Simulator for Smart Load Management in Home Appliances

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***Abstract*—This paper describes a simulator for smart load management of standard household appliances as a base for later on-chip integration. The idea is to optimize and balance the overall power consumption of a household. Implemented devices in this work provide different stages of internal management intelligence in the view of shifting and forecasting their energy load profiles. This enables customers and energy suppliers to utilize the available electrical power in an optimized way. The simulated appliances can be run together with real household appliances to predict energy consumptions for bigger and more complex households.**

Keywords-load profile modelling; electrical load management strategies; virtual appliances simulation.

I. Introduction

Today's advances in computational technologies combined with state of the art electrical energy management systems will become a key technology for future home applications. Modern home automation systems offer for customers continuous information about their device's power consumption [1]. Energy feedback and optimized customer promotion for energy saving actions increases the usage of available electrical energy in a more effective way. As of now, no standard appliances available at the market offers the feature of being directly controlled by an external instance. That is why external measurement plugs or additional sensor/actuator hardware inside of a device are the common for consumption measurement and control function realization. Another way for power measurement of individual devices is through nonintrusive load monitoring systems analyzing a household's aggregated consumption [2].

In the near future, appliances will get more and more intelligent in the view of an increased economic and flexible operation. A main fact is that a device has the intelligence integrated itself and can react on commands and data provided by an energy management gateway. Advanced functionalities are:

- Power measurement information as previously mentioned. The current device's power consumption can be returned to the customer and energy supplier for informal feedback purposes.
- Coordinated switching and control of appliances to combine the fields of energy supply and informational technology to a smart grid application [3].
- Load forecasting for effective planning and power plant management at the energy supplier's side and similarly for customers to avoid device activations at times of high energy prices [4] [5].
- Different behaviors of the device at varying internal parameters caused by a shifted activation must be managed. The influence of user interactions have to be taken into consideration at any time. For some device classes the customer can set up a point in time the appliance must have finished its operation. For some other devices there must be immediate support.

To fulfill all these functional requirements the development of embedded hard- and software with a dedicated integration in each appliance is needed. This paper introduces in a preliminary software implementation which is able to support all the bullets listed above. The output of the simulation is a real power value indicating the current energy consumption. As a target platform for the simulation an portable Android tablet PC is chosen (see Figure 1). This hardware offers an integrated touchscreen, a high resolution display and enough computational power for load forecasting, virtual appliance management and communication tasks. Finally this portable simulator application can be used for development, prototyping and demonstration purposes of home automation and appliances control systems.

The paper follows the following structure: In Section 2, modeling techniques of home appliances are introduced; a concrete realization in the simulator application is described in Section 3. In Section 4, the implementation of the concept is stated. Finally, the paper concludes and identifies future activities in Section 5.

II. Appliances Modeling

For the simulation of typical household appliances, their load profiles must be modelled. Each device has its unique signature in real and reactive electrical power consumption. The abstraction level of the used model is chosen in a way that specific characteristics of an appliance are highlighted. To increase the clarity in the process of device power profile modelling three types of basic characteristics are defined [6]:

- ON/OFF states
- Finite State Machine (FSM)
- Continuously variable

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Figure 1. Simulator main screen on a Motorola Xoom tablet PC. The screen shows the twelve virtual household appliances which can be selected for simulation.

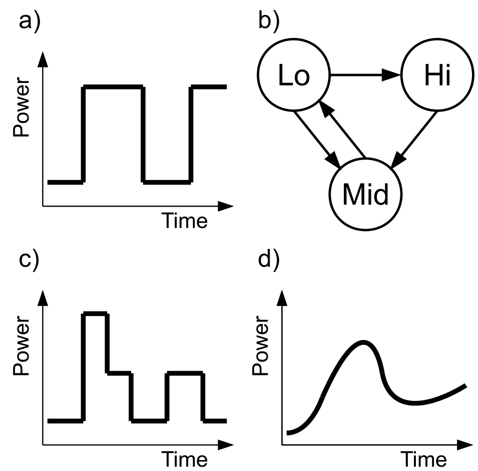

Figure 2. a) ON/OFF model with only two defined power states, b) Finite state machine model for the power profile illustrated in c), d) Continuously variable power profile.

For an ON/OFF state model a boolean variable is used to identify whether a virtual appliance is activated or deactivated. Only one single power level during the on state is allowed [6]. The off state power level can be defined by a standby consumption of the device. This type of model is ideal for the description of two level stepwise loads like heating elements, light bulbs, water pumps, etc. (see Figure 2-a).

Finite state machine (FSM) models enable a defined number of constant power states which describe the operational characteristics of a device [6]. At a graphical representation of the model, these power states (which can be specified by the activation of internal appliance components) are linked by transitions describing all possible sequences of operations (see Figure 2-b). The duration of staying in one power state is not defined in this model [6]. Devices, which are described with this modelling type, are dishwashers, washing machines, coffee machines and an increasing number of microprocessor controlled appliances (see Figure 2-c).

Finally, continuously variable load models describe appliances which power consumption is not specified as a discrete stepwise profile. The continuous load characteristic is often based on internal closed loop controllers where a rotation speed, servo position, etc., is influencing the electrical power consumption [7]. Appliances that can be described with a continuously variable model are typically all HVAC (Heating, Ventilating and Air Conditioning) devices (see Figure 2-d).

A. Modelled Load Profiles

Load profiles used for this simulator have basically a rectangular shape. They can be described as a stepwise composition of discrete and steady power levels. The advantage of modelling a load is having a mathematical representation of the power consumption signature. The description of the model and as a consequence the behaviour of the virtual device can be modified during a running simulation by updating its parameters. This modification possibility is important for a coordinated load management. The more management functionalities implemented in an appliance the more capabilities in the view of shifting the load profile in time, delaying, or a dynamic forecast of consumptions are provided [4]. These methodologies are integrated in the described simulation and discussed in more detail in Sections III-A and III-B. For time shifting and load management functions, simulation input parameters are also required. These input values can be set by widgets at the graphical user interface or received via an external hardware interface.

B. Measured Load Profiles

Figure 3-a illustrates a typical load profile structure for refrigeration devices. A two-level controller thermostat will keep the inner temperature of the appliance between the specified bounds (hysteresis of the controller). The time periods for switching on and off depends on the adjusted set-point temperature, temperature difference between in- and outside and user actions (e.g. opening and closing the device's door). Figure 3-b shows a measured real power load profile of a washing machine. The profile can be partitioned into several blocks which identifies the internal operations of the machine. At 300 seconds of measurement time a high amplitude power consumption block of $1900W$ with a duration of eight minutes caused by the heating up phase of water is shown. The constant height power peaks between 1000 and 2000 seconds describe the cyclic rotation of the washing drum. The peaks with a height of $600W$ at

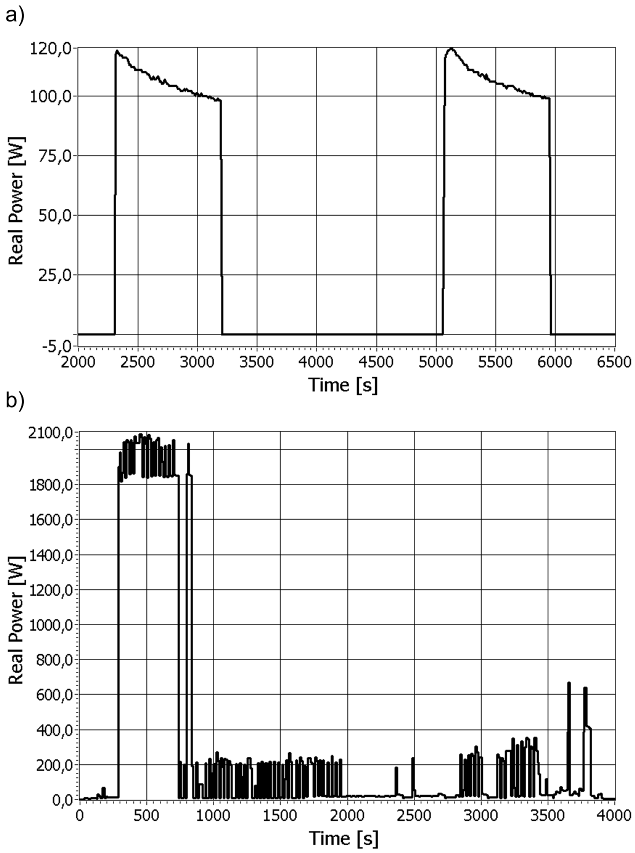

Figure 3. a) Measured real power load profile of a typical cooling device. b) Measured load profile of a washing machine at one dedicated programme.

2700 to 3900 seconds are caused by the spinning-dry and finalization period of the washing programme.

The measured load profiles of the refrigerator and the washing machine are used as a basis for the design of realistic simulation models. Power states and possible transitions can be directly applied to an appropriate model.

As a proof of a high influence of model parameters on the behaviour of a virtual device, and in the real world on the energy efficiency potential, we will give an example. If the temperature tolerance in a refrigerator for stored frozen products is defined with 1°C, all warehouses distributed in the European Union could act as a 50000 MWh "virtual energy buffer" [5].

III. Simulation System Design

The simulation application is basically partitioned into three stages. The first one is the selection of a device type. In the current version, the simulation application offers a choice between twelve typical household appliances. The second stage is the configuration of the selected virtual device. Parameter default values are displayed at appropriate screen widgets. The third stage is the simulation itself. At this simulation mode a diagram area containing the current load profile, an information field and control buttons are displayed.

Requirements on the simulation system can be divided into functional software requirements and hardware properties, which must be fulfilled at the target system. Functional requirements describe the methods provided by the application to fulfill the mentioned objective of the simulation. The model based simulated appliances are introduced in the following itemization.

- **TV, electrical heater, computer:** These devices are represented by an ON/OFF model. The power consumption level of each virtual appliance can be set in a configuration field. The simulated virtual appliance can be turned on an off by a button widget. The activation of these appliances may not be shifted in time and the operation of the device must begin immediately.
- **washing machine, laundry dryer, dish washer:** These three types of devices allow to choose a specified operation program provided by the appliance. Depending on the program a load profile based on a FSM model with steady power states is displayed on the simulator's diagram area.
- **refrigerator, freezer, air conditioning, e-car charger, e-bike charger, general accumulator charging device:** For this class of loads the power profile shape is not fixed in time and influenced by the operation of the device. As an example the on and off periods of the refrigerator depend on the temperature inside the device and can change without notice if, e.g., the door is opened. The parameters shaping the basic power profile can be configured at the appliance's setup page.

The next two subsections describe types of devices stated at the last two itemization bullets having automatized internal load management functionalities.

A. Virtual Devices with Static Load Profiles

Appliances with a static load signature (i.e. a washing machine programme) are described. The setup of the device contains two parameters for timing configuration. At the first parameter date and time of the load profile's earliest start is configured. The second timing parameter holds the latest allowed end time and date of the washing process. If the chosen time interval is too short for the selected profile a conflict message is displayed. Finally, the energy profile for simulation is displayed at a diagram view. A second trace, configured for the simulation is an envelope function. This describes the maximum level of allowed power consumption for the operation of the appliance. This is provided by the energy supplier in order to limit the consumption of a device at high demand times [4]. The setup of the envelope function can be accomplished by drag and drop functionality at significant timing points.

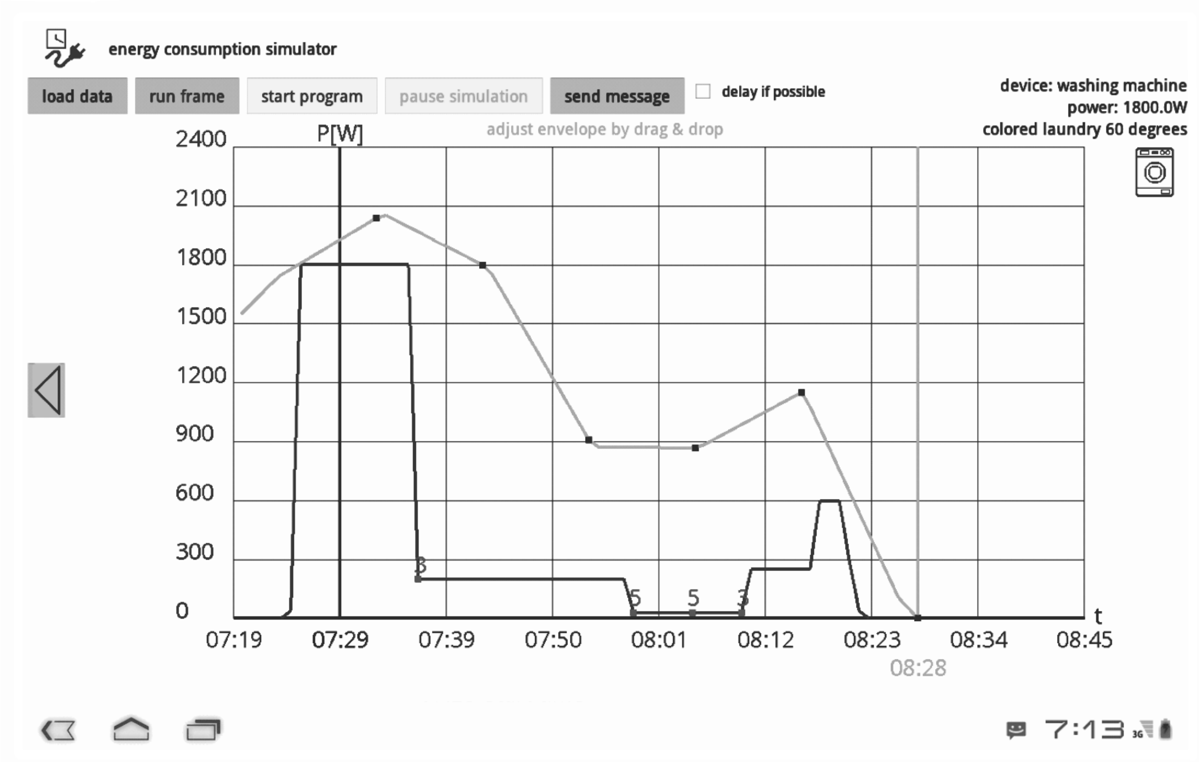

Figure 4. Screenshot of a washing machine simulation with a typical load profile. The dark curve is the objected load profile (corresponding to the chosen washing programme, in this case "colored laundry 60 degrees") and the gray curve is the envelope function showing the maximum allowed (by a central energy balancing unit, e.g. an enhanced smart meter) energy consumption at all times. The numbers stated at the load profile curve depict minutes the point of the profile can be delayed without influencing the washing process (e.g. the start of the spin cycle might be delayed a few minutes). 08:28 is the configured latest allowed end for the completion of the washing programme.

During a simulation, the program is started automatically if the complete desired load profile is less or equal than the envelope function. In other words the area under the envelope function must form a full inclusion of the simulation profile. If this condition cannot be fulfilled before the configured finish time a `no start in envelope possible` warning message is displayed. The start of the program can also be manually forced by the user. The simulation can be paused for modifying the envelope function shape. In this case, it can happen that a successful continuation of the profile is not longer possible and an error message `conflict unavoidable` is displayed. So these types of devices provide an increased ability in managing the objected load profile. The simulator can also receive the described envelope trace via the implemented external hardware interface form a higher instance energy gateway controller or home automation system.

Figure 4 illustrates a static load profile of a washing machine. The dark curve in the diagram is the desired load profile. The gray trace is an envelope function, which is defined by the user. It is shown that the starting point of the load profile is shifted in a way to fulfill the defined envelope function. In the shown simulation run, it is possible to finish the full operation of the washing machine before the latest allowed endpoint and under the constraints defined by the envelope.

B. Virtual Devices with Dynamic Load Profiles

These types of household appliances have a load profile which is not constant over its operation process. The load signature depends on external parameters influencing the device's behaviour. This can be user interactions performed on the virtual appliance, environmental parameters or configurations at the virtual appliance. In simulation run mode a forecast of the load profile and internal parameters of the device are calculated. If one of the simulation input parameters change, the according forecast is not longer valid and must be recalculated. The load forecasting ability of a device is a significant advantage for the energy supplier. These data can be used for planning proposes, coordinated load management and increasing the efficiency of generation and distribution of electrical energy.

A class of appliances having a dynamic load profile implemented in this simulator is charging devices

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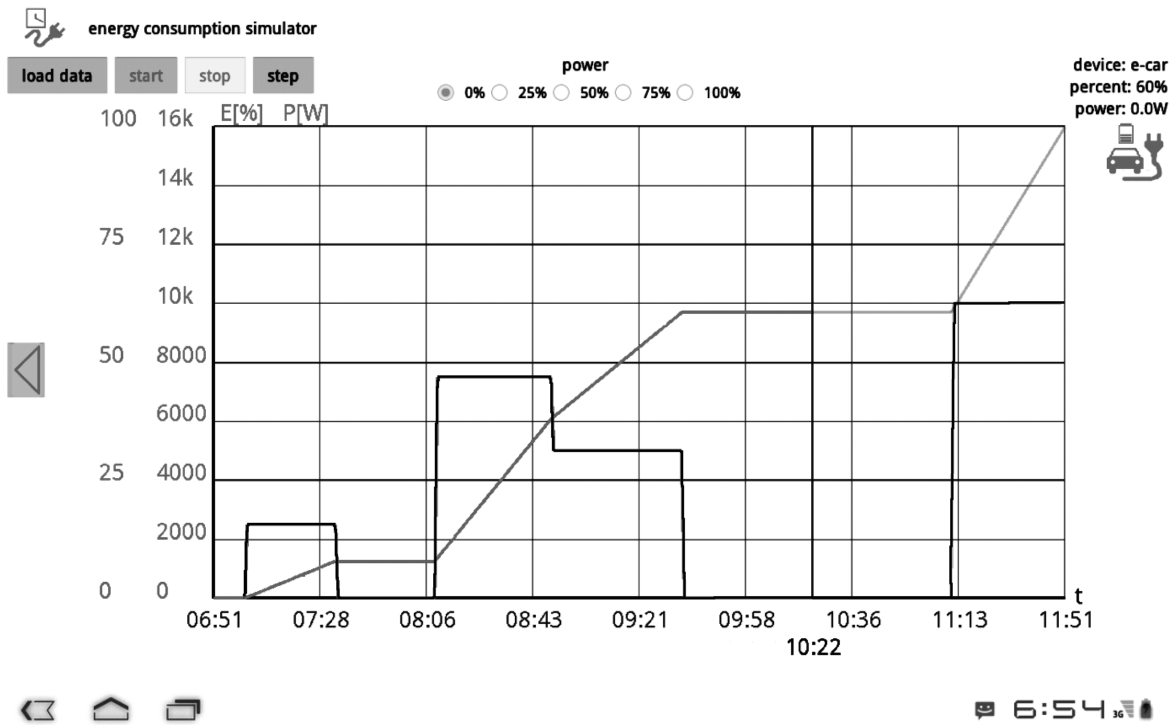

Figure 5. Simulation screenshot of an electrical car charger. The black curve is the resulting load profile dynamically influenced by the user. The gray curve is the corresponding charging state of the accumulator. 10:22 is the current time of simulation. The curves displayed on the right side of 10:22 are the predicted (by the simulation) load profile and percentage of the charging process.

for electrical accumulators (i.e. e-car, e-bike). At the configuration page start and the latest desired end time and date can be set up. Two additional parameters configure the capacity of the accumulator and the maximum charging power. If the device can not be fully charged under the specified timing and accumulator properties, a warning message is displayed. During the simulation a planned load profile for fully charging the accumulator and the charging percentage level is displayed. The charging power can also be modified manually. After this action, the forecasted profile is recalculated in a way that the timing requirement for the end of the charging process is still fulfilled. If the manual setup of charging power would not lead to a fully charged accumulator at the specified end time, the charging power value will be forced and increased automatically to 100%.

Figure 5 for example shows the charging process of an electrical car. With the radio buttons the charging power can be manually modified. The slope of the charging percentage state is proportional with the configured charging power. The forecasted increase of charging power to 100% at 11:13 is calculated automatically to fulfill the requirement of a fully charged accumulator at the configured end time.

IV. Implementation

This section describes the concrete implementation of the functionalities described in prior sections. Some details about system requirements, software structure, user interaction and external interfaces are introduced.

A. Software Structure

The simulation software is implemented as a package of Java classes. The main class instantiates all other modules and manages the control flow through the application. The user can select a device and is lead to the configuration page of the virtual appliance. For each type of appliance, a specific configuration class is implemented. After configuring the device parameters the simulation can be started. All simulation algorithms of a device are implemented in a simulation run class and, called after each step of simulation time. The run can be executed in real time or in an accelerated simulation time scale where one second equals to one minute of real time. The simulation run class of a device also handles the touchscreen input events and update visible information fields. At the start of the simulation, an additional thread for the handling of the graph view is started. All calculations, update methods, redrawing functions, etc. concerning the diagram area are outsourced to this additional thread. Basic thread functionalities (create, cyclic call, etc.) are realized by using implemented Android API classes.

A process started in the background handles the USB (Universal Serial Bus) communication for simulation input parameters. Functions for receiving and sending commands are sequentially called in this process. The functions for handling the USB interface are described in more detail in the next subsection.

B. Hardware Interface

Outputs of the simulation (current power consumption of a virtual device) can be written into a data buffer. The buffer content can be forwarded into a file or provided for external units via the USB-OTG interface of the tablet PC. For the simulation of virtual devices which are able to manage their load consumption automatically also additional simulation input parameters, such as envelope functions, start commands, etc. are required. For the demonstration of the simulator in the GREEN HOME project this commands will be transmitted by a smart energy gateway board. The external interface is realized with a USB to serial conversation chip. For a successful communication between tablet PC and external conversation chip the USB interface of the tablet PC must work as a host device. Finally, for future applications and compatibility with different controller units an interface software layer at the Android system supporting byte transfer is implemented. For test and demonstration purposes, a human readable text based command and data protocol is realized. This allows setting power states, requesting information about the simulation and the manipulation of envelope curves.

V. Conclusion and Future Work

In this paper, the development of a household appliances simulator was described. The simulator is implemented on the freely usable operating system Android. Three classes of virtual appliances are implemented: devices which can be turned on and off, devices with a static load profile, and devices with a dynamic reconfiguration of the load profile. A desired point in time for the end of the device operation can be configured. Depending on the current price constraints for electrical power the activation is delayed. Another management functionality is the forecast of a load profile. Depending on the device's internal parameters and under the consideration of a conventional operation, the load profile can be forecasted for a defined future time window. To be able to couple the simulator with a real world application, a serial communication is implemented. As a summary, it can be said that the implemented simulator is optimized for demonstration purposes and can act as a portable prototyping platform for energy management functions which will be included in future home appliances.

For future work and research, several additions and functional extensions are identified to improve the performance and usability of the simulator application.
A parallel simulation of more than one device can be implemented. The virtual devices can be simulated on one or distributed on several tablet PCs. An appropriate management of the simulation instances (i.e., time synchronization) must be fulfilled. An additional task at running multiple device simulations on a single tablet PC is a performance and benchmarking analysis.

A class of appliances not implemented yet are devices with a continuously load profile as described in Section II. For a future implementation of such appliances, a model of internal electrical drives and control loops must be considered.

Advanced features at the charging devices can be simulated, e.g., the desired charge state of the accumulator at the end of the charging process might be given by the user as opposed to always ”full charge”.

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