

A MULTI-AGENT HOME AUTOMATION APPROACH FOR POWER MANAGEMENT

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Abstract: This paper presents the principles of a Home Automation System dedicated to power management that adapts power consumption to available power resources according to inhabitant comfort and cost criteria. The system relies on a multi-agent paradigm. Each agent supports a service achieved by several devices, it cooperates and coordinates its action with others in order to find an acceptable near-optimal solution. The control algorithm is decomposed into two complementary mechanisms: a reactive mechanism, which protects from constraint violations, and an anticipation mechanism, which computes a plan for global consumption according to predicted productions and consumptions and to inhabitant criteria. The paper shows how to compute a global consumption plan relying on Bellman-Ford's algorithm and how to reduce the problem complexity by dividing the whole problem into independent sub-problems.

Keywords: Home Automation System, Multi-Agent Systems, Automatic Control, Power Management.

1. INTRODUCTION

A building is both a place of power consumption and potentially a place of decentralized power production using resources like wind, solar, geothermal, etc. The resort to the renewable power resources comes up in buildings knowing that they represent 47% of the global power consumption (Fontaine, 2003). Therefore, the development of a control system which allows the exploitation of the different resources, while managing in a global manner the power needs and the production capacity of a home, is important.

The role of a Home Automation System dedicated to power management is to adapt the power consump-

tion to the available power resources, and vice versa, taking into account inhabitant comfort criteria. It has to reach a compromise between the priorities of the inhabitant in terms of comfort and in terms of cost while satisfying technological constraints of devices.

Algorithms based on Multi-Agent Systems are nowadays used in several areas such as Computer Science or Automatic Control. The first MAS approaches for energy distribution have been presented in (Jennings, 1994) and (Hägg and Ygge, 1995).

The development of solutions based on Multi-Agent Systems, which are well suited to solve spatially distributed and open problems, facilitates the development of an intelligent Multi-Agent Home Automation

System (*MAHAS*). This paper presents a Multi-Agent Home Automation System (MAHAS). It focuses on the solving strategy and, in particular, on the way of reducing problem complexity. The paper is organized as follows: section 2 describes, from a general view point, the MAHAS and its two main mechanisms: the reactive and the anticipation mechanisms. Section 3 presents the agent modelling for the anticipative mechanism. Section 4 deals with the solving strategy. Then, an illustrative example is presented in section 5. Section 6 concludes the paper.

2. MULTI-AGENT HOME AUTOMATION SYSTEM

A Multi Agent Home Automation System consists of agents, each agent supports one type of service achieved by several devices such as heating, cooking, etc. The objective of H.A.S. dedicated to power management is to adapt power consumption to available power resources and vice versa, according to inhabitant comfort and cost criteria. The main features of the Multi-Agent Home Automation System are the following:

- Distributed: the energy resources and devices are independent and spatially distributed.
- Flexible: some devices can accumulate energy (heating service, etc) or satisfy with a timed delay the demands of the inhabitant (washing service, ...).
- Open: the number of connected resources and devices may vary with time without having to completely redefine the control mechanism.
- Extendable: agents dedicated to new kinds of services may appear.

In Multi-Agent Systems, the notion of control involves operations such as coordination and negotiation among agents, elimination of agents and adding new agents when needed.

Depending on weather forecasts, power resource information and inhabitant habits:

- an agent, dedicated to a power source, should be capable of calculating the future available power production.
- an agent, dedicated to a load, should be capable of calculating the prediction of power consumption: to determine what are the future power needs taking into account the usual behaviour of inhabitants.

In MAHAS, an additional agent is responsible for broadcasting the computed predicted plans to the other agents.

The structure of the MAHAS is decomposed into two main mechanisms working on a different time scale: the reactive mechanism and anticipation mechanism.

2.1 Reactive mechanism

The reactive mechanism is a short time adjustment mechanism which is triggered when the level of satisfaction of an agent falls below weak values (10% for example). This mechanism, which relies on the negotiation protocol (Abram *et al.*, 2006), reacts quickly to avoid violations of energy constraints and to guarantee a good level of inhabitant satisfaction. Therefore, the reactive mechanism adjusts, at a short sample, the set points coming from the predicted plan, the device's current state (device satisfaction value) and the constraints and inhabitant criteria. The predicted set points can be directly transmitted to the device or modified in case of emergency.

2.2 Anticipative mechanism

The reactive mechanism is sufficient to avoid constraint violations but a MAHAS can be improved in order to avoid emergency situations. This improvement is obtained due to the anticipation mechanism. The objective of this mechanism is to compute plans for production and consumption of services in a house. The anticipation mechanism benefits from the fact that there is, on the one hand, some devices which are capable of accumulating energy, and on the other hand, some services that have a variable date for their execution: some services can both be delayed or advanced. From these preliminary observations, it is possible to imagine that if the device consumption can be anticipated, there is a way to organize it better.

It works on a time window, which corresponds to a sampling period called the anticipative period. This period is greater than the one used by the reactive mechanism. Because of the large sampling period, it considers average values of energy. This is an advantage when considering prediction because it is difficult to make precise predictions. A large sampling period is also important to keep the reactive mechanism transparent.

A third mechanism may exist: the local control mechanism i.e. the controllers endowed into devices by manufacturers. Its time response is very fast. This mechanism receives set points from the agents. In addition, some information on its current state (power needs) are sent back to the agents so that they can be taken into account in the future plans.

Because the reactive mechanism has been presented in detail in (Abram *et al.*, 2006), this paper focuses on the anticipative mechanism.

3. AGENT MECHANISM FOR ANTICIPATION

One of the objectives of the MAHAS is to fulfil inhabitant comfort. A notion which is related directly

to comfort is the satisfaction function (Lucidarme *et al.*, 2002). Satisfaction functions have been defined for power resources as well as for devices. A satisfaction function is expressed by a function defined from the domain of characteristic variables to the interval $[0, 1]$. In the MAHAS, satisfaction characterizes the inhabitant's feeling about a service where zero means "unacceptable" and 1 means "fully satisfied". For example, the satisfaction function for a thermal air environment is based on room temperature values (figure 1). The satisfaction function of a power re-

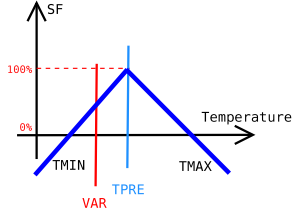


Fig. 1. Thermal air environment satisfaction function.

source agent is also expressed by a function where the level of satisfaction is defined by the energy supplier. A satisfaction function can be modelled by a set of characteristic points. For instance, figure 1 can be represented by $\{(TMIN(heating), 0), (TPRE(heating), 1), (TMAX(heating), 0)\}$.

A power profile of a service represents a series of consumed or supplied powers corresponding to consecutive sampling periods.

3.1 Agent modelling

In the MAHAS, an agent supports a service $SRV_i \in SRVS$ where $SRVS$ is the set of all services. A service SRV_i may be either a timed service, denoted SRV_i^T , or a permanent service, denoted SRV_i^P , achieved by one or several devices, knowing that a device may also achieve many services (figure 2).

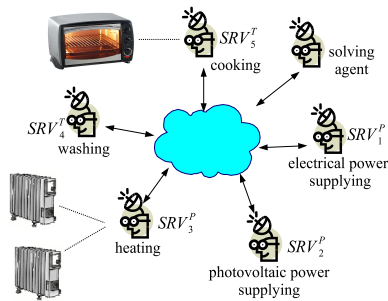


Fig. 2. Example of agents in M.A.H.A.S.

3.1.1. Modelling of the timed service agent A timed service corresponds to power profiles during a given period; the flexibility of the service comes from the possibility that it may be shifted.

The internal knowledge of a timed service agent, which represents the knowledge that cannot be formalized in a general way, is modeled by:

- a characteristic variable which corresponds to the starting time of the service.
- a behavioral model that defines the possible power profiles once the service has been started.
- a set of characteristic points: $\{(EST(SRV_i), 0), (RST(SRV_i), 1), (LST(SRV_i), 0)\}$ that represent respectively the earliest (unacceptable satisfaction), requested (fully satisfied) and latest starting times for the timed service.

A realization for a timed service agent represents the shared knowledge about a timed service. It is composed of:

- a power profile: $\Pi = [POW(SRV_i)_0, \dots, POW(SRV_i)_n]$ where $POW(SRV_i)_j \neq 0; j \in [0, n]$ represents the average power consumption/production of the service during the k^{th} sampling period. The duration of a service is determined by the length of the power profile length(Π).
- a satisfaction value which depends on the starting time of the service.

A realization corresponds to an instantiated power profile denoted: $REAZ(SRV_i^T) = (k, \Pi, \sigma)$, where k is the actual starting sampling period, Π is the power profile and σ a satisfaction value modelling the inhabitant's feeling about this realization.

3.1.2. Modelling of the permanent service agent A permanent service corresponds to power profiles covering a given period. The flexibility of the service comes from the possibility of adjusting energy allocation from time to time.

The internal knowledge of a permanent service agent is modeled by:

- a behavioral model linking the power profile to effect an inhabitant environment.
- a satisfaction function represented by a set of characteristic points. Considering a HAVAC(Heating, Ventilation and Air Conditioning) system, among these characteristic points, there is the inhabitant requested temperature and the inhabitant unacceptable temperatures.

A realization for a permanent service agent represents the shared knowledge of a timed service. It is composed of:

- a power profile: $\Pi = [\dots, POW(SRV_i)_k, \dots]$ where $POW(SRV_i)_k$ represents the average power consumption/production during the k^{th} period. The duration of a service is determined by the length of the power profile length(Π).
- a satisfaction value. Even if a realization covers several periods, there is only one value that models the inhabitant resulting satisfaction for the whole considered period: it is usually equal to the

minimum of the satisfaction values computed for each period.

A realization corresponds to an instantiated power profile denoted: $REAZ(SRV_i^P) = (k, \Pi, \sigma)$, where Π is a power profile from the sampling period $k + \text{length}(\Pi)$ and σ is a satisfaction value modelling the inhabitant's feeling about this realization.

Let's define the notion of impact of a service for a given sampling period k . It corresponds to the set of realizations for a service SRV_i , which is affected by a change of power affectation at a given time k . For a permanent service, the impact corresponds to $[k - p, k + p]$ where $p \times \Delta$ corresponds to the time response of the related devices. For a timed service, it corresponds to the set of realizations defined at k .

3.2 MAHAS modelling

A Home Automation System aims at reaching a compromise between the comfort and the cost for inhabitants while satisfying technological constraints of devices. The MAHAS takes into account the energy price variation because the energy suppliers charge the inhabitant for the actual energy production cost. Therefore, the MAHAS aims at minimizing the cost while maximizing the inhabitants comfort which depend on the realizations of the service agents.

Energy cost criterion:

According to energy cost, an realization of a service SRV_i can be cost: $\text{cost}(SRV_i) = f(REAZ(SRV_i)) = f(k, \Pi)$ The energy cost criterion is defined when one realization for each requested service has been defined.

$$EC_{SRV} = \sum_{SRV_i \in SRV} (\text{cost}(SRV_i))$$

Where $ESRV$ stands for all the requested services.

Comfort criterion:

The Comfort criterion corresponds to a weighted average satisfaction of all the selected realizations when one realization for each requested service has been defined. It is denoted: CO_{SRV}

Even if the methods for solving the optimization problem may provide good solutions, they still require long computation times and considerable working memory because the complexity is NP-Hard (Garey and Johnson, 1979). A relevant optimization strategy (section 4), due to the nature of the Home Automation System problem, would seem to be a promising avenue for performance improvement.

4. OPTIMIZATION STRATEGY

A Home Automation System problem can be divided into sub-problems involving different agents because, generally, inhabitants do not use their devices most of the time. The basic principle is to divide the whole problem into independent sub-problems (figure 3) then to solve each sub-problem independently (in sequence or in parallel) in order to find a solution for

the whole problem. The advantage of this method is to reduce the complexity of the whole problem which depends on the number of periods for each sub-problem and on the number of devices. When the whole problem is divided into sub-problems, each sub-problem does not contain all of the devices (for example: some inhabitant vacuum clean in the morning and not in the evening). Because the number of considered periods in a sub-problem is lower than the number of periods of the whole problem (Habbas *et al.*, 2005), the complexity of solving the sub-problems is less than the complexity of solving the whole problem at once.

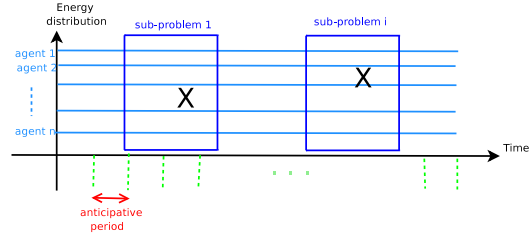


Fig. 3. Whole problem energy distribution.

The principle of the division of the problem into sub-problems is described in the following procedure:

- **procedure solving of the whole problem**
- distribute the energy over all periods for all the services according to the inhabitant's satisfaction;
- **if insufficient energy for some periods then**
- detect sub-problems;
- determine the time interval for each sub-problem;
- solve each sub-problem separately;
- merge the sub-problems solutions to obtain the general solution;
- **else a solution according to the inhabitant's satisfaction is selected;**
- **end if;**
- **end procedure;**

This procedure is described in the next sub-sections.

4.1 Energy distribution

The search for the whole solution starts by distributing the available energy over all the periods for all the services according to the inhabitant's satisfaction (100%) where agents provide realizations with a satisfaction value equal to 1. At the end of the energy distribution, if there is enough energy for all devices, the search for a solution is stopped and a solution according to the inhabitant's satisfaction is selected. But if there is not enough energy for all devices, sub-problems will be detected (4.2) and then will be solved (4.3).

4.2 Determination of the sub-problem interval

When the service agents supplying power have not enough energy for all devices, the solving agent sends

the periods for which there is not enough energy to all permanent and timed service agents. For obtaining independent sub-problems, it is necessary to determine the service influences over these periods. The principle of the sub-problem interval determination is described as follows:

First, compute the earliest and the latest starting time for the timed services:

- each realization of a timed service agent is characterized by a starting time, an ending time (equal to the starting time plus the length of the power profile).
- each timed service agent sends their intervals to the solving agent.

Each permanent service agent sends its impact to the solving agent (for example: the impact of a heating service corresponds to its time response; the impact of lighting is zero).

The solving agent creates several intervals (sub-problem intervals) depending on the number of periods where there is not enough energy.

- The solving agent verifies the intersection between the sub-problem intervals and the earliest and the latest time of the timed services; it chooses the minimum value between the earliest time and the inferior bound of the interval and the maximum value between the latest time and the superior bound of the interval.
- The solving agent adds the impact of the permanent agent to the sub-problem intervals; the fact of adding the impact of permanent service agents increases the interval of the sub-problem but it guarantees that there is no influence on the previous or next periods.
- The solving agent merges two sub-problem intervals if there is an intersection between these two sub-problem intervals.

Then, at the end, the solving agent sends the sub-problems intervals to all agents.

4.3 Resolution of a sub-problem

The solving agent computes a predict plan for each sub-problem using the Bellman-Ford's algorithm (Cherkassky *et al.*, 1994). The solving agent collects the set of realizations for the services, it verifies if they are acceptable or not according to the available energy taking into account the inhabitant criteria. It amounts to choose an agent realization in order to find the shortest path for the services belonging in the sub-problem.

5. APPLICATION EXAMPLE

An illustrative example of a system composed of six devices and a power resource limited to $4kW$, for a

sampling period of 30 minutes, is presented in this section.

The first device *washer* will be used twice:

The first timed service on the washer $SRV_1 = \text{washing}_1$ is characterized by:

$RST(\text{washing}_1) = 09h00$, $EST(\text{washing}_1) = 08h30$,
 $LST(\text{washing}_1) = 10h00$, $POW(\text{washing}_1) = 2.2kW$ over three sampling periods

The second timed service on the washer $SRV_2 = \text{washing}_2$ is characterized by:

$RST(\text{washing}_2) = 19h00$, $EST(\text{washing}_2) = 18h30$,
 $LST(\text{washing}_2) = 20h00$, $POW(\text{washing}_2) = 2.2kW$ over three sampling periods.

The second device $DEV_2 = \text{dishWasher}$ will be used twice as well:

The first timed service on the dishWasher $SRV_3 = \text{dishWashing}_1$ is characterized by:

$RST(\text{dishWashing}_1) = 9h00$, $EST(\text{dishWashing}_1) = 9h00$,
 $LST(\text{dishWashing}_1) = 10h30$,
 $POW(\text{dishWashing}_1) = 2.4kW$ over four sampling periods.

The second timed service on the $DEV_2 = \text{dishWasher}$ $SRV_4 = \text{dishWashing}_2$ is characterized by:

$RST(\text{dishWashing}_2) = 19h00$,
 $EST(\text{dishWashing}_2) = 19h00$, $LST(\text{dishWashing}_2) = 20h30$,
 $POW(\text{dishWashing}_2) = 2.4kW$ over four sampling periods.

The third device $DEV_3 = \text{oven}$ will be used once, the timed service on the oven $SRV_5 = \text{cooking}$ is characterized by:

$RST(\text{cooking}) = 11h00$, $EST(\text{cooking}) = 9h00$,
 $LST(\text{cooking}) = 12h00$, $POW(\text{cooking}) = 1.5kW$ over one sampling period.

The fourth device $DEV_3 = \text{vacuum cleaner}$ will be used once, the timed service on the vacuum cleaner $SRV_6 = \text{vacuuming}$ is characterized by:

$RST(\text{vacuuming}) = 21h00$, $EST(\text{vacuuming}) = 19h00$,
 $LST(\text{vacuuming}) = 22h00$, $POW(\text{vacuuming}) = 1.5kW$ over one sampling period.

The fifth device is a heater in the living room ($DEV_5 = \text{heater}_1$), the permanent service on the heater $SRV_7 = \text{heating}_1$ is characterized by:

$TMIN(\text{heating}_1) = 19$, $TPRE(\text{heating}_1) = 19$,
 $TMAX(\text{heating}_1) = 19$, $POW(\text{heating}_1)_{max} = 1.5kW$

the thermal dynamic model of temperature change (Nathan, 2001) in the living room is:

$TEMP(\text{heating}_1)_{k+1} = e^{(-1800)}TEMP(\text{heating}_1)_k$
 $+ 40(1 - e^{-1800})POW(\text{heating}_1)_k + (1 - e^{-1800}) \times 10$.

The sixth device is another heater ($DEV_6 = \text{heater}_2$) in the bedroom, the permanent service on the heater $SRV_8 = \text{heating}_2$ is characterized by:

$TMIN(\text{heating}_2) = 18$, $TPRE(\text{heating}_2) = 19$,
 $TMAX(\text{heating}_2) = 20$, $POW(\text{heating}_2)_{max} = 1.5kW$

the thermal dynamic model of temperature change in the bedroom is similar to the living room's thermal dynamic model.

The solving agent starts the search by initializing the heating service to their inhabitant preferred temperature and the timed services to their requested

starting time. After the energy distribution for all services over all periods, the solving agent states that the power consumption exceeds the available power twice; the first time is during the 9th and 10th periods, the second one is during the 18th and 19th periods. Instead of solving the complete problem (eight services) over 48 sampling periods, it is better to split the initial problem into easier sub-problems to be solved by the solving agent. Therefore, if the algorithm of sub-problem area determination (4.2) is applied, two independent sub-problems are obtained. The first sub-problem involves $SRV_1, SRV_3, SRV_5, SRV_7$ and SRV_8 and the second sub-problem involves $SRV_2, SRV_4, SRV_6, SRV_7, SRV_8$. Each sub-problem deals with five services over four hours and thirty minutes which reduces the complexity of the whole problem.

The results of Bellman-Ford's algorithm is drawn in figure (4) showing a solution for the first sub-problem where the power consumption does not exceed the available power during the sub-problem₁ area. Without MAHAS, services would have been

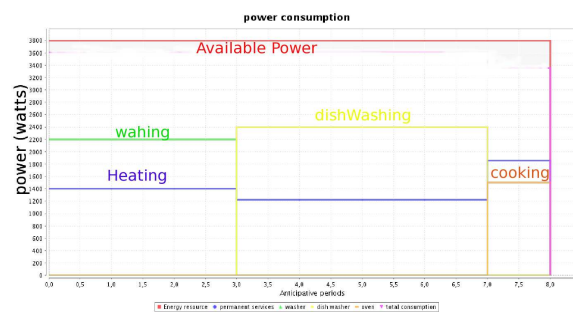


Fig. 4. Sub-problem 1 solution.

performed according to the inhabitant's requests and the available power would have been exceeded. Due to negotiations and coordinations, MAHAS has converged to a feasible solution which is acceptable for inhabitants. Figure 4 only points out results obtained for sub-problem 1 but the second sub-problem can be solved in the same way and merged in order to get a global acceptable solution in a very short time (less than 1 second).

6. CONCLUSION

This paper has presented the principles of a Multi-Agent Home Automation System which allows the agents to cooperate and coordinate their actions in order to find the accepted near-optimal solution for power management. The division of the whole problem into sub-problems has been detailed. This paper has shown how the problem complexity can be decreased by dividing a problem into sub-problems.

The results provide evidence that the cooperation and the negotiation capabilities of Multi-agents Systems can be advantageously used to control spatially distributed, flexible, open and extendable systems. This

feature is a clear improvement over the capabilities provided by current Automatic Controlled Systems.

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