A Methodology to Evaluate Demand Response Communication Protocols for the Smart Grid

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***Abstract*—Not far into the future, the power grid will be supported by response from the consumers, helping the grid operators in making more informed decisions about administrating electricity distribution. A critical enabler for a stable solution is the communication protocol between the consumer and the grid operator. Currently, there exist many evaluations of demand response strategies for shifting consumers' usage, but these often do not consider the performance of the demand response protocol enabling this. In this paper, we present a methodology for evaluating the performance of demand response protocols for the Smart Grid in combination with a demand response strategy. The methodology shows how to formalize a household scenario, reuse existing specifications of demand response protocols, and strategies for this evaluation. The results are used to enhance the protocol behavior by tuning its parameters. Smart Energy Profile 2.0 (SEP2) communication protocol is used in a case study to validate the proposed methodology.**

***Index Terms*—Demand Response, Protocols, Smart Grid, Modeling, SEP2, UML, MARTE, Simulation, Evaluation.**

I. Introduction

The power grid reliability and stability come from the continuous balance between power generation and the consumption. The move towards a large-scale integration of renewable energy sources, with its high degree of fluctuations on the generation site, fosters an urgent need for solutions to control the consumption side. Demand Response (DR) in the smart grid is proposed as a mechanism to ease the balance in the power grid. It relieves the undesirable stress in a power grid by providing flexible consumption without requiring expensive storage solutions to be deployed [1].

Recent advances in DR technology have focused on the standardization of control protocols for home appliances to provide a flexible electricity demand. More generally, to be applied for offering intelligent automation services in the smart grid [2]. Two diverse industrial alliances have set course towards standardizing and simplifying DR. The OpenADR Alliance has created product profile specifications based on the OASIS Energy Operation Standard [3]. In contrast, the ZigBee Alliance and HomePlug Powerline Alliance have published the Smart Energy Profile 2.0 (SEP2) Application Protocol Standard [4] which has recently been adopted by the IEEE 2030 project. The SEP2 protocol is based on a RESTful communication model that uses HTTP over TCP/IP with a series of function sets to support smart energy applications. Aggregation service providers can utilize SEP2 to control an aggregated DR from a set of residential households.

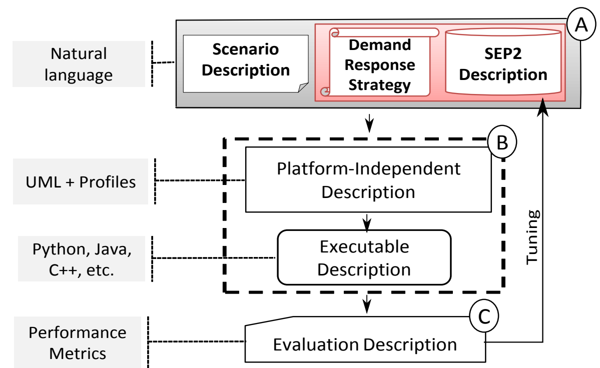

Fig. 1. Proposed methodology.

However, to the best of our knowledge, the following requirements are not yet meet by the current state of the art:

1) A formal way to describe, model, and synthesize a DR communication protocol combined with the user scenario and the DR strategy;
2) A unique method for modeling, simulation, and evaluation of DR protocols;
3) A structured method to fine-tuning protocol parameters;
4) A way to evaluate the performance of a DR communication protocol.

This paper presents a design methodology to model, simulate, and evaluate DR communication protocols together with DR strategies for smart grids applications. Figure 1 shows the methodology design flow; alphabetic labels are used to show the item to be explained below. The methodology starts by the natural description of the user's behavioral scenario (e.g., turn ON/OFF the lights), the chosen DR strategy, and a protocol under test (label A). These descriptions are then formalized, modeled, and simulated to validate the overall system functionality (label B). From simulation results, the DR protocol is evaluated based on predefined performance metrics. In order to improve the protocol performance, the evaluation results (label C) can be used to adjust the protocol's tuning parameters. System developers and power grid engineers can benefit from using the methodology by shortening the design and deployment time of DR programs. DR strategies can be validated before launched and the results can be applied to reliability and stability analysis for the power grid. Furthermore, the methodology allows for a heuristic way to couple end-user behavior with the system performance.

II. State of the Art

The envisaged smart grid is a complex system consisting of multiple subsystems each calling for advanced simulation tools to gain enough knowledge before deployment. Domain experts from computer, electrical, and control engineering are some of those roles that must collaborate for creating a smart grid. Furthermore, the amount of data to be collected and processed requires for novel methods that can partition into manageable units, while also being able to do comprehensive simulation of the entire system. Recent attempt in [5] has created a framework for large-scale analysis of the smart grid control mechanisms that performs co-simulation of existing domain specific simulators. It performs a unified evaluation by simulating different compositions of scenarios, grid topologies, and control strategies. Nevertheless, it ignores the network layer and messages are exchanged reliably and securely between different domains. Therefore, a unified modeling approach seems a feasible solution for coping with the complexity.

Model-driven development methods of the smart grid are currently limited and not well supported. The authors in [6] also recognize this issue and propose a semantic-driven design method using the Common Information Model (CIM), and the IEC 61850 and IEC 61499 standards. The standards include different domain specific views for control, communication, power grid and the application. Niebe et al. in [7] propose a holistic process model that uses a system engineering approach, where the focus lies on bridging the gap between theory and practice in the smart grid. Their main message is to change development methodology from an application-oriented research to a commercialized software development when developing distributed control algorithms. However, the evaluation and validation for both of these methodologies [6, 7] are not done, and do not specifically address DR protocols.

Unified Modeling Language (UML) [8], high-level modeling language, is widely applied for the modeling and specification of software. Several studies have demonstrated that it is also applicable for hardware/software/network co-design [9]. There are studies that make use of UML and derive network simulation models from its description. For instance, De Miguel et al. [10] introduce UML extensions for the representation of temporal requirements and resource usage for real-time systems. Their tools generate a model for the OPNET simulator. Therefore, validation by simulation is considered one of the appropriate solutions to verify such models and for that several simulators have been combined to perform co-simulation for smart grid applications [11]. Moreover, other studies are proposing methodologies to generate executable models from UML for model verification by simulation such as in [12]. Nevertheless, UML profiles such as the Modeling and Analysis of Real-Time and Embedded Systems (MARTE) profile [13] are widely used by system level designer to enhance the UML models by embedded systems semantics.

The OpenADR 2.0 is an application layer protocol designed to ease DR actions like load reducing/shifting within DSO, service providers, and consumers' energy management systems [3]. The SEP2 protocol is another application layer protocol that can be used for DR purposes [4]. Some of the SEP2 functionalities overlap with OpenADR 2.0. Being the main difference that the former is targeted to Home Area Network while the latter covers a wider range of DR applications and market rules. For a comprehensive comparison between these protocols, the reader is referred to [14]. Both protocols are specified using UML diagrams and have received the highest scores by the Association of Home Appliance Manufacturers (http://www.aham.org/). DR strategies use protocols to manage the electricity loads. This can be done by using actuators to control residential appliances. Common approaches to model control strategies establish rules (e.g., not to run if the price excesses the threshold) [15] while others use more complex control algorithms. An alternative is to use multi agent-based systems on the decision making allowing more complex solutions [16]. The reader is referred to [17] for an overview of different control strategies, where model predictive control is presented to regulate loads in a residential building.

This paper rests on the model-driven approach of current smart grid research using UML. It provides a methodology to evaluate DR protocols in a holistic way that takes into account protocol specifics in combination with a chosen DR strategy.

III. Proposed Methodology

The viability of a DR protocol in a real world setup depends on multiple factors each having an impact on the performance of the protocol. For instance, a given user behavior impacts on the grid control. Likewise, a change of DR strategy will influence on how the user is requested to change behavior. The proposed approach allows modeling the user behavior while also taking into account a DR scheduling algorithm.

In order to assess if a given DR protocol is suitable for a smart grid environment, evaluation parameters associated with the DR protocol and the resulting consumption pattern of all households are considered. The evaluation parameters for the protocol can include transmission overhead and time responsiveness between the device client and the DR server. These metrics allow DR protocol developers to benchmark the protocols against timing requirements, but also for making comparisons between them. Furthermore, the specification of DR protocols often gives the possibility of adjusting parameters of the protocol. Tuning these parameters may have an impact on the protocol evaluation, but also on how successful the DR strategy is in shifting the electricity consumption. Figure 2 details each part of the proposed methodology and is labeled (A, B and C) referring to the sections III-A, III-B, III-C below.

A. *Describing Household Scenarios, Demand Response Strategy, and Protocol*

The description of household scenarios accounts for the majority of the dynamic behavior in the system. Their compositions are essential for the evaluation but also the alignment with the real world. Descriptions should be written in a natural language such that a non-technical person can understand and

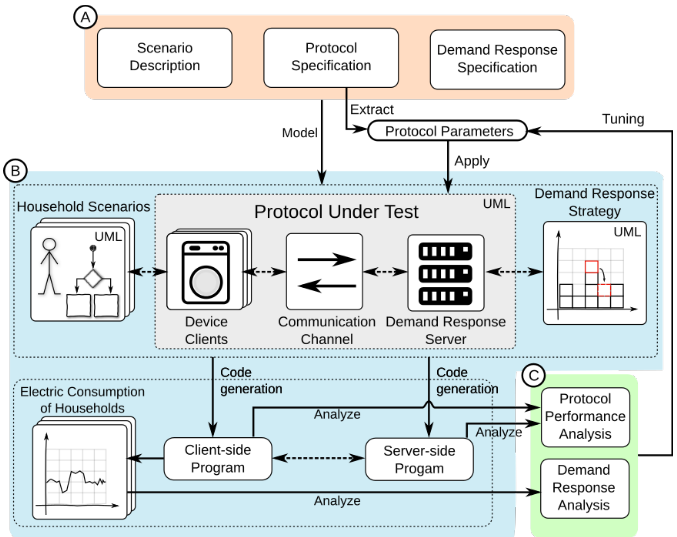

Fig. 2. Detailed overview of the proposed methodology for evaluating and tuning demand response protocols.

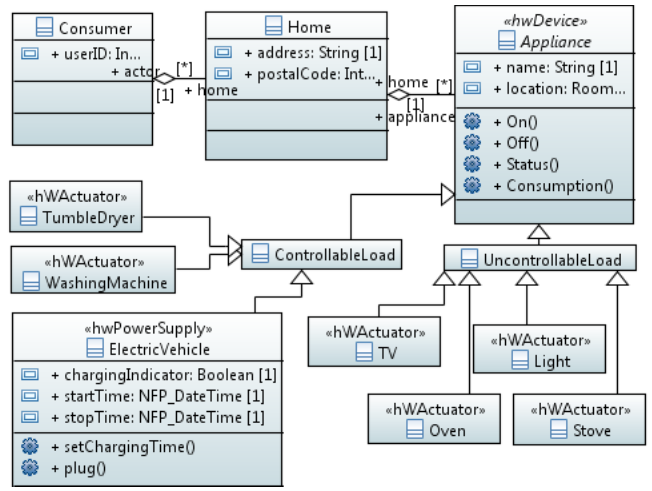

Fig. 3. Home automation UML class diagram with MARTE profile annotations.

create these. The household scenarios should only include information relevant for the scope of the simulation, however the order of execution is obligatory for the formal transformation. To gain greater insight into the temporal progress, details about the execution time can be included.

Protocols are generally implemented based on their specifications, i.e., a document that contains communication requirements and protocol parameters which can be adjusted for conforming the needs of the domain. Together with a schema (or a data format hereof), these form the building blocks for the communication. These specifications can occasionally be found modeled in UML (e.g., in SEP2).

DR is a temporary adjustment on an electricity consumption to provide flexibility to the power grid. A goal of a DR strategy is to reduce or shift load. The former implies a reduction on electricity usage while the later entails changing the electricity consumption to a more suitable time period. The creation of a DR strategy is typically done by minimizing grid operation costs. These are first formulated as mathematical expressions that later on can be modeled.

B. Platform-Independent and Executable Descriptions

UML and its profiles are the core of the proposed methodology (Figure 1) as a standard and interoperable representations of the scenario, DR strategy, and protocol descriptions. Therefore, a combination of UML structural and behavioral diagrams have been used to model such descriptions.

UML class diagrams capture the structure of the whole system. *Sequence diagrams* depict the interactions between the consumer and the appliances and describe the DR protocols (e.g., SEP2). *Activity diagrams* capture the behavioral aspect of smart grid components (e.g., electric vehicle). The MARTE profile [13] has been used to enhance the UML models with semantics for electrical appliances and timing, thus enabling system simulation by code generation from UML models.

Therefore, MARTE `HWDevice`, `HWPowerSupply`, and `DeviceActuator` stereotypes with MARTE's non-functional properties are used to extend the semantics of the used models. Figure 3 shows a model of part B of Figure 2. The model is developed as a class diagram with annotations of the MARTE profile which then will be used in Section IV for implementing the case study. For instance, the *Appliance* class is specified by the MARTE stereotype ⟨⟨`HWDevice`⟩⟩ for denoting that this class describes a hardware component.

Model validation by simulation is a complementary approach to validate high-level models. One approach is the Models-to-Text transformation which aims to synthesize such high-level models by generating textual artifacts from them. For example, Acceleo (http://www.eclipse.org/acceleo/) is a pragmatic implementation of the Object Management Group (OMG) model to text language standard. It can be used to generate executables descriptions from high-level models.

1) UML to Code Generation: In this work, Python, high-level programming language, has been used as an executable description of the high-level models. Table I shows the correspondences between UML and Python syntaxes. The structural diagram (i.e., the class diagram) is directly mapped into Python's class syntax. The behavioral diagrams (i.e., sequence and activity diagrams) are firstly formalized and then synthesized into executable code. One way to formalize sequence diagrams is to use finite state machines that can be converted into *IF-THEN-ELSE* statements. More details about the high level synthesis step can be found in [18].

C. Evaluating Demand Response Strategy and Protocol

The assessment of a DR strategy depends on the evaluation metrics considered. On the household side, these metrics can be thermal comfort, saved money, and waiting time for appliances to run. On the DSO side, these can be the power peak reduction, economic benefits, and time responsiveness [19].

The time responsiveness of DR specifies how fast an electricity load can be shifted/reduced. For frequency reg-

TABLE I
MAPPING BETWEEN UML AND PYTHON ELEMENTS

UML	Python
Class	Class
Attribute	Variables
Operations	Method Objects
Constraints	Assertions
Sequence diagram	IF-THEN-ELSE

ulation this response is more important than for day-ahead DR. The quantity of load shifted/reduced, difference between baseline DR and DR load, is also an important metric for the DSO because monetary remuneration to the consumer may depend on it. A common purpose of DR is to reduce electricity consumption in peak hours, thus indices such the variance/standard deviation of the power consumption, Peak-to-Average Ratio (PAR), and Root Mean Square (RMS) of the divergence of power reference and actual value are usually considered [19, 20]. The PAR is the fraction of the maximum power consumption and the average power consumption. For a more comprehensive list of demand response performance metrics the reader is referred to [19].

To assess a protocol in a client-server architecture, the number of packets exchange can be considered. For a DR scenario, it should also include other metrics, like the waiting time between client requests to start, to it is allowed to start. Too long waiting times decreases consumers' willingness to follow DR strategy. Furthermore, the presence of rebound peaks provides a key indicator, since a massive reconnection of loads after a failure event, can lead to grid instability.

IV. EXPERIMENTAL RESULTS

The proposed methodology is demonstrated through a case study. As starting point, a real scenario has been described, a DR strategy has been chosen, and the SEP2 protocol has been set to be evaluated. All the latter have been formalized and modeled using UML. From the models, executable Python code has been manually synthesized and simulations have been performed. The results have been analyzed based on performance metrics to tune SEP2 protocol parameters.

In an experiment to evaluate the simulation performance, 6,000 appliances were simulated with a 24-hour time horizon and a set of load profiles with 6 seconds resolution. The experiment was performed on a PC equipped with a 3.21 GHz quadcore CPU and 4 GB of memory. However, the simulation software runs on a single CPU core. The simulation time is depending on the number of protocol messages used in the demand response signaling. The experiment showed that the simulation time increased linearly from 8.3 minutes for a total of $100{\times}10^3$ messages to 68 minutes with $485{\times}10^3$ messages.

A. Describing Household Scenarios, Demand Response Strategy, and Protocol

A deterministic scenario with one household has been considered. A simple DR strategy based on a *soft threshold*

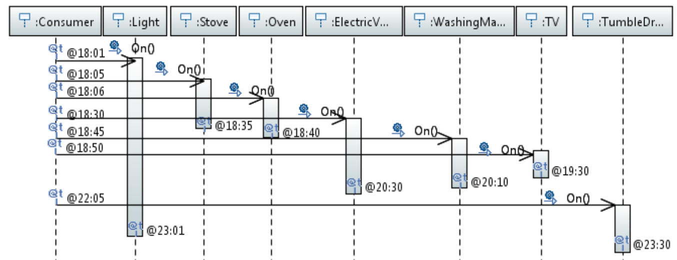

Fig. 4. The consumer's scenario description.

constraint has been chosen; if instantaneous power consumption is below 3,000 W allow appliances to run in the immediate future. SEP2 has been considered as a protocol under test. SEP2 is described from its specification document [4]. Two parameters from SEP2 have been considered in the evaluation process. First, the time between pooling events: waiting time for a client before sending new petition to start (max 5 minutes). Second, the randomize starting time: aleatory time added to the starting time to avoid rebound peak originated from all client reconnecting at the same time (max 60 minutes).

B. Platform-Independent and Executable Descriptions

A UML/MARTE class diagram has been developed to capture the structural aspect of the case study as shown in Figure 3. The timed scenario of the consumers' interactions with its appliances is capture by UML sequence diagram as shown in Figure 4. The power consumption function in the abstract class *Appliance* is extracted from real appliances consumption profiles. Appliances can be divided in two main categories: controllable (e.g. electrical vehicle) and non-controllable (e.g. television).

The DR strategy has been modeled with an activity diagram as shown in Figure 5. It is important to highlight that this strategy only manages controllable appliances thus leading in some circumstances to exceed the threshold.

Sequence diagrams have been used to model SEP2 communication protocol between the appliances and the DR server as shown in Figure 6. During the high-level synthesis of the protocol, a subset of the SEP2 specification has been implemented considering the Demand Response and Load Control (DRLC) function set with HTTP and XML as a data format. The Python library SimPy (pypi.python.org/pypi/simpy) has been used as a simulation environment to model the case study by creating both HTTP servers and clients having socket communication.

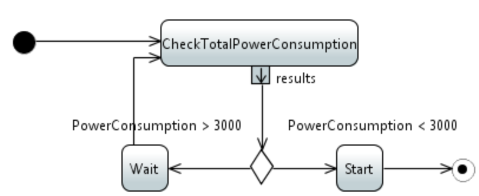

Fig. 5. Activity diagram of the demand response strategy.

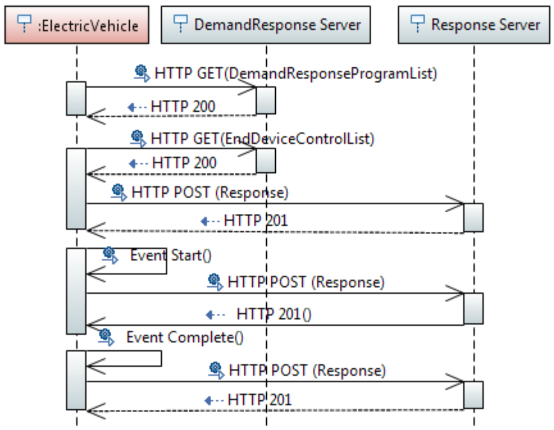

Fig. 6. Communication between the electric vehicle and demand response server with SEP2 [4].

C. Evaluating Demand Response Strategy and Protocol

Having the simulation environment in place, an iterative process has been conducted considering three different values of the randomized starting time (0, 20 and 40 minutes) and two values of the time between pooling events (1 and 5 minutes). The results have been evaluated considering performance metrics for the DR strategy and communication protocol. A naive approach has been followed when tuning the protocol parameters. The following indexes have been considered for the DR strategy: RMS of the difference between the soft threshold set by the DSO (3,000 W) and the power consumption, standard deviation (stddev.) on the power consumption, the power peak in each scenario, the PAR and the consumption overflow, i.e., percentage of the total kWh used above the soft threshold (area above red-dashed line in Figure 7A). From the protocol side, two metrics are analyzed: amount of HTTP GET messages sent by all controllable appliances in the consumer's household and waiting time of the appliances, i.e., difference between real starting time and time when the appliance first ask to start.

TABLE II
RESULTS OF THE DR STRATEGY AND PROTOCOL.

Metric	Baseline	$X \in [0,0]$		$X \in [0,20]$		$X \in [0,40]$	
		$T=1$	$T=5$	$T=1$	$T=5$	$T=1$	$T=5$
RMS(Ref-Pow) (W)	2101	1845	1845	1758	1755	1755	1751
Stddev. (W)	1838	1539	1539	1434	1430	1429	1425
Peak (W)	6536	6536	6536	4200	4200	3762	3762
PAR	3.3	3.3	3.3	2.12	2.12	1.9	1.9
Total overflow (%)	20.79	13.8	13.8	11.66	11.66	11.58	11.58
HTTP GET (#)	0	100	26	131	35	142	37
Waiting time (min)	0	95	96	127	148	139	160

X: uniform random variable for the starting delay in minutes when permitted to start.
T: waiting time in minutes between a client's request for a possible permission to start.

The results of the six combinations of both tuning parameters and the DR baseline (operation without shifting electricity usage) are presented in Table II. One can observe that the RMS and the standard deviation values are reduced when compared with the baseline and for the specific scenario both decrease with the incrementation of the randomized start. A lower standard deviation implies a more even distributed electricity consumption, goal pursued by most DSOs. The results show that the power peak, the PAR and the percentage of overflow is decreased as the randomized starting time increases. This is because most of the consumption in the described scenario is concentrated at the beginning. The shorter the time between pooling events is, the more messages are sent. Subsequently, the waiting time of appliances is reduced. From a DSO perspective, a suitable scenario is where: the power peak is reduced, the messages sent are low, and the waiting time of the appliances does not affect much to consumers' comfort. Therefore, in the presented experiment a randomized starting time of 40 minutes with 5 minutes between pooling events is considered as the favorite solution by a DSO. Figure 7 follows the timed scenario in Figure 4. In Figure 7A, the DR baseline operation (blue-dotted line) is compared with the scenario with the chosen protocol parameters (green-solid line) with the soft threshold strategy (red-dashed line). The observed peak in the DR baseline is a typical problem faced by DSO and TSO in many countries. The figure shows the generated peak from the charging time of the electric vehicle and shifting the usage of the washing machine and tumble dryer can be decreased significantly by means of DR. In the DR case, the threshold set by the DSO (red-dashed line) is exceed due to the uncontrollable loads of the household (i.e., oven, television, stoves, and light). It should be noted that the electricity used (11.9 kWh) is the same in both situations. However, the experiment shows that the scenario with DR is more convenient from a grid reliability perspective but may be more uncomfortable for the consumer. Additionally, Figure 7B shows the status of the three controlled appliances for the chosen DR scenario: electrical vehicle (EV), washing machine (WM) and tumble dryer (TD). It can be observed that the washing machine has to wait until the electrical vehicle has completed its charging.

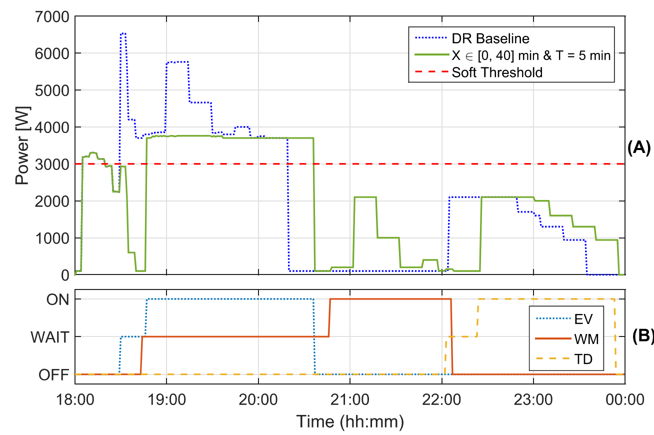

Fig. 7. (A) Comparison of electricity consumption with and without DR strategy. (B) Appliances status for $[X \in [0,40]$ & $T=5]$. The soft threshold in (A) is exceeded due to uncontrollable loads.

V. Conclusion and Future Work

In this paper, a methodology for evaluating the performance of DR protocols along with a DR strategy for the smart grid is presented. The methodology shows how to formalize, model, and simulate a household scenario. It reuses existing specifications of DR protocols, and strategies for its evaluation. It offers a model-driven approach for evaluating DR by combining strategy, scenario and protocol models that can be synthesizing into executable code. Using a simulation environment, the protocol is evaluated by observing a set of performance metrics. The results are used to optimize the protocol behavior by tuning its parameters. Furthermore, the proposed methodology is validated through a case study using the DRLC function set of the SEP2 protocol. The case study showed that it is possible to apply the methodology on the SEP2 protocol for a household scenario description and a specified DR strategy for evaluating its performance.

A future extension to this work, is a modeling technique to capture the user behavior in a stochastic manner. Trends indicate that agent-based modeling might be a possible path to follow. Treat modeling techniques may profitably be used for this purpose. Additionally, considering more complex control strategies can also be of interest. Optimal scheduling algorithms can be used for the decision making on allowing appliances to run. Last but not least, the fine-tuning process of the protocol parameters may be performed in a more comprehensive way, by using multi-objective optimization for doing multiple-criteria decision making.

Acknowledgement

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