Smart Household
Selected Problem Solutions using Intelligent Controllable Electric Appliances

Miroslav Prýmek and Aleš Horák
Faculty of Informatics, Masaryk University, Botanicka 68a, 602 00 Brno, Czech Republic

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Abstract: In the current perspectives, renewable power sources bring new challenges for the power distribution. Substantial advances in the reliability and flexibility in the overall power consumption can be achieved via a network of intelligent and controllable appliances, especially on the micro level, i.e. on the level of individual electric appliances within the scope of one household or one institution. In the paper, we identify the typical problems of the smart household approach and present a communication and control model which offers a solution to these problems based on the multi-agent system approach.

1 INTRODUCTION

Within the search for new alternative energy sources the percentage of electricity produced by renewable power sources grows rapidly in the worldwide measures. The irregular nature of these sources brings new demands on the control of the power distribution network (Ibrahim et al., 2008). A possible solution lies in the design of smart power grids on all levels of the energy flow ranging from the wide distribution networks to housing estates, institutions or individual households. A combination of a set of small decentralized sources of electric power, photovoltaic systems being a typical example, and a smaller or larger set of intelligent or intelligently controlled electric appliances offers new operation scenarios of power consumption profiles (Roncero, 2008).

In order to analyze the design details of new intelligent elements of a power network in the smart household concept, we have identified typical implementation problems connected with combined power distribution from heterogeneous sources. The solutions to these problems have been incorporated in the development process of a new Smart Home Simulation (SHS) system that is implemented at our institution and is used as a research testbed for this topic.

1.1 Common Power Distribution Problems Connected with Heterogeneous Sources

In this section, we identify the major problems caused by the inflexibility of the traditional power grids in the environment with increasing number of unstable sources.

The biggest problem of new renewable sources of electrical power is that their production is driven by natural conditions and their production profile cannot be changed to suit the consumption profile of the users. This limits the usability of renewable sources not even on the national level but even more as sources in the off-grid arrangement.

One of the possible approaches lies in the effort to improve the means of energy storage. This approach surely attracts attention (Carrasco et al., 2006). The parameters of the energy storage facilities are improving but the usability is still very limited.

Another approach works with adjusting the power consumption profile to better suit the profile of the source – in contrary to the conventional control of the particular sources. This brings new problems of communication between the sources and the consumers (or consumer appliances), consumption planning and appliance control itself. These problems are complicated but the effect is obvious and the limitations are often not as strict (physical) as in the abovementioned problem of energy storage.

Next issue of the renewable sources is their unavoidable instability. To increase the grid control effectiveness, the supply changes must be either predictable or the appliance must be capable of very fast reactions to the situation and it must adjust its parameters accordingly. This puts strong requirements on the flexibility and speed of the control system.

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Nevertheless, the grid control system can solve not only the problems connected with new power sources. The ability to quickly, flexibly and specifically control particular power consumers (up to the appliance level) brings also new possibilities from the whole power network perspectives. One of them is the ability to appropriately react on negative external influences like blackouts, brownouts and other non-standard situations.

In the next section we will present a model of an intelligent power grid and in Section 3 we will show how an implementation of this model can diminish the described problems.

2 PRIORITY-BASED POWER GRID CONTROL MODEL

The problem of power grid control is in general a problem of coupling between the providers (power sources) and consumers. A general solution to this problem is to employ standard market mechanisms to establish deals between providers and consumers, mainly in the form of an energy auction. Block et al. (Block et al., 2008) present a good review and comparison of many proposed auction styles and their implementations presented in the literature. They conclude that the main disadvantage of the market approach is the lack of sufficient flexibility (*immediacy requirement*) of the underlying algorithms. The grid control model construction obviously is a matter of trade-off between the complexity and feature-completeness on the one hand and interactivity and ease of implementation on the other.

In our work, we focus on the micro-grids on the household level and therefore we stress the later criterion in the presented model to make the model more straightforward and implementable even in low-cost embedded controllers dedicated to particular household appliances. The whole model is built using the multi-agent system approach, where the required global operation model is obtained purely by means of inter-agent communication (the details are presented further).

The central notion of the model is a *priority*. Instead of providing a complicated way to reach a consensus between a producer and a consumer by the means of an auction, the model assumes that the price along with other criteria constitutes the summary value determining the coupling between a producer and a consumer. The coupling is based on the fundamental rule that high-priority consumers must, in every moment, be satisfied before the lower-priority ones.

The system priorities are also assigned to producers, the second system rule is: consumers with priority p can only be satisfied by producers with the priority $\leq p$. The resulting behavior of the system approximates the auction result in the way where non-necessary (low-cost) appliance effects are not acquired for the price of inappropriate costs. E.g. long-term heat accumulation is not performed when the system is in an outage and running on an expensive power source such as a diesel power generator. And vice versa: the lowest priority is assigned to the "no-cost" power sources like photovoltaic panels such that, in an ideal case, all power from them is consumed instead of more expensive power from the grid.

In the Smart Home Simulation (SHS) model implementation (Prýmek and Horák, 2012), the following navigation labels are used as a hint for user to decide which priority to assign to particular appliances and their states:

1. unnecessary, time unlimited
2. small outcome
3. significant outcome
4. user inconvenience avoidance
5. financial loss avoidance
6. significant user inconvenience avoidance
7. significant financial loss avoidance
8. health risk avoidance

2.1 Appliance Categories

The grid appliances are classified into several types according to their *control mechanism*, *user expectancies* and *power consumption profiles*.

2.1.1 Interactive Appliance

An interactive appliance (IA) is directly controlled by the user and the IA's reaction cannot be deferred. Also the power consumption is mostly constant and cannot be controlled.

A typical examples of such an appliance is electric light, electric kettle or television.

2.1.2 Intelligent Interactive Appliance

Intelligent Interactive Appliance (IIA) is a special case of the previous type. The main difference lies in the IIA's power control. The appliance can have more power consumption profiles which can be chosen according to the current situation or it can be driven by special extra communication/control treatment (e.g. a server computer power cannot be cut off immediately, instead a control signal must be emitted and the computer will undergo the internal shut down process as soon as possible).

Table 1: Summary of system messages used between agents in the Smart Home Simulation system.

`power_available(from,amount,priority)`	The power source agent advertises the amount of power it can supply to the network starting at the time `from`
`power_request(from,amount,priority)`	An appliance agent requests `amount` power starting at time `from`
`power_granted(from)`	The scheduler agent authorizes the given consumption request
`power_denied(until)`	A consumption request is denied
`power_release(from)`	The agent's consumption will end in time `from` and the power will be freed
`power_grant_proposal(from)`	An appliance agent advertises that the appliance can defer the consumption to time `from`
`accepted()`	A given proposal is accepted
`refused()`	A given proposal is refused
`not_implemented()`	A response that the previous message is not understood or the requested functionality is not implemented (e.g. the appliance can not defer its consumption)

A typical example of IIA is a computer.

2.1.3 Deferrable-operation Appliance

This appliance is also controlled by the user but an immediate operation is not necessary. When the user commands the appliance to operate, he/she only expects it to begin the work in a reasonable (configured) amount of time. The user does not depend on the precise time of the operation start and end, only the operation result must be delivered appropriately.

Typical examples of deferrable-operation appliances are washing machine, dryer, dishwasher, slow cooker, car battery charger and generally all appliances which require some user intervention before the operation and whose products are expected to be available in a longer time.

2.1.4 Feedback-controlled Appliance

A feedback-controlled appliance (FCA) is usually designed to keep a predefined and (repeatedly) measured value within specified limits. The value is spontaneously tending in one direction and the power supply is needed to push it in the opposite direction. A conventional operation cycle is as follows: whenever a feedback value reaches the lower bound, the appliance engine is powered up to push it to the opposite bound and powered off as soon as this value is reached. This way the power profile of the appliance consists of alternating periods of maximal and none power consumption of a more or less constant duration.

A generalization of the feedback-controlled appliance model in SHS is based on the assumption that the boundaries of the appliance operation should not be defined as hard limits that cannot be exceeded but rather as gradually increasing measures of the power demand priority. From this point of view, a FCA appliance can be seen as a highly flexible device whose power consumption can be efficiently planned to fit together with a power consumption profile of other less-controllable devices. From the most general point of view it can be seen as a *power storage* device. Of course, FCA cannot store arbitrary amount of power – low amounts of stored power would have unintended consequences such as e.g. food going to rotten in an under-cooled refrigerator.

2.2 The System Communication

In contrast with the auction-style planning, the presented model is designed to achieve good planning results without the need of a complicated communication schema and slow decision-making algorithms. Hence it is well suited for implementation even in small embedded devices without a substantial computing power.

The final power consumption plan of the whole system is driven by a scheduler agent with its decisions based on the communication of consumption requests between the scheduler and the appliances. The architecture of the system is centralized and directive from the decision-making point of view. However, the planning and primary reasoning is decentralized. The field agents (particular appliance controllers) make up suitable individual plans and present them as suggestions to the scheduler agent. The scheduler then prepares the final authoritative decision. With this approach the whole system is user-controllable and predictable.

Of course, the centralized architecture is not suitable for control of an arbitrarily large number of devices. Instead of a flat horizontal scaling, the hierarchical scalability must be used. This corresponds to the energy distribution model where every distribution point has a limited number of sub-branches which are to be controlled as a solid blocks. Therefore, we focus on the control of a relatively small unit (household) with the aim to make it a more predictable unit on the higher level of the power distribution topology.

A list of the main system messages is presented in Table 1. All communicated values are considered valid until changed. That is why the system uses only the ”from” property with no ”to”. Examples of particular communication scenarios are presented in the next section.

3 SMART GRID PROBLEM SOLUTIONS

In this section, we refer to the power grid problems identified above and we offer their solutions justified by the solution implementation within the presented Smart Home Simulation system.

3.1 Surplus Power

The conventional not-controllable appliances can usually be only in on or off mode. Electronics usually add some sort of power-saving mode which does not limit the user experience as much as the off mode while consuming substantially less power than the full-on mode.

This principle can be generalized as “provide maximal effect to the user for the minimal amount of power.” Such general principle is applied in many areas and is undoubtedly the right one as an effort to minimize the cost/effect ratio.

But in the environment with uncontrollable and hardly predictable sources of energy, the mere savings do not necessarily present the best result. With many renewable source types the price of the energy mostly consists of the share of the fixed purchase-price of the facility. Therefore to minimize the cost/effect ratio, there is a need to increase the effect, not to lower the cost.

Without intelligent appliance control, the surplus power can only be stored for future use or sold. The first solution surely is the best one, but the efficiency of power storage is still insufficient and the costs are high. Selling the surplus power can have complicated administrative or technical preconditions and so cannot be easily applied to small amounts of energy. Also it is unusable for the off-grid operation.

In the smart grid environment with controllable appliances, the problem of surplus power can be solved in a flexible way. The precondition is that intelligent appliances in the network support several consumption level modes (ideally arbitrarily selectable consumption level with fixed consumption/effect ratio) and the control system can quickly negotiate the right consumption level according to the amount of power currently available in the system.

3.2 Intelligent Sources Allocation

The next identified problem consists in searching the correspondence between the consumption and the power supply such that:

- the cheapest sources are used to the maximal extent
- peaks are minimized
- the user experience is not substantially affected

These goals can be met with intelligent consumption planning according to the predicted power supply. In the SHS priority-driven model, this is solved by rearranging particular appliances operation in such a way that the priority constraints are met.

The problem is illustrated in Figure 1. Three small charts on the left side depict the consumption plan of the three appliances (the first two are feedback-controlled and the third is an IIA). The cumulated demand chart on the right side shows the overall requested power consumption of these three appliances. Darker color of a bar means higher priority. The cumulated demand must be matched with the supply prediction. The algorithm is as follows:

1. the demand and supply plans are approximated by discrete values (bars on the chart),
2. both plans are partitioned to have equal timespans with constant values,
3. each timespan of the demand plan is compared to the corresponding timespan of the supply plan.

The third step is illustrated by the “matching” label in the chart. In this graphical representation, the priority rule can be described as: the darkest bars of the demand are preferably matched with the lightest bars of the supply and each bar of the demand must not end higher than the corresponding supply bar of the same or lighter color. We can see that the rule is not satisfied with the bars marked with the “X” sign – i.e. the corresponding consumption requests do not fulfill the constraints and will be denied by the scheduler.

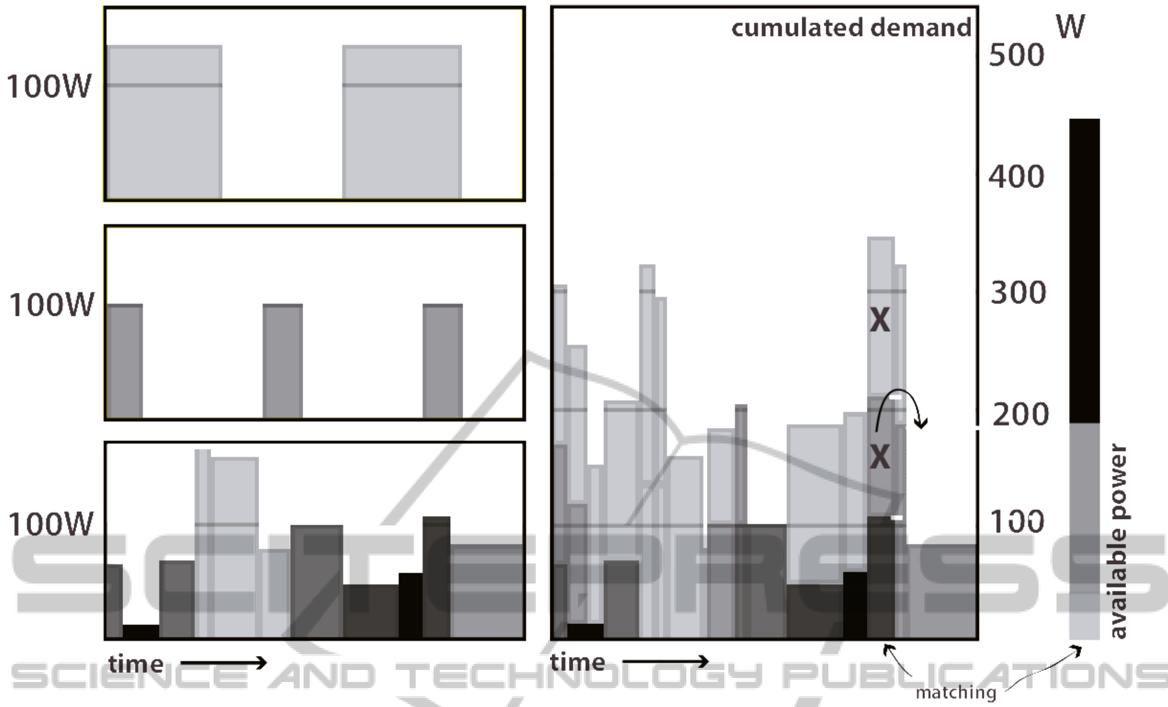

Figure 1: Visualization of the supply/demand matching algorithm.

In addition to the binary decision whether to approve or reject a particular consumption request, the scheduler also proposes a solution to the situation: in this example to shift the consumption to the timespan where it would satisfy the priority constraints (marked with an arrow and a dotted bar in the cumulated demand chart). The scheduler sends the `power_grant_proposal` message to the appliance agent and the appliance agent decides whether the postponement of this particular consumption request is acceptable or not. It will communicate its decision to the scheduler with the `accepted()` or `refused()` message.

This way the peaks in the consumption plan will be eliminated if possible without a negative impact on the appliances operation (they autonomously decide whether the proposal is acceptable or not).

3.3 Unexpected Events

In a similar way, the scheduler can react to the unexpected drop of the power supply. We can again illustrate the situation in Figure 1. If the lightest bar of the supply will not be in place, even the above-described time-shift of the consumption would not solve the situation. This consumption request will be denied because it has lower priority than any available power source of the appropriate capacity. Nevertheless, this one-source outage will not affect the appliances with higher priority. This way the network will automatically adapt its operation to the changed conditions caused by external influences.

4 PROTOTYPE

The research of SHS is directed to testing in real-world situations. In the following sections, we describe the hardware and software parts of the SHS testbed.

4.1 Hardware

The efforts to develop standards for home automation communication infrastructure have a long history (e.g. see (Murata et al., 1983)). But none of the proposals gained dominance in the field and up today there are many incompatible standards of the hardware infrastructure (lines level), communication protocols and software solutions. Many of them are proprietary and patented so they are not well suited for open, vendor-independent solution development.

One of the oldest solutions is an X10 standard using the house electrical wiring as the physical layer for communication. There were attempts to improve the standard and overcome some of its limitations, namely CEBus and LonWorks (for their comparison see (Strassberg, 1995)). These standards are often limited in purpose – the type of information to be communicated is limited to the specific home automation commands like "dim lights to $x\%$" or "switch the device on."

Another approach is to utilize the standards used in the industrial communication – e.g. RS485, Modbus, or the standards used in the computers or consumer electronics: I2C, 1-Wire, SMBus, Ethernet, USB. The disadvantage of the consumer electronics standards (except Ethernet) is that they were not designed for large-scale communication.

The Ethernet standard seems as a best solution due to its widespread use. Moreover, Ethernet networks are used as convergence networks for once separated networks like phone lines (VOIP), TV wiring (IPTV) etc. Nevertheless, the Ethernet standard is not usable for our scenario mainly because its complexity – its implementation in low-power microcontrollers is inconvenient, hard or even impossible. The best approach is to use chips specialized for the Ethernet communication, however, this makes the solution more expensive and complicated.

For our prototype implementation, we have decided to choose the RS485 standard (Electronic Industries Association, 1983). Its main advantages can be summarized as:

- it is widespread and highly tested, mainly in the industrial environment
- it is designed to be very interference-resistant – RS485 uses differential signaling (two symmetric signal wires)
- it does not place high demands on the wire quality – the common twisted pair cable is used, so standard existing house wiring (e.g. Ethernet Cat5 or phone cables) can be used
- it can achieve high transmission speed or long distances (about tens of megabits over tens of meters or up to hundred kilobits over one kilometer long cable)
- its electronic implementation is simple and cheap
- unlike its predecessors (mostly RS232, also known as the computer "serial port"), the RS485 is a multi-drop bus, so multiple clients can be connected to the same wire

The main disadvantage of the RS485 standard is that it defines only the physical layer of the communication. The communication protocol must be chosen/developed independently. It is common to use a custom-developed protocol over the RS485 line. This is also the case of our prototype. To keep the prototype flexible for future extensions, we have decided to use a "meta-protocol" encapsulating the communication data itself. The communication protocol is based on the master/slave principle, so we have used the same approach for the data exchange on the line level. The cooperative master/slave communication can also be implemented in simple microcontrollers because it does not need complicated collision detection like in other shared-media protocols such as the CSMA/CD used in a coaxial-cable Ethernet standard. The details of the communication protocol implementation are outside of the scope of this paper.

4.2 Software

The overall controlling system consists of a central agent implementing the main scheduling and planning logic (*scheduler*) and many autonomous agents controlling particular household appliances (*nodes*). The nodes are autonomous because the scheduler does not instruct them with precise orders. Instead the nodes just inform the scheduler about their knowledge of the situation and future predictions. The scheduler then summarizes the knowledge and instructs the nodes about which actions are viable and which are not.

In this arrangement, the assumptions about the capabilities necessary in each network node are kept as low as possible. In combination with the chosen physical layer (RS485), a device controller can be implemented with the cheapest low-power microcontrollers. For instance the above-described *interactive appliance* needs just the following capabilities:

- one sensor for user interaction
- one actuator for device control
- implementation of a few communication acts (see Table 1)
- one cheap-chip RS485 line driver

This functionality can be implemented e.g. with Atmel ATtiny microcontroller (priced about USD 3) with one RS485 driver chip. Due to the chosen cooperative master/slave protocol, the line driver can be only half-duplex, so again very cheap (under USD 1). In our prototype we have used software implementation for Arduino prototype boards (Banzi, 2008). The Arduino board is based on the Atmel microcontroller so the developed software can be uploaded to the above-mentioned Atmel ATtiny with only minor or no modification.

As we have argued earlier in the paper, the SHS protocol is very scalable. It is possible to implement the basic functionality with a small microcontroller, but at the same time sophisticated behaviour can be implemented with more-computing-power chips or computers.

The scheduler is a standard-computer software implemented in the Erlang programming language, which is well suited for this purpose due to its capabilities:

- highly-concurrent programming
- distributed computing and multi-agent systems with highly autonomous nodes
- it is well tested in the industrial environment
- it is designed for high-availability and fault-tolerance
- it provides good performance
- it is portable

The scheduler software is used not only to manage the information in the network and to control the devices operation but also to provide an overview of the network functionality and immediate state of the resources planning.

The SHS software also implements agents for virtual appliances. This way, we can use the software for the simulation of the household appliances planning, or to control real appliances through the physical network and microcontroller-controlled devices. Probably the most interesting feature is the ability to freely mix these types of agents to form a semi-virtual, semi-real network and simulate its behavior with different scheduling scenarios.

5 CONCLUSIONS

We have identified the main problems that are common to most of the smart grid consumption control systems, such as the treatment of the surplus power from renewable power sources, intelligent allocation of multiple power sources to consumer appliances or the reactions to unexpected events in the power network.

Besides the references to standard solutions to these problems with the description of the respective drawbacks such as high costs of the requested facilities or high demands on the computing algorithms, we have presented a new Smart Home Simulation (SHS) system that is based on priority matching algorithms and flexible communication infrastructure which can incorporate large variety of nodes from the simplest microcontroller-driven appliances up to sophisticated and intelligent computer-driven systems. We have shown how the SHS system can be advantageously used to solve the identified smart grid problems.

Nowadays, SHS has been used for simulation and post-hoc analysis of real-world systems and basic real devices control. The future research of SHS is directed to the evaluation of the system in connection with networks with live intelligent appliances.

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