On The Design and Implementation of a Home Energy Management System

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***Abstract*—To reduce energy consumption and wastage, effective energy management at home is key and an integral part of the future Smart Grid. In this paper, we present the design and implementation of Green Home Service (GHS) for home energy management. Our approach addresses the key issues of home energy management in Smart Grid: a holistic management solution, improved device manageability, and an enabler of Demand-Response. We also present the scheduling algorithms in GHS for smart energy management and show the results in simulation studies.**

***Index Terms*—smart grid, home energy management**

I. Introduction

Today the rate of energy demand increase in many countries far out-strides the growth of energy production capability. A consequence of this discrepancy is the noticeable rise in electricity price over the past decade and the increasingly frequent power curtailment and blackouts during peak demand. In the effort to reduce energy consumption and wastage, effective home energy management is key, and an integral part of the future Smart Grid. Following the Smart Grid vision, we believe there are three major issues to address for future home energy management:

- **All-encompassing management solution**: Consumers lack structured information about floating energy price (especially if Real-Time Demand Response is implemented) and their home-wide energy consumption. There is no standard protocol or data format for obtaining these information from various metering devices and smart appliances. The planning and control capability at home is also severely lacking.
- **Improved device manageability in home area networks**: multiple communication technologies (e.g. Power-line communication, ZigBee, Ethernet, etc.) and myriads of heterogeneous data formats and device-specific protocols dominate home area networks. There needs to be a flexible and extensible system design that not only inter-work heterogenous devices but also allows easy inclusion of future smart appliances and meter/control devices. The ability to auto-configure communication parameters according to changing environment is also essential. This is particularly important for low-power wireless communication technologies such as ZigBee.
- **Enabler of Demand-Response program**: it is envisioned that the regulation of demand-side energy consumption at the global level will be realized through Demand-Response (DR) programs. It is up to the homes to comply with the DR program or suffer its harsh consequences (e.g. energy outage and/or expensive electricity bills).

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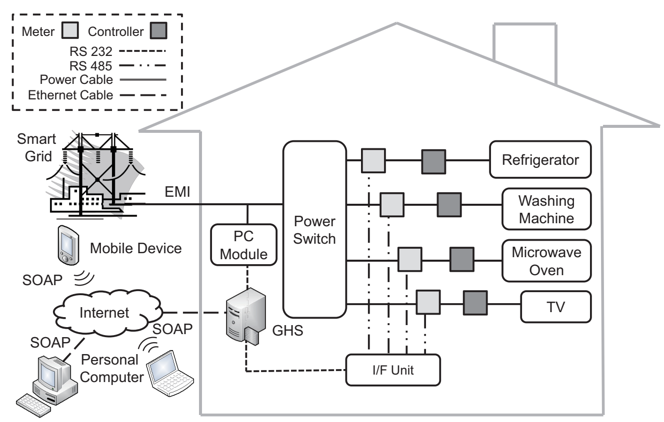

Fig. 1. Green Home Service Deployment in POSTECH for Smart Grid

Consequently, there is a strong need for an effective and comprehensive home energy management system. In this paper, we present the design and implementation of Green Home Service (GHS) which provides automated metering/control and decision making capabilities to the home owners. Figure 1 depicts the GHS deployment in our test home. GHS interfaces with the

Smart Grid through the Energy Management Interface (EMI) and can send home energy usage information and receive Demand-Reponse pricing and control signals. It communicates with the home appliances through diverse monitoring and control protocols. Our GHS design has the following key features: 1) GHS facilitates the automatic monitoring and control of home appliances with heterogenous interfaces and communication protocols. Through the use of Aspect-Oriented Programming (AOP) paradigm with Event-Condition-Action (ECA) Policy rules, GHS is able to not only inter-operate with heterogenous devices, but also affords easy integration of new home devices without modifying the existing system. 2) GHS embeds smart task scheduling algorithms that can automatically schedule home owners' daily tasks according to consumer-specified deadlines and the energy price.

The remainder of this paper is organized as follows. Section II presents related works on architecture of energy management system and demand-side energy management, and Section III presents the GHS architecture and a case study. In Section IV we briefly describe the task scheduling algorithms. Section V reports on a number of simulation studies performed. Section VI concludes the paper.

II. Related work

Some home energy management architectures are proposed in literature. They can be categorized based on where the decision making capability resides:

- **Device side**: decision making module is implemented inside the device. The Home Energy Saving System (HESS) [1] is based on this architecture. It aims at reducing the energy consumption by cutting off stanby power. A dedicated module inside the device monitors the appliance's status. Device side architecture can utilize device specified functions. On the other hand, a standardized protocol and device-specific system must be built for each new device.
- **Neighborhood side**: in this architecture, decision making is done at the neighborhood level. The implementation can be either at each home (distributed) or at the neighborhood server (centralized). The work on energy consumption scheduling [2] adopts a distributed approach using incentive-based mechanism. Because the optimization is done at neighborhood level, ensuring consumer satisfaction for each home is not the focus if these types of approach.
- **Server side**: decision making resides inside home gateway. Centralized decision making is thus easy to implement, however server-to-device communication requires device-specific modules and thus extensibility is a major issue as new devices are introduced. Work such as [3] proposes a rule-based framework that is based on this type of design.

Open Service Gateway Initiative (OSGi) is a popular technolopgy for implementing home gateway. For instance the framework proposed by Zhang et al. [4] is based on OSGi. It uses agent based decision making for managing different services and devices in smart home. OSGi platform realizes interoperability between home gateway and home devices by applying a standardized platform, it requires the gateway and devices to use Java Virtual Machine (JVM). Such reliance is not technology neutral and does not fit well with the heterogeneity in device designs that we observe in today's smart home context. Furthermore, many of the smart appliance/devices prefer low capacity and low computing platforms for cost and energy saving reasons and therefore JVM support is not guaranteed.

Task scheduling is a classic area in computer systems research where majority of the interesting problems are NP-Hard. We skip the related works for brevity, and note that our algorithm approach is developed based on the well-known Longest Process First heuristic for task scheduling.

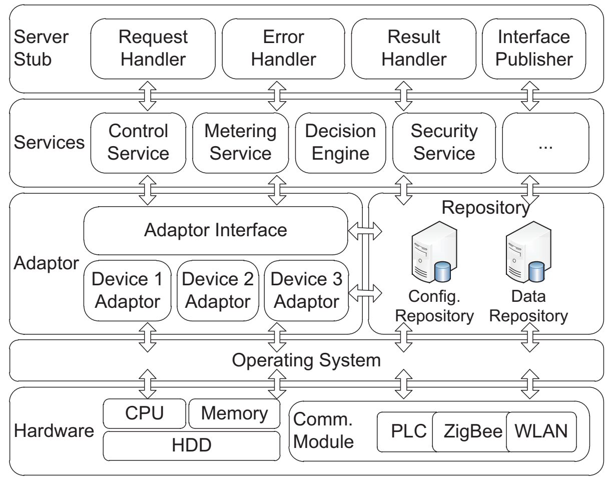

Fig. 2. Green-Home Service Architecture

III. Green Home Service (GHS)

A. GHS architecture

In this section, we discuss the design and implementation of GHS. After considering the different architectural approaches we find that, device side model is easy to construct and implement but many of the appliances we work with do not provide the programmable capability to receive and process the client request, and building device-specific controller is cost prohibitive; the neighborhood side model is not focused on home energy management and therefore is not suitable in our context. Therefore we choose to design the Green Home Service (GHS) using a server side architecture and tackle the interoperability and extensibility shortcomings with Aspect-Oriented Programming (AOP) approach.

GHS is a home-based server application that interacts with the Smart Grid through standardized Energy Management Interface (EMI) to receive Smart Grid pricing signals and control messages. It also conducts automated monitoring, planning and control of the home appliances with heterogenous access technologies. The GHS architecture consists of four components (Figure 2):

- Server Stub: Web service interface to the client applications and a dedicated EMI interface to the Smart Grid.
- Services: GHS functions such as metering, decision engine, control, etc. The task scheduling algorithms reside in the decision engine. Through service invocation, GHS monitors and controls home appliances for energy management, and execute the decisions of the scheduling algorithms.
- Repository: stores metering data and device information such as adaptor-to-appliance mapping.
- Adaptor: each adaptor is appliance specific. Multiple communication technologies are supported through the use of appliance specific adaptors.

To deal with the diversity of today's smart appliances and meter/control devices, our GHS design ensures:

- **Interoperability**: GHS must be able to interwork with multiple communication protocols and technologies seamlessly, without exposing the proprietary protocols to the applications/users.
- **Extensibility**: new appliances with new communication protocols must be able to join the GHS home environment with minimum service interruption.
- **Efficiency**: appliance specific operations must be optimized and exceptions handled gracefully.

An Aspect-Oriented Programming (AOP) approach is applied to the GHS Adaptor design which offers a viable and effective solution that meets the above requirements.

B. *Aspect Oriented Programming in GHS*

Aspect Oriented Programming (AOP) [5] based system design allows for a master process (i.e. the GHS services) to be kept separate from system specific logic. In our case, if an adaptor requires special trap calls to handle specific commands and/or events, these calls can be kept separate (Pointcuts) and are automatically weaved in during execution. Thus, special code logics and function calls (Advices) for specific appliance protocols can be gracefully added/removed to GHS without affecting the master architecture. This feature offers a clean approach to achieve interoperability and extensibility. An aspect in GHS is defined by its advices and pointcuts modulated via policies.

Figure 3 shows the AOP-based adaptor framework in GHS. An Adaptor Master Process (AMP) executes a general process flow and is specialized at runtime to fit specific adaptors following these steps: 1) The server stub receives request from the client. 2) Server stub differentiates each request and forwards to the corresponding service. 3) The service communicates with a home appliance to fulfill the request. 4) AMP is invoked in this step but not executed. It selects the corresponding aspects based on the pre-defined policies. 5) Finally, corresponding aspects are integrated into AMP to form an integrated appliance-specific process and executed. Four aspects are defined in GHS:

- Adaptor instantiation aspect: instantiate an adaptor for an appliance based on context information. These aspects deal with protocol specifics, such as those of the Power Line Communication protocol and the ZigBee protocol (IEEE 802.15.4).
- Communication control aspect: protocol specific algorithms are designed as aspects in order to handle operational constraints. For the ZigBee protocol, GHS includes Speed Accelerator Aspect to reduce communication delay by adjusting duty cycle length; and Channel Selector Aspect to minimize interference with WLAN through channel hopping.
- Quality assurance aspect: monitor key communication metrics, including delay and interference (i.e. collision time and SINR) such that appropriate communication control aspects can be deployed if required.
- Exception handling aspect: handles appliance specific errors that the upper layers (i.e. the services) are not aware of and thus cannot process properly if thrown.

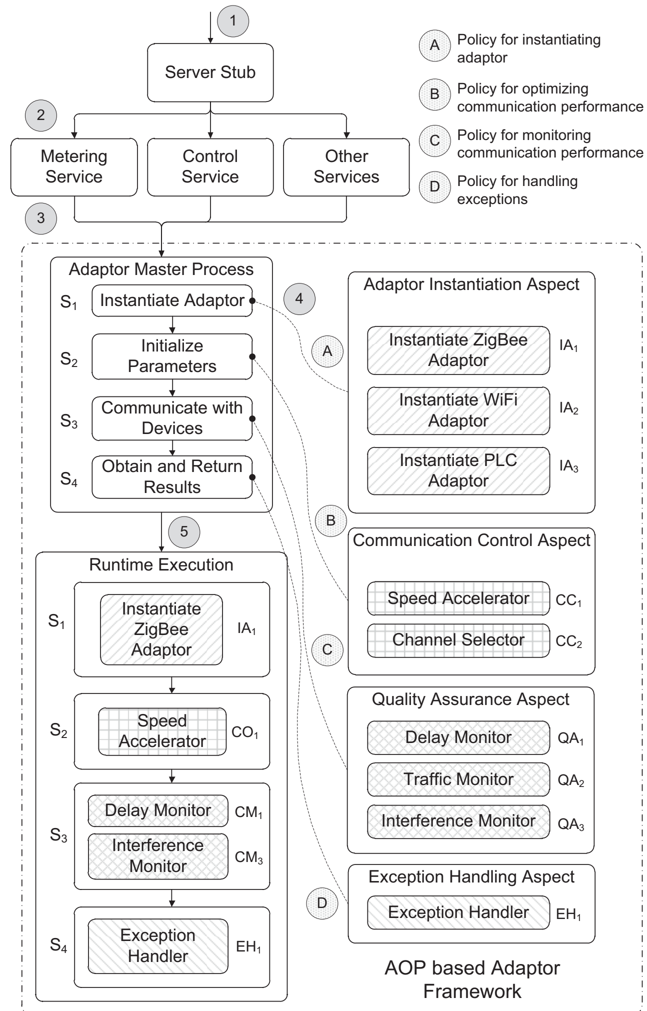

Fig. 3. AOP-based Adaptor Framework

C. *A Case Study of Applying Aspects*

As the case study, we show the application of communication control and quality assurance aspects for assuring device com-

```
<aop:config>
   ...
   <aop:aspect id="qualityAssuranceAspect"
               ref="qualityAssuranceAdvice">
      <aop:pointcut id="intercepOfAllCommMethod"
            expression="execution(* ghs.*.Comm*(..))" />
      <aop:around pointcut-ref="interceptionOfAllCommMethod"
                          method="delayMonitor" />
   </aop:aspect>
   ...
</aop:config>

<bean id="qualityAssuranceAdvice" class="ghs.QualityAssurancer" />
```

Fig. 4. A policy for monitoring communication matrix

```
<aop:config>
   <aop:aspect id="commControlAspect" ref="commControlAdvice">
      <aop:pointcut id="intercepOfAllInstInitMethod"
            expression="execution(* ghs.CommAdaptor.instInit*(···))
                                                   and args(···)" />
      ...
      <aop:before pointcut-ref="intercepOfAllInstInitMethod"
                          method="speedAccelerator" />
      ...
   </aop:aspect>
</aop:config>

<bean id="commAdaptor" class="ghs.CommAdaptor"/>
<bean id="commControlAdvice" class="ghs.CommController">
   <property name="delay" value="4s" />
</bean>
```

Fig. 5. A policy for optimizing communication performance

munication QoS. Suppose the following scenario: a request is issued for obtaining the current energy consumption of TV, and the TV's metering device uses ZigBee communication. Moreover, for the sake of saving energy, the ZigBee is configured to have a default duty cycle of 1% and a Superframe Order (SO) value of 3. Since this is the first time to communicate with metering device, there is no reference data available to trigger the communication control aspect. In parameters initializing step, the default values (duty cycle=1%, SO=3) are set as communication parameters. Based on theoretical study of ZigBee [6], we estimate the round-trip communication delay to be 7 seconds, which exceeds our QoS delay bound. This delay value is monitored and recorded by the delay monitoring aspect of our quality assurance aspect.

More specifically, a timer resides in delay monitoring aspect to measure the communication speed. The master process is invoked after we start the timer, and ending timer is followed. Based on the two measurements, the round-trip communication delay is computed. This aspect is defined as a combination of communication metric monitor advices as well as the pointcuts for intercepting all communication related methods (Figure 4). To make the pointcuts intercept all communication related methods, the name of each method follows a naming convention. In this example, we set the names of those methods starting with "Comm" prefix, to denote that the methods are related to communication. Thus we are able to obtain accurate application-appliance delay metric at runtime without relying on specialized hardware devices or modifying/wrapping the core GHS code.

The delay time is compared with a quality coefficient (4s in this case) which is assigned as a property value of communication control advice (Figure 5). Several aspects for ensuring communication performance have been defined in the communication control advice class to realize our policy, but only the speed accelerator aspect is triggered and injected into AMP in this case. Thus, when the GHS experiences parameter initializing phase second time, speed accelerator aspect would be triggered, consequently a new duty cycle as well as SO value is now applied to the communication protocol. In this way, GHS system is able to auto-configure itself based on the changing environment.

IV. Optimal Home Energy Management

A. Problem formulation

The decision making capability of the GHS resides in its Decision Engine service, implemented as scheduling algorithms that automatically schedule home owners' daily tasks according to their deadlines and the electricity price. A home owner's daily activities can be characterized by a list of tasks to be scheduled at preferred time intervals. Some of these tasks are persistent, as they consume electricity throughout the day (e.g. refrigerator), while others are somewhat flexible within a reasonable time interval (e.g. washer/dryer). We define the task as an energy demand d such that $d_j = (s_j, f_j, r_j, l_j) \in D$ where s is a start time, f is an end time, r is electricity requirement per hour, and l is the task length. Figure 6 illustrates the home energy management problem. The objective is to find an optimal assignment of tasks to time slots such that

$$\min\{\max_t\{\sum_{d_j \to t} r_j\}\}$$

while obeying the constraint that, the schedule of a task $d_j \to t$ does not violate its deadline, i.e.

$$s_j \leq t \textit{ and } f_j \geq t + l_j - 1$$

Specifically, we consider a task d_j to have a schedule interval $\{s_j, f_j\}$, an electricity requirement r_j and a length of use l_j. To schedule a task to a time slot ($d_j \to t$) means to assign d_j to a set of contiguous time slots from time slot t to time slot $t + l - 1$, such that it falls within the schedule interval $\{s_j, f_j\}$. Or in another word, how to best time-shift home energy usages while still obeying deadlines. The relaxed version of this problem is similar to deadline constrained task scheduling problem which is known to be NP-Hard. When we attempt to obtain the optimal solution of our problem for 28 tasks, the runtime was over 1 hour, hence an approximation or heuristic solution is necessary.

B. Task-scheduling Approach

We have designed a $minMax$ scheduling algorithm based on Longest Process Time (LPT) greedy search heuristic. The $minMax$ algorithm is started from sorting tasks based on

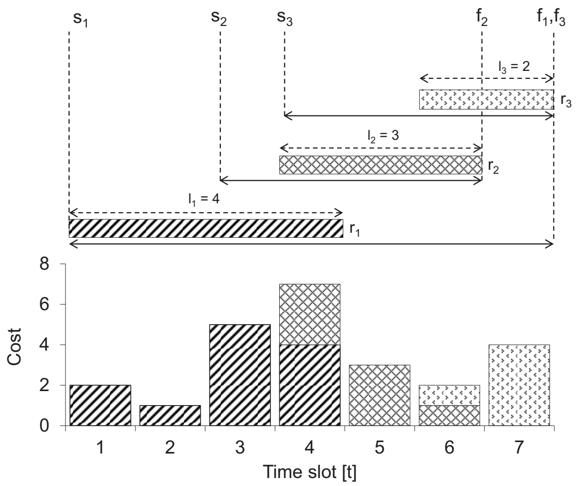

Fig. 6. The Demand-Side Energy Management Problem

Algorithm 1 BatMax Scheduling

Use output of *minMax* as input:
n number of time slots, m number of demands
For each time slot $t \in T$ where $1 \leq t \leq n$:
Aggregate energy demand $E_t = \sum_j r_j$ for all task j assigned to t
b_t is the battery buffer at time t and B is the charging rate of battery per hour.
Output:
b_t for all time slot t

Initialize b_t to zeros
Compute $avg = \sum_t^n E_t/n$
for $i = n$ to 2 **do**
  if $E_t + b_t < avg$ **then**
    $avg = avg + \frac{avg - E_t - b_t}{i-1}$
  end if
  if $E_t > avg$ **then**
    $o = E_t - avg$
    for $k = i - 1$ to 1 **do**
      Find time slot k where $E_k + b_k < avg$
      Fill b_k with o such that $E_k + b_k = avg$, or $b_k = B$, or $o = 0$
      Break loop when $o = 0$
    end for
    if $o > 0$ **then**
      $E_i = E_i + o$
      $avg = avg - \frac{E_t + b_t - avg}{i-1}$
    end if
  end if
end for

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r as major key and l as minor key in descending order. Then, the tasks are assigned within time frames from s to f while minimizing the maximum of accumulated hourly energy demands. The $minMax$ algorithm always assigns tasks before deadline, thus guaranteeing home owners' satisfaction. We have proven that minMax is a near-optimal approximation [7]. The gist of our proof is that our algorithm is a near-optimal approximation of the energy scheduling problem without deadlines, and through relaxation we can obtain a worse approximation factor when deadlines are added.

Here we present an enhancement algorithm, the $BatMax$ scheduling algorithm which incorporates the use of electric vehicle (EV) chargers as a high-capacity battery (Algorithm 1). The goal is to charge the battery at off-peak times in order to supplement the home energy usage during peak times. The algorithm operates as follows: 1) as input we take the schedule produced by the $minMax$ algorithm, in particular the aggregate demand at each time slot. 2) Starting with the last time slot, we attempt to shift extra demand that is above average forward to time slots where demands are below average. 3) We continue this process forward across all the time slots and update the running average whenever a gap (a time slot with demand below the running average) is encountered. The complexity of $BatMax$ is $O(n)$, where n is the number of time slots. The solution produced by $BatMax$ is optimal. We skip the proof here due to lack of space. In gist, we can show the algorithm is sub-optimal in each iteration and by updating the running average it is optimal overall. The performance of our energy management algorithms is demonstrated in Section V.

V. Implementation and Simulation

A. Implementation Environment

The following implementation technologies are used to realize the GHS system design and our AOP-based approach:

- **SOAP protocol**: SOAP as a Web Services technology can be used to invoke remote procedures between GHS client and GHS server which is platform independent.
- **Spring framework**: Spring framework is a J2EE based open source framework. Spring framework version 2.5.6 contains an AOP module which is a light weight implementation with basic AOP features.

To date, we have developed two types of client applications, one for windows platform, and the other for Google android smart phone (Figure 7). The PC version is implemented using .NET Framework and programmed in C# language, it is currently deployed on the PC of our test home. While the mobile version is developed based on android OS 2.2 (froyo) and programmed in Java, allows for location-free access to GHS even when the user is not at home.

B. Simulation

We have also performed simulation studies to evaluate the performance of our GHS in terms of home energy management. We have constructed a task generator that reproduces the typical appliance usage patterns in Korea, based on the data provided by the Korea Power Exchange for 2009. We have also constructed a market-based Demand-Response pricing using the current Korean home energy price as the mean and created an incentive-based exponential price function: energy consumption on peak hours is exponentially expensive, while energy consumption off peak hours is fractionally discounted. Table I shows the parameter setting for each of the 10 appliances being surveyed.

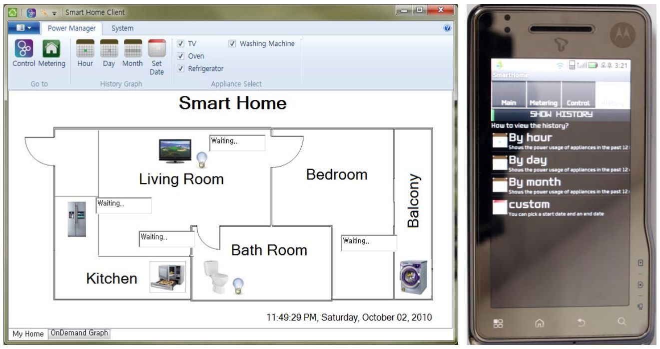

Fig. 7. GHS Client deployed as pc and mobile phone application

TABLE I
APPLIANCE CHARACTERISTICS

Category	Appliance	Time Shift	Energy Rate (Watt/hr)	Task length
Fixed	TV	0	200	3
	Cooker	0	1400	2
	Microwave Oven	0	100	1
Tight	Computer	1	500	3
	Hair Drier	1	500	1
	Iron	1	900	1
Flexible	Audio	3	70	4
	Washing Machine	3	130	2
	Vacuum Cleaner	3	600	1

The home task generator generates a data set of 1,000 homes, where each home contains 30 to 45 tasks to be scheduled in a 24-hour period. We execute our algorithms for each home. We start the 24-hour scheduling period at 3:00 am because it is off peak time and therefore ideal for battery charging (a high capacity battery with 1.71 kW/hr charging rate and 24 Kw storage is used).
Figure 8 shows the cumulative effect of running the GHS system in 1,000 homes. The top figure shows the aggregate energy demand of each home without running GHS. During peak-time (9 PM), maximum energy demand shows 2,345.320 kW and total energy cost is 8,407,215.706 KRW. The bottom figure shows the effect of running GHS (with the minMax and BatMax scheduling algorithms). It yields 1,697.194 kW maximum peak demand and 7,377,056.486 KRW total energy cost. That is 27.6% in peak demand reduction.

VI. CONCLUSION

We have presented the design and implementation of the Green Home Service, a comprehensive home energy management solution that provides automated metering and decision making capabilities in Smart Grid. GHS can interact with the Smart Grid through EMI, communicate with diverse home appliances with runtime QoS support, and intelligent scheduling of tasks based on user preference. Our approach achieves high interoperability, is extensible and efficient. We have shown the practical use our approach by deploying GHS prototype in a test home. The simulation studies we have conducted on energy management over 1,000 homes demonstrates the effectiveness of our approach in terms of energy saving by time shifting and battery buffering. As future work, we will continue to mature the GHS implementation in inhabited homes and extend our work to enterprise ICT context.

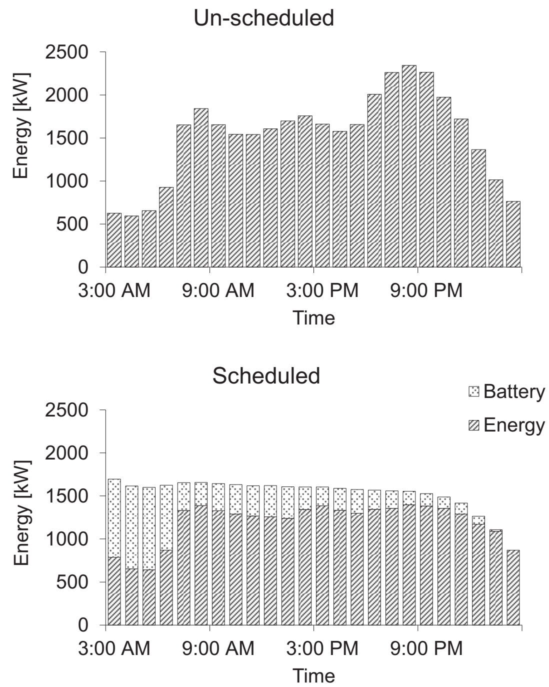

Fig. 8. Demand smoothing through *minMax* and *BatMax* scheduling with 1000-house accumulation

REFERENCES

[1] K. S. Choi, Y. K. Ahn, Y. C. Park, W. C. Park, H. M. Seo, K. M. Jung, and K. H. Seo, "Architectural design of home energy saving system based on realtime energy-awareness," *Ubiquitous Information Technologies Applications, 2009. ICUT '09. Proceedings of the 4th International Conference on*, pp. 1–5, December 2009.

[2] A.-H. Mohsenian-Rad, V. Wong, J. Jatskevich, and R. Schober, "Optimal and autonomous incentive-based energy consumption scheduling algorithm for smart grid," in *Innovative Smart Grid Technologies 2010 (ISGT 2010)*, January 2010.

[3] C. Y. Leong, A. R. Ramli, and T. Perumal, "A rule-based framework for heterogeneous subsystems management in smart home environment," *Consumer Electronics, IEEE Transactions on*, vol. 55, no. 3, pp. 1208–1213, August 2009.

[4] H. T. Zhang, F. Y. Wang, and Y. F. Ai, "An osgi and agent based control system architecture for smart home," *Networking, Sensing and Control, 2005. Proceedings. 2005 IEEE*, pp. 13–18, March 2005.

[5] G. Kiczales, J. Lamping, A. Mendhekar, C. Maeda, C. Lopes, J.-M. Longtier, and J. Irwin, "Aspect-oriented programming," in *Proceedings European Conference on Object-Oriented Programming*, 1997, pp. 220–242.

[6] M. Petrova, J. Riihijarvi, P. Mahonen, and S. Labella, "Performance study of ieee 802.15.4 using measurements and simulations," *Wireless Communications and Networking Conference 2006 (WCNC 2006)*, vol. 1, pp. 487–492, April 2006.

[7] J. Xiao, J. Chung, J. Li, R. Boutaba, and J.-K. Hong, "Near-optimal demand-side energy management under real-time demand-response pricing," in *IEEE Conference on Network and Services Management (CNSM 2010), mini-conference*, October 2010.