Project no.:	**318490 (FP7-ICT-2011-8)**
Project full title:	**Self Energy-Supporting Autonomous Computation**
Project Acronym:	**SENSATION**

Deliverable no.: D1.2

Title of Deliverable: Energy Aware Automata

Contractual Date of Delivery to the CEC:	**M12**
Actual Date of Delivery to the CEC:	**M13**
Organisation name of lead contractor for this deliverable:	**AAU**
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Work package contributing to the deliverable:	**WP 1**
Nature:	**R**
Version:	**0.5 (draft)**
Total number of pages:	**12**
Start date of project:	1 Oct. 2013 **Duration:** 36 month

Project co-funded by the European Commission within the Seventh Framework Programme (2012-2015)

Dissemination Level

PU	Public	X
PP	Restricted to other programme participants (including the Commission Services)	
RE	Restricted to a group specified by the consortium (including the Commission Services)	
CO	Confidential, only for members of the consortium (including the Commission Services)	

Abstract:

This deliverable describes the first effort of the SENSATION project towards extending well-established modeling formalisms such as finite-state automata, modal transition systems, timed automata, probabilistic automata, discrete and continuous time Markov Chains and Decision Processes to allow additional quantitative aspecst, e.g. energy- and memory consumption, to be modelled and analysed.

Keyword list: Energy games, weighted Kripke structures, weighted modal transition systems, stochastic priced timed games, stochastic hybrid systems, Markovian models and metrics, cost-preservation, probabilistic automata, cost-bounded reachability, Markov Chains.

Contents

1 Introduction

This deliverable summarizes the advances that have been made by the SENSATION partners on the topic of Energy Aware Automata during the first year of the project. In particular, quantity-decorated automata, rooted in timed automata and Markov chains, have been developed to supportthe design-time analysis of time and resource-related computational problem.

The first three results we report on in this deliverable are all based on weighted extensions of finite-state specification formalisms:

Section 2 consider so-called energy games concerned with the existencec of infinite runs (one-player version) or strategies (two-player version) that guarantees that given lower (and possible upper) bounds on the accummulated weights are satisfied. For finite state energy games an algorithm for synthesizing tightest upper and lower bound-vectors is given. For weighted timed games it is shown that the existence of lower-bounded runs is undecidable. Clearly the notion of energy game is highly relevant for the GOMSPACE case study. Section 3 gives an efficient (symbolic) on-the-fly algorithm - and implemented tool- for model checking Weighted Kripke structures with respect to weighted CTL properties. Section 4 contains a sequence of results leading to a complete quantitative specification framework based on weighted modal transition systems.

Section 5 turns to the timed automata-based modeling formalisms of the tool UPPAAL. Here a natural stochastic of networks of timed automata providing the basis for the statistical model checking engine of UPPAAL-SMC. Moreover the semantics and the SMC-engine has been extended to priced timed automata, hybrid systems and systems with dynamic creation of components.

The remaining contributions are concerned with cost-extensions of various Markovian modeling formalisms:

Section 7 introduces effective notions of cost bisimilarities for probabilistic automata, with application to wireless communication scenarios. Section 8 focus on the problem to compute max/min resource-bounde reachability probability on Continuous-time Markov Decision Processes equipped with multiple rewards (or costs). Finally Section 8 introduces the notion of bisimilarity metrics between Markovian models (Markov Chains, Markov Decision Processes and Markov Reward Models) allowing for more drastric reduction of components than classical bisimulation. Moreover, a Mathematica Library for efficient on-the-fly computation of the bisimulation distance between two Markovian models is given.

2 Energy Games

Partipants

- Line Juhl, Kim Guldstrand Larsen (Aalborg University, Denmark)
- Jean-Francois Raskin (Universit Libre Bruxells, Belgium)
- Patricia Bouyer-Decitre, Nicolas Markey (ENS Cachan, France)

Contribution The notions of priced timed automata (PTA) and energy games (EG) provide useful modeling formalisms for energy-aware and energy-harvesting embedded systems. The paper [14] review these formalisms and a range of associated decision problems covering cost-optimal reachability, model-checking and cost-bounded infinite strategies.

Energy games have recently attracted a lot of attention. These are games played on infinite weighted automata and concern the existence of infinite runs subject to boundary constraints on the accu- mulated weight, allowing e.g. only for behaviours where a resource is always available (nonnegative accumulated weight), yet does not exceed a given maximum capacity.

Multiweighted energy games are two-player multiweighted games that concern the existence of infinite runs subject to a vector of lower and upper bounds on the accumulated weights along the run. In this work [12] we assume an unknown upper bound and calculate the set of vectors of upper bounds that allow an infinite run to exist. For both a strict and a weak upper bound we show how to synthesize this set by employing results from previous works, including an algorithm given by Valk and Jantzen for finding the set of minimal elements of an upward closed set. Additionally, we consider energy games where the weight of some transitions is unknown, and show how to synthesize the set of suitable weights using the same algorithm.

In [5] we investigate a number of problems related to infinite runs of weighted timed automata, subject to lower-bound constraints on the accumulated weight. Closing an open problem from, we show that the existence of an infinite lower-bound constrained run isfor us somewhat unexpectedlyundecidable for weighted timed automata with four or more clocks. This undecidability result assumes a fixed and known initial credit. We show that the related problem of existence of an initial credit for which there exists a feasible run is decidable in PSPACE. We also investigate the variant of these problems where only bounded-duration runs are considered, showing that this restriction makes our original problem decidable in NEXPTIME. Finally, we prove that the universal versions of all those problems (i.e, checking that all the considered runs satisfy the lower-bound constraint) are decidable in PSPACE.

Perspective The problem of synthesizing upper capacity bounds allowing for the existence (and synthesis) of winning strategies ensuring infinite runs within these bounds is highly relevant for the SENSATION case study provided by GOMSPACE. Here the bounds corresponds to the capacity of batteries and the strategies ensuring infinite runs, while be based on suitable scheduling of transmission of data to earth given information about possibility of harvesting energy from solar energy.

3 Weighted Kripke Structures

Participants

- Jonas Finnemann Jensen, Kim G. Larsen, Jiri Srba, Lars Kaerlund Oestergaard (Aalborg University, Denmark)

Contribution Within the area of model checking a number of state-machine based modeling formalisms has emerged, allowing for such quantitative aspects to be expressed. In particular, timed automata (TA), and the extensions to weighted timed automata (WTA) are popular and tool-supported formalisms that allow for such constraints to be modeled.

Interesting behavioural properties of TAs and WTAs may be expressed in natural weight-extended versions of classical temporal logics such as CTL for branching-time and LTL for linear-time. Just as TCTL and MTL provide extensions of CTL and LTL with time-constrained modalities, WCTL and WMTL are extensions with weight-constrained modalities interpreted with respect to WTAs. Unfortunately, the addition of weight now turns out to come with a price: whereas the model-checking problems for TAs with respect to TCTL and MTL are decidable, it has been shown that model-checking WTAs with respect to WCTL is undecidable [9].

In this paper we reconsider this model checking problem in the setting of untimed models, i.e. essentially weighted Kripke structures, and negation-free WCTL formula with only upper bound constraints on weights. As main contributions, we show that in this setting the model-checking problem is in PTIME, and we provide a novel efficient symbolic, local (on-the-fly) model checking algorithm.

The tool MKTool[1] offers a web-based front-end to implementations the model checking algorithms. The tool provides a weighted extension of the process algebra CCS as a means for conveniently describing quantitative models of practical interest.

Perspectives This work propose to use the simplest possible quantitative extension of finite-state machines – namely weighted Kripke structures or essentially weighted graphs – as a formalism for modeling resource constraints systems. The clear advantage is the high performance obtained for model checking properties expressed in a weighted extension of CTL. The adequacy of this modeling formalism – and application to the case studies of SENSATION – should be investigated in the next period. Also, we will investigate extension of the on-the-fly method to multi-weighted Kripke structures and possibly even parameteric models in the next period.

[1] `http://jonasfj.github.com/WKTool/`

4 Weighted Modal Transition Systems

Participants

- Line Juhl, Kim G. Larsen, Claus R. Thrane (Aalborg University, Denmark)
- Uli Fahrenberg, Axel Legay (INRISA/INRIA, France)
- Sebastian S. Bauer (Ludwich-Maximilians Universitaet, Munich, Germany)

Contribution In [11] we proposed weighted modal transition systems, an extension to the well-studied specification formalism of modal transition systems that allows to express both required and optional behaviours of their intended implementations. In this extension each transition is decorated with a weight interval that indicates the range of concrete weight values available to the potential implementations. In this way resource constraints can be modelled using the modal approach with a suitable extended notion of refinement between specifications.

However, the notion of refinement (and satisfaction) introduced in [11] is qualitative in nature: an implementation either satisfies a given specification or it doesn't; a specification either refinemes another specification or it doesn't. This is gives a rather fragile framework, in the sense that the inevitable approximation of systems by models, combined with the fundamental unpredictability of hardware platforms, makes it difficult to transfer conclusions about the behavior, based on models, to the actual system. We propose in [4] the first specification theory which allows to capture quantitative aspects during the refinement and implementation process, thus leveraging the problems of the qualitative setting.

Our proposed quantitative specification framework uses weighted modal transition systems as a formal model of specifications. Satisfaction and refinement is lifted from the well-known qualitative to our quantitative setting, by introducing a notion of distances between weighted modal transition systems. We show that quantitative versions of parallel composition as well as quotient (the dual to parallel composition) inherit the properties from the Boolean setting.

Perspectives We believe that weighted modal transition systems could provide a useful quantitative specification formalism for the case studies of SENSATION. In addition, on-the-fly model checking algorithms deviced for weighted Kripke structures in the previous section may possibly be generalized to weighted modal transition systems.

5 Stochastic Priced Timed Automata and Hybrid Systems

Participants

- Alexandre David, Kim G. Larsen, Marius Mikucionis, Danny Poulsen (Aalborg University, Denmark)
- Axel Legay, Sean Sedwards (IRISA/INRIA, Rennes, France)

Contribution The notions of priced timed automata (PTA) and energy games (EG) provide useful modeling formalisms for energy-aware and energy-harvesting embedded systems. Decidability of several problems associated with these models require tight bounds on the number of clocks and cost variables. Thus, we turn to statistical model checking (SMC), which has emerged as a highly scalable simulation-based approximate validation technique.

In a series of recent work [6, 7] we have developed a natural stochastic semantics for PTAs allowing for statistical model checking to be performed. The stochastic semantics is based on repeated races between the components of a system for who should perform the next discrete actions. In each iteration each component is independently choosing – according to a state-dependent and component-specific delay distribution – *when* to perform a discrete action; the winner is the component that has chosen the earliest action time-point. In fact this principle has been extended to obtain a stochastic extension for hybrid systems (SHA) [13] and even dynamic networks of hybrid systems [8], where new hybrid components may be spawned during the execution of discrete actions.

The resulting techniques have been implemented in UPPAAL-SMC, and applied to the performance analysis of a number of systems ranging from real-time scheduling, mixed criticality systems, sensor networks, energy aware systems and systems biology.

Perspectives The expressive power of stochastic hybrid systems will be key to adequate modelling of batteries in the GOMSPACE case study. In fact – based on a Kinetic model – initial such hybrid UPPAAL-SMC models have already been created, and used for evaluating energy-aware scheduling principles. Future work includes investigation of the SHA modeling formalism with non-determinism with the goal of extending statistical model checking towards synthesis of near-optimal control strategies.

6 Cost Preserving Probabilistic Automata

Participants:

- Holger Hermanns, Saarland Univiersity
- Andrea Turrini, Saarland University

Contribution Probabilistic automata constitute a versatile and elegant model for concurrent probabilistic systems. They are equipped with a compositional theory supporting abstraction, enabled by weak probabilistic bisimulation serving as the reference notion for summarising the effect of abstraction. As such, they are one of the base models considered in the SENSATION project context.

The work in [10] considers probabilistic automata augmented with costs, as this is pivotal to model energy applications. We propose Cost Probabilistic Automata (CPAs), a model where cost is any kind of quantity associated with the transitions of the automata, and we aim to minimise the cost. For instance, we can consider as the cost of a transition the power needed to transmit a message, but also as the time spent in the computation modelled by the transition, the (monetary) risk associated with an action, the expense of some work, and so on. Costs for weak transitions are interpreted in line with the vast body of literature on Markov decision processes, and we describe how that interpretation can be linked to the weak transition encoding as LP problems.

We extend weak probabilistic bisimulation to also account for costs. As a strict option, we require weak transition costs to be matched exactly for bisimilar states, inducing cost-preserving weak probabilistic bisimulation. As a weaker alternative, we ask them to be bounded from one PA to the other, leading to the notion of minor cost weak probabilistic bisimulation. We provide polynomial time algorithms for both variations.

Finally we consider an energy aware application scenario of minor cost weak probabilistic bisimulation: We apply it to a multi-hop wireless communication scenario where the cost structure represents transmission power which in turn depends on physical distances. It turns out that adding hops may reduce the overall transmission power needed, rooted in a quadratic dependency between transmission distance and transmission power needs. Therefore minor cost weak probabilistic bisimulations can be established across different energy consumption scenarios.

Perspective This work sets the ground for model compression techniques for energy models with probabilistic aspects. We now are investigating how compositionality properties of weak probabilistic bisimilarity extend from PA to CPA. With this, we will arrive at compositional construction and compression techniques that can be rolled out to the SENSATION case studies, and beyond: to operations research, automated planning, and decision support applications.

7 Multi-Cost-Bounded Reachability Probability on Continuous-Time Markov Decision Processes

Participants:

- Hongfei Fu, RWTH Aachen University

Contribution Continuous-time Markov Decision Processes (CTMDPs) (or controlled Markov chains) are a stochastic model that incorporates both features from continuous-time Markov chains (CTMCs) [6] and discrete-time Markov decision processes (MDPs). A CTMDP extends a CTMC in the sense that it allows non-deterministic choices, and it extends an MDP in the sense that it incorporates negative exponential time-delays. In a CTMDP, non-determinism is resolved by schedulers. Informally, a scheduler determines the non-deterministic choices depending on the finite trajectory of the CTMDP so far and possibly the sojourn time of the current state. Schedulers are divided into categories of early schedulers and late schedulers. A scheduler that makes the choice solely by the trajectory so far is called an early scheduler, while a scheduler utilizes both the trajectory and the sojourn time (at the current state) is called a late scheduler. With schedulers, one can reason about quantitative information such as the maximal/minimal probability/expectation of certain property.

In [9], we focus on the problem to compute max/min resource-bounded reachability probability on a CTMDP equipped with multiple rewards. Typical resource types considered here are time and cost, where a time bound can be deemed as a special cost bound with unit-cost one. In general, the task is to compute or approximate the optimal (max/min) reachability probability to certain target states within a given resource bound (e.g., a time bound). Whereas time-bounded reachability has been studied intensively, on optimal cost-bounded reachability probability, much less is known. Instead we consider multi-dimensional maximal cost-bounded reachability probability (MMCRP for short) over CTMDPs under the setting of both early and late schedulers, for which the unit-cost is constant. We prove that the MMCRP function is the least fixed-point of a system of integral equations. Then we prove that deterministic cost-positional measurable schedulers suffice to achieve the MMCRP value. Finally, we describe a numerical algorithm which approximates the MMCRP value with an error bound. The approximation algorithm relies on a differential characterization which is derived from the least fixed-point characterization. The complexity of the approximation algorithm is polynomial in the size of the CTMDP and the reciprocal of the error bound, and exponential in the dimension of cost vectors.

Perspective This work forms the basis for analyzing energy consumption in models that encompass non-determinism and continuous-time stochastics. Whereas current work focus on the conjunction of multiple individual energy constraints, a more liberal combination of such constraints is anticipated, and we plan to generalize the approach to models that incorporate hybrid features.

8 Markovian Models and Metrics

Participants

- Giorgio Bacci, Giovanni Bacci, Kim G. Larsen, Radu Mardare (Aalborg University, Denmark)

Contribution In the context of stochastic and probabilistic systems it has been argued that the concept of bisimilarity, which equates systems with identical stochastic/probabilistic behaviours, is too strict to be of any practical use, since small differences in probabilities will represent systems which are not bisimilar. To cope with this problem, a concept of bisimilarity distance has been proposed which measures the similarity of the behaviours of two such systems. The paper [2] proposes an algorithm for exact computation of bisimilarity distances between discrete-time Markov chains introduced by Desharnais et. al. The work is inspired by the theoretical results presented by Chen et. al. at FoSSaCS12, proving that these distances can be computed in polynomial time using the ellipsoid method. Despite its theoretical importance, the ellipsoid method is known to be inefficient in practice.

Based on a fixed-point characterization of the bisimulation distance, an efficient on-the-fly algorithm is proposed and implementad. Unlike other existing solutions, the algorithm computes exactly the distances between given states and avoids the exhaustive state space exploration. It is parametric in a given set of states for which we want to compute the distances. Our technique successively refines over-approximations of the target distances using a greedy strategy which ensures that the state space is further explored only when the current approximations are improved. Tests performed on a consistent set of randomly generated Markov chains shows that the algorithm improves, in average, the efficiency of the corresponding iterative algorithms with orders of magnitude.

In [1] we propose a general definition of composition operator on Markov Decision Processes with rewards (MDPs) and identify a well behaved class of operators, called safe, that are guaranteed to be non-extensive w.r.t. the bisimilarity pseudometrics of Ferns et al. [10], which measure behavioral similarities between MDPs. For MDPs built using safe/non-extensive operators, we present the first method that exploits the structure of the system for (exactly) computing the bisimilarity distance on MDPs. Experimental results show significant improvements upon the non-compositional technique

The BisimDist Library [2] contains a Mathematica Library for compu pseudometrics between Markov Chains, Markov decision processes and Markow Reward Models [3].

Perspectives Ongoing work includes extended the on-the-fly algorithm for computing bisimulation distances for Stochastic Markov Models. These are models of probabilistic transition systems where the moment when a transition is fired in a given state is governed by some time-distribution that characterizes that state; continuous-time Markov chains are particular cases of SMMs.

[2] `http://people.cs.aau.dk/ giovbacci/tools.html`

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