovative services regarding residential electricity usage. The utility or other third-party systems can use web services to interact with the HEM system. The intelligent user interface depends on the web services as well.

7.1 Motivation

To address the lack of available HEM systems offering machine-to-machine interaction, VT HEM system is equipped with a set of services—which are able to be invoked by third party systems, if authorized—as a backdoor for innovation. As smart grid functionalities are becoming more mature, secure and distributed generation from renewable sources are being more affordable, it is expected that getting people engaged in energy management activities and participating in the marketplace would gain momentum in the current and the next decade.

Web services-based interface has the potential to serve as one of the enabling technologies for the Smart Grid. Demand Response (DR) can be implemented for residential customers without the need for an Advanced Metering Infrastructure (AMI). When AMI is available, web services-based alternative signaling can remain for redundancy of connection between the utility and the residence.

There are commercial implementations of the Gateway Device specification [54] from ZigBee [550, 56]—known as ZigBee Gateway Devices (ZGD). ZGDs offer SOAP (Simple Object Access Protocol) and/or REST (Representational State Transfer)-based access to the low-level and generic network services of a ZigBee Personal Area Network (PAN). Without an additional layer of abstraction, this web services-based interface is not of much help for developers of client systems. It is still quite challenging for application developers, for these web services do not achieve reasonable level of abstraction. Most web services are designed to be a suitable Service Access Point (SAP) for a very broad range of application profiles – hence unsuitable for HEM applications, in which the problem and solution space has to be conceptualized in terms of appliances, their power consumption, price signal, user choices and restrictions, etc.

7.2 Technologies for Implementation of HEM Web Services

The system proposed in this work emphasizes on offering web services for machine-to-machine (M2M) communications—without dealing with lower level complexities—using structured and predefined data models. Two different systems using these data models interpret the data in the same way—syntactically and semantically. XML is used to structure the data. The proposed system also emphasizes on user experience. It offers information visualization regarding appliance's energy consumption in an intuitive manner.

In this section various technologies that have been used to implement the HEM web services are discussed briefly.

7.2.1 XML over HTTP

The external interface connected to the public Internet will offer a REST interface, where information is encoded as XML (eXtensible Markup Language) text and transported over HTTP communication protocol. This is very intuitive and easy for the developers who will be building innovative HEM applications. The reason to choose XML over HTTP is that it is one of the most prevalent protocols. Almost every device including the PMDs has implementation of the TCP (Transmission Control Protocol), on which HTTP depends. HTTP client side implementation is available in web browsers, who also have XML processing capabilities. In fact, XHTML (the presentation markup language for web pages) is an XML language. This ubiquity of XML and HTTP is the motivation behind selecting REST based web services over HTTP. It also has strong security features.

For EUI (Energy Usage Information) communication data model, VT HEM system adheres to the XML schema—syntactically and semantically—used by Green Button [38]. The XML format is very straightforward and obvious from the NAESB PAP10 class diagram in [57]. The machine interface managing NAESB PAP10 [39] information system also offers REST, and the message formats are according the XML schema defined by on the NAESB server [58].

7.2.2 HTTP (Hyper Text Transfer Protocol) and REST (Representational State Transfer)

Development of REST web services for the PAP10 information model is performed in this work. In the paradigm of REST, each entity of interest is considered as a resource. Resources can be acted upon by a client. Available actions are: Create, Read, Update, and Delete (CRUD). These four methods nicely maps with the methods of the Hyper Text Transfer Protocol (HTTP). REST is a not a concrete set of libraries or protocols, rather it is a philosophy of developing interoperable, secure, scalable and loosely coupled distributed applications. The emphasis is on the loose coupling, which is important for reliability. The less one system—say the client—knows about internal implementations of another system—such as the server—or depends on that knowledge, the more loosely coupled they are. Since one system knows little about another, it does not make any assumption and therefore it doesn't fail in case the other fails. The scalability stems from the philosophy of doing less. The server implementation is recommended to have minimal processing, i.e., basic CRUD functions and search capabilities. Clients are expected to have more processing ability. For human user interface the client should be responsible for rendering the interface and provide interaction. Therefore, generic web browsers are not sufficient where rich interaction is necessary.

Corresponding resources are determined from entities identified in Section 7.4 "EUI Information Model Standards for External Systems." For example, ApplianceType is an entity of interest in home energy management applications. Therefore, VT HEM offers web services for the corresponding resource of the entity ApplianceType. Web services are made available at the URL: "/hems-api/appliancetype." Here the symbol '^'is used to represent the server address and the http protocol with which each URL begins. To create a new Appliance Type an HTTP request with the method, POST is necessary.

HTTP has several methods such as GET, POST, PUT, DELETE, HEAD, etc. GET corresponds to the action read from CRUD. GET method is used by clients to indicate its interest in receiving a resource. Here the term resource is used abstractly. It can be any document, such as any html file, or image, or any other file. Resource can also be nonexistent at the time of request and based on the request the server can dynamically generate a request and send back some information. The HTTP request message, sent by the client at the address of the server, contains the method name and an identifier identifying the resource. A web URL is the prevalent approach for using as the identifier. The server domain name or IP address does not identify the resource, instead it identifies the server—one or machines on which the server process is running. The rest of the URL after the address or domain name part is used to identify the resource. REST gives high emphasis of clean, simple, intuitive and elegant URL design. The URLs are expected to be self-describing. In the case of above URL "^/hems-api/appliancetype," it is clearly understandable that the client is interested to have learnt about appliance types in the HEM. The HEM then sends the client back a list of appliance types. Each appliance type entry in the response list would contain the URL of the individual appliance type, and its id. The URL "^hems-api/appliance" corresponds to the appliances knowledgeable to the HEM. Upon receipt of the GET request with resource identifier "^hems-api/appliance," the server would send a list, which would contain the id numbers, names and URLs of those individual appliances. An example URL for an individual appliance would be "^hems-api/appliance/14." Here 14 is the id of the appliance Electric Vehicle. Now to obtain more information about the appliance Electric Vehicle, the client would make a HTTP GET request to the URL of the individual appliance. Upon receipt of this GET request, the server would send details of the appliance. HTTP GET requests only have request header.

Another widely used HTTP method is POST. A request which is used for the POST method usually contains POST data. This is widely used by web browsers when any form is filled up and the submit button is pressed. In this case a HTTP request packet is created which has both a request header and a body. HTTP POST requests have request body where the POST data is transported as payload. Conventionally a POST method is used to create or store new information on the server. This is the reason POST corresponds to the 'C' (Create) operation of CRUD. In the REST web services context, HTTP POST methods are used to create new resource. Therefore, a new appliance can be created by submitting a POST request at the URL "^hems-api/appliance." The body of the request is expected to carry details of the appliance to be created, such as name, appliance type, rated power, etc. On receipt of this request the server creates the appliance and sends the client back the id number and the individual URL of the newly created appliance. Both GET and POST methods are used by Internet browsers extensively to help us retrieve information from various websites, create profiles, etc.

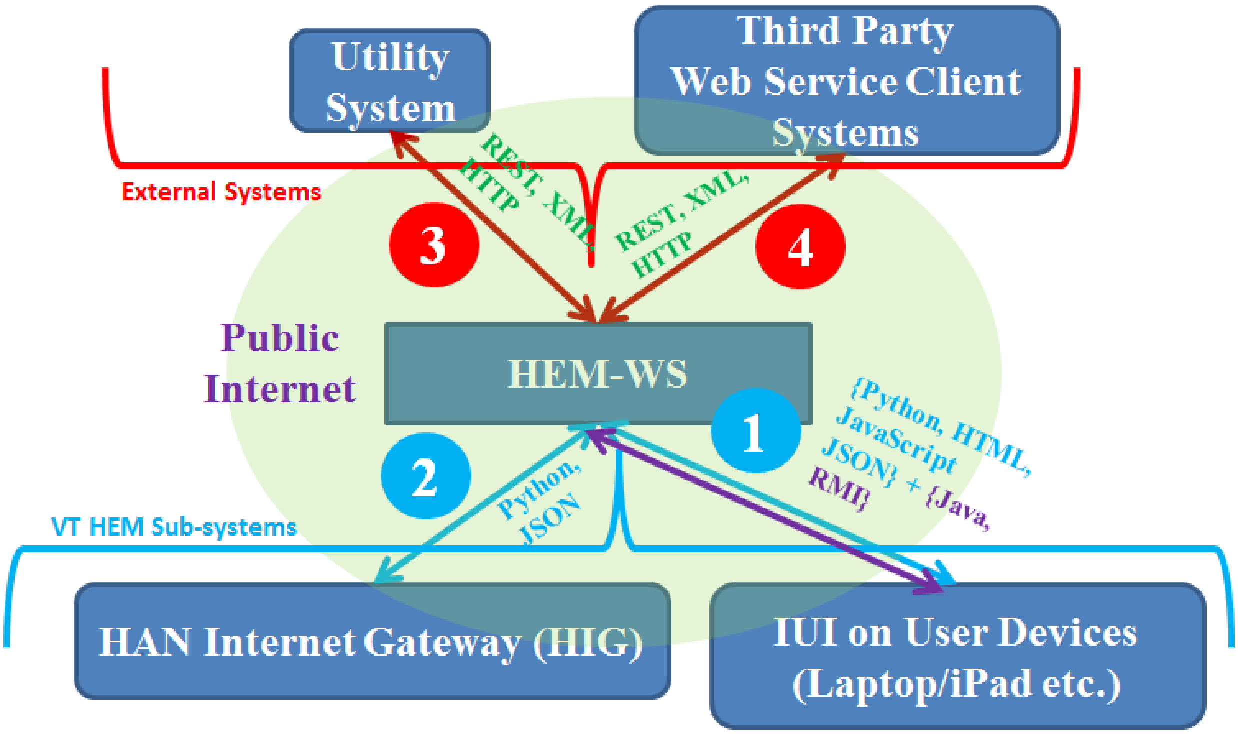
The third HTTP method of interest is PUT, which corresponds to the entity operation ‘U’ (Update) operation of CRUD. Like the POST method, the PUT method also contains a body within which information necessary to perform update is passed. The request is made to an individual resource URL. For example if the newly created appliance from the previous paragraph was assigned an id number of 15, upon creation, and if the individual appliance URL becomes “^hems-api/appliance/15,” this appliance can be updated by sending the server a HTTP PUT request with the new values of the attributes of the resource.

The next HTTP method of interest is the DELETE method which corresponds to the ‘D’ (Delete) operation of CRUD. This request is sent by the client to the server at an individual resource URL. This method does not have a body. Upon receipt of a DELETE request the server deletes the resource and makes in unavailable for future GET/PUT requests. For example, if an HTTP DELETE request is sent to the UIRL “^hems-api/appliance/15,” the appliance would be deleted on the server.

7.3 Web Services for VT HEM System

With web services-based system signaling available with well-known and defined interface there is no limit on what can be achieved. Anyone can come up with an unforeseen innovative application for users or householders whose systems have such a high degree of interoperability. Solutions to known problems can be found as well. In this subsection, several important achievements using this communication architecture are discussed.

The HEM website component is responsible for rendering the user interface and responding to user actions. In Fig. 7.1 the communication path between the Intelligent User Interface and the HEM-WS is shown as Link 1. The HEM IM WS Interface offers web services to monitor and manage appliances. The DR algorithm routine can be invoked when there is a DR request from the utility. The communication path is shown as Link 2 in Fig. 7.1. Link 3 stands for communication path between a utility system and the HEM-WS. The PAP10 WS interface offers web services for the EUI in the PAP10 format. The communication path, shown as Link 4 in Fig. 7.1, serves this purpose.



REST: REpresentational State Transfer; **HTTP**: Hyper Text Transfer Protocol; **HTML**: Hyper Text Markup Language, **XML**: eXtensible Markup Language; **JSON**: JavaScript Object Notation; **RMI**: Remote Method Invocation; **IUI**: Intelligent User Interface; **HAN**: Home Area Network; **HEM-WS**: Home Energy Management (HEM) Web Server

Fig. 7.1: Various web services clients for the VT HEM system.

7.3.1 Link 1: User Interface Communication

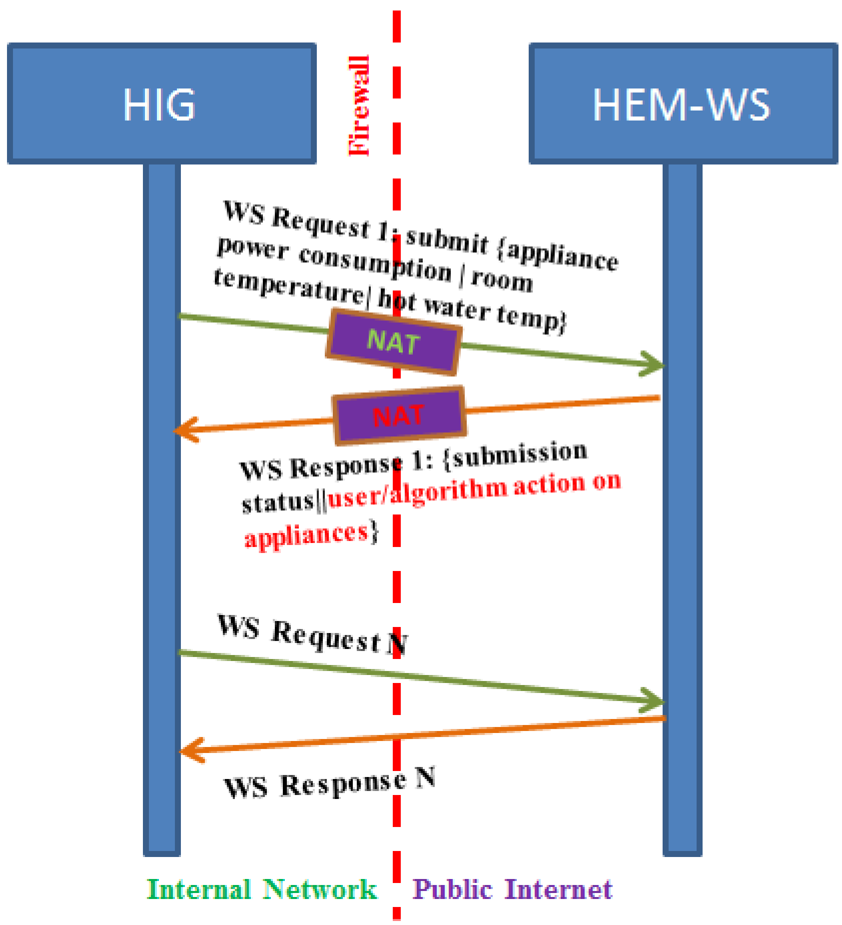
Developing web services-based interaction has been implemented to develop the user interface as well. The user interface uses AJAX (Asynchronous JavaScript and XML) requests in the background to retrieve live data. In the future, these services would be used for the development of interactive native applications and user interfaces applications for the major PMD platforms—such as Android, iOS, Windows Mobile OS. In addition to that it would be possible for other HEM system designers and developers to employ the web services of VT HEM to offer their users remote monitoring and management solutions, and even participation in a DR program.

7.3.2 Link 2: HEM-WS and HIG Communication

Data about the real-time power consumption of the state of the appliances are submitted using this web services interface. Data about various operating conditions such as hot water temperature, indoor temperature at home, etc., are submitted as well.

The information about user interactions on appliances is sent to the HIG from the HEM-WS. Since the HIG resides at home it is usually protected behind a firewall. Typical broadband Internet connections for residential customers do not offer a public IP address for any of the computers running at the residence. Network Address Translation (NAT) is used instead where the IP address of the gateway router is used for the client request and the server can respond to this IP address which the router routes back to the client. For this limitation no connection could be in initiated with the HIG from outside the network.

To get around this limitation user commands are piggybacked within the responses to the requests initiated by HIG while submitting the real-time power consumption data.



NAT: Network Address Translation; **HIG**: HAN (Home Area Network) Internet Gateway; **HEM-WS**: HEM (Home Energy Management) Web Server;

Fig. 7.2: Piggybacking of user action data within responses to the HIG operating from within an internal network.

7.3.3 Link 3: Web Services-based Signaling Instead of PLC or AMI Network

The web-based HEM system presented here can serve as an alternative low-cost solution to the Smart Energy Network (SEN) based on AMI. In Fig. 4.1, SEN with Customer Private HAN (Home Area Network) with ESI (Energy Service Interface) option has been shown. In the original recommendation, the ESI is connected with the Utility network with via a Non-ZigBee backhaul network. This network can be Power Line Communication (PLC) network, cellular network, broadband, WiMAX, etc. This leaves room for vendors to develop their own communication protocols which can cause barriers to system integration and interoperability. For the client systems of VT HEM system, this is a nonissue. More details about demand response signaling using this approach has been offered in Chapter 8.

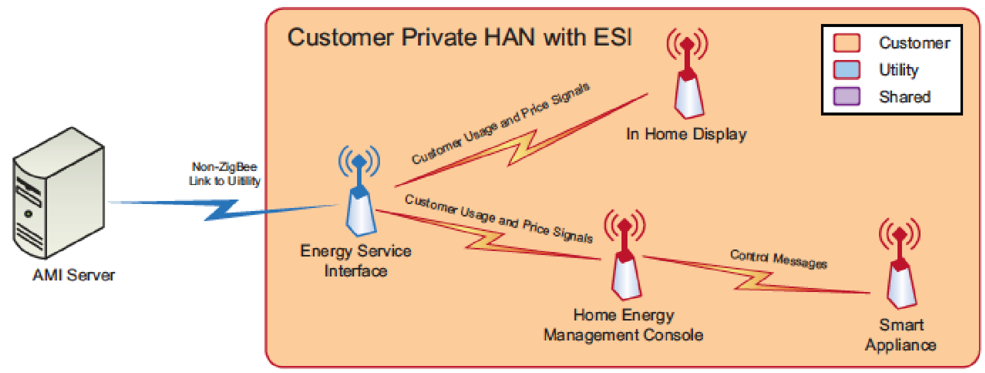


Fig. 7.3: Customer Private HAN Smart Energy Network from ZigBee Smart Energy Profile.

From the system architecture in Chapter 4, it is obvious that that multiple households can be served by the HEM system proposed in this work. Also utility systems can connect to the VT HEM system, and they can register information about distribution transformers and identify and group homes served by those transformers.

7.3.4 Link 4: Web Services Interface for Third-party Systems

Just like the user and the DR algorithm, a utility system or a third party system, if allowed, can send signals intended for individual appliances. In addition to that, these external systems can request information about appliance types, other information about appliances such as power rating, EUI (Energy Usage Information Data) etc. This flexibility has been offered to facilitate development of unforeseen innovative applications.

7.4 EUI Information Model Standards for External Systems

In this simple information model the major object or resource is appliance, which represents any individual device that consumes electric energy. The Attribute Record Listener module stores temporarily measurement samples of load level, and the HIG quickly submits this information to the HEM-WS. Third-party systems developers—who may provide innovative applications involving EUI—can obtain data from the PAP10 WS interface. Data in the PAP10 information model is generated on the fly from the HEM IM data stored in the HEM-WS. For example, PAP10 IM contains IntervalReading and MeterReading data (Fig. 7.4), which can be computed from the Measurement Sample data stored in the database.

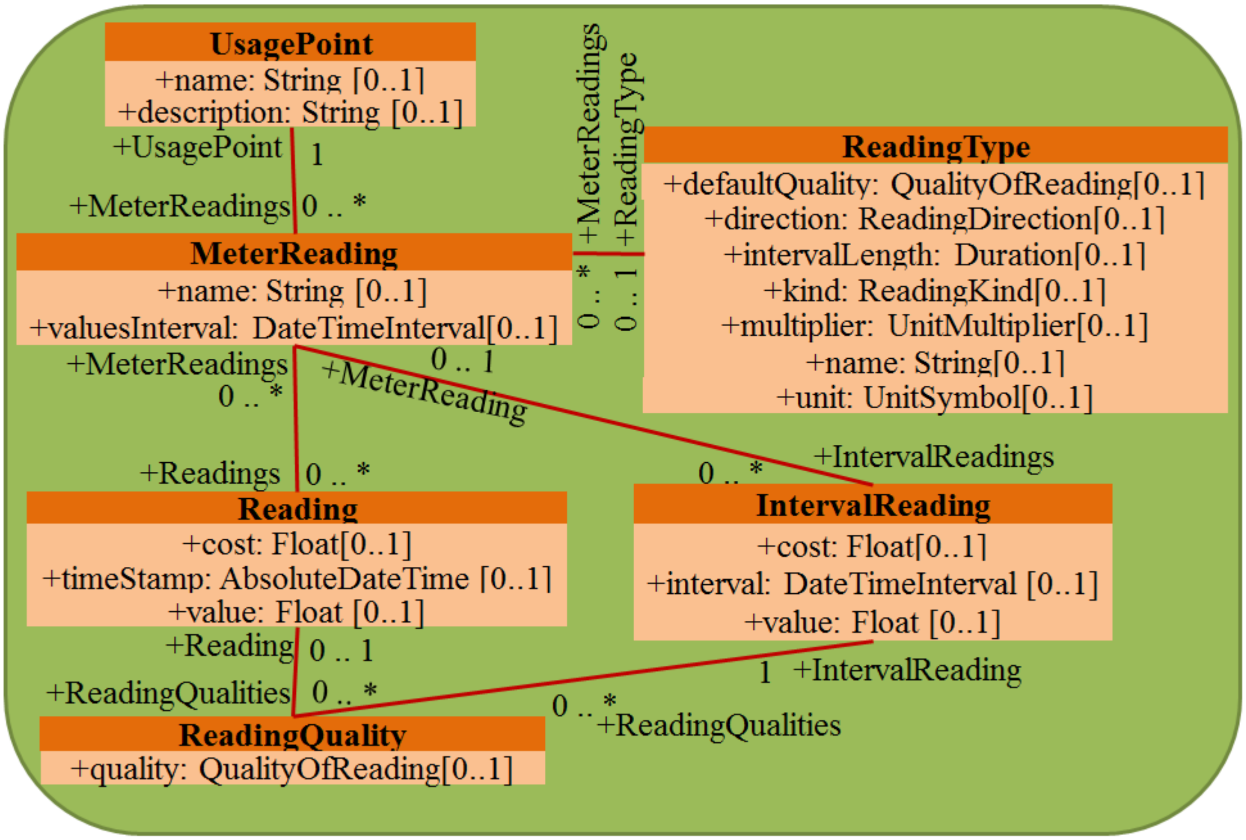


Fig. 7.4: Important classes of NAESB EUI model and their inter-relationships.

There can be other applications, which will need the HEM IM data. These are represented by IPHA (IP Host Application) in Fig. 4.2. How interaction with a Home Networking system can be simplified is explained here using the ZigBee network. The proposed system offers IPHA development that uses information in a more intuitive HEM IM format, instead of the analogous IPHAs relying solely on ZigBee Gateway Device—which offers generic lower level interface and has not customized for home energy management application. Understanding and working with the low level and generic ZigBee services can be a barrier for most IPHA (IP Host Application) or EUI System developers. But it will be far more convenient to work with the information model proposed in this work, and PAP10 entities over the Internet or IP network. The schema of the proposed HEM IM is summarized in Table 7.1.

TABLE 7.1. HEM INFORMATION MODEL (HEM IM) ENTITIES AND ASSOCIATED DESCRIPTION

Entity	Description
Appliance Type	**Enumeration:** heating/cooling unit, pump, on/off light, dimmable light, washing machine, clothes dryer, electric vehicle, thermostat, light sensor, occupancy sensor, etc.

Appliance	**Attributes**: voltage rating, current rating, power rating, Appliance Type ID
Measurement Sample	**Attributes:** current value, timestamp, Appliance ID
Room Temp. Preference	Time range, temperature range
Hot water temp. preference	Time range, temperature range
Runtime Length Preference	Appliance Type ID, runtime
Operation Time Pref.	Appliance Type ID, time range
Load Priority	Appliance Type ID, priority level

As shown in Table 7.1, the ‘Appliance’ entity corresponds to individual smart device present at home. It helps to track and deal with multiple devices of the same ‘Appliance Type’ entity. For example, dimmable light is an ‘Appliance Type’ entity, and a home can have more than one dimmable lights. Each of these individual lights is an ‘Appliance’ entity. Two different dimmable lights can have different power ratings. In addition to that it is necessary to track or identify ‘Measurement Sample’ entity of each different light. Therefore, having only the ‘Appliance Type’ entity in the HEM IM would not be sufficient. Hence the ‘Appliance’ entity has been defined in HEM IM. At the core of this information model is the ‘Measurement Sample’ entity, which are instantaneous readings of its attribute ‘PresentValue’. These values are stored with timestamp.

HEM IM is a simple and intuitive information model, yet it captures necessary information for providing intelligent Home Energy Management Service and PAP10 EUI service. Therefore, the interval readings can easily be calculated which is required for conversion to the NAESB PAP10 model. Room temperature, hot water temperature, and load priority preferences are self-explanatory. Runtime length preference indicates how long an ‘Appliance Type’ entity, such as a clothes dryer, should run once it becomes operational. Operation time preference is for storing user preference of time range of operations of appliances, such as charging time of an electric vehicle, and operation time of a washing machine, etc. This information helps the intelligent HEM to respond to a DR request, while maintaining a comfortable environment for a homeowner.

For interaction among ZigBee devices, and for being managed and monitored by other applications or systems, such as HEM system, these devices need to support commands, attributes, and agreements on defined behaviors. A cluster is a collection of commands and attributes defined by an application profile designer. Each of these commands and attributes has defined interpretation and behavior in the context of an application profile. ZigBee Home Automation (ZHA) Profile [59] defines various types of generic and specific devices. A generic device example could be “level controllable output,” and a more specific device can be “level controllable light.” ZHA defines various domains of devices, which are generic, lighting, closures, HVAC, and intruder alarm systems (IAS). The ‘Appliance Type’ entity in the HEM IM corresponds to various devices in these domains. Various types of devices such as simple ON/OFF or level control switches, occupancy/ heat/pressure sensors, thermostats, controllers, remote control, level control, lights etc., belong to these domains. All these can be controlled and inquired using attributes, commands related to ZHA and the clusters of ZHA. And the client systems of the web services employing this information model do not have to deal with all these lower level generic and application agnostic communication issues.

7.5 Conclusion

VT HEM system provides all these functionalities from the web interface so that the user can enjoy the home automation from his/her finger's tip. On the other hand machine-to-machine communication interface has been provided through the REST web services. This enables DR communication even when PLC or AMI network is not available. In addition to that, developers of home management applications can use this system and have a convenient API (Application Programmer's Interface), without worrying about details of ZigBee profiles and specifications at all.

The design of the proposed system is intentionally kept simple, so that the user of this API does not have to be concerned with the lower level details such as network address, IEEE address, cluster identifier, profile identifier, etc. The HEM system designed in this research deals with all these complexities at the ZigBee Abstraction Layer.

Chapter 8

Communication Solutions for Demand Response

In this chapter it has been shown how web services based interface has been utilized to perform Demand Response over the general purpose internet connection available at utility and at the households. VT HEM system is expected to work as low cost communication infrastructure which can increase demand response participation without AMI (Advanced Metering Infrastructure) Network.

8.1 Background and Motivation

Demand Response Research Center (DRRC) at the Lawrence Berkeley National Laboratory (LBL) has published a communication specification based on web services and other open technologies. It is known as Open Automated Demand Response or OpenADR [60]. This standard was intended for commercial buildings and industrial Demand Response programs. In their publication it has been mentioned that continuing evaluation of end-use DR control strategies for homes is one of their future research goals, and this is one of the tasks accomplished in this thesis. Like the OpenADR, the work conducted in this thesis is expected to serve as one of the enabling technologies for the Smart Grid.

The communication solution offered here is expected to increase the DR participation and intended to be an option for the majority of the households which are not part of the AMI network. It can coexist with an AMI network as well.

8.3 Advanced Metering Infrastructure

AMI has a penetration rate of just 6% in the U.S. and for the utility with the highest penetration this Fig. is 13% [61]. It is expensive to install AMI which involves installation cost, meter data management, project management, IT (Information Technology) integration costs, etc. Hardware costs involve end point hardware, such as a smart meter, as well as network hardware. Software cost includes meter modules, network infrastructure, and network management software for the AMI system.

8.2 Sending Demand Response Signal

In Chapter 4, the system architecture of the VT HEM has been shown. In Fig. 4.1 and 4.3 it has been shown that the HEM-WS subsystem interacts with external systems including the utility systems. The utility companies can identify their customer households using the VT HEM system. Upon doing that a utility system can make a request to the VT HEM-WS where it can submit the demand limit, start time and duration of demand response programs. This would be done according to prior agreement between the customer and his/her utility company.

8.2.1 Common Information Model

The interaction between the utility system and the HEM-WS happens by exchange of messages. The information exchanged between these systems has a structured format. A simple information model has been defined and implemented to trigger demand response events. The Fig. 8.1 shows the schema using DTD (Document Type Definition), which is used by the utility system to structure DR Event notification information and sent to the HEM-WS. This has been designed by merging and adapting three OpenADR schemas: UtilityDREvent, EventInfo and DRASClient (Demand Response Automation Server). The utility demand response event notification contains the following information:

- EventIdentifier
  This is a unique identifier which is used to retrieve information about a particular demand response event. Its definition is shown in line 45 in Fig. 7.5.

- ProgramIdentifier
  This is used to provide information about the demand response program for which the notification is being used.

- Destinations
  Destination is used to indicate the target households. One or more destinations can be addressed using a single notification in a sophisticated manner. Destination is a list of participants, groups, locations or DRAS clients. DRAS stands for Demand Response Automation Server specified in OpenADR. In the context of VT HEM, the HEM-WS system replaces DRAS. In the schema DRAS has been used so that it becomes easier for vendors and users of OpenADR systems to understand/implement the schema necessary for interacting with VT HEM system.

  Location can be used request demand response for all households within a zip code, or city, which are customers of the utility sending the signal. Geographical coordinate of grid location identifier can also be used in necessary. The schema allows that flexibility.

- EventTiming element contains information about start time, end time, and notification time of a demand response event.

- EventInformation supports load limit. It is flexible enough to optionally provide maximum or minimum load amount or level.

```
<!DOCTYPE UtilityDREvent [
<!ELEMENT UtilityDREvent (destinations, eventTiming, eventInformation)>

<!ELEMENT destinations (participants?, groups?, locations?, drasClients?)>
<!ELEMENT eventTiming (notificationTime, startTime, endTime)>
<!ELEMENT eventInformation (eventInfoType, eventInfoInstance)>

<!ELEMENT participants (participantID+)>
<!ELEMENT groups (groupID+)>
<!ELEMENT locations (location+)>
<!ELEMENT drasClients (drasClientID+)>

<!ELEMENT participantID EMPTY>
<!ELEMENT groupID EMPTY>
<!ELEMENT drasClientID EMPTY>

<!ELEMENT location (address|coordinate|gridLocation)+>
<!ELEMENT address (street1?, street2?, city, state, zip)>
<!ELEMENT coordinate (latitude, longitude)>
<!ELEMENT gridLocation (#PCDATA)>
<!ELEMENT street1 (#PCDATA)>
<!ELEMENT street2 (#PCDATA)>
<!ELEMENT city (#PCDATA)>
<!ELEMENT state (#PCDATA)>
<!ELEMENT zip (#PCDATA)>
<!ELEMENT latitude (#PCDATA)>
<!ELEMENT longitude (#PCDATA)>

<!ELEMENT notificationTime (#PCDATA)>
<!ELEMENT startTime (#PCDATA)>
<!ELEMENT endTime (#PCDATA)>

<!ATTLIST participantID value ID #REQUIRED>
<!ATTLIST groupID value ID #REQUIRED>
<!ATTLIST drasClientID value ID #REQUIRED>

<!ELEMENT eventInfoType (minValue?, maxValue?)>
<!ELEMENT eventInfoInstance (eventInfoValue)>
<!ELEMENT eventInfoValue (value)>
<!ELEMENT minValue (#PCDATA)>
<!ELEMENT maxValue (#PCDATA)>
<!ELEMENT value (#PCDATA)>

<!ATTLIST eventInfoType typeID (LOAD_LEVEL|LOAD_AMOUNT|LOAD_PERCENTAGE) "LOAD_AMOUNT">
<!ATTLIST UtilityDREvent eventIdentifier ID #REQUIRED>
<!ATTLIST UtilityDREvent programName ID #REQUIRED>
]>
```

Fig. 8.1: DTD schema for utility DR event notification.

8.2.2 Reliability of Demand Response Communication System

Communication between the utility and HEM occurs over the Internet. Communication between the HEM-WS and the HIG happens over the Internet as well. Both of these communications are essential for successful execution of Demand Response. Internet offers quite reliable service because of redundancy in available routing paths.

8.2.3 Availability Issue of HEM Web Server

The HEM-WS is not susceptible to failure either. This is achieved by means of replication of the servers in different geographical locations. Such services are offered by various utility computing providers such as Amazon, Google, Microsoft, etc. Service availability of 99.99% (4 Nines) is commonplace which means unavailability of 50 minutes/year. High-availability services guarantees 99.999% (5 Nines) uptime (5 minute unavailability per year). 6 Nines (0.5 min/year) and 7 Nines (0.05 min/year) availability are possible to implement as well.

In case any communication failure occurs, the HIG will be able to operate autonomously. This is possible since the sub systems of the VT HEM system has been developed in a loosely couple manner, meaning one subsystem does not depend on another subsystem except for information exchange. In case of failure, the HIG will perform the demand response.

8.2.4 Security

Client certificate based authentication and end-to-end encrypted communication are employed to secure demand response signaling discussed here. Security issues of web services-based Demand Response signaling have been discussed in Chapter 10.

Chapter 9

Wireless Home Area Networking for VT HEM System

The Home Area Network (HAN) Internet Gateway (HIG) contacts with the HEM web server, (HEM-WS) to submit aggregated status report for selected appliances within a household. The gateway also receives user commands to control selected appliances from the HEM web server. The home network is a wireless network, where IEEE 802.15.4-2003 is used as the Media Access Control (MAC) layer for point-to-point communications. On top of it, ZigBee mesh networking protocol operates. This ZigBee network has a node Personal Area Network (PAN) Coordinator which starts the network and all other nodes are dependent on it. In the context of VT HEM system, in this thesis this coordinator node is called the HAN coordinator. The HIG depends on the HAN coordinator to collect the status of all appliances connected with the VT HEM system. HIG also gives the user action commands to the coordinator, which transmits the commands to the other nodes of the network, which are known as ZigBee End Device (ZED). Each of these ZEDs is paired with an appliance/load to control it and to measure the power consumed by the appliance. A brief review of the technologies is given in Sections 9.1-9.4. Discussion about how the HEM operations are implemented is presented in Section 9.5.

9.1 IEEE 802.15.4 Wireless Communication Protocol

The Physical Layer (PHY) is responsible for the transmission and receipt of individual bits using the radio transceiver. IEEE 802.15.4 offers a very low power data transmission service over one of the channels on the supported frequency bands. Available options for supported bands are: 2.4 – 2.4835 GHz anywhere supporting 16 channels, 902-928 MHz for North America supporting 10 channels or 30 channels, and 868 – 868.6 MHz for Europe supporting 1 to 3 channels.

On top of the PHY layer, IEEE 802.15.4 defines the Media Access Control (MAC) layer, which manages the access to the PHY layer and works as the interface for Networking Protocols at higher layers, such as ZigBee Mesh Network that offers multi-hop routing. The PHY layer has no concept of data or bit frames, and only deals with bit-by-bit basis, which would be too difficult to interpret without using a context of a frame. Since a bit can only have two states—0 or 1—synchronization of the clock between the transmitting node and the receiving radio is also necessary to receive the bits correctly. Unfortunately very tiny deviations ad up and drifting of more than one bit occurs after some time, when the receiver either misses one bit or reads one bit twice. Sending bits as a group, called frames, alleviates these problems. A frame always begins with a start sequence, which helps the receiver detect the start of a frame. Frame also ends with a checksum, which allows the MAC to readily reject or discard a frame when it is possible to detect that the frame has been corrupted.

MAC employs CSMA/CA (Carrier Sense Multiple Access with Collision Avoidance) technique to test the channel and transmit if there is no ongoing transmission by any other node. IEEE

802.15.4 dictates how multiple entities should use the shared medium to transmit packets. Like the cable counterpart of the wired world, the wireless communication is also a single hop communication. Although a transmission can be received by more than one listening devices, it is still called point-to-point communication and it is limited by distance. The communications can be either unicast or broadcast. In case of unicast communication the transmitted frame has a destination address. The relevant address in the context of wireless transmission is the 64-bit IEEE address. Every radio interface has a unique IEEE address. Unless a node is trying to sniff frames intended for other nodes, it would ignore all transmissions except those explicitly addressed to it, or the frames, which have been broadcasted. Multi-hop routing is not supported in this layer, since this is the considered as a service of the Network Layer, which is the upper layer of IEEE 802.15.4.

In the IEEE 802.15.4 paradigm, there can be two types of devices, FFD (Fully Function Device), and RFD (Reduced Function Device). The FFD devices have complete protocol implementation and can act as the PAN Coordinator and multiple RFD devices can associate with it. On the other hand the RFD nodes have limited implementation of protocol and cannot be a Coordinator node. An RFD node can only associate with one FFD node, in which case the FFD node is called the parent node. The RFD node can go to sleep mode to conserve energy and upon waking up it can poll its parents for any transmission stored on behalf of it when it had been sleeping.

9.2 ZigBee Network Layer Protocol

ZigBee Protocol Stack has been discussed starting from the lowest level. Each ZigBee node has a single IEEE 802.15.4 radio interface. ZigBee extends the function of the IEEE 802.15.4 wireless communication service by implementing a network layer on top of the MAC layer. ZigBee networking layer has three types of nodes: PAN coordinator, Router and ZigBee End Device (ZED). The first two must be IEEE 802.15.4 FFD devices, and the end device can be an RFD device. There can be only one PAN Coordinator node. The network layer has a new type of address other than the permanent 64 bit IEEE address. This address is called network address and it is 16 bits long and it is assigned when a node joins the network. Unlike the permanent IEEE address, NWK address is invalid outside the context of the PAN in which the node has joined and operating. This address is used to implement multi-hop routing. The PAN coordinator and the router nodes perform the function of forwarding a packet—Network Layer Data Unit (NLDU)—over multiple point-to-point links so that the destination device eventually receive it.

After being powered up, a newly added device attempts to join a network. Joining the network involves a series of message exchanges. First step is to scan the channels for discovering existing Personal Area Networks (PAN). The device that is looking for the PAN to join is known as the "joiner." When one of the routers or the coordinator of a PAN decides to allow the joiner, it responds to the beacon request of the joiner, where the flag "*macAssociationPermit*" is set to TRUE. Upon receipt of such permits—potentially more than one from multiple PANS operating on multiple channels—the joiner identifies/selects the designated PAN and attempts to join it by sending Association Request Command. The router or coordinator—with which the joiner is trying to associate—now sends confirmation and upon receipt of this both the coordinator and the joiner assumes that joining has been commenced. At this stage the joiner is said to be in joined but unauthenticated state. If the network where the joiner is trying to join is a secured network, the joiner must complete the authentication step. Provisions are available for the initiation of this authentication step either by the router/coordinator or the joiner. Smart Energy Profile (SEP) specifies that the joiner should immediately issue the authentication process. If not the router with which the new device has associated would initiate it anyway. If the router/coordinator is the Trust Center itself, it can start the authentication immediately. If not, the router or coordinator will send an Update Device request to the trust center with the address of the newly joined device. This is done by the ZDO of the router/coordinator with which the joiner has associated. The ZDO issues an APSME-UPDATE-DEVICE.request primitive to the management entity of the underlying Application Support Sub-layer (APS) of the coordinator/router node.

If the joiner initiates the AUTHENTICATION procedure, it would do so by issuing an "APSME-AUTHENTICATION.request" primitive to its underlying Management Entity (ME) of the APS layer which will in turn result in transmission of an authentication request by the joiner addressed.

9.3 ZigBee Device Organization

It could have been possible to have a radio interface—hence any bits can be transmitted or received—and implement any application. But from the observation at the Subsection 9.1, "IEEE 802.15.4 Wireless Communication Protocol," it can be realized how troublesome it would have been without the organization of data bits in frames. The same philosophy continues but in a different way in case of the organization of devices. A device with access to services offered by the ZigBee network layer can send data/command/message to—or receive those from—far nodes even those residing out of the range of the wireless transmission. If all applications logics are implemented on top of this Network Layer service, it would be too difficult to manage. Some of the common functions would need to be implemented again and again in case of such spaghetti implementation. Therefore, necessary functions are organized so that it is possible to focus on the implementation of the unique service being offered, and employ existing implementation of common functionalities. Also without following a common standard, it would not be possible for two devices to interact. Binding, Device Discovery, Service Discovery, etc., are few examples of higher layer functions that can only succeeded if multiple nodes are communicating using same protocol.

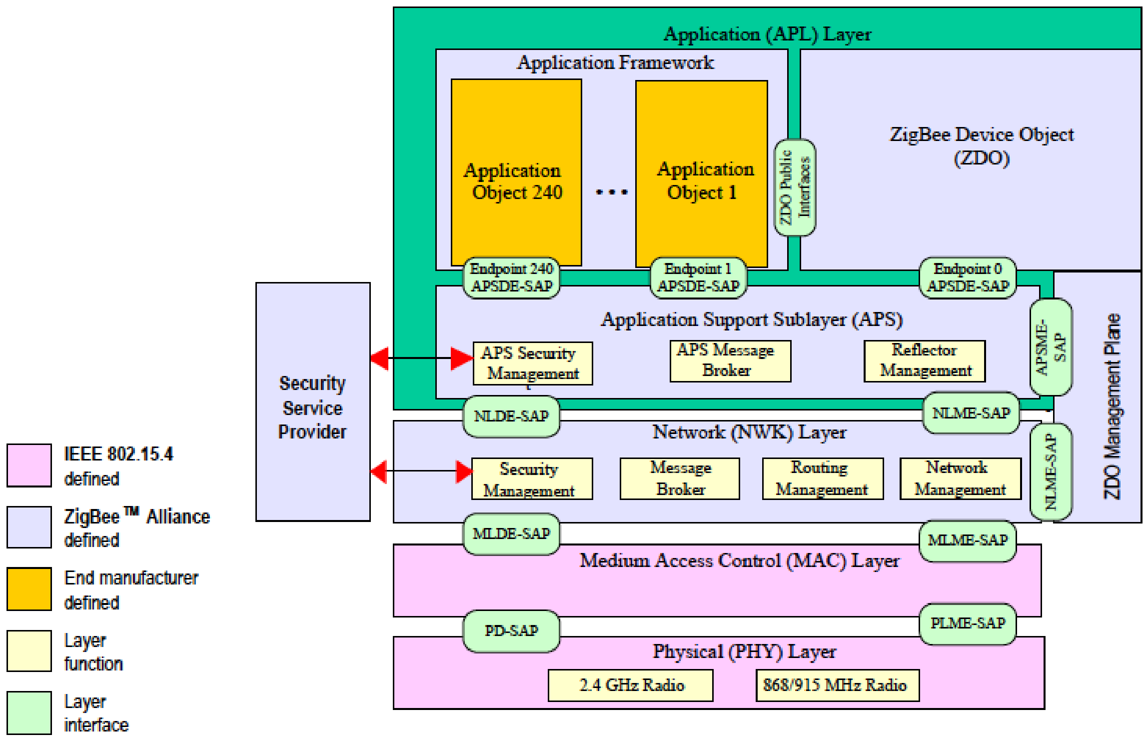


Fig. 9.1: Outline of the ZigBee device architecture (Fig. 1.1 from [50]).

In Fig. 9.1 the outline of the ZigBee stack architecture is shown from [50]. At the bottom there are the PHY and MAC layer which are discussed in Subsection 9.1 (IEEE 802.15.4 Wireless Communication Protocol). On top of the MAC Layer, there is the Network (NWK) Layer. The NWK offers two Service Access Points (SAP): NLDE-SAP and NLME-SAP. The NLDE stands for Network Layer Data Entity, and the NLME stands for Network Layer Management Entity. NLDE offers the service—to the upper layer or the NLME—of transmission of data over the network.

Application Support Sub-layer (APS) depends on NLME for network services. The ZigBee Device Object (ZDO) resides on top of APS. A node can host up to 240 applications on a single physical device, each of which can be addressed by an endpoint number. Endpoint 0 is reserved for the ZDO, and Endpoint 255 is reserved to address all applications analogous to a broadcast. The ZigBee Device Profile (ZDP) offers specifications of all functions necessary for any ZigBee device, and this specification is implemented in ZDO.

A physical ZigBee device can host up to 240 application objects, which can be invoked by addressing the ZigBee device and the corresponding endpoint number. Available endpoints are between 1 and 240.

9.4 ZigBee Smart Energy Profile

ZigBee Device Profile (ZDP) is application agnostic. For example, it does not offer any service using which it can be known if a Demand Response (DR) event is going on. Another example would be: If a ZDP implementation is asked to fix the set point temperature of the HVAC, it would not recognize such a request. To enhance a ZigBee device with the ability to solve the problem of a particular domain, it is necessary to implement custom application objects for the ZigBee device. The generic device object that implements ZDP is known as ZigBee Device Object and is made available at Endpoint 0, and its services are necessary to design and develop new application profiles, such as the Smart Energy Profile (SEP).

ZigBee Device Profile specifies how the functions of the ZigBee Device Object (ZDO), such as Device Discovery, Service Discovery, etc., are implemented. Implementation of ZDO is mandatory for all ZigBee nodes, since it offers such fundamental services, without which the upper level application profiles cannot function. For example, device and service discovery allows node to identify the Trust Center, ESI, etc., upon joining a smart energy network. Without the service discovery feature, it wouldn't be possible to identify those devices. Here identifying means determining the network address or the IEEE address of the node and the endpoint number of the object running on that physical device. The data exchanged for these functions is called simple descriptor.

Application specific objects serve at other endpoints between 1-240. In case of defining domain specific application object, it is possible to define proprietary services, or implement public application profiles. A public application profile is a specification—defined by the experts and industry alliance—of the necessary services and implementation requirements. ZigBee Smart Energy Profile (SEP) is such a public and standardized application profile that defines services, communication messages, expected behaviors, etc., with the goal of performing variable Time of Use (ToU) pricing of Electricity, Gas, Water, etc., and also to perform Demand Response and Load Control (DRLC) functions according to the suggestions by the Utility company on the smart appliances.

SEP also provides several options for connecting SEP devices to a utility network. These networking options are known as Smart Energy Network (SEN). In a smart energy network, the Home Area Network (HAN) can be either utility private or customer private [51]. For VT HEM implementation, a slightly modified version has been used which has several advantages over the standard SEN—of the customer private HAN. Fig. 4.1 shows the architecture of the standard SEN with a customer private HAN with an ESI. The modification is, instead of Power Line Communication or dedicated AMI (Advanced Metering Infrastructure) Network, web services based communication framework for Demand Response signaling, developed in this thesis, has been used.

Since demand response is an integral part of VT HEM, the SEP DRLC feature has been merged with the with the demand response mechanism in this work. Operation of the VT HEM depends on a load limit signal from a utility, and its embedded algorithm (DRA) decides about load control decisions. On the other hand the SEP specifies DRLC decisions from a utility. In VT HEM the DRLC is controlled by the HEM server, since it can take into consideration customer's preferences and comfort settings. VT HEM has been designed to engage users in actively managing energy consumption. For this reason, it is expected to be more acceptable than direct load control by utility which is not sophisticated enough to process user preferences or give the user a sense of ownership.

Since SEP is an application profile, it does not specify much about networking and communication issue. For the networking layer, SEP just mandates that fragmentation must be supported. It also mandates the utilization of standard security features offered by the ZigBee security manager and network layer. At the application level it defines eight logical devices, which are: Energy Service Interface (ESI), metering device, in-premises display device, programmable communicating thermostat (PCT), load control device, range extender device, smart appliances device, and prepayment terminal device. In the context of HEM, not all of the above devices are of equal interest.

- For a Smart Energy Home Network, the ESI (Energy Service Interface) acts as the coordinator of the network which is responsible for starting the network and is considered the owner device of the network. It performs many important functions and implementation and operation of the ESI is not optional.
- Metering device is another mandatory device, which is capable of reporting energy consumption information resembling a traditional meter. However, it does not have to have a traditional meter.
- In-premise display is another SEP device, which can show users information about important events, and there is no hard and fast restriction on technical nitty-gritty how the implementation of the In-Premises Display would be done. In other words, ESI, Metering Device, and In-Premises Display, all are defined in terms of expected behavior and not defined based on concrete implementation. It is also allowed to implement two or more of these logical devices within one physical device. In our VT HEM system, the ESI, metering device and PCT are implemented on a desktop computer.
- PCT – programmable communicating thermostats can be controlled the operations of the HVAC system. In the context of SEP, the mandatory functionalities it needs to have is the ability to respond to DRLC events and retrieve accurate Time from the ESI for synchronization purpose. Functionality to retrieve price, metering data, incoming message, etc., if it has any other functionality that depends on these.
- Load control device is the one, which is capable of receiving demand response signals from a utility.
- Range extender device – Range extender works as a router. Since, the ZigBee Network Layer already defines Router nodes/devices (albeit in an application agnostic manner), the SEP range extender device could be mapped to the ZigBee routers.
- Smart appliances are the devices, which can participate in energy management activities. A physical device can implement the behaviors of multiple of these logical devices. An SEP Smart Appliance Device must implement the function of inquiring about electricity price as well as inquiring for time to remain synchronized. It is expected that the SEP Smart Appliance Device would make rational choices about its operation to reduce cost.
- Prepayment terminal device is expected to be useful for HEM, especially for users who get motivated to save while on a prepayment plan.

The above discussion defines the expected behavioral features/functionalities of the standardized SEP devices. Now the above functional requirements are described in a more concrete manner by specifying exactly what messages/commands/attributes, defined in the SEP, must be supported by the devices listed above.

In the ZigBee application standards, behaviors are defined using clusters. A cluster is a specification of syntax and semantics of a set of messages, commands and attributes, which have known interpretation and can be used to convey information about states or give commands. An example cluster from SEP would be the Price cluster offering a protocol for conveying the price information about electricity, gas or water pricing. The pricing information is distributed to the ESI from the utility using the backhaul network.

ESI is the SEP device that works as the interface for the utility interaction, hence ESI is the only device that can receive price information through the utility backhaul network (or in this research, through the HIG and web services based communication), it is mandatory for the ESI to share this information with other interested appliances when any of those devices ask. This ability answer about Price inquiry from other SEP devices within the HAN is known as the server functionality of the Price cluster, meaning that the price information is “served” by the ESI. Smart Appliance Devices must implement the client side of the Price cluster.

Another important SEP cluster is the Time cluster. The ESI must implement the server side of the Time cluster as well; and upon receipt of any request from any client device, it should deliver the time information. A client device (of Time cluster), e.g., SEP Smart Appliance Device, uses Time information for synchronization purpose. For SEP Smart Appliance Devices, it is mandatory to implement the client side of the Time cluster. Demand Response and Load Control (DRLC) cluster is another important SEP cluster, implementation of which is mandated for several of the SEP devices. This cluster is used to convey information about demand response events. Since such events are scheduled by the utility, and since ESI is the only device connected to the utility system, naturally ESI is propitious to receive DRLC event information and act as a server. Therefore, it is not surprising that ESI is required to implement the server side of the DRLC cluster. The SEP Load Control devices are required (mandatory) to implement the client side of the DRLC cluster, but for the Smart Appliance Devices it is optional.

From this it is evident that one physical device can implement the functionality of multiple logical devices by implementing the necessary clusters as specified by the standards. These facilitates interaction and compatibility among devices from different manufacturers. The formats of these commands and messages are quite cumbersome; hence have been adapted and simplified to suit the user requirements of the VT HEM system.

9.5 VT HEM Implementation in Zigbee

In this section implementation of the Home Area Network and the device organization and interface for end-use appliances have been discussed. The first Subsection introduces the modem, which has been used as the ZigBee mesh network implementation. Then one of the problems faced with the modem discussed. After that how various functionalities of the HEM system—regarding the Home Wireless Networking—have been implemented is discussed.

9.5.1 XBee PRO Series 2 RF Module

IEEE 802.15.4 is a low power, short range and reliable protocol with strong security features, which is suitable for home environment. ZigBee defines mesh-networking protocol (Network Layer) that runs on top of the IEEE 802.15.4 point-to-point wireless protocol. Within the network, ZigBee nodes can perform multi-hop routing. VT HEM utilizes XBee programmable wireless modules. These generic modules have several firmware options those run on top of ZigBee wireless communication protocols and offer management functions for the module. XBee modules are marketed by Digi. XBee has two types of modems. One is called Series 1, and the other is Series 2. Series 1 is based on a chip developed by Free Scale. XBee Series II is based on Ember chipset. Both of these series utilizes IEEE 802.15.4 wireless communication protocol, which is a Media Access Control Protocol (MAC).

XBee Series 1 has mesh networking capabilities that utilizes a proprietary protocol called DigiMesh. On the other hand XBee Series 2 modem has implementation of multi-hop routing using mesh networking according to the ZigBee Network Layer standards. ZigBee defines numerous other higher layer application profiles and standards intending to facilitate development of solutions to real life problems. But those features are not included in XBee Series 2 hardware, as this modem's primary purpose is to provide application agnostic network layer functionality. Basic ZigBee Device Profile features are not offered, either. In VT HEM XBee Series 2B (S2B) modem has been employed. This version is same as regular Series 2 modems but offers additional feature of low power consumption, and additional antenna options. XBee S2B modules are generic and different firmware can be installed on those. In the ZigBee network layer paradigm, there are three types of devices: coordinator, router and end device. Although higher layer application profiles are not supported, still the firmware offered by ZigBee come with flavors of higher layer profiles for which it is intended to be used. For example, Smart Energy firmware can be installed on this generic XBee S2B hardware, which is suitable for the implementation of the ZigBee Smart Energy Profile. The Smart Energy Firmware also offers very limited functionality of ZigBee Device Object, which is mandatory for any ZigBee device to implement. However, it has been found that the ZDO functionality implemented in XBee RF module is insufficient and not usable.

9.5.1.1 AT Command Mode

XBee RF modems offers several modes, such as AT command mode, transparent mode and API mode. In the AT command mode, the XBee responds to various commands that come in through the data input pin of the module. Many AT commands are available to manage and configure the modem. In most cases configuration is performed by writing values to the registers. Also configurations—i.e., the register values—can be read using AT commands. For example, the hardware version, firmware version can be read by AT Commands ATHV and ATVR. Command ATSH can be used to read the higher 32 bits of the 64-bit IEEE address, whereas ATSL can be used to read the lower 32 bits of that address. ATMY command can be used to read the 16-bit network address. Many of these values that are read can also be set using AT commands. The ZigBee Smart Energy firmware does not support the AT command mode. However, AT commands themselves are supported when passed using API mode. This is the reason why the AT commands are discussed here.

9.5.1.2 Transparent Mode

In the transparent mode, anything typed by the user is directly transmitted to one or more remote node. To use this mode, first a destination address is needed to be set. It can be the address of another IEEE radio module, in which case the transmission would be point-to-point. Or it can be a broadcast address in which case the communication would be a star topology type one-to-many communication. After setting the destination address, it is possible to switch to transparent mode. In this mode whatever typed is directly passed to the remote node or nodes based on the destination address. So, it would be possible to send texts to remote nodes. The ZigBee SE firmware does not support the transparent mode.

9.5.1.3 API Mode

The API mode is useful for communicating programmatically. In this mode a frame—series of bytes—is formed and written to the pin of the modem. Based on the frame, the modem takes proper action. Frame can be intended to run local AT commands, remote AT commands or transmission of any messages as payload to the remote nodes over the network. Frames start with a fixed sequence of bits, which is called start sequence. The start sequence is 8 bits (1 byte) long, and it is 0x7E in hexadecimal representation. The next two bytes contain length of the frame. The first byte is the MSB (most significant byte) and the second byte us the LSB (least significant byte). This helps the recipient of the frame to determine the end of the frame. After the length byte, the recipient expects that many number of bytes plus one additional byte as the Frame Check Sequence, which is the error detection code or checksum. This is a common practice for wireless communication protocols, and this technique has been discussed in the Subsection 9.1. After length comes the 1 byte frame type. This is one of the most important bytes of this frame. It indicates what action the local RF module should take. Based on this the modem can determine what to do with the rest of the frame and how to interpret the rest of the frame. For example, the frame type can indicate that it is meant to run an AT command locally. In that case subsequent bytes will contain the command that need to be run. Another frame type indicates Remote AT command. In this case the RF module knows it doesn’t have to execute any command locally but to request a remote node to execute the command. In such a frame, the address of the remote node is provided within the frame. The command to execute must also be provided. Every frame in the API mode contains a frame id. If the frame id is 0, the modem doesn’t provide any response to the upper layer, i.e. the program that is using the modem. But in case of frame id other than 0, the program that hands the API frame, receives a response from the underlying local XBee RF modem. This response is an API frame, but with a different frame type, but with the same frame id.

The XBee SE firmware can be installed on generic XBee RF modules. The SE firmware only supports the API mode. In this firmware, an API frame with type 0x1A indicates an explicit addressing frame, which means it should be passed up for application layer processing. Since the frame needs to be processed by an upper layer, the endpoint of the upper layer application has to be provided. Also, the application profile id, cluster id, etc. are needed. For a particular endpoint on a device, the application profile id must be always same, since an object cannot implement two different application profiles. But the cluster id can vary based on which service is being requested. Our Smart Appliance Device object supports the client sides of the clusters Price, DRLC, and Time. Based on address or the frame, the local XBee Module transmits the API frame to the remote XBee Module whose address is provided in the destination address field. The Remote XB module's MAC layer detects the beginning of the frame from the frame start sequence 0x7E. The next two bytes are length and after the number of bytes indicated by the length it expects the checksum. If the checksum indicates no error, the MAC handles the frame to the upper layer by invoking *NLDE-DATA.indication* primitive. The NLDE passes the data to the Application support sub-layer (APS) by invoking the *APSDE-DATA.indication* primitive. The APS checks the frame and extracts the endpoint number, based on which the target application object running on a ZigBee device receives the data sent as payload of the frame. Upon successfully delivery to the remote node, the RF modem of the sending program/application gives response frame to the upper layer program. This frame is has the frame type of 0x8B, and called ZigBee Transmit Status. For the name it is evident that this is the feedback regarding the explicit addressed frame issued by the upper layer, which was destined to a remote node. The frame id field is used to match the request frame with the status response frame, when the frame id is not equals to 0. When the upper layer application or program does not wish to have a status response frame, the frame id is set to 0. The RF module then creates a frame of type 0x91 and sends it to the remote node, whose address was provided as the destination address of the requested explicit transmission request. Upon transmission of the frame to the ZigBee node having the address same as specified in the original frame, the receiving nodes RF module finds that, the frame is of type explicit address receive frame, so it passes the frame payload up to the application addressed by the endpoint number.

9.5.2 Implementation Issues with XBee SE RF Module

On any ZigBee node ZDO is responsible for performing several important functions, related to service discovery. Service discovery is the process of determining which functionalities are offered by a particular entity, or which node offers a particular service being sought. If a node contains offers the service, on which Endpoint it is hosted. It was not possible to find any way to configure the ZDO to serve such service discovery requests. If a service running on an endpoint on a ZigBee node cannot be registered with ZDO, there is no way the ZDO can respond to requests asking for that service. XBee RF modems allow setting the AO register to a value of 0x3, which will cause to transfer all the requests targeted towards the ZDO (by using the destination endpoint 0), to upper layer.

In our implementation the ZDO functionality was also made available on Endpoint 1 as a work around for the XBee RF module. Therefore, other devices would contact on Endpoint 1, for discovering services. But on production environment, where it is expected to interact with third party nodes, the ZDO must be available on Endpoint 0.

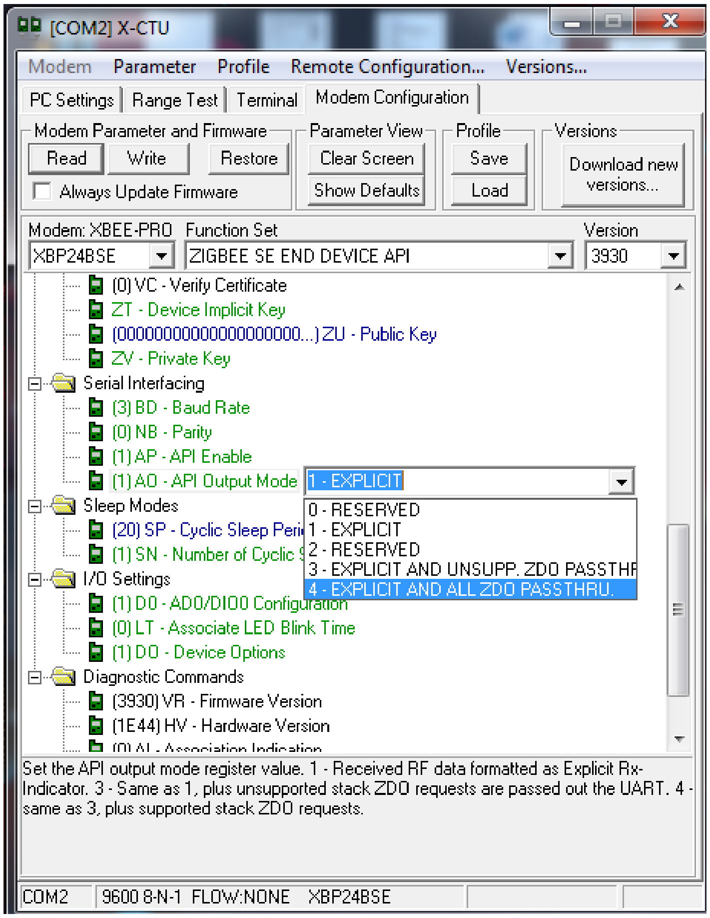


Fig. 9.2: Configuration of the AO register for the XBee RF Module.

For, the value of 0x1, ZDO PASSTHRU is disabled. Therefore, our external processor cannot receive the message. The device (and firmware) doesn't support the value of 0x4, as the only valid values are: 0x1, 0x3, and 0x7, as shown in the table below. Therefore, the value was set to 3. But even after setting it to 3, the RF module won't pass the ZDO messages to the external processor. For this reason it was decided to make the ZDO listen on both Endpoint 0x01 so that it becomes possible to send the cluster messages to the upper layer implementation of the ZDO.

AO	**API Options**. Configure options for API. Current options select the type of receive API frame to send out the UART for received RF data packets. CRE 1 - Default 1 - Explicit Rx data indicator API frame enabled (0x91). ZDO Passthru is disabled. 3 - Explicit Rx data indicator API frame enabled (0x91). ZDO Passthru is enabled. ZDO requests which are not supported by the stack, and the ZDO requests Simple_Desc_req, Match_Desc_req, and Active_EP_req are passed out the UART port to the external processor in a 0x91 API frame. The external processor is responsible for their processing and response generation. If you enable option 3, the external processor needs to do the following: 1) respond to Simple_Desc_req; 2) respond to Match_Desc_req; 3) respond to Active_EP_req; 4) respond to other ZDO requests which are not supported by the stack. For example, remote devices which are attempting to Authenticate after joining will send a Match_Desc_req in an attempt to discover the endpoint which supports the Key Establishment Cluster in the Smart Energy Profile, which usually resides on the Coordinator (Energy Service Portal or Meter Device). 7 - Explicit Rx data indicator API frame enabled (0x91). ZDO Passthru of supported and unsupported ZDO requests are passed out the UART port to the external processor in a 0x91 API frame. For example, binding requests will be passed through.	CRE	1 - Explicit Rx data indicator API frame enabled (0x91) 3 - Explicit Rx data indicator frame enabled (0x91) and ZDO passthru enabled. 7 - Explicit Rx data indicator API frame enabled (0x91), supported and unsupported ZDO passthru is enabled.	1

Fig. 9.3: Documented AO register behavior for XBee SE module [62].

The API commands do not fully adhere to the ZigBee specification. For example, when sending a cluster message or ZCL Commands, the frame control field should be followed by the endpoint number as shown in Fig. 9.4 from [50], but it cannot be found in the here XBee SE RF Module.

Octets: 1	**0/1**	**0/2**	**0/2**	**0/2**	**0/1**	**1**	**0/ Variable**	**Variable**
Frame control	Destination endpoint	Group address	Cluster identifier	Profile identifier	Source endpoint	APS counter	Extended header	Frame payload
	Addressing fields							
APS header								APS payload

Figure 2.2 General APS Frame Format

Fig. 9.4: The ZigBee specification for payload field for the APS layer above the network layer.

Below the format of a frame of type 0x11 has been shown for the cluster with identification 0x05 in Fig. 9.5. The payload field of the Network Layer Protocol Data Unit (NLPDU) is highlighted in Fig. 9.5. Here, the required APS header is entirely missing, Usually, the NLPDU's Payload is an APS PDU, where the above Data Payload is supposed to remain as APS Header followed by APS Data, as specified by the ZigBee Spec, [50], Sec: 2.2.5.1 (Page: 52). Within the APS Data, the ZDO Payload is supposed to be embedded, but in case of the XBee SE frame, the ZDO Payload directly comes after the transaction sequence number. This is same as skipping the entire APS layer and directly transferring the received packet to the Next Higher Layer Entity (NHLE) of the APS.

	Frame Fields			Offset	Example	Description
API Packet	Start Delimiter			0	0x7E	
	Length			MSB 1	0x00	Number of bytes between the length and the checksum
				LSB 2	0x17	
	Frame-specific Data	Frame Type		3	0x11	
		Frame ID		4	0x01	Identifies the UART data frame for the host to correlate with a subsequent transmit status. If set to 0, no transmit status frame will be sent out the UART.
		64-bit Destination Address		MSB 5	0x00	64-bit address of the destination device (big endian byte order). For unicast transmissions, set to the 64-bit address of the destination device, or to 0x0000000000000000 to send a unicast to the coordinator. Set to 0x000000000000FFFF for broadcast.
				6	0x00	
				7	0x00	
				8	0x00	
				9	0x00	
				10	0x00	
				11	0xFF	
				LSB 12	0xFF	
		16-bit Destination Network Address		MSB 13	0xFF	16-bit address of the destination device (big endian byte order). Set to 0xFFFE for broadcast, or if the 16-bit address is unknown.
				LSB 14	0xFE	
		Source Endpoint		15	0x00	Set to 0x00 for ZDO transmissions (endpoint 0 is the ZDO endpoint).
		Destination Endpoint		16	0x00	Set to 0x00 for ZDO transmissions (endpoint 0 is the ZDO endpoint).
		Cluster ID		MSB 17	0x00	Set to the cluster ID that corresponds to the ZDO command being sent. 0x0005 = Active Endpoints Request
				LSB 18	0x05	
		Profile ID		MSB 19	0x00	Set to 0x0000 for ZDO transmissions (Profile ID 0x0000 is the ZigBee Device Profile that supports ZDOs).
				LSB 20	0x00	
		Broadcast Radius		21	0x00	Sets the maximum number of hops a broadcast transmission can traverse. If set to 0, the transmission radius will be set to the network maximum hops value.
		Transmit Options		22	0x00	All bits must be set to 0.
	NL PDU	Data Payload	Transaction Sequence Number	23	0x01	The required payload for a ZDO command. All multi-byte ZDO parameter values (u16, u32, 64-bit address) must be sent in little endian byte order. The Active Endpoints Request includes the following payload: [16-bit NwkAddrOfInterest] Note the 16-bit address in the API example (0x1234) is sent in little endian byte order (0x3412).
			ZDO Payload	24	0x34	
				25	0x12	
	Checksum			26	0xA6	0xFF minus the 8 bit sum of bytes from offset 3 to this byte.

Fig. 9.5: MAC Frame format for the API mode frame type 0x11 where the NL PDU does not include necessary information for the APS layer, which is the next higher layer entity (NHLE) of the network layer. Instead it contains the PDU for the NHLE of the APS.

Octets: 1	Variable
Transaction sequence number	Transaction data

Fig. 9.6: The ZDP command format [50], Section 2.4.2.8, Page 99.

Again the NL-PDU's Payload for another ZigBee Cluster (Basic Cluster, whose identifier is 0x0000) is in another format, as shown in Fig. 9.7. For this cluster it again violates the APS layer frame format as shown in Fig. 9.3. Only the Frame Control Sequence of the APS frame is available. Transaction sequence number, as shown in Fig. 9.7, is part of the APS Payload (as shown in Fig. 9.3), and the header of the PDU of the NHLE, which is ZDO Command Frame in this case as evident from Fig. 9.6.

Data Payload	**ZCL Frame Header**	**Frame Control**	23	0x00	Bitfield that defines the command type and other relevant information in the ZCL command. See the ZCL specification for details.
		Transaction Sequence Number	24	0x01	A sequence number used to correlate a ZCL command with a ZCL response. (The hardware version response will include this byte as a sequence number in the response.) The value 0x01 was arbitrarily selected.
		Command ID	25	0x00	Since the frame control "frame type" bits are 00, this byte specifies a general command. Command ID 0x00 is a Read Attributes command.
	ZCL Payload	**Attribute ID**	26	0x03	The payload for a "Read Attributes" command is a list of Attribute Identifiers that are being read. Note the 16-bit Attribute ID (0x0003) is sent in little endian byte order (0x0300). All multi-byte ZCL header and payload values must be sent in little endian byte order.
			27	0x00	

Fig. 9.7: Data payload for network layer which is supposed to be the APS PDU (Fig. 9.4), but does not contain all the fields of the APS sub-layer, except the Frame Control field.

Here, they have provided for the option for frame control byte, but still other fields are missing, such as APS Counter field. The receiving device's APS Layer maintains a separate counter for each of the sending devices, to avoid redundant processing of the same frame. The APS Counter requirement could not be found in the ZCL, but it is in ZigBee Specification [50] and Page 119 of ZigBee Smart Energy Profile Specification [51]. To absolutely sure and have full knowledge of conditions which dictate the use of APS Counter before claiming this inconsistency. Also, the XBee RF Module's SE guide doesn't provide detailed information about how other attributes of the device, and other Endpoints support can be configured. Because of these uncertainties it was decided to implement the ZigBee APS and APL layer ignoring insufficient support available from Smart Energy RF Module of XBee.

9.5.3 Home Area Network (HAN) Coordinator

The coordinator is responsible for starting the home wireless network on one of the wireless channels within the supported frequency band. Participating appliances join the network on that channel. Upon joining they can exchange messages. The coordinator can either ask an appliance for its power consumption data for every sample; or it can configure the appliances so that the appliances perform dynamic attribute reporting to send power consumption data periodically.

An XBee RF module has been connected to the HAN coordinator. In the jargon of the ZigBee mesh networking the device responsible for starting the network is known as the PAN (Personal Area Network) coordinator, but that is a generic term for any application domain. For a car parking application, a parking manager or car coordinator device might employ the PAN Coordinator. In the context of HEM, the system—that manages the PAN coordinator—is called HAN coordinator. The RF module employed by the HAN coordinator must be a full-function IEEE 802.15.4 device (FFD) as explained in the Subsection 9.1.

9.5.4 Attribute Report Listener

The Analog Value (Basic) cluster has the standard cluster id of 0x000C. This cluster defines an attribute named PresentValue (attribute id 0x0055), which is configured for reporting, using the command "Configure Attribute Reporting Request." This command has command id: 0x06. This command is a profile wide command, meaning not limited within the scope of any particular cluster. Therefore, reporting of other attributes defined in other clusters can be configured using this command as well. The ZCL (ZigBee Cluster Library) defines this command. When the ZigBee device for an end-use appliance receives this command it creates a binding between the cluster and information of the device issuing the command. It then responds with "Configure Attribute Reporting Response" command, which has a command id 0x07.

Upon completion of the configuration process of "attribute reporting" described above and creating the binding table entry for this cluster and the attributed report recipient (the device which sent the Attribute Report Configuration command), the device for end-use appliance would be issuing the Report Attribute command periodically according to the interval set by the prior configuration command.

The PresentValue attribute indicates the power consumed by the end-use appliance. It has the ZigBee data type "Single Precision (Data Type Id: 0x39)," which is 4 bytes long. This is why the value field of the Report Attribute command is 4 bytes long. It is similar as the primitive data type "float," found in major programming languages such as C++ or Java. The Report Attribute command is issued by the device for end-use appliance and it is targeted for the HAN Coordinator, where the ARL behavioral component (Fig. 4.2) implemented, in implementation of the VT HEM system.

9.5.5 Sampling of Appliances

As carried out in [27], polling appliances continuously in a loop has been implemented as the sampling option. This has been implemented as an alternative mechanism of the attribute reporting feature described in 9.5.4 when additional microprocessor is not used or available.

9.5.6 Actuation

When the HIG receives instruction to act upon an appliance it uses the XBee RF module to transmit a frame over the shared wireless medium, which represents a command. The RF module or wireless interface of the recipient appliance then receives the command and the command is implemented.

This is accomplished by utilizing a smart plug that incorporates a relay and an IEEE 802.15.4.RF module. Upon receipt of a command to turn the corresponding device off, the relay can be used to cut the power supply to the appliance. If a command is received to switch an appliance on, it can also be done in using the relay. This is called the simple mechanism, since in this technique implementation of the higher layers in the ZigBee Protocol Stack—such as the Application Support Sub-layer and ZigBee Device Object (higher layers are discussed in the Subsection 9.3, "ZigBee Device Organization")—is not necessary. They are just managed by a generic smart switch or plug. Such generic smart plug is not aware whether the device being controlled is a light, or alarm, or a fan. An option would be to implement application logic within an appliance. Such appliances would support more functions beyond just on/off command. For example, a Programmable Communicating Thermostat (PCT) device could be issued a command to make the set point at a supplied temperature. This would not be possible if the appliance does not implement the PCT behavior on some processing device. Devices from any domain can utilize the ZigBee mesh networking protocol: A car, a sensor, or an appliance. But appliances at a home have a wide range of characteristics and attributes, which would not be found in a car. This is why ZigBee application profiles are defined with the aim of devising specialized solutions. Smart Energy Profile is such an application profile to standardize the functionalities related to Home Energy Management and Demand Response.

9.5.7 Device Organization and Interface for End-use Appliance

In case of the HEM system developed in this work, the smartness or behavioral logic of appliances are implemented and coupled with the appliance. The vision is that, in the future appliances will come with an embedded system or systems on a chip, containing implementation of the communication and application frameworks. They can either be replaceable or not. Because of the increased interest of standardizing the communication and behavioral aspects of appliances, it would not be a barrier for appliances from different vendors to participate and cooperate within a home network.

This approach overcomes many of the limitations of fixed outlet based solutions. It is expected that such communication and remote control of appliances would be a norm of the future, where users will have the practice of reading labels to identify protocols it supports along with the energy rating while buying an appliance. As soon as the user input the installation code of the appliance into his/her HEM system, and plugs in the new appliance, it would be able to join the home network. The householder will not have to do any manual configuration or worry about which outlet the appliance must be plugged in. The HEM system will be able to inquiry the appliance for important information, to determine its type and other characteristics. The prices of chips are dropping dramatically. It has been envisioned that by 2020, about many of the devices would be equipped with computers. Even there would be computers around us which we won't be able to notice.

This work is an endeavor towards that vision, hence the coupling of end-use appliances with a wireless communication modem and a computing device, such as a microcontroller, have been implemented, based on ZigBee Device Profile (ZDP) and Smart Energy Profile (SEP). The implemented clusters are: Network Address Request/Response, IEEE Address Request/Response, Simple Descriptor Request/Response, Active Endpoint List Request/Response, Match Service Descriptor Request/Response, Configure Attribute Reporting, Report Attribute, etc., from the ZDP, and from the ZigBee Cluster Library (ZCL). Adapted versions of the clusters: Price, Time, Demand Response and Load Control (DRLC) and Meter, from the SEP have been implemented as well. The operation of the Network Address Request cluster is shown in Fig. 9.8 below.

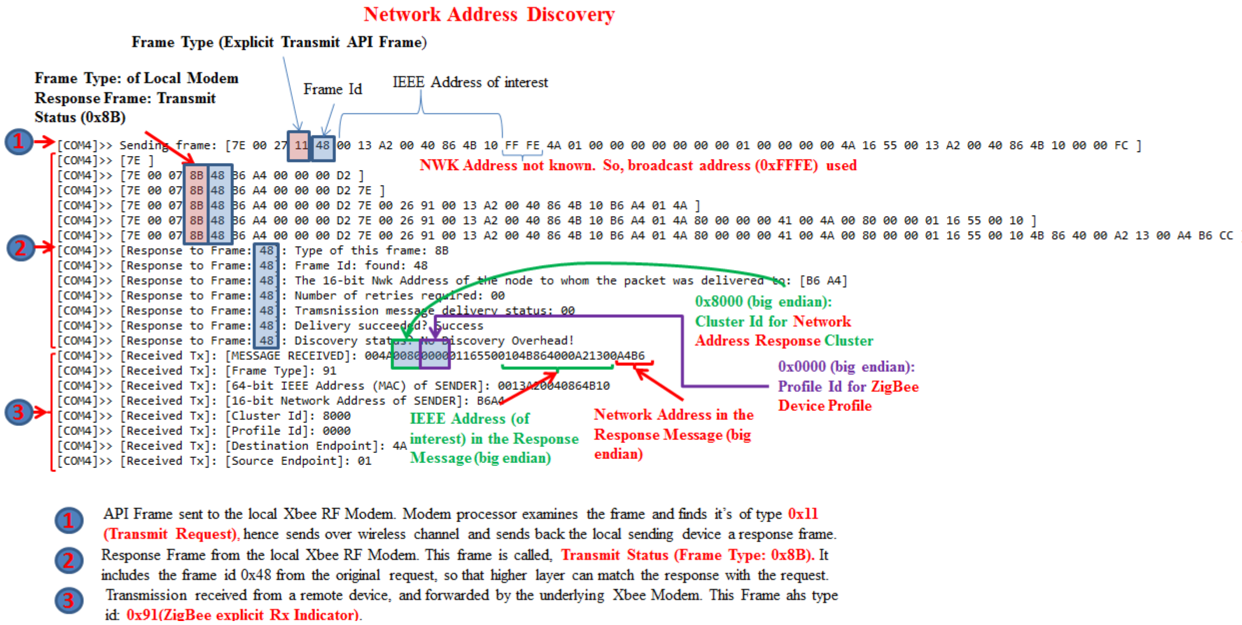


Fig. 9.8: Demonstration of the “Network Address Request/Response” clusters.

The difference between a Smart Appliance and a normal appliance is that the Smart Appliance can be discovered, queried for services, secured, controlled and interacted with. In the case of VT HEM this happens by means of communication over the wireless network. To implement the smart behaviors, MSP430F247 microcontroller has been used which has been connected with the regular appliance.

The MSP430F247 has been interfaced with the XBee PRO Series 2 radio. XBee PRO Series 2 is an implementation of the ZigBee Mesh wireless mesh networking protocol by Ember Networks. The hardware has an IEEE 802.15.4 radio, which work as the MAC (Media Access Control) on top of a PHY layer. ZigBee Device and Application standards define Application Support Sub-layer on top of the Network Layer. Therefore the Application Support (APS) sub-layer and Application (APL) layer within the MSP430 family microcontroller has been implemented. Smart Appliances rely on the XBee S2B radio hardware to form a network and provide data delivery service.

Chapter 10

Implementation of selected HEM Security Features, and Review of HEM Security Risks

Security of any computer system is one of its most important aspects, especially if the system is a highly distributed one and depends on many different technologies and protocols. When some of the components of this distributed system operates from within the public Internet and depends on its services the need for security becomes even higher. For a fully operational system every security details and possibilities should be taken care of. In this research various relevant security issues have been brought into consideration and some of these features have been implemented and incorporated within the prototype implementation of the HEM system.

In this section the security features implemented has been discussed. A thorough review of ZigBee security concerns has been conducted. To tackle or assuage some of the concerns existing ZigBee features as well as new techniques have been proposed.

10.1 HEM System and its Generic Security Goals

Security goals are high-level objectives, one or more of which are achieved by implementing a security system or technique. Relevant security goals are: confidentiality, integrity, availability and non-repudiation.

10.1.1 Confidentiality

Confidentiality is the property of the content or meaning—of a communication—of being unable to be retrieved by an interceptor or eavesdropper. Only the eligible receivers of the data should be able to understand the information being transmitted.

It is possible for both the wireless and wired communication to be intercepted or sniffed by some eavesdroppers listening to or processing all data traffic. For example, when a wireless device makes any transmission over a channel within a frequency band, it is possible for other devices within the transmission range to receive the transmission passively or stealthily. For this reason it is necessary to encrypt the original information or data into some cipher data to hide the content. Ideally only the eligible recipient should be able to decipher that data and retrieve the original content and to the eavesdropper it should appear completely arbitrary.

In the context of an HEM system confidentiality is very important. Because of the ubiquity of wireless networks, it is no longer practical to connect multiple devices within a home using wires. One of the main reasons why wireless networks are more susceptible to such “passive” attack is the ease of conducting such activity. Unlike tapping into a wired system an eavesdropper does not need any conduct any physical intrusion. For this reason it would be a trivial matter for a stalker to read wireless messages being exchanged among devices. ZigBee PRO can have range of up to 1,600 meters. Therefore, it might be possible for an eavesdropper to "listen" to the communication from afar.

10.1.2 Integrity

It is the assurance that the data received is the same as what has been originally transmitted. Any modification, insertion or deletion must be able to be detected so that tampered data can be ignored or discarded.

In the case of multi-hop communication where data passes through an intermediate routing device, data can be altered. Another way of conducting such attack would be to record a legitimate transmission and later replay that transmission by an illegitimate device. The latter attack is known as a reply attack.

Wireless networks are susceptible to replay attacks as well. An external device can easily send/inject data into the network by making a transmission on the shared wireless medium. The transmission can have the address of an intended recipient device. If no measure is taken to prevent the compromise of this security goal, the recipient device can be easily duped.

10.1.3 Availability

A system or system resource should be accessible and available—to authorized entities—on demand basis in accord with expectation. But it is possible to compromise this goal by making the service unavailable to legitimate users.

The most common are the Denial-of-Service (DoS) attacks. This is can be done in many ways. An HEM coordinator can be inundated by arbitrary messages, which may cause it to become unresponsive. Resilience against DoS attacks should be implemented at every level from the wireless end devices to the web server.

10.1.4 Non-repudiation

Non-repudiation is to ensure that any message already exchanged or any communication already happened between two parties or systems cannot be denied in a later time period. This is very important to ensure, especially in the context of Demand Response communication, since messages exchanged may affect sensitive issues, such as incentives, electricity bill, price, etc.

10.2 Web Services Security Implemented

The first-level defense of the designed system is the AUTH (Authentication and Authorization) tier as shown in Fig. 4.2 in Chapter 4. All requests and responses sent over HTTP pass through this layer. All systems or users using web services or websites must have a valid username and password or certificate for authenticating themselves. The free Intrusion Detection System (IDS) Snort has been used to safeguard the HEM Web Server as shown in Fig. 4.3 in Chapter 4.

Permission-based access to web services is used to implement authorization. Permissions can be assigned to groups or individual clients. The following technologies and/or protocols are used to secure communication between two devices and prevent unauthorized access from illegitimate devices.

10.2.1 Transport Layer Security (TLS)

The communication is secured using TLS (Transport Layer Security). TLS offers end-to-end encryption of all packets. Therefore, even if packets are sniffed by some eavesdroppers in intermediate nodes of the network, the confidentiality is not compromised. If more security is needed, traditional approaches of securing an Internet gateway server can still be used, such as Firewall, IDS (Intrusion Detection System), or even IPSec (Internet Protocol Security), which implements encryption at the Network Layer.

The web—used by the human users—and Web services-based for autonomous machine-to-machine communication, both are run by means of interaction among computers which are either server or client and talking to each other using the Hyper Text Transfer Protocol (HTTP). HTTP is considered an application layer communication protocol. HTTPS is HTTP employing the services offered by the TLS protocol, which utilizes the TCP (Transmission Control Protocol) protocol.

10.2.2 AES (Advanced Encryption Standard)

This is an encryption technique standardized by NIST (National Institute of Standards and Technology). It takes the message or data and divides it into 128 bit blocks. It applies a 128-bit key to produce a cipher data from the original message. The cipher data appears totally random and gives no indication about the original data/message. The recipient of this message can decrypt the cipher data into plaintext data, i.e., original message. To perform decryption, the recipient must also know the exact 128-bit key. Using this key recipient deciphers the 128-bit long block of the original data. The Cipher Block Chaining (CBS) method is employed to ensure that the encrypted message cannot be changed or rearranged. If changed, it would totally destroy the subsequent data and would be detectable by the recipient.

10.2.3 Server Access Control List

The server maintains an Access Control List (ACL) to filter out unauthorized request at upstream—few steps before the application logic of the server. This helps reduce load on the server. It is by default denies all requests. Only the third party systems or utility systems which are listed in the Allow list or White list can have their requests successfully sent to the application logic on the HEM-WS.

10.2.4 Intrusion Detection System (IDS)

An Intrusion Detection System (IDS) inspects the packets originated from outside of the system or internal network and detect the packets that are intended for some malicious intent. The free intrusion detection and prevention system software Snort has been used to protect the HEM WS. Snort [63]. Real-time packet analysis, packet logging, protocol analysis and a host of other tasks can be performed to monitor incoming traffic. Various types of attacks or probes can be detected such as: stealth port scan, buffer overflow, fingerprinting of the operating system, etc.

10.2.5 SHA-1: Secure Hash Algorithm

Passwords are used to compute a salted one-way hash (for which inverse computation is impractical) using SHA-1 (Secure Hash Algorithm), and this hash function outputs are stored with in the AUTH tier. In addition hiding passwords, SHA-1 based MAC (Message Authentication Code), known as HMAC-SHA-1 is used within the TLS protocol.

SHA-1 was designed by NSA (National Security Agency), and NIST (National Institute of Standards and Technology) has published it as a U.S. Federal Information Processing Standard. This is done to make it difficult to compromise the plaintext password.

10.3 Security Measures Implemented in VT HEM

Securing all communication channels or paths is very crucial. The HEM system developed in this thesis is distributed in nature and involves communication among those distributed components over the public Internet as well as wireless network. The objective of this chapter is to describe what security measures have been taken to safeguard these communication channels. In Fig. 10.1, all communication links used by the VT HEM are shown. Below the mechanisms employed to secure these communication links have been discussed.

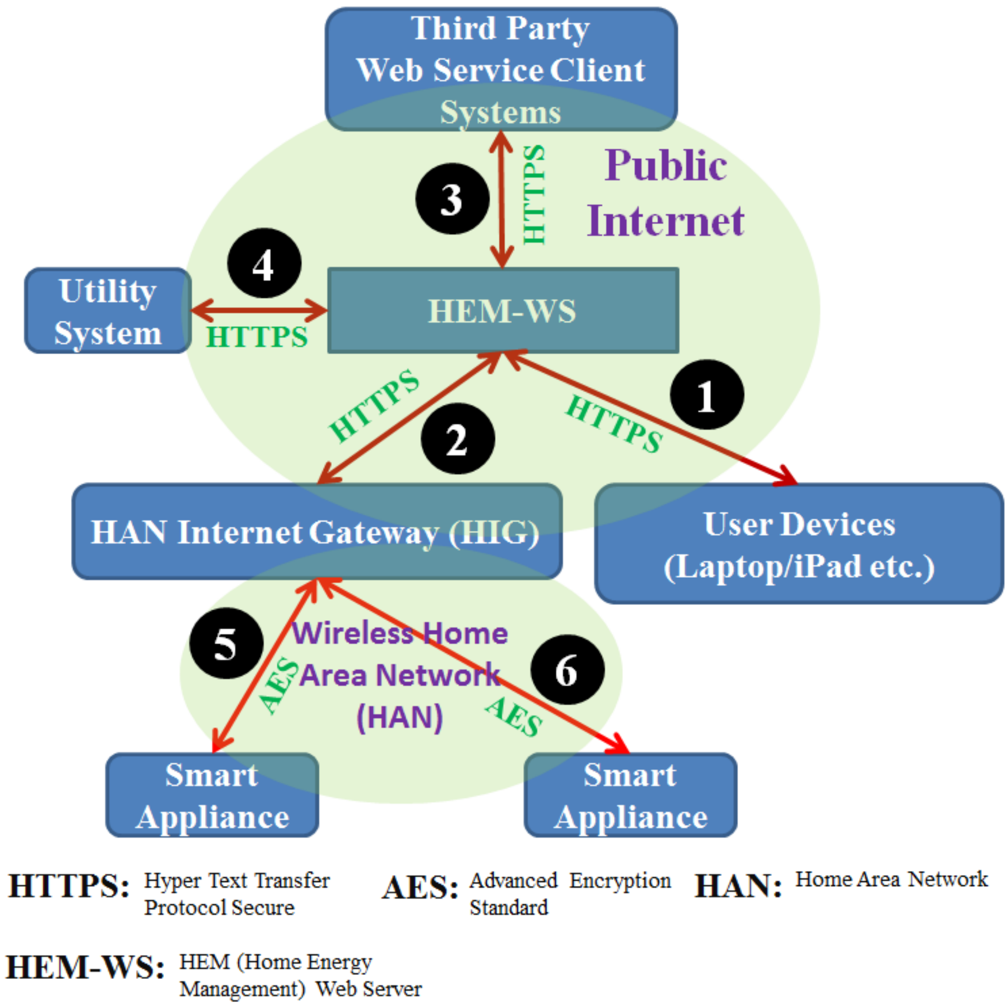


Fig. 10.1: Communication paths of VT HEM.

10.3.1 Link 1: HEM-WS and Client Device Communication

This is the link 1 shown in Fig. 10.1. The client devices such as Laptop or iPad or any other computer using which a user views or interacts with the web server uses this link to contact with the server. Using this connection the intelligent User Interface (UI) is retrieved and actions of the user on appliances are sent back to the server. Client device authentication is not performed by means of client certificate in case of this connection. Instead a user is asked for a password to authenticate himself or herself. Since all these communications occur using the service of the SSL/TLS (Secure Sockets Layer/Transport Layer Security) protocol, all information—including the password of the user transferred between the client device and the HEM-WS—appears gibberish to any eavesdropper who might be sniffing traffic at an intermediate router or on a shared Ethernet connection on the public internet.

Here server authentication is performed using server certificate, meaning the server presents its certificate to the web browser running on the client device. This way the user can be sure that the system claiming to be the HEM-WS is true. The client agent (Internet browser) software verifies the server certificate by examining if it has been signed by a well-known Certificate Authority (CA). This verification allows the client to thwart impersonation by malicious servers claiming to be the HEM-WS server.

The ACL is not utilized for this communication path since this is human user interface and the user might use different computers of devices to access user webpage.

User authorization is discussed in details in Section 10.4.

10.3.2 Link 2: HEM-WS and HIG

HTTPS is utilized to secure the communication between the HIG and the HEM-WS. This is the link over which the status data is sent to the server for storage and display to the user by means of the intelligent user interface. The user interaction is also retrieved from the server over this link.

In this case both the client and server mutual authentications based on certificate are performed. The server (HEM-WS) certificate is stored on the HIG; and the client (HIG) certificate is stored during an initial setup on the server so that one can recognize the other.

The ACL is applied to filter out all illegitimate requests. The HIG is added to the White list of the access control list.

10.3.3 Link 3: HEM-WS and Third Party WS Client Systems

This link is secured by using HTTPS protocol, i.e., HTTP over TLS. Both client and server certificate based mutual authentication is performed to carry on with this encrypted session. ACL is implemented in this case as well for further security.

10.3.4 Link 4: HEM-WS and Utility

TLS is used as the underlying encryption mechanism and both client and server certificate-based mutual authentication is employed. ACL is employed to ensure that illegitimate entities claiming to be a utility system cannot receive any service and their messages are filtered out at an early stage.

10.3.5 Links 5-6: HAN Coordinator and Device Organizations and Interfaces for End-use Appliances

Communications between an appliance and the HIG takes place over a wireless channel and the Internet protocols stack is not involved. Therefore it is neither necessary nor convenient to utilize TLS.

10X.3.5.1 Securing Wireless Communication

To secure these links AES encryption has been used. The keys on an end-use appliance are stored at the HIG during the time of installation. For each different end-use appliance a different key is used. More details are available in Subsections 10.5. and 10.6.

10.3.5.2 Secure Implementation

Development of device organization and interface for end-use appliances based on of ZigBee and SEP based Smart Energy has been conducted carefully so that no exploitable vulnerability is introduced. This can result in weak programming practices. Caution has been taken by implanting ZigBee functionalities in an organized manner. Custom memory manager has been implemented to sidetrack the unreliability of libraries. Default dynamic memory allocation library was found to be very unreliable for the low memory devices. No unsafe data access has been conducted. Data structures have been maintained and book-keeping of bounds have been conducted, to ensure that invalid memory address is not accessed accidentally.

10.4 User Authorization

In this section the authorization mechanism is described. In the previous section, implementation of certificate based system authentication and password-based user authentication techniques have been addressed. Authentication is ensuring that someone is indeed who he/she says he/she is. On the other hand authorization is the mechanism to ensure that a certain user has access to a certain resources.

A sophisticated role-based authentication mechanism has been implemented for the proposed VT-HEM. Various types of authorizations performed by the VT HEM are discussed next.

10.4.1 Home Appliance Information and Preference Settings

First, without logging into the system, no service can be received from the HEM-WS. A user is always directed to a login page. Upon a successful authentication, i.e., logging in using a valid password, the user is authorized to access the page for preference settings and comfort settings of his/her own household.

Upon approval, a user can be associated with a home on the HEM-WS so that multiple users from a single home can have access to the information. To facilitate such feature group-based access control has been implemented where a group of people can be given specific permissions.

10.4.2 Role-based Access Control

Role-based access control has been implemented so that different users within a single home can be assigned different levels of control. In Fig. 10.2 it has been shown roles can be applied both on groups and directly on individual users.

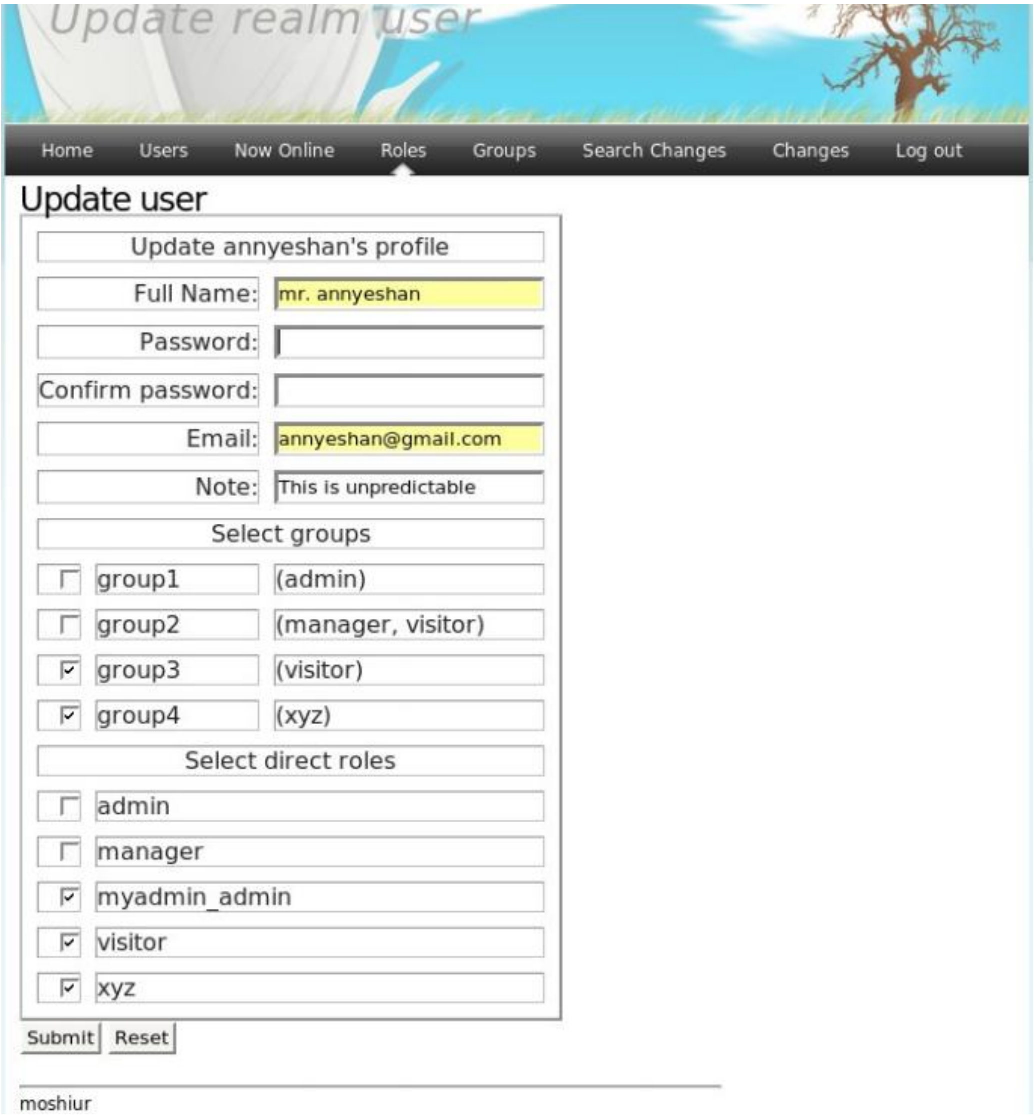


Fig. 10.2: Role- and group-based sophisticated access control system.

All requests that reach the HEM-WS system is intercepted by a filter before the application logic is reached. Based on the requested path, the action is matched against the roles of the logged in user.

10.4.3 Operational Log

To detect malicious intent and also for management convenience, operations performed by other users are stored and an administrator can monitor if any of the users are trying to access or modify any setting or data which he/she is not authorized to perform. In Fig. 10.3 this has been demonstrated.

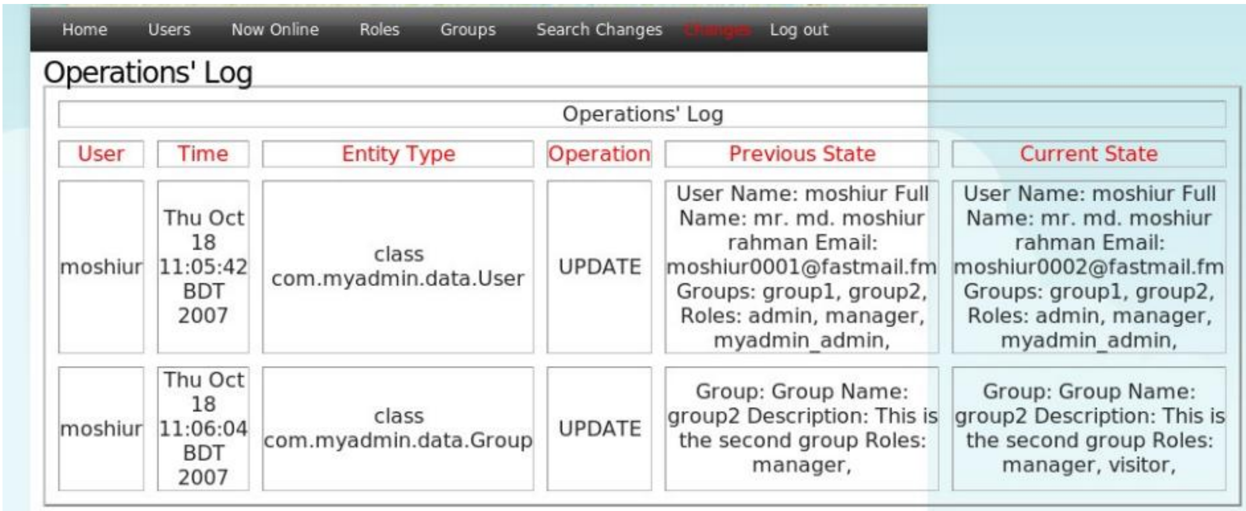


Fig. 10.3: Operational logs maintained by the HEM-WS.

The operational log can be searched as well. Using the interface shown in Fig. 10.4, it is possible to track what changes a user has made.

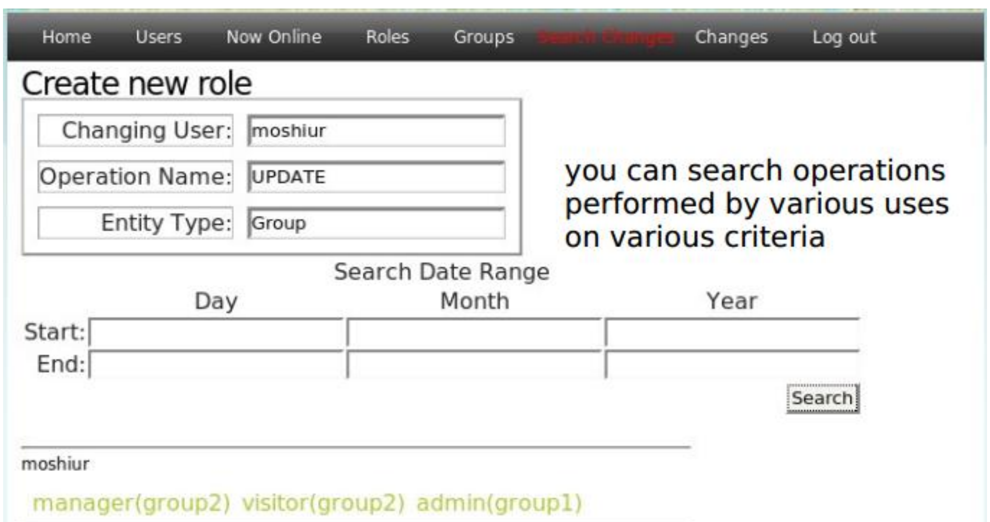


Fig. 10.4: Searching the changes made by a user.

10.4.4 Monitoring of the Users

An administrator can monitor which users are logged in and if necessary can forcibly log him/her out. This can be useful if a system administrator notices from the operational log that malicious activities are attempted. One such attempt would be to try to access unauthorized services or other users' home settings or operational conditions.

Fig. 10.5: Forcing a user to logout in case malicious intent.

10.5 ZigBee Security Review based on Technical Specifications

In this section, potential security issues of the HEM systems have been reviewed.

10.5.1 Security Concerns

10.5.1.1 Transportation of Network Key in ZigBee Smart Energy Profile

According to ZigBee's security requirement for residential applications, the network key is allowed to be transported from the Trust Center using unsecured communication.

10.5.1.2 Open Trust Model

ZigBee's open trust model is another important issue worth addressing. The ZigBee protocol and application standards demonstrate a highly structured, modular and layered design approach, which are essential traits of any complex computing device. But ZigBee devices are expected to be very low power and with limited computing resources, such as memory, clock speed, etc. Logical ZigBee device or application objects run on different end points on a physical ZigBee node. Despite design resemblance to a full computer, ZigBee devices usually cannot afford to have complete isolation and protection among applications from one another. Considering the resource constraints, ZigBee has not mandated any such isolation and/or protection. This results in the persuasion of an Open Trust Model.

Only the network interface provides the complete isolation, meaning that if one logical device/application cannot contact another without wireless transmission—i.e., internally—then they are assumed to share all secrets. Therefore, while incorporating third party implementation of an appliance—say display—caution should be exercised so that it is not programmed to perform any malicious behavior. Because of the Open Trust Model, appliances running on the physical ZigBee device where the ESI (Energy Service Interface) and Trust Center are running will have access to all secrets of the Trust Center.

10.5.1.3 Single Point of Failure

ZigBee mesh networks define three types on nodes based on the two types of physical devices (FFD and RFD) standardized by the IEEE 802.15.4. These are the Coordinator, Router and End

Device. The Coordinator is responsible for starting a network and it is the most important node of the network from the viewpoint of the network's existence. All other nodes—router or end device—join the network started by the end device. If the coordinator fails, the network ceases to exist. Although such a design has many necessary features, it also makes it more vulnerable. The Coordinator becomes the single point of failure. If the device malfunctions or any fault occurs, other nodes cannot keep working. In that sense it is less resilient than homogeneous networks, e.g., DigiMesh network, where all nodes are of a single kind and share equal responsibility.

10.5.1.4 Limitations in Power, Memory and Processing Capabilities

ZigBee devices are low cost devices, therefore lacks in some resources. One of such weaknesses is a single key used by all applications on a device; in other words, it employs an open trust model. Related experimental results have been given in the literature review section.

10.5.1.5 Key Distribution and Management

Key distribution and management is another challenge for devices with limited resources. ZigBee uses Symmetric key encryption and decryption for the confidentiality of the communicated messages—data or commands. Simplicity of symmetric keys is that encryption and decryption can be done using one key and only one key. The entities those are supposed to be allowed to decrypt have to have the knowledge of the key. In ZigBee there is a service called Key Establishment, which can be used by two devices to establish a secret key. However, if these two devices do not already share a secret key from the beginning, the Key Establishment could not have run initially without message being exchanged in plain text, which can be listened by any malicious device operating in a promiscuous mode—receiving messages sent to other devices. Therefore, the secret key negotiated between the devices can easily be stolen. To alleviate this problem, ZigBee utilizes a third device called Trust Center, which performs a pivotal role in the Key Establishment between two devices.

10.5.1.6 Unencrypted Acknowledgement Messages

Acknowledgement (ACK) messages are not encrypted. This can be exploited by an eavesdropper to identify devices and gain knowledge about households. But it would require significant motivation and effort.

10.5.1.7 Random Number Generation Problem

Lack of the ability of generating true random numbers can result in successful guessing of one or more keys by an attacker. In this work such weaknesses and practical solutions have been determined and incorporated within our VT HEM.

Random Number Generation is another implementation issue which can result in compromise of security by making it possible for an adversary to guess a secret key. Without hardware implementation of a true random number generator, all random numbers generated by software techniques would be pseudo random number. Usually in computers timestamp in millisecond ticks is used as the default seed for pseudo random number. There are Systems on a Chip (SoC) with true random number generator hardware along with ARM Cortex processor. Such a SoC when available can be utilized to mitigate this vulnerability stemmed from the lack of ability of true random number generation. The random number generators capabilities must pass the Federal Information Processing Standard (FIPS) test publication 140-2.

ZigBee specification provides some suggestions on selecting seed, which would result in increase in the difficulty level—by many folds—that would be necessary for the adversary to guess the seed. One method is to use random clock or counter from the ZigBee hardware. Also random external physical events can be measured or tracked to generate a random seed.

10.5.2 Available ZigBee Solutions

10.5.2.1 Installation Code to Avoid Plain Text Key Transport

Smart Energy Profile (SEP) devices can come with an installation code from the manufactures using which a key can be generated. This installation key is communicated to the Energy Service Portal using some reliable and secure out of band protocol. ESP is run by the utility company. So, the out of band mechanism can be phone all or email or using the utility company's website. Upon submission, this installation key is shipped to the ESP at the household using the utility backhaul network. Now when the new device tries to join the network, it is possible for it derive the "key-transport" key necessary to transport the active network key. Matyas-Meyer-Oseas hash function is used with the installation code as input to derive the link key. If implemented, this obviates the need for insecure transportation of any key.

10.5.2.2 Parent-Child Interaction Model to Invalidate Sleeping Device Concerns

In selected prior publication concern has been raised that a sleeping device can miss messages necessary to continue secured communication. For example, when an old encryption key is replaced by a new key, the sleeping device may miss the update.

In IEEE 802.15.4 communication, the sleeping RFD device has to pair with a Fully Functional Device for its continuous operation in the network. This FFD is called parent of the RFD. ZigBee network protocol defines three types of logical devices, PAN Coordinator, Router and End Device. Physically speaking, the Coordinator and the Router are FFD, and the End Device is usually RFD. The End Device cannot communicate with any other device on the network except for the Router (or the Coordinator) with which it joins the network. The End Device is not allowed or expected to receive any command or message directly from any node, either. All communication has to come through the parent device. This FFD Router/Coordinator is the parent of this End Device. According to the ZigBee protocol, when an End Device sleeps, the parent device stores the messages intended for it. Upon waking up, the End Device queries its parent for any message that it might have to process. This way it the sleeping of a node does not hinder the normal operations. Also, the node that sends a message to a RFD node, takes into consideration this sleeping period, and waits for an extended timeout period. Therefore, a communication is not considered a failure if the ACK is not received immediately. For some other functions, the parent node might respond to a message on behalf of the child node. An example is a service discovery message, in which case the parent node can send the Simple Descriptor of the End Device so that the inquiring device learns about the availability of a service. The lack of key establishment feature is not a problem at all, since it is assumed that upper layer protocols or applications would handle this issue. This functionality is briefly described below.

10.5.2.3 Authentication Requirement

Selected prior work says that a malicious node can cause other nodes to run out of power by constantly sending messages. Enforcing authentication can alleviate this problem to a great extent. In case of VT HEM, A node has to be authenticated to have its message propagated to other devices. This is the required behavior of the ZigBee network when operating in secured mode. Also a new joiner node cannot stay in “joined but unauthenticated” state indefinitely. It is supposed to initiate the process of authenticating itself. If not, the parent device of it would issue an UPDATE-DEVICE request to the Trust Center, and the Trust Center would then initiate the authentication process. If the joiner device cannot pass this authentication step, a NETWORK-LEAVE message is given to it, and the joiner is cut-off from further communication. All other messages sent by the device would be discarded by the router with which it attempted to join first.

10.6 VT HEM Security Measures for the HAN

10.6.1 Initial Key Installation

The HEM system developed in this work has support for the encryption of wireless communications. A device organization and interface for end-use appliances device of VT HEM has an initial key which it uses to encrypt all its messages. Like the installation code mechanism, this initial key is uploaded to the HEM server by means of out of band communication. The ESI (Energy Service Interface) running on the same machine as the HIG downloads this key.

10.6.2 True Random Number Service

In the Smart Energy Profile (SEP)-based implementation, a new application object has been implemented which offers a service of supplying true random numbers. The Energy Service Interface (ESI) is used as the PAN Coordinator, that is, the initiator of the network. The ESI usually runs many features and connected to the utility backhaul network. The ESI is resourceful and connected to main power outlet. In this work a personal computer has been used as the ESI, and Smart Meter Appliance device (defined within the Smart Energy Profile). The true random number provider service is run on the same machine. Here the set is like on a single ZigBee physical device there are three application objects in total, ESI, Meter and RandService. The RandService collects true random number using web services from the website www.random.org. This connection is out of band of the VT HEMS PAN, therefore, it has been assumed to be a secure process. Using this service in combination with the installation code feature, higher level of security is achieved. Therefore, pseudo random number generation would still be necessary.

10.6.3 Assuaging the Open Trust Model

The important elements of the prototype HEM system—including the ZigBee wireless network coordinator—have been developed in a desktop computer. It is recommended not to run any other end-use appliance or application (logical device) on the device hosting ESI and Trust Center so that a malicious application object cannot steal critical information. Since, the ESI is supposed to be mains powered, it is recommend to be operated on a resourceful Systems-on-a-Chip, such as ones containing ARM Cortex-A (application) Series multi-core processors. Such a processor would have enough resource host a full-blown operating system and high-level language execution environments. This is also important because this node will also have to be connected to the utility backhaul network and/or the general purpose residential broadband network to fulfill Smart Energy Profile signaling requirements. It will also be connected to the Internet for contacting the VT HEM server. All these different interfaces would require their own standard security requirements. Implementing all these on a limited resource constrained device and/or environment would introduce too many loopholes and result in wasted engineering effort.

On this node, each application has its secrets protected. This would cause limited damage in case the system is compromised.

Chapter 11
Conclusion and Future Work

11.1 Conclusion

The importance of reducing peak electricity demand and implementing demand response cannot be overstated. The web-based HEM system developed in this work is intended to enable residential consumers to automatically manage their electricity consumption. The following tasks have been accomplished in this work:

- *Developed and demonstrated a web-based feedback and control system for homeowners*

A web-based feedback and control system has been developed which engages a homeowner in active management of residential energy consumption. It offers the user feedback using dynamic and intuitive visual elements about appliance operating states, historical electrical energy consumption information, etc. Appliances can be manually controlled ON/OFF from anywhere with an Internet connection. The smart user interface lets the user perform important tasks with as little cognitive load as possible. As the VT HEM is web-based, it can be accessed using ubiquitous handheld Personal Mobile Device (PMD) computers.

- *Designed and incorporated intelligent Home Energy Management (HEM) algorithms*

In addition to the ability to manually turn ON/OFF appliances by a homeowner, the HEM system itself can also automatically manage appliance operation ensuring that household comfort settings and scheduling preferences are satisfied during a DR event. This automation enables a homeowner to participate in a DR program. Suitable algorithms have been identified, implemented and incorporated within the HEM system.

- *Enabled communication and interoperability between the proposed HEM system and third-party systems, including demonstration of a web-based control system for an electric utility*

Now with the advent of automated HEM, it is reasonable to expect it to act as a platform for new innovations that would make it possible for third-party systems to be seamlessly integrated with the system offering HEM services. The proposed system architecture and web services make it possible for a customer to participate in a DR program where an Advanced Metering Infrastructure (AMI) is not present. With the proposed HEM system, DR signals can be sent from an electric power utility via a web server to a dedicated customer-based device, which can be an iPad or a panel on a kitchen wall. Once the signal is received, it will be used to allow appliance-level control within a home based on customer's preset preference settings. In this work, the chosen HEM algorithm has been extended and demonstrated for a multi-home scenario, where it showcases a utility performing DR on multiple homes within a neighborhood.

- *Implemented selected features of device organization and interface for end-use appliances based on ZigBee Device and Smart Energy Profiles (SEP)*

Wireless networking within a home has been implemented using selected communication standards and applications. For communications between various components resided within a home, the ZigBee mesh networking protocol has been utilized as the Network Layer protocol, which is capable of routing when multi-hop communication is necessary. It in turn depends on the IEEE 802.15.4-2003 wireless communication standard as the Media Access Control (MAC) layer for point-to-point single-hop communication. Device organization and interface for end-use appliances have been implemented based on ZigBee application framework and Smart Energy Profile.

- *Implemented selected security measures for the web-based HEM system over the Internet and the Home Area Network*

All necessary measures to secure communication links of the web-based HEM system that goes through the Public Internet have been implemented. Wireless communications within the home private network has been secured as well. In addition, detailed analysis of security requirements and potential vulnerabilities for the proposed web-based application are presented.

11.2 Future Work

As a future work new algorithms, which would be able to intelligently assign load limits based on transformers, need to be developed. Metrics should be developed to validate and compare performance of demand response algorithms. End-users should be interviewed in scientific manner to characterize the objective function of the algorithms. More work would be necessary in estimating/learning physical parameters dynamically and applying for better optimization by the algorithms. For interoperability, systems from other researchers or commercial products should integrated with the VT HEM-WS. There is room for conducting experimental evaluation of the ZigBee security related issues in the context of Application Layer and Network Layer. In addition to the developed web-based interface presented in this work, native user interfaces for handheld devices, e.g., iPhone, iPad, can also be developed for end users. IP-based HAN implementation using Wi-Fi and Smart Energy Profile version 2.0 could also be explored.

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