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Acoustic Comfort-Aware Home Energy Management System

Hoang Phuong Lien Than[1], Fengji Luo[2*], and Zhao Yang Dong[1]

1 School of Electrical Engineering and Telecommunications, The University of New South Wales, NSW 2052, Sydney, Australia

2 School of Civil Engineering, The University of Sydney, NSW 2006, Sydney, Australia

(*Corresponding Author, email: fengji.luo@sydney.edu.au)

ABSTRACT

With advances of Internet-of-Things and home automation technologies, design and development of Home Energy Management Systems (HEMSs) have become an active research area in recent years. This paper proposes a new HEMS that performs operation scheduling for household appliances by coordinately considering the household's energy cost and the occupant's acoustic comfort. A noise gain model is established for the electric household appliances and an acoustic comfort model is proposed for the occupant. Based on this, an optimal appliance scheduling model is formulated that balances the objectives of minimizing the home energy cost and maximizing the occupant's acoustic comfort. A biological intelligence inspired optimizer is applied to solve the proposed model, and case studies are designed to validate the proposed method.

Keywords: Demand side management, home energy management system, acoustic comfort, demand response

NONMENCLATURE

Sets	
Φ	Set of controllable appliances
Parameters	
T	Total number of time slots
Δt	Duration of a time slot (hour)
$\mathbf{a}$	Weighting factor vector of the noise disturbance degree.
M_l	Sound pressure level of appliance *l* (dB)
M'	Ambient noise level
δ_l^1, δ_l^2	Indices of the starting and end time slot of the allowable operation range of appliance *l*
D_l	Number of time slots needed for appliance *l* to complete its task
P_l^{rate}	Rated power of appliance *l* (kW)
Variables	
$s_{l,t}$	Status of appliance *l*: 1-ON; 0-OFF
NDD	Noise disturbance degree for the occupant
x_l	Index of the starting operation time slot of appliance *l*
M_t	Aggregated home sound level at the *t*th time slot (dB)
A_t^{SPL}	Magnitude gain of sound pressure level at the *t*th time slot
A_t^{LU}	Loudness gain at the *t*th time slot

1. INTRODUCTION

The past decade has witnessed the rapid development of smart grids. One significant feature that distinguishes smart grids from traditional bulk power systems is the bilateral communication between end users and the utility through the Advanced Metering Infrastructure (AMI). This facilitates the participation of end users in the grid's operation by actively managing their on-site energy resources and re-shaping their

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energy consumption and production profiles (known as "demand response" [1]).

In recent years, the increasing prevalence of AMI, Internet-of-Things (IoT) devices and building automation technologies further fostered the research and development of Home Energy Management Systems (HEMSs) [2]. A HEMS is an expert system that manages the operation of household energy resources subjected to certain objectives. In academia, the design of HEMSs has been extensively studied. For example, Ref. [3] develops a HEMS to optimally determine the operation of multiple household appliances, aiming at minimizing the home energy cost subjected to a combined real-time electricity tariff and inclining block rate tariff model. Ref. [4] develops a HEMS based on artificial neural networks to enhance residential demand response. Ref. [5] develops an appliance commitment framework to minimize the household operation cost. In the second and third authors' previous work, a multi-stage home energy management scheme is proposed to perform both day-ahead scheduling and real-time control for multiple appliances and a home battery energy storage system (Ref. [6]); a HEMS is developed to manage home energy resources subjected to both a time-of-use tariff and a demand charge tariff (Ref. [7]).

In the development of HEMSs, occupant's comfort is an important consideration. Existing work adopt several strategies to maintain the occupant's indoor thermal comfort subjected to air conditioning systems as well as usage convenience subjected to non-thermostatically controlled household appliances. In addition to these comfort indices, acoustic comfort, which is related to environmental noises, is also recognized as having direct influence on the occupant's health and working efficiency [8]. Despite its widely recognized importance, to the best of the authors' knowledge, the occupant's acoustic comfort is not well considered in the design of HEMSs in literature.

Motivated by this, this paper proposes a new HEMS that considers both the occupant's usage convenience on household appliances and acoustic comfort. We establish noise gain models for the appliance and evaluate the occupant's acoustic comfort subjected to the appliance operation. Based on this, we formulate a HEMS model that optimally schedules the operation of a set of appliances by simultaneously minimizing the home energy cost and maximizing the occupant's acoustic comfort. Simulations are conducted to validate the proposed HEMS.

The rest of the paper is organized as follows. Section 2 presents the acoustic comfort model for the occupant; Section 3 presents the proposed HEMS model; Section 4 presents the solving approach for the proposed HEMS; Section 4 reports the numerical simulation results; Section 5 concludes the paper.

2. ACOUSTIC COMFORT MODEL

In this section, we present the acoustic comfort model for the occupant.

2.1 Appliance acoustic model

Denote the set of the controllable appliances is Φ. Each appliance emits a sound with a constant magnitude of sound pressure level (dB) when it operates, denoted as M_l, $l \in \Phi$. The total appliance noise is estimated as a summation of incoherent noise sources [9]. At the *t*th time slot, the aggregated sound level emitted by the appliances is calculated as:

$$M_t = 10 \cdot \log_{10}\left(10^{\frac{M'}{10}} + \sum_{a \in \Phi}(10^{\frac{M_a}{10}} \cdot s_{a,t})\right) \tag{2}$$

where M' is the constant ambient noise level (dB).

2.2 Acoustic comfort model for the occupant

The occupant could have different tolerance levels to the household noise during different hours of a day, based on their routine and subjective preference. We use $M_t^{\max}$ to denote the maximum tolerable noise level of the occupant at the *t*th time slot. At any time slot, If the actual sound level magnitude surpasses the occupant's tolerable threshold, the magnitude gain of sound pressure level at the *t*th time slot can be calculated [10]. Firstly, we convert M_t and $M_t^{\max}$ from the measure of logarithmic dB to standard atmospheric pressure (Pa):

$$M_{p,t} = 10^{\frac{M_t}{20}} \cdot p_0 \tag{3}$$

$$M_{p,t}^{\max} = 10^{\frac{M_{\max,t}}{20}} \cdot p_0 \tag{4}$$

where p_0 is the reference sound pressure, which is human's auditory threshold at 20μPa. The magnitude gain can finally be expressed as:

$$A_t^{SPL} = \frac{M_{p,t}}{M_{p,t}^{\max}} = \frac{p_0 \cdot 10^{\frac{M_t}{20}}}{p_0 \cdot 10^{\frac{M_{\max,t}}{20}}} = 10^{\frac{M_t - M_{\max,t}}{20}} \tag{5}$$

Due to the non-linearity in human auditory perception, the amplification in sound is experienced at a lower intensity. According to literature [11], the psychophysical impact is better projected from the change in loudness. As loudness is subjective, it can only be estimated through generalized conversion methods. In this paper, the loudness gain at the *t*th time slot is approximated from Steven's Power Law [12]:

$$A_t^{LU} = (A_t^{SPL})^{0.67} \tag{6}$$

Based on A_t^{LU}, the total Noise Disturbance Degree (NDD) for the occupant over *T* time slots caused by the appliances' operations is estimated as:

$$NDD = \sum_{t=1}^{T}\left(a_t \cdot \tilde{A}_t^{LU}\right) \tag{7}$$

$$\tilde{A}_t^{LU} = \begin{cases} A_t^{LU} & \text{if } A_t^{LU} > 1 \\ 0 & \text{otherwise} \end{cases} \tag{8}$$

$$\sum_{t=1}^{T} a_t = 1 \tag{9}$$

where $\mathbf{a} = [a_1, ..., a_T]$ is the weighting factor vector of the acoustic comfort preference at different time slots, in which each element a_t (*t*=1:*T*) is the weighting factor at the *t*th time slot. Different value choices of a_t at different time slots reflect the significance of noise disturbance to the occupant in different periods of the day. For example, if an occupant wants to treat the noise disturbance equally in different time periods, they can set $a_1 =,...,= a_T = 1/T$; if an occupant pays more attention on acoustic comfort in evening hours, they can set larger values of a_t during that period.

3. FORMULATION OF THE HEMS

Based on the acoustic comfort model presented in Section 2, in this section we present the mathematical formulation of the HEMS. The HEMS aims to determine the value of each appliance's starting operation time slot (x_a). The objective of the home energy management task is to balance the home energy cost and the occupant's acoustic comfort subjected to a time-varying electricity tariff:

$$\min F = C + w \cdot NDD \tag{10}$$

$$C = \sum_{t=1}^{T}\left(P_t^{tot} \rho_t \Delta t\right) \tag{11}$$

where *w* is the weighting factors of the two objectives; *C* is the total home energy cost over the *T* time slots ($); ρ_t is the electricity price at the *t*th time slot ($/kWh). P_t^{tot} is the total power consumption of the controllable appliances:

$$P_t^{tot} = \sum_{l \in \Phi} (P_l^{rate} \cdot s_{l,t}) \tag{12}$$

where P_l^{rate} is the rated power of the appliance *l* (kW/h).

The model is subjected to the following constraints:

$$\delta_l^1 \le x_l \le \delta_l^2 \tag{13}$$

$$\sum_{t=\delta_l^1}^{\delta_l^2} s_{l,t} = D_l \quad l \in \Phi \tag{14}$$

Constraints (9) and (10) ensure that appliance a operates and completes its task within the occupant-specified allowable operation time range [δ_l^1 , δ_l^2].

4. SOLVING APPROACH

In this study, we use an evolutionary optimizer previously proposed by the second and the third author – Natural Aggregation Algorithm (NAA) [13] to solve the proposed HEMS model. By imitating group-living animals' aggregating behaviors, NAA distributes a population of individuals into multiple sub-populations; it then uses a biology-based stochastic migration model to migrate the individuals among the sub-populations and performs both generalized search and located search to search for the global/sub-global optimal solution in the given problem space.

4.1 Encoding scheme

By applying NAA to solve the proposed home energy management model (10), each individual in NAA represents a candidate solution. Considering there are N controllable appliances, i.e. $|\Phi| = N$, each individual $\mathbf{I}_i$ is encoded as a *N*-dimensional vector:

$$\mathbf{I}_i = [x_{i,1}, ..., x_{i,N}] \tag{15}$$

where *i* is the index of the individual in the population.

4.2 Solving workflow

The overall workflow of applying NAA to solve the proposed HEMS is shown in Fig 1. The parameters are set and inputted into the NAA solver. The solver then iteratively updates the population based on its embedded evolutionary mechanism. When the termination criteria is met, the solver outputs the best individual (the one that has the minimum value of Eq. (10)), which represents the optimal appliance operation schedule.

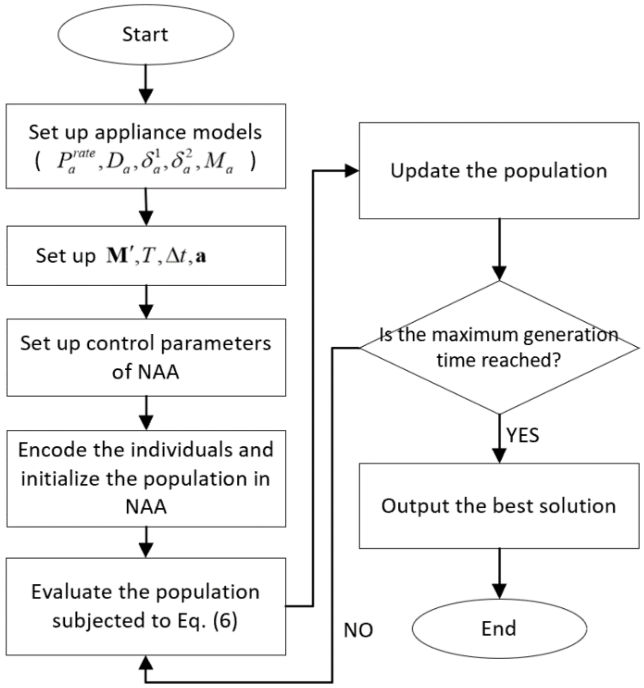

Fig 1 Solving workflow for the HEMS

5. CASE STUDY

In this section, we report the numerical case studies we conducted to validate the proposed HEMS.

5.1 Simulation setup

We simulate a smart home environment consisting of 7 controllable appliances. The types and configurations of the appliances are shown in Table 1. The home energy management period is set from 6am the given day to 6am the next day, with each control interval of 5 minutes. Therefore, there are totally 288 time slots (*T*=288). The ambient noise level (M') is set to be constant as 25dB. The maximum tolerable noise level of the occupant is set according to the occupant's activities in different hours, as shown in Table 2. The specific levels of $M_t^{\max}$ and a_t values are assigned to reflect the noise mitigation requirements during each of these periods (Table 2, Table 3).

The weighting factor vector of noise disturbance (***a***) reflects the occupant's lifestyle preference in terms of acoustic comfort. We simulate three lifestyles, as shown in Table 3. In each lifestyle, different values of a_t are set for the different activity periods, representing different acoustic comfort preferences in those periods. For example, as for lifestyle 1, noise mitigation is significantly prioritized during sleep; as for lifestyle 2, the significance of noise during sleep is twice that during work, and noise mitigation for all other hours is relative insignificant.

Table 1 Configurations of the controllable appliances

Appliance name	M_a	P_a^{rate}	d_a	$[\delta_a^1, \delta_a^2]$
Air Conditioner	45dB	1.2kW	2hrs	[12pm, 3pm]
Space Heater	30dB	2kW	5hrs	[11pm, 6am]
Dishwasher	33dB	1.8kW	1hr	[7pm, 6am]
Humidifier	30dB	0.05kW	2hrs	[8pm, 6am]
Washing Machine	33dB	0.8kW	1hr	[6am, 6am]
Dryer	35dB	2.5kW	0.7hrs	[6am, 6am]
Coffee Maker	30dB	0.8kW	1/6hrs	[6am, 8am]

Table 2 User-specified maximum sound level thresholds

Activity	Time range	$M_t^{\max}$
Sleep	10pm – 7am	32
Work	9am – 5pm	50
Other	All other times	60

Table 3 Setting of ***a*** for different lifestyles

	Sleep	Work	Other
Lifestyle 1	0.80	0.15	0.05
Lifestyle 2	0.60	0.30	0.10
Lifestyle 3	0.33	0.33	0.33

Table 4 TOU tariff structure

TOU tariff	Time range	ρ_t
Peak	2pm – 8pm	0.54
Off-peak	10pm – 7am	0.14
Shoulder	All other times	0.23

The home is considered to be charged by a TOU tariff, provided in Table 4. The tariff structure is from the Origin Energy NSW, Australia [14] for a typical summer weekday. The control parameters of the NAA solver are as follows: population size = 200, generation time = 300, N^S = 8, Cp^S = 25, δ = 1, Cr_{local} = 0.9, α = 1.2, and Cr_{global} = 0.1.

5.2 Evaluation of trade-off between energy cost and acoustic comfort

We examine the effect of different value settings of the weighting factor w on the scheduling result. We vary w from 0 to 8, with increment of 0.5. For each value of w, we solve the proposed home energy management model and calculate the total home energy cost and *NDD*. We perform the simulation for each ratio setting of a_t, and the results are shown in Fig 2.

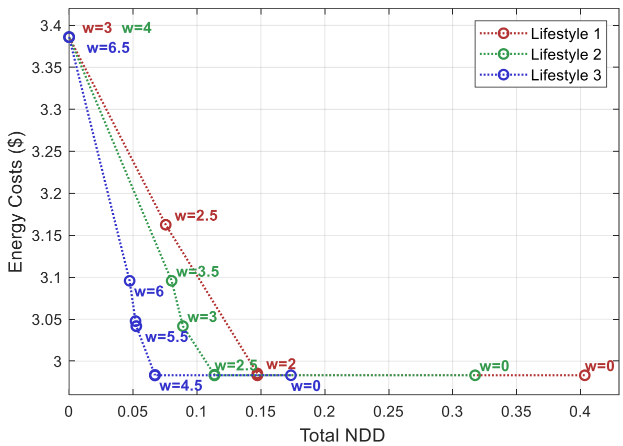

Fig 2 Trade-off between home energy cost and the NDD with different values of *w*

The results reflect a general trend of trade-off between the home energy cost and the occupant's acoustic comfort: with low values of *w*, the HEMS focuses more on minimizing the home energy cost. This leads to higher energy cost savings at the expense of reduced acoustic discomfort (i.e. increase of *NDD*). It is also observed that under the simulation settings in Section 5.1, for each lifestyle, the minimum home energy cost ($2.98) is always achieved when *w* varies in a range of low values. When *w* is larger than that range, the home energy cost increases with increase of *w*; in the meantime, the occupant's acoustic comfort increases, which is reflected in the reduced value of *NDD*.

Lowering w causes the cost minimization objective to be more dominant in the objective function, leading to higher savings at the expense of increased user disturbance due to noise.

5.3 Demonstration of appliance scheduling

Fig 3 demonstrates the optimal appliance scheduling details and the resulted sound profiles under three different values of the objective weighting factor *w*: 1, 2.5, and 5, respectively. The total home energy cost and *NDD* values under each setting of *w* are shown in Table 5. The results show that even for the case of lifestyle 1 where larger value of a_t is set for off-peak electricity price hours (which means the occupant prioritizes quiet for those hours), significant energy cost savings can still be achieved at a marginal expense in the occupant's acoustic comfort. As w decreases, more load is shifted to off-peak periods, thereby decreasing the home energy cost and increasing the total noise disturbance level.

The optimal home energy cost is achieved at $w = 1$, with one hour of over-threshold sound levels and peak loudness gain A_t^{LU} of 1.68. At w = 2.50, the length of disturbance is decreased to 50 mins, incurring negligible

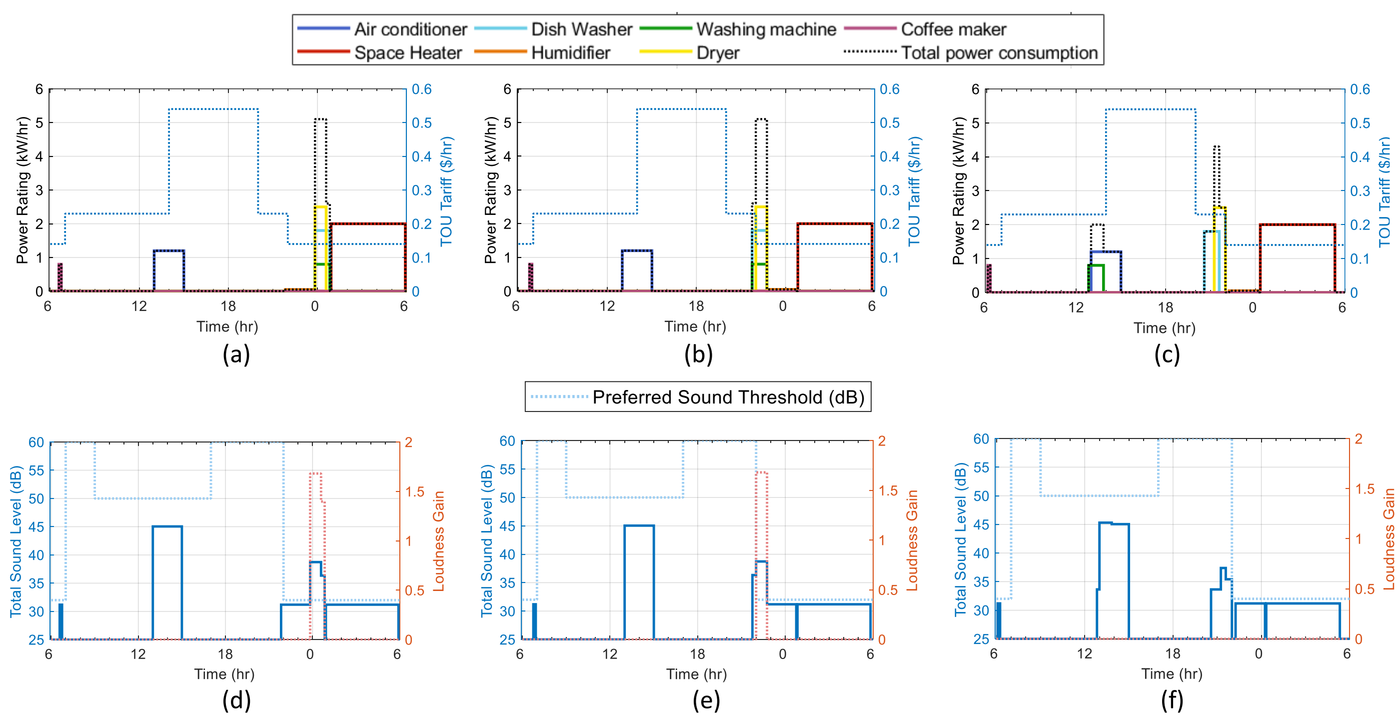

Fig 3 Appliance scheduling results and sound profiles: (a) appliance scheduling results with *w*=1.0; (b) appliance scheduling results with *w*=2.5; (c) appliance scheduling results with *w*=5.0, (d) sound profile due to scheduling with *w*=1.0; (e) sound profile due to scheduling with *w*=2.5; (f) sound profile due to scheduling with *w*=5.0

Table 5 Energy cost and *NDD* under different values of *w*

w	Total energy cost	*NDD*
1	2.9835	0.1472
2.5	3.0417	0.1153
5	3.3859	0

energy cost increase (about $0.03). Fig 3(c) and Fig 3(f) show the case (*w*=5) where maximum acoustic comfort is achieved, i.e. *NDD*=0. This means that the noise levels in the home environment in all time slots are below the occupant's preferred thresholds. Under the home operation environment settings in this simulation, this will lead to approximately $0.40 energy cost increase compared to the cases of *w*=1 and 2.5.

In general, the increase in sound level perceived by the human auditory system is much more subdued than its actual gain in intensity [15]. It is possible that a variation of around 68% for one hour would not create a significant degree of acoustic discomfort for most people, or many people might be willing to tolerate that level of disturbance, if it can create significant reductions in electricity bills.

6. CONCLUSION AND FUTURE WORK

This paper proposes a new home energy management system that is aware of both home energy cost and the occupant's acoustic comfort. An acoustic comfort model is established that quantifies the disturbance degree of the noise caused by appliance operations to the occupant. Based on this, an optimal appliance scheduling model is proposed that optimally determines the operation plans for the controllable appliances. The simulation results show that the proposed home energy management scheme can well achieve a trade-off between the two objectives and can help to increase the occupant's acoustic comfort based on their lifestyle preferences.

In the future, fine-grained acoustic comfort models are expected to be developed by considering the layout of the home and the real-time locations of the occupant and the appliances. In addition, other comfort indices (such as thermal comfort and visual comfort) can be integrated into a comprehensive home energy management framework along with the acoustic comfort model.

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