DESIGNING SELF-ADAPTIVE SMART SPACES FOR ENERGY SAVING

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ABSTRACT

This paper presents a SystemC-based framework for the simulation of smart spaces that focuses on energy aspects. Indeed, an efficient energy management plays a key role for the global reduction of carbon emissions. For this reason, the design of energy-aware smart spaces, able to self adapt to the surrounding environment, is becoming more and more interesting from the research point of view. However, it presents several challenges for their design, mainly due to the complexity of these complex and distributed systems and their cooperative behavior. This framework thus aims at facilitating the design of such complex cyber-physical systems.

1. INTRODUCTION AND RELATED WORK

Energy sustainability is becoming a central point in research to move towards a sustainable planet and research frameworks, like European Union Horizon 2020 [1], are currently encouraging to develop solutions to pursue these objectives. In this context, in both academia and industry, there is a growing interest for *smart spaces* [2]: they are environments such as apartments, offices, museums, hospitals, schools, malls, university campuses, and outdoor areas that are enabled for the co-operation of objects (e.g, sensors, devices, appliances) and systems that have the capability to self organize themselves, based on given policies.

Thanks to their main characteristics, these cyber-physical systems [3] are self-aware, heterogeneous and distributed for an efficient management of the energy consumption. Indeed, to realize these smart spaces, dozens of distributed computation, perception and actuation modules are usually adopted [4]. Sensors will gather a huge quantity of information that must be elaborated from the computation nodes and then efficiently transmitted to the actuators. For these reasons, efficient hardware infrastructures, software systems and design flows are in great needs. Dedicated techniques for their design, implementation and validation are definitively required, especially by means of simulation methodologies to analyze how the components affect each other and the interaction with the external physical environment, especially when considering energy aspects.

Even if there exist many approaches for the energy management of smart spaces, also the evaluation of the dynamic policies would be very attractive to self adapt the system to the surrounding environment. In such a scenario, system-level modeling through SystemC and TLM [11] has been demonstrated [12, 13] a viable solution to easily describe an overall system architecture and to simulate the computation of big amounts of data. On the other hand, an example of simulation environment can be found in [14] where a time-domain simulation environment for smart spaces with probabilistic appliance events is presented, but the appliance behavior is only represented as a Poisson random variable. In [15] the *Bit-Watt system* is presented to evaluate the performance of energy management in a home environment by computer simulations. However, the physical behavior of the surrounding environment is not actually simulated, potentially limiting the analysis that the designer can perform. Another simulator is presented in [16] to coordinate the execution of the residence appliances to minimize system cost assuming a time-of-use electricity rate structure.

In conclusion, to the best of our knowledge, it does not exist any modular and extensible framework that allows to efficiently design the systems (e.g., also integrating models of newer appliances) and evaluate them (and their cooperation) at different levels of abstraction, including the interaction with the physical environment.

This paper thus introduces *EA-SIM*, a novel and open-source framework for designing, simulating and validating self-adaptive and energy-aware smart spaces. EA-SIM is based on SystemC TLM-2.0 and it allows a functional validation of the generated systems and also the analysis of non-functional properties, such as performance and power consumption, at different levels of abstraction. Moreover, it can integrate the simulation of the physical environment (e.g., thermal trends, power consumption) to validate the decisions taken by the control units with respect to the information gathered by the sensors. *EA-SIM* offers an extensible component library that allows to model the different elements of a smart space: the control units, the computational nodes, the appliances, along with their sensors and actuators. Moreover, it is also possible to associate local batteries with each appliance and control their usage to reduce peaks.

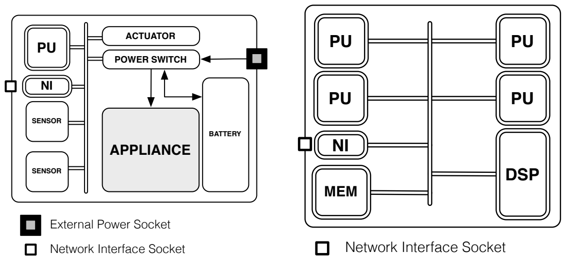

Fig. 1. High-level organization of the smart appliance (left) and the energy box (right).

2. EA-SIM SIMULATION FRAMEWORK

An energy-aware system can be defined as a context-aware architecture that can sense its physical environment, and adapt its behavior accordingly. Therefore, in order to simulate such kind of systems, it is necessary to create a framework able to evaluate the concurrent activity of all the components (i.e. the nodes), how they exchange the data and how they consume energy with respect to the users' requests and the policies defined by the control unit. For this reason, we propose *EA-SIM*, a simulation framework based on SystemC TLM-2.0 [11] that allows to easily evaluate the behavior of an energy-aware smart space. In particular, different architectural solutions can be evaluated, as well as different policies to control the dynamic behavior of the overall system. EA-SIM is an under development framework that allows to design and to simulate energy-aware smart spaces that are represented as composed of *power generator nodes*, *appliance nodes* and *energy boxes*. It should be noticed that this representation is flexible enough to represent a great variety of different spaces but simple to use at the same time.

A **power generator** is a component that produces electric current as, for example, the one representing the incoming current from the national power system. Also **accumulators** (batteries) are modeled in the proposed simulation framework. The use of batteries in a grid of appliances has been proved to be effective [9]. In fact, supplying energy from accumulators during peak electricity consumption times allows lowering peak demands and reduce both energy costs and carbon emissions. Furthermore, they can be used to compensate for the variability of typical renewable resources (e.g., wind, wave, solar), thus making the integration of such facilities more viable in practice [17].

In our view, two different appliances can be inserted in the simulation: standard and "smart" appliances. A simple **standard appliance** does not provide any sensors, actuators or digital interface to customize the behavior that can be modeled through mathematical models (including electro-mechanical behavior) or through the profiling of actual users' experience. A **smart appliance** is a more sophisticated appliance, also providing a socket interface to receive commands. It can have sensors to read the current status of the appliance and actuators to modify the status. The representation of such smart applicances is shown on the left side of Figure 1. It is thus possible to lower peak demand and reduce both energy costs and carbon emissions. Furthermore, storage devices can be used to compensate for the variability of typical renewable electricity generation (e.g., wind, wave, solar) and supporting their practical integration [17]. The *power switch* is used to select which is the the current power supply: the battery or the external power generator. A *processing unit* (PU) coordinates all the other elements: this can be connected to a *Network Interface* (NI - to communicate with an external energy box), sensors and actuators through a bus or similar communication infrastructures. The power switch is then responsible for the selection of the right power source for the appliance. The selection is performed by the PU and it is based on the policies suggested by the external *energy box*. Three situations are envisioned in a smart appliance: (1) the appliance is powered through the external power socket and the battery is not recharging; (2) the appliance is powered through the external power socket and the battery is recharging; (3) the appliance is powered through the internal battery. The processing unit is instead the module responsible for the coordination of the entire smart appliance.

The **energy box** nodes (as shown on the right side of Figure 1) are adopted to monitor and manage all installed appliances, generators and accumulators (batteries). They are designed to potentially elaborate a large amount of sensing data and implement dynamic control policies. For such reason, an energy box is an embedded and heterogeneous multi-core architecture. Also a memory module can be available in order to store temporary data. A network interface is responsible for the connection with the other nodes. Moreover, a energy box can be connected to the NI to provide a remote interface to access features exported by the appliances. It will also build profiles inferred from the behavior of connected devices, for example to recommend and actuate energy conservation policies.

3. CASE STUDY

This section presents two case studies as preliminary examples to show the validity of the proposed simulation framework. Figure 2 shows the corresponding architecture. This architecture contains one *power generator* and one *energy box* to control the energy consumption of two *appliances*. Then, only one of them is "smart", i.e., it has been enhanced with a *power switch*, a *battery* and finally a *CPU* to implement the policies decided by the *energy box*. To show the effectiveness of the proposed framework, different situations have been evaluated. In all these cases, the charge of the battery is always maintained between 30% and 60%, as soon as it enters in this interval. Moreover, the *energy box* imposes

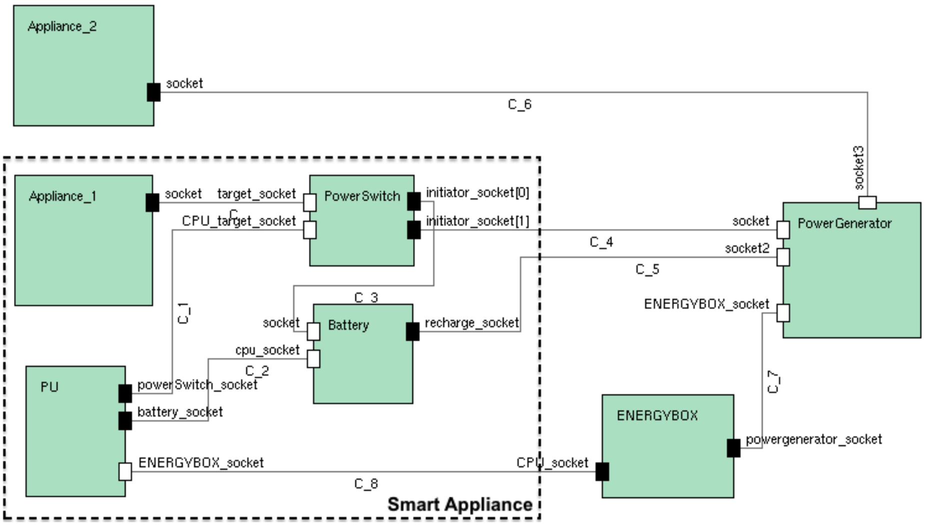

Fig. 2. Schema of the simulated architecture.

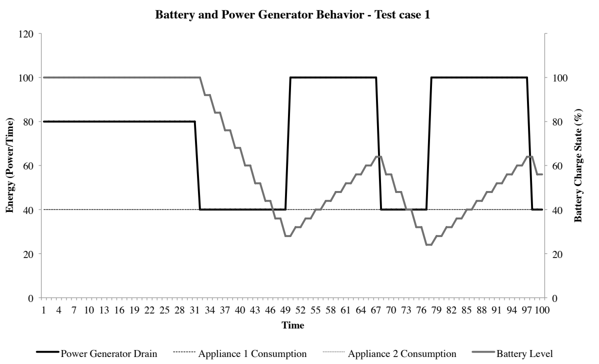

Fig. 3. Results of experiment #1: two appliances with constant energy consumption, where one of them is equipped with a battery.

the *smart appliance* to use the *power generator* instead of the *battery* for the first 30*ut*s in the first example and for 20*ut* in the other ones. All the experiments have been conducted through Synopsys Platform Architect [18] that offers a GUI to easily connect all the components of the system, execute the simulations and analyze the results.

In order to better understand the meaning of the case study, it must be known that using EA-SIM it is possible to set the desired units of measurement for both the energy consumption and the time. In fact, based on the appliances under analysis, the designer can configure the system to simulate the power, for instance, as *mW* or *W*. Then, based on the granularity of the dynamic behavior to be simulated, the evolution of time can be represented, for instance, in *seconds* or *minutes*. As a consequence, since in this paper we are only interested in analyzing the dynamic behavior of the energy-aware system not from a quantitative but from a qualitative point of view, in the rest of this work, the quantity of energy is indicated in *unit of energy* (*ue*) and the time is represented in *unit of time* (*ut*).

In the first experiment, the two appliances have a constant consumption of 40*ue/ut* and the battery has a consumption of 20*ue/ut* when it recharges. As shown in Figure 3, for the first 30*ut*, the two appliances are powered through the generator that thus consumes 80*ue/ut* (40*ue/ut* for each of the two appliances). After 30*ut*, the energy box switches the power source of the smart appliance to the battery and, as it is possible to see, the battery starts to discharge and the consumption of the power generator drops down to 40*ue/ut* (since one appliance is still powered using the generator). As soon the battery charge level is less than 30%, the energy box decides to switch again the smart appliance to the generator. The energy provided by the generator is now 100*ue/ut* since it has to power two appliances (40*ue/ut* for each of the 2 appliances) and the battery (40*ue/ut*).

Let us consider another experiment. While the the behavior of the battery is the same as before (it consumes 20*ue/ut* during the recharge phase), in this case the standard appliance (i.e., the one that is directly connected to the power generator) has a different dynamic. In fact, it has a step-based energy consumption, instead of a constant one. More precisely the step function has a value of 10*ue/ut* in the intervals (0;10) and (40;100) and 60*ue/ut* in the interval (10;40). In this case, the behavior of the power generator becomes really interesting, as shown from its curve in Figure 4. In fact, in the first 10*ut*, the drained energy is 50*ue/ut* since the two appliances are consuming 10*ue/ut* and 40 *ue/ut*, respectively, and the battery is not used (due to the pre-defined policy of the energy box). In the interval (10;20), the battery

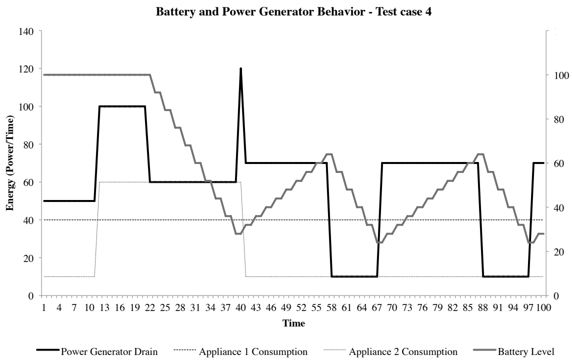

Fig. 4. Results of experiment #2: the energy consumption of one of the appliances is characterized by a step.

is then activated and the curve of the power generator drops down to 60*ue/ut* (i.e., the consumption of the standard appliance). An interesting phenomenon occurs at 10*ut*, where it is possible to find a peak of 120*ue/ut*: this value is due the fact that in that moment the battery starts to recharge (20*ue/ut*), the smart appliance is not using the battery since it is in charging (40*ue/ut*) and the standard appliance is still draining 60*ue/ut*. The other important interval that must be considered is the one between 57*ut* and 67*ut*: here the battery is in use and consequently the power generator has to take care only of the standard appliance (10*ue/ut*). These experiments demonstrated that the proposed EA-SIM framework is effectively able to simulate complex behaviors of interacting appliances in a smart environment, where the designer can evaluate simple yet effective policies to control the energy consumption of the system. For instance, it is possible to use EA-SIM to explore different solutions to mitigate peaks in the architecture, e.g., by changing the battery policies or evaluating the behavior of different possible components.

4. CONCLUSIONS AND FUTURE WORK

We presented EA-SIM, a modular, open-source and extensible framework for supporting the design and the validation of energy-aware smart spaces, allowing the easy evaluation of different aspects at both hardware and software levels.

Future research is oriented to design efficient system architectures and policies for supporting energy sustainability of existing spaces. Moreover, novel guidelines will be also investigated to suggest the design of future smart spaces.

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