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# PWM SYNCHRONIZATION FOR INTELLIGENT AGENT SCARCE RESOURCE AUCTION

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## ABSTRACT

*This paper is focuses on modulating a shared resource, power demand on the electricity grid, among intelligent agents charged with modulating residential HVAC systems. We discuss the use of synchronized control actuation signals (PWM) to simplify scarce resource auctions for control of a network of intelligent home agents. By synchronizing the actuation signal with the auction times, identification and prediction becomes simpler, and modulation of the shared resource is as easy as adjusting the saturation limits of the controller. We show results through simulation.*

## INTRODUCTION

The goal of this work is to develop a framework for distributing shared scarce resources amongst intelligent autonomous agents. In particular we are interested in modulating the total power consumption of a group of independent agents responsible for residential HVAC operation. Our system is hierarchical, consisting of independent home agents responsible for comfort and a super-agent responsible for the power regulation. The coupling between the home agents and the super-agent occurs through shared communications.

These goals fall within the domain of load management which is a well studied field, and a good overview is contained in [1]. Directly manipulating the on/off cycles of the HVAC unit via a radio operated compressor switch has been examined in detail, see [2] for example. Adjusting the thermostat set-point has also been discussed in [3, 4]. Further, a group of researchers is working on autonomous devices that adjust their power consumption in response to the grid frequency [5]. The problem with all of these approaches is that they only consider the effect on the system, and not the fairness of re-appropriating energy. The fact is, many consumers want and need resources more than others, and this fact needs to be accounted for in order to maximize the effectiveness of load management.

In this paper, we propose a market based approach to load management using a scarce resource auction. Each home agent knows a demand function that defines its price versus demand desires, but in order to effectively operate in the auction, it must be able to predict its future power consumption. By synchronizing the low frequency PWM of the home agents with the auction time windows, the complexity for learning and predicting local power consumption is drastically reduced. Additionally, adjusting the power consumption in response to the time varying price is simplified.

Previously, we used the idea of energy price manipulation for load regulation in [6], but there we used a traditional controls perspective of identifying the aggregate system and apply feedback controls to manipulate the cost. Previous researchers have also proposed market based approaches to load management, [7–9]. We build on their work by presenting an inexpensive autonomous method for information poor residential HVAC systems.

## MOTIVATION

Thermostatically controlled devices are well suited for load management because they are ubiquitous and heavy electricity consumers. Specifically, air conditioning contributes heavily to the summer peak loads throughout the United States. Pro-

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grammable Communicating Thermostats (PCTs) were recently proposed as a method to provide load management. PCTs were envisioned to be low cost residential thermostats with the ability to communicate with some central authority for the purpose of reducing power when needed. Using the model of the PCT, we want to extend their capability by providing more intelligence while keeping their price low.

Traditional non-linear control of thermostatically controlled devices complicates energy consumption analysis and manipulation. The inherent non-linearities make system identification and prediction difficult and unreliable. Furthermore, direct load control is crude and complicated with hysteresis control. Traditionally, it has been provided by communicating switches placed directly on the compressor to deny it power, bypassing the temperature controller altogether as in [2].

With the coming advances of the "Smart Grid" communications and control are taking a prominent role in load management. By distributing inexpensive communicating thermostats and developing appropriate controls, effective and inexpensive load management could be implemented with little effect on personal comfort.

## SCARCE RESOURCE AUCTION

The market operates using the Tâtonnement Process [10] – the auctioneer (operations agent) suggests a price, and the bidders (consumption agents) respond with their expected average power during that period conditioned on the suggested price. Starting with the lowest allowed price, the auctioneer raises the price through successive suggestions until the expected power meets or exceeds the objective. By starting bidding at the lowest allowed price, this mechanism is an ascending price auction with the price suggestions never decreasing. The final price is set once the objective is achieved.

The market operates only sporadically with the notion that there are "normal" periods and "control" periods. When closed, the cost of the resource (energy) is fixed at the normal price. When the market is open, price control periods last 15 minutes and are consecutive. The price during every period is determined during the 15 minutes prior to the start of the period.

Throughout this paper we will abstract exact price away and consider the price ratio instead. The price ratio is the ratio of the current price to the normal price (which does not have to have the same dollar value for every period, it is simply "normal" for that period). Therefore, the normal price has a price ratio of 1, and higher prices have price ratios greater than one.

During the "normal" period, the agent can consume as much resource as they like. Alternatively, during the "control" periods, the agent cannot consume more energy than bid under fear of a heavy penalty. The notion of this penalty will be kept vague at this point, and we will just assume that nobody invokes it. The exact penalty is more a question of market design and is left for related works.

## AUCTION SYNCHRONIZED HOME AGENTS

The home agents interacting within this market could take many forms, but we have a few design constraints. Primarily, we want to keep the cost spent on computing resources for each agent low, which means very little additional sensing and an inexpensive (i.e. slow) processor. Two-way communications is the only luxury we have. Therefore, we need a robustly simple design that includes the following elements:

- Temperature control to maintain, or seek, comfort.
- On-line system identification and prediction to enable power demand bidding.
- Computable demand function to direct the cost to comfort decision making.

Our solution to this design criteria is synchronized PWM, and in the following sub-sections we elucidate why synchronized PWM is such an elegant solution.

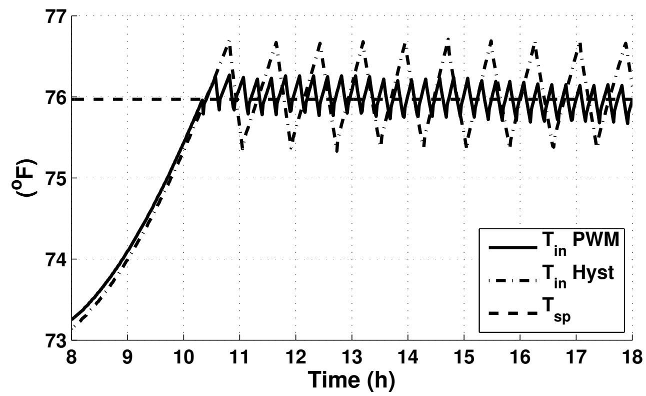
### PWM Control and Synchronization

Traditionally, temperature control using HVAC systems is accomplished with non-linear hysteresis controllers. Recently we developed an alternative to this that treats the unit as a proportional actuator using low frequency PWM [11]. With low frequency PWM the on/off HVAC unit is operated proportionally as a fraction of a long period. As an example, using our PWM period of 15 minutes, a 30% duty cycle would result in the unit being on for only 5 minutes of the period. Low frequency PWM enables the use of linear control laws for temperature regulation. We use a simple PI controller, but any linear (or non-linear) controller with proportional output would work. Figure 1 shows the difference between low frequency PWM and traditional HVAC controls.

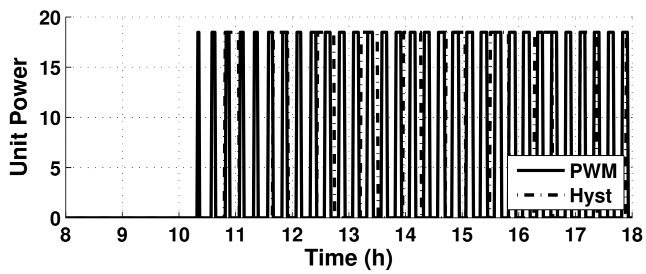
The major advantage of using low frequency PWM to operate the HVAC system is the ability to synchronize the actuation period (PWM period) with the auction period. Synchronization offers up two key advantages. First, the power consumed during the next auction period is known at the start of the period making power limiting very simple using tunable saturation. Second, prediction of power consumption for the auction reduces to a single step look ahead.

The only drawback to synchronized PWM is the possible load diversity issues. In general, the power grid relies on all of the different loads to operate asynchronously, and in particular, it relies on HVAC systems to operate at random times. If all of the HVAC systems turned on at the same time, the peak power would be tremendous, but with them operating, more-or-less, randomly, a much lower peak is maintained. This is referred to as load diversity.

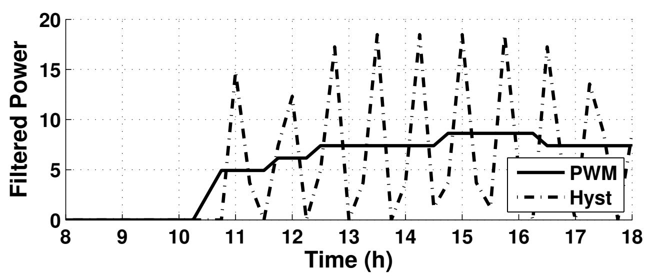
With synchronized PWM, the load diversity must be forced upon the system. There are at least two ways to handle this. The first way randomizes the start time of the on-pulse for every new period. While simple to implement, this method suffers from random controller bias and reduced performance. The second




(a) Output

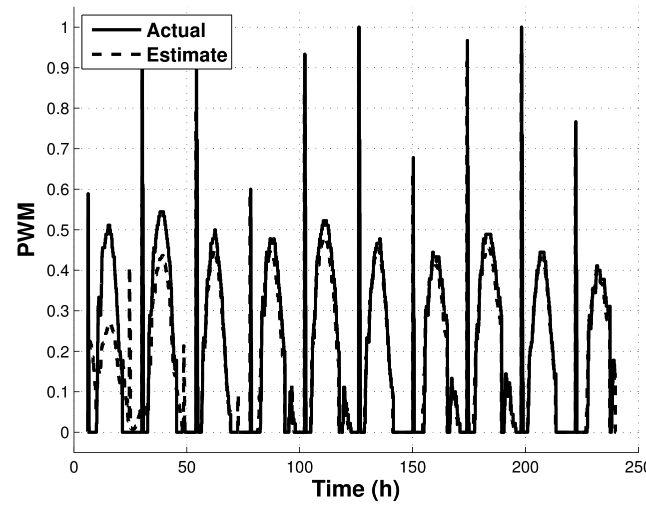



(b) Input

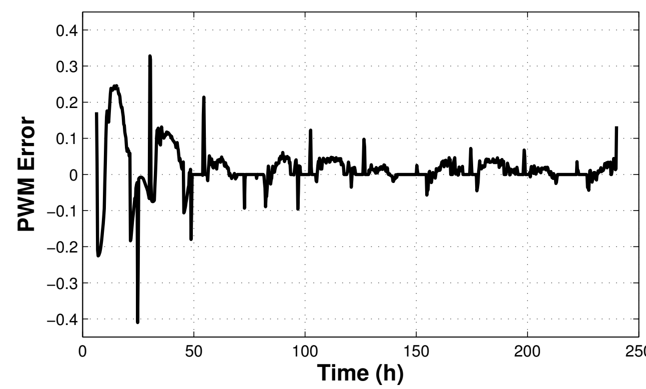



(c) Filtered Input

Figure 1. Simulation of the same house/HVAC under hysteresis control and low frequency PWM with PI control




(a) PWM




(b) PWM Error

Figure 2. Simulation results showing the convergence of the power estimation to the actual value.

way randomizes the middle time of the on-pulse at the initialization of the controller. From initialization forward, the middle time of every on-pulse is at the same time in the period. If the pulse is so big that the specified middle time would result in the pulse extending outside of the PWM period, the middle time is shifted to obey the period boundaries for that pulse. Luckily, PWM theory does not really care when during the period the on-pulse occurs as long as it occurs at the same time each period. Therefore, this method results in very little controller bias and good performance.

## System Identification and Prediction

The primary desire for system identification and prediction is to estimate power consumption correctly. With the simplest view, we need to estimate power given our available information – inside temperature, set-point temperature, previous power consumption, and outside temperature. With our design goal of reduced cost and minimized additional sensing, outside temperature and previous power consumption become slightly more difficult to come by. We get the outside temperature through communications with the super-agent. Previous power consumption is estimated from the duty cycle and rudimentary knowledge about the HVAC compressor – SEER rating and compressor size.

Synchronized PWM makes this task easier in two ways. First, the linear control turns the previously on/off operation of the HVAC system into a proportional, nearly linear, signal sampled at the PWM period. Second, since the sample period is synchronized with the auction period, one-step look ahead is all that is required to participate in the auction.

Unfortunately, the system is still not *easy* to identify. The PWM does not totally linearize the system, because saturation is still present. The power consumption of the HVAC system will never be less than zero or greater than some maximum value. Further, the actual system is of huge order and has many unmodeled inputs, like solar radiation.

Traditional, on-line linear least squares resulted in erratic and unstable performance. A non-linear least-squares like identification system resulted in much better performance. The non-linear system is shown in Equation 1 with parameter vectors $\psi$ and $\theta$. The index, $j$, of parameter $\psi$ is chosen based on the time of day, with each 15 minute interval receiving its own entry in the vector. Further, saturation is applied to the estimated power to keep the signal greater than zero.

$$\hat{P}(k+1) = \psi_j + (T_{out}(k+1) - \theta_2)\theta_1 + (T_{in}(k) - T_{sp}(k))\theta_3 \quad (1)$$

The parameter update law is shown in Equation 2 with parameter convergence variable vector $\gamma$.

$$\begin{aligned}
&\text{for} \quad P(k) > 0 \qquad (2)\\
&\theta_1(k+1) = \theta_1(k) + \gamma_1(P(k) - \hat{P}(k))(T_{out}(k) - \theta_2(k))\\
&\theta_2(k+1) = \theta_2(k) + \gamma_2(P(k) - \hat{P}(k))\theta_1(k)\\
&\theta_3(k+1) = \theta_3(k) + \gamma_3(P(k) - \hat{P}(k))(T_{in}(k) - T_{sp}(k))\\
&\psi_j(k+1) = \psi_j(k) + \gamma_4 * (P(k) - \hat{P}(k))\\
&\text{for} \quad P(k) \leq 0\\
&\theta_1(k+1) = \theta_1(k)\\
&\theta_2(k+1) = \theta_2(k)\\
&\theta_3(k+1) = \theta_3(k)\\
&\psi_j(k+1) = \psi_j(k)
\end{aligned}$$

Figure 2 shows the convergence of the power estimate with time. The identification system was initialized at $t = 0.0$, and the error converged pretty quickly. This obviously does not prove stability, but the testing shows no significant stability issues.

### Demand Function

The consumption agents are autonomous and intelligent, and in general, each agent is interested in achieving its own goal that does not align perfectly with the super-agents (and could potentially be orthogonal). The primary objective of our home agents is to maintain comfort of the house. However, in the presence of time varying energy price they have an additional objective to manage cost verses comfort. Toward the later goal, our home agents use a cost limiting demand function to regulate their energy costs. The demand function (Equation 3) uses an estimate of the power needed to regulate the temperature ($P_{est}$), a user input neutral factor ($f_n$), and the energy price ratio ($p_r$) to calculate the power demand ($P_d$) during the bidding period.

$$P_d = \min\left\{\frac{P_{est} f_n}{p_r}, P_{est}\right\} \quad (3)$$

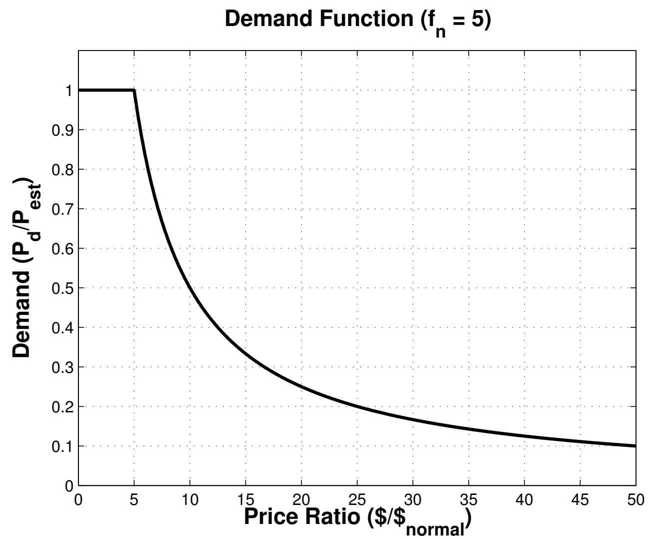



Figure 3. Characteristic cost limiting demand function with neutral factor of 5.

The cost limiting demand function guarantees that the total cost of energy used during an auction period is bounded by the Neutral Factor times the the normal energy consumption. Figure 3 shows a normalized demand curve for a neutral factor of 5 ($f_n = 5$).

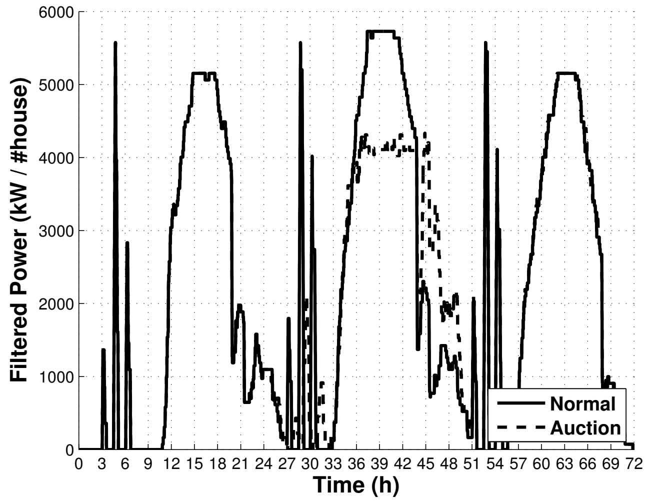
With the use of synchronized PWM control, the power demand is easily regulated using a tunable saturation limit on the temperature controller. With traditional temperature regulation schemes, like hysteresis control, power limiting is considerably more difficult.

## RESULTS

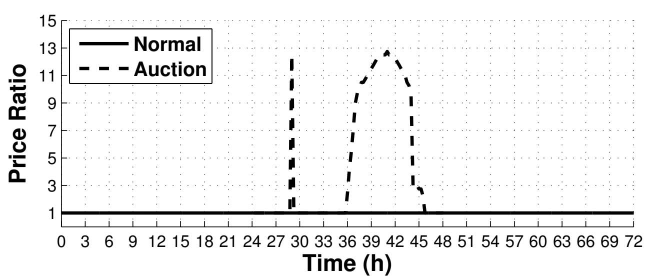
In order to inexpensively and safely test our intelligent agent scarce resource auction system, we built upon the systemic control simulation we previously outlined in [12]. The simulation makes independent houses with randomly chosen properties, including the neutral factor. Simulation is advantageous for this testing because of the ability to experiment with identical networks with and without control to see the exact difference that the control makes.

This testing was conducted on three houses to make the data visualization easier. We initialized the group of houses and let them operate for 7 days in order for the learning to settle. Then, at midnight the auction began with the intention of keeping the normalized time average power below 4000kW. Figure 4 shows the filtered power and price ratio with and without control.

Notice that the power does not exactly track 4000kW when the price exceeds 1. During this period, the price was chosen so that the bid power is lower than the target power, and in response to the auction each house is limiting its power (if necessary) to its bid demand using tunable saturation. Therefore, if the total system power is above the total estimate, then the power esti-

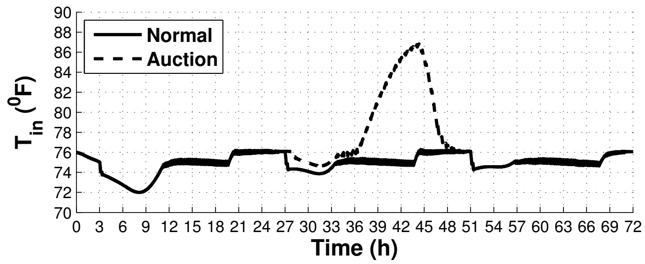



(a) Power

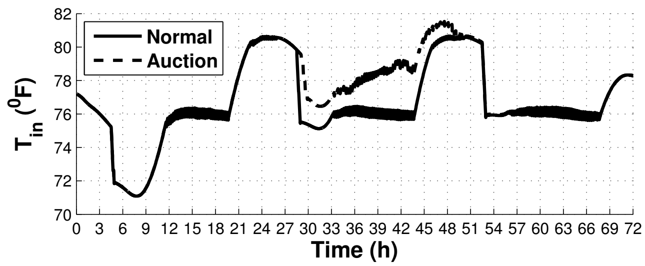



(b) Price

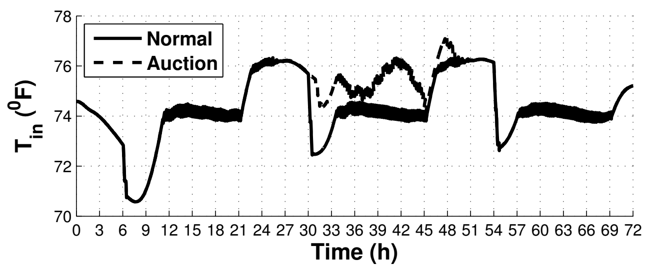
Figure 4. Simulation results showing the filtered power for 3 houses under auction control. The auction began at hour 24.




(a) House 1




(b) House 2




(c) House 3

Figure 5. Simulation results showing the inside temperature of the houses with and without control. Each house is different with different neutral factors.

mate does not match with the saturation limit. This mismatch is primarily due to the rudimentary PWM to Power conversion that each house uses for estimation. While SEER rating and unit size are primary factors in the total power consumption of a compressor, they are not the sole factors. The outside temperature, age, and service history also play a role in the power consumption of the unit.

Figure 5 shows the inside temperature with and without control for each of the houses in this simulation. Notice that the inside temperature deviates before the price goes above 1. This is due to inaccuracies in the power prediction. When the price does move above 1, each house responds differently because each house had a different neutral factor.

## DISCUSSION

Synchronization of PWM with the auction periods yields a huge simplicity advantage with very little cost. PWM control allows the use of linear control which is well studied and easy to implement. It helps to linearize the system, making identification and prediction simpler. Further, synchronization enables power modulation with a simple tunable saturation on the controller.

The primary open controls issue relates to refinement of the system identification. By improving identification and prediction accuracy, the effect on home comfort will be reduced, especially during low price auction control times. Further, a systematic stability analysis is needed for any identification system to be distributed throughout such a diverse systems as residences.

There are also a number of open issues related to the market design that are outside the scope of this analysis. We assume that each home is honest with its power bid, and we skirted the over-consumption penalty issue. These two issues are interwoven and in need of further study. Also, this mechanism was chosen from the standpoint of simplicity, but it does not scale well with increasing number of market participants. Are there better ways to compute the market clearing price that are less communication intensive? Game theory and economics helped us answer this important question, and we showed a truthful clearing algorithm using only one message per user agent in [13].

Another major open issue is the effect these control strategies have on personal comfort. With our simulation, we model occupants, and their personal preferences, directly. We hope to model our way out of this issue.

## CONCLUSION

The major conclusion is that implementation of intelligent agent auctions is simplified by synchronizing the agents control with the auction times. This paradigm eases identification and prediction and makes resource modulation as simple as adjusting saturation limits.

For this treatment, we assumed that the power reference is known a-priori, but from an power systems perspective, the reference is as important as how to maintain it. In future work we are directly targeting the controls/operations research issue of choosing the power reference.

## ACKNOWLEDGMENT

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