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Home Appliances Coordination Scheme for Energy Management (HACS4EM) using Wireless Sensor Networks in Smart Grids

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Abstract

In this paper, a home energy management (HEM) scheme based on appliances coordination has been proposed for future smart grids. This scheme is based on communication among home appliances, a central energy management unit (EMU), smart meter and the storage unit inside home. A wireless sensor home area network (WSHAN) using ZigBee protocol is employed for relaying messages among different entities involved in our proposed HEM scheme. The performance of WSHAN is analyzed with respect to different networking properties. HEM implementation will lead to socially and economically beneficial environment by addressing the consumers' and utilities concerns. Increased savings, better peak load management and reduction in peak to average ratio are some of the benefits achieved by proposed scheme. Appropriate use of HEMs in a system integrated with distributed resources along with appliances co-ordination and dynamic pricing scheme provides the optimized solutions for energy management issues in smart grids as confirmed by simulation results.

Keywords: Smart grid; Home energy management; Demand side management; Appliances coordination.

1. Introduction

Electrical grid consists of the four major parts: electricity generation, transmission, distribution and utilization. Real time monitoring and control will become possible in future smart grids by integration of advanced Information and Communication Technologies (ICTs). Provision of reliable energy services in context of increased environmental concerns will become possible in future smart grids[1]. Various technologies are being developed by researchers for realization of smart grid including: Advance Metering Infrastructure (AMI), Home Area Networks (HANs), Distribution Automation (DA), etc.[2]. Services of the traditional grid have been used by the humanity since decades. Global population and the dependency level of humans on electricity are increasing exponentially. There exists a huge po-

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tential of research and innovations for conversion of traditional grid into smart grid in order to meet the challenges of twenty first century[3].

Applications of smart grid include various areas like transmission and distribution automation, optimized utilization, commodity trading of electricity in competitive markets etc. Our focus is home energy management which can be optimized in smart grid environment. Home appliances equipped with sensors along with AMI make the real time energy monitoring possible which is a parameter of extreme importance for utilities. This will help in reducing carbon print because of the excessive use of the peaker plants which are a big source of green house emissions[4,5].

Demand Response (DR) and Demand Side Management (DSM) based on bi-directional communication is enabled by smart grid in order to smoothen the load curve of the traditional grid. DSM programs influence the behaviour of the consumers regarding electricity consumption. Authors in[6] have used day ahead pricing scheme for home energy optimization. The objective of minimizing the peak load demand can be achieved by scheduling the home appliances and/or Distributed Energy Resources (DER). For this purpose various energy management schemes have been proposed. In[7] a Linear Programming (LP) model has been presented that aims at minimizing the cost of electricity consumption at home. In this scheme, a day is divided in consecutive time slots of equal lengths with varying prices of electricity consumption similar to Time of Use (ToU) tariff. The objective function devised in[2] minimizes the home energy expenses by scheduling the house loads in appropriate time slots. Inputs of LP model are consumer's requests and the model gives optimum appliance scheduling at the output. An energy management scheme, namely iHEM, is presented for domestic energy management in [2]. The scheme involves smart appliances, EMU, WSHAN and communications among these entities. iHEM uses ZigBee protocol for the implementation of wireless sensor network (WSN) organized in cluster-tree topology. The application is based on appliance coordination system. Unlike the LP model the consumer demands are processed in near real time in iHEM.

In[8] ACORD scheme aims at ToU pricing benefit and decreased energy cost. Objective of ACORD scheme is to shift the consumer load to off-peak periods. In-home WSNs are used for delivery of consumer requests to EMU. In[9] the authors have devised a Decision support Tool (DsT) for smart homes. The DsT based scheme coordinates only the DERs. As a case study, a space heater, a Plug-in Hybrid Electric Vehicle (PHEV), a pool pump, a Photo Voltaic (PV) system and a water heater are scheduled based on various ToU prices by applying the co evolutionary particle swarm optimization (CPSO) technique. DsT is composed of DER scheduling algorithm and an energy service model. The net benefit of the consumer is maximized by scheduling the controllable DER according to the scheduling algorithm. Using this scheme the consumer electricity bill is reduced by 16-25%[9]. In[10] an optimal and automatic residential energy consumption scheduler has been proposed for a scenario where real time pricing (RTP) is combined with inclining block rates (IBR). Load control programs for real time pricing need price estimation hence the scheduler is combined with a price predictor. This strategy reduces energy bill by 8-22%[11]. Comprehensive reviews of smart grid applications including HEMS have been conducted in[12,13]. Section 2 elaborates the proposed scheme and section 3 explains the algorithm used. Section 4 and 5 are reserved for network explanation and simulation results respectively. Conclusions are drawn in section 6.

2. Proposed Scheme

In this section we propose our scheme for energy management: the Home Appliances Coordination Scheme for Energy Management (HACS4EM). HACS4EM is a communication based domestic energy management scheme which is primarily aimed at reducing home electricity consumption charges. The scheme involves communications among smart appliances, a central EMU and WSHAN. Conceptual interaction of different entities of this scheme is elaborated in Fig. 1. The aim of this scheme is to decrease the electricity bill of the consumer by shifting the appliances operation from peak demand hours to off-peak. HACS4EM is an appliance coordination system based application. The concepts of smart appliances, smart meters and WSHAN are the basis for HACS4EM. A central processing unit is the decision making centre and we call it energy management unit (EMU). The consumer may turn on any appliance at any moment irrespective of the peak hours concern and then HACS4EM suggests a convenient start time to the consumer. On switching the appliance on, a START-REQ packet is sent by the appliance to the EMU. Upon receiving the START-REQ packet, EMU corresponds with the storage system to inquire about the available stored energy by sending AVAIL REQ packet. EMU also communicates with smart meter to know about the updated prices. The storage unit sends an AVAIL-REP packet in reply, containing the information about the amount of stored energy.

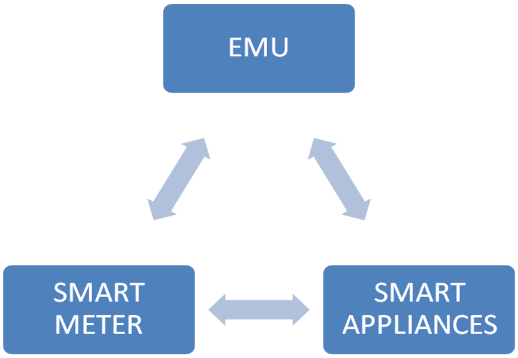

Fig. 1: Interaction among Major Entities of HACS4EM.

When EMU receives the AVAIL-REP packet, it schedules a convenient start time for the appliance according to the HACS4EM algorithm and notifies it to consumer by sending a START-REP packet. The consumer, at this stage may be willing to negotiate with EMU, through the NOTIFICATION packet. The message flow is shown in Fog. 2.

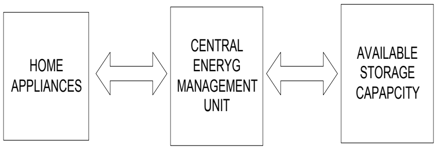

Fig. 2: Message Flow in HACS4EM Application.

3. HACS4EM Algorithm

Proposed algorithm consists of nine steps which are depicted in Fig. 3 and are elaborated as follows:
Step-1: In first step of the proposed algorithm, the consumer turns on his ith appliance which generates and sends a packet to the EMU. In our simulation we have generated these packets randomly.
Step-2: On receiving the START-REQ the EMU communicates with smart meter and storage through AVAIL-REQ to know about the time of use (ToU) prices. The ToU prices tell the EMU the corresponding energy consumption prices at that particular moment. The EMU can easily find whether the current time lies within peak hours. EMU checks the starting time of the appliance S_{t_i}. If it lies outside the peak hours, the EMU replies to the appliance through a START-REP packet and the appliance is started immediately, otherwise the algorithm moves to the next step.
Step-3: This step is taken if S_{t_i} is found to be in peak hours. In this step the EMU checks for all the standby appliances in home and turns off all irrespective of their requests to be switched on, as it has been reported that standby appliances have played a reasonable role in energy wastage
Step-4: If the starting time of appliance S_{t_i} falls inside the peak hours the EMU communicates with the local energy storage (solar, wind, PHEV, UPS battery etc.) inside the home to inquire about the locally generated or stored energy in the system. If there is enough energy in the storage system for the appliance, it is started immediately without any delay otherwise the algorithm moves to the next step.
Step-5: After switching off all the standby appliances in home and in accordance with storage capacity, the EMU checks the power ratings of $\imath$th appliance P_i. Here we set a threshold value of power P_{max}. After the standby appliances are switched off and for every appliance request its power ratings are compared with the threshold value P_{max} . For all $P_i \leq P_{max}$ the appliance is directed to start immediately otherwise the algorithm moves to the next step. In our simulation we have set the value of P_{max} to be 1 kWh.
Step-6: This step is taken if the power ratings of $\imath$th appliance is greater than the threshold value i.e. if $P_i \geq P_{max}$. If the condition is true the appliance operation is shifted from peak hours to off peak hours. Hence a delay is introduced

in the operation of appliance cycle. Different techniques of DSM have already been discussed in our work and we have selected the load shifting technique in our proposed HACS4EM scheme.

Step-7: As the appliance operational cycle has been delayed, and it is shifted from peak to off peak periods, a delay

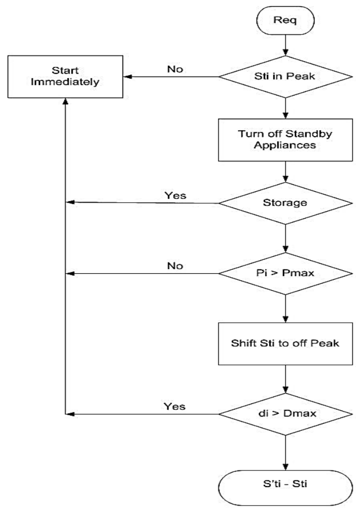

Fig. 3: HACS4EM Flowchart.

d_i is introduced which is equal to the difference of the scheduled time suggested by EMU and the request start time. This delay is inversely proportional with comfort level of consumer. They are never satisfied with large delays so we have introduced a threshold value of delay called D_{max}. If d_i is greater than D_{max} the appliance is directed to start immediately otherwise the operation cycle of the appliance ι is shifted.

Step-8: If the condition $d_i \geq D_{max}$ is not satisfied for any appliance request, appliance cycle is shifted to hours where electricity prices are comparatively low. To let the appliance know about its starting time the EMU calculates the delay in appliance cycle and sends it to appliance. The scheduled delay can be found from the following difference.

$$S'_{t_i} - S_{t_i} \tag{1}$$

where

S'_{t_i} is the starting time of appliance ι scheduled by EMU.

S_{t_i} is request start time by appliance ι. This value is returned to appliance ι and notified as its delay.

Step-9: At this point the consumer may be willing to negotiate with the EMU. The consumer may deny or accept the schedule provided by the EMU. EMU informs storage unit and smart meter about the consumer's decision through UPDATE-AVAIL packet.

4. Wireless Sensors Network in HACS4EM

WSHANs are deployed for data exchange between different entities involved in the operation. We assume that the WSN implements ZigBee protocol. ZigBee is an IEEE 802.15.4 based wireless technology with a typical range of 10-75 m; its main characteristics are low cost and low power consumption. Two types of devices are allowed by ZigBee. i.e. full function devices (FFDs) and reduced function devices (RFDs). FFDs are interconnected in a mesh topology which means an FFD can communicate with its peers. On the other hand RFDs can be edge nodes in a star topology where they cannot communicate with its peers. In HACS4EM model, the WSHAN is organized in a cluster-tree topology as shown in Fig. 4. The nodes in different rooms, associated with different appliances may be RFDs while the nodes in smart meter are FFDs. EMU coordinates the Personal Area Network (PAN). Smart meter may act as PAN coordinator however; EMU is better choice for this purpose due to its central location. There are two modes of PAN coordinator: one is beacon-enabled mode and the second is beaconless mode. Beacon-enabled mode defines the duty cycle with the Super-frame Duration (SD) of the super-frame structure. Node synchronization is performed by super-frame in the network. Nodes are able to communicate in the active period only. Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) technique is used by nodes in Contention Access Period (CAP) of the super-frame to transmit data. Guaranteed Time Slots (GTS) are available in Contention Free Period (CFP) are provided to the nodes which have previously set aside these slots for communication.

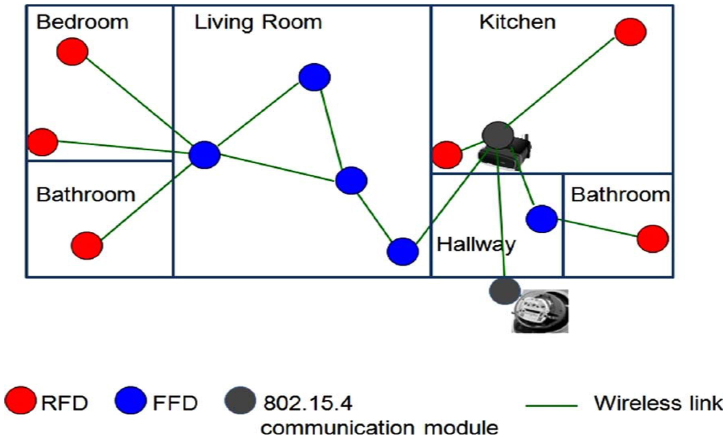

Fig. 4: WSHAN Topology in HACS4EM.

5. Simulation Results for HACS4EM

For simulation purposes, we have used a scenario of five loads: a washer, a dryer, a dishwasher and a coffeemaker with energy consumption ratings of 0.89 kWh, 2.46 kWh, 1.19 kWh, 0.4 kWh respectively while an extra load has been supposed whose electricity consumption value varies randomly between 0 kWh and 4 kWh. 80% of the extra load is the miscellaneous load and the remaining 20% is of standby appliances. Peak hours change with days and seasons. We have taken peak hours between 8 AM to 2 PM in our simulation. In [29] the authors have shown experimentally that the electricity consumption behavior can be modeled as a Poisson random distribution which is a discrete random distribution. In our case switching on of an appliance is considered as a Poisson distribution. For peak hours we have selected the inter arrival rate of request from an appliance to be negative exponential with an average of 4 hours while for off-peak hours we have selected two hours.

There is an opportunity for various pricing schemes in smart grid like time of use (ToU) pricing scheme, real time pricing (RTP), day ahead pricing (DAP), and Critical peak pricing (CPP). We have used the ToU pricing schemes in our scheme where the utilities charge the consumers differently depending on the time of use of electricity. The electricity charges are lower for off-peak periods and higher for peak duration. In our simulation we have used the rates of 8.5 Rs/kWh for off-peak hours and 13.2 Rs/kWh for the peak periods.The simulation results for HACS4EM show that our scheme is quite efficient in terms of reducing peak load demand, electricity consumption charges with an increase comfort level of consumers. All what the HACS4EM does is basically shifting and clipping the off peak load but with a different approach. Our scheme has referred to the problem of electricity wastage by standby devices in home. Standby power of an appliance is the power consumed by the appliance when it is not functioning or when switched off [13]. Standby appliances consume 10% of electricity [14]. Standby devices have been reported to be contributing to electricity wastage and hence it was necessary to tackle the wastage due to standby appliances in the new HEM scheme.

Next is the issue of appliances with high active and reactive powers. High reactive power means high amount of electrical energy loss which implies that load demand will be high. HACS4EM tackles this problem by introducing a threshold value of active or reactive powers in the peak hours. If an appliance ratings are higher than the threshold

value, its operation cycle is shifted to off peak periods.
Furthermore HACS4EM contributes more to comfort level of the consumer by putting a limit on the delay factor of an appliance. We do not want to have any inconvenience in the consumer mind. If the appliance cycle is shifted to off peak hours and the delay goes beyond the limit the cycle is retained and the appliance is switched on immediately.

5.1. Peak Load Reduction

Simulation results of HACS4EM and the case when no energy management is employed, is shown below in Fig. 5. The figure shows the electricity consumption pattern for a time duration of 24 hours. It is clear from the figure that HACS4EM algorithm shifts loads from peak hours to off peak hours efficiently. Percentage of load in peak hours is a ratio between the amount of load in peak hours to the total load. High value of this ratio results in high electricity charges due to the ToU pricing tariffs. HACS4EM reduces the percentage of load in peak hours in order to provide monetary benefits to the consumer. Fig. 6 shows the comparison of percentage of load in peak hours.

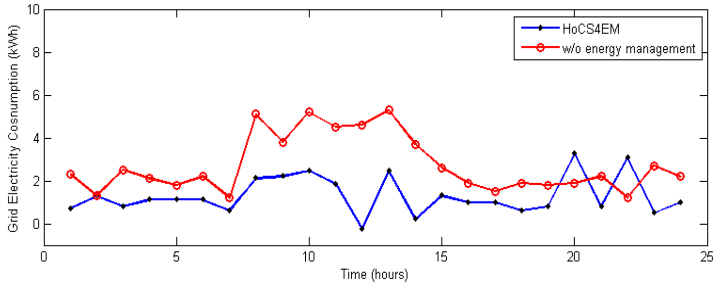

Fig. 5: Peak Load Reduction Comparison.

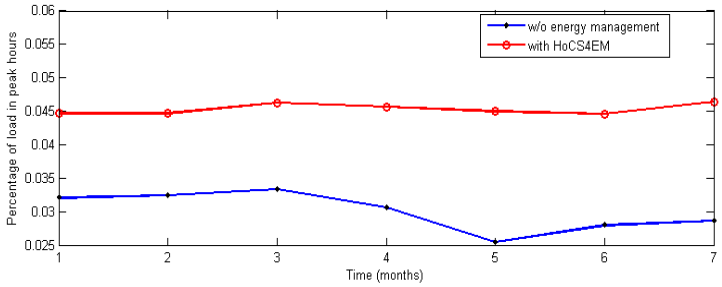

Fig. 6: Percentage of the Contribution of the Appliances to the Total Load on Peak Hours.

5.2. Monetary Cost Reduction

Utilities across the world have implemented various tariff schemes for peak load management. Our proposed scheme implements Time of Use (ToU) tariff. In ToU tariff, pricing rates are different for different hours. Water and Power Development Authority (WAPDA) charges 8.5 Rs/kWh in off peak hours and 13.2 Rs/kWh in peak hours. We have supposed peak hours from 8 AM to 2 PM and used the same rates as charged by WAPDA. We have simulated the electricity consumption cost of a single home when no energy management is applied and compared the results with the case when HACS4EM is employed for energy management purposes. The simulation results for seven months electricity bill is shown in Fig. 7. Note that the electricity bill increases with increasing months because the bill is calculated cumulatively.

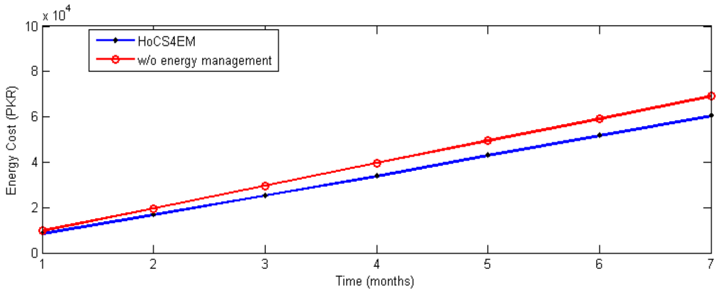

Fig. 7: Peak Load Reduction Comparison.

5.3. *Performance of Wireless Sensor Home Area Network*

The WSHAN uses ZigBee protocol and the network topology for our WSN is shown in Fig. 4. The PAN coordinator manages HEM and other WSHAN applications. ZigBee supports two types of devices i.e. Reduced Function Devices (RFDs) and Full Function Devices (FFDs). Total 14 RFD devices are used, out of which five are connected to the appliances, 5 FFDs are used for the purpose of packets routing. The Zigbee protocol utilizes a bandwidth of 250 kb/s using 2.4 GHz ISM band. Deploying a WSHAN only for relaying HACS4EM packets is costly. Hence, we assume that WSHAN relays the packets of monitoring application as well as HACS4EM. The overall performance of the network is affected by the packet size. The packet size of this application is varied between 32B and 128B. We assume here that the packets are generated at node at 10 min intervals. Fig. 8 shows that when packet size of the HACS4EM application increases the packet delivery ratio of the network decreases. With 32B packet size, the delivery ratio of the WSHAN is almost 85% and a delay (end-to-end) of almost 0.75 s is seen as shown in Fig. 9. Contention period is decreased by shorter packets hence delay is less and delivery ratio is high for those packets. Jitter is also an important parameter for HACS4EM performance. It is the variation in latency and a low jitter value means that consumers may experience less variation in end-to-end delay when they are exchanging data with the EMU. From Fig. 10, it can be seen that jitter is less than 0.06 s, which is negligible.

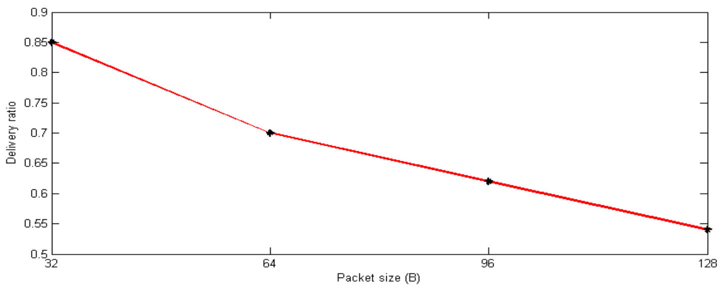

Fig. 8: WSHAN Performance in Terms of Delivery Ratio.

6. Conclusion

In this work, we have revisited the need of efficient electricity consumption in smart grid and proposed an appliance coordination based HEM scheme. WSHANs have been deployed in smart homes for monitoring applications. Our work has used the existing WSHAN mechanism for HEM purposes. HACS4EM addresses the role of standby appliances and high power rating loads in peak hours to the energy consumption charges of a consumer. The simulation results have been provided for daily load demand, consumers electricity charges for a period of seven months and percentage of load in peak hours. We have also shown the effect of packet size on delivery ratio, delay and jitter in the

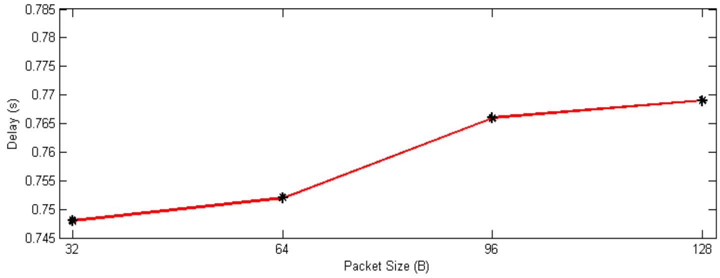

Fig. 9: WSHAN Performance in Terms of Delay.

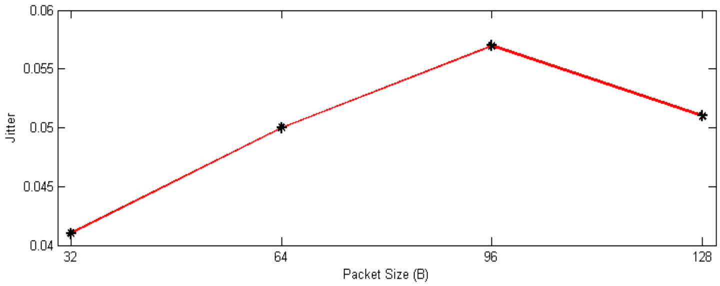

Fig. 10: WSHAN Performance in Terms of Jitter.

network.

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