Probabilistic Deadline Miss Analysis of Real-Time Systems Using Regenerative Transient Analysis

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Probabilistic frameworks

Some motivations

- Non-functional requirements prescribed by certification standards
  e.g., performance requirements on response time and scalability
- Increasing relevance for verification of RAMS requirements:
  not only Safety, but also Reliability, Availability, Maintainability

Some areas of investigation

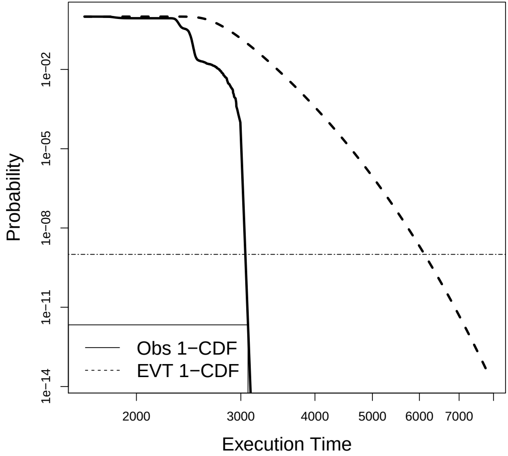
- WCET (Worst Case Execution Time) estimation
  - Static methods (Thesing et al, Healy et al, etc.)
  - Measurement-based methods (Puaut et al, Santinelli et al, etc.)
- Analysis of probabilistic real-time systems
  - Analytical methods (Diaz et al, Cucu-Grosjean et al)
  - State-space based methods (Lindemann et al, Vicario et al, etc.)

The contribution

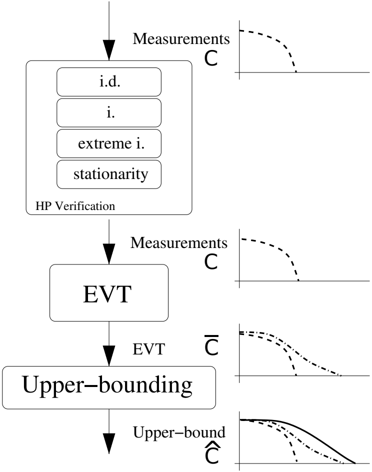
- A probabilistic approach for the analysis of real-time systems with stochastic parameters estimated from real measurements
- Combines results consolidated in the areas of:
  - Estimation of probabilistic WCETs (Extreme Value Theory)
  - Probabilistic analysis (method of stochastic state classes)
- Experimented on a case study including probabilistic WCETs estimated from benchmarks and real system executions
- Targeted to the evaluation of the probability of deadline miss

Probabilistic Worst Case Execution Time (pWCET)

- Given C_k the distribution of the execution time of a task measured in a certain configuration / condition k, the probabilistic Worst-Case Execution Time distribution $\overline{C}$ is an upper-bound on the execution time distribution C_k of all the possible execution conditions of the task



Probabilistic WCET estimation



- Check *identical distribution* (KS test)
  - If OK, verify subsequent hypothesis
- Check *independence* (AR test)
  - If KO, check *stationarity* (LB test) <u>or</u> *independence of extremal samples* (extremogram / extremal index)

- If hypothesis verification is successful, apply the Extreme Value Theory (EVT) to derive a Generalized Extreme Value (GEV) distribution (Gumbel / Fréchet / Weibull)

- Derive the tightest Erlang distribution $\hat{C}$ that upper-bounds the GEV distribution $\bar{C}$

Probabilistic WCET estimation: experimental results

- Environment for tasks implemented from the Mälardalen benchmark [1]
  - A machine with 2 Intel®Xeon®E5620 2.4 GHz sockets
    each machine having 4 cores and 3 cache levels
  - SchedMCore[2], for precise real-time execution
  - LTTng (Linux Trace Toolkit new generation)[3], for performance monitoring
- Results of hypothesis verification

Task	**KS** (Identical distribution)	**LB** (Independence)	**AR** (Stationarity)	$\hat{\rho}(5)$ (Extremogram)	θ (Extremal index)
ns	0.90	$AR(40)$	0	0.005	0.995
cnt_isol	0.56	$AR(9)$	0.0005	0.003	1
cnt_mc	0.26	$AR(38)$	0	0.005	1
edn	0.82	$AR(39)$	0	0.01	1

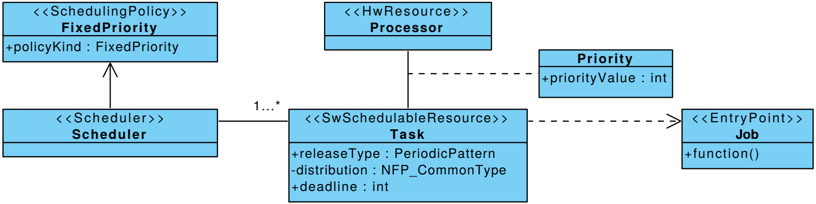
- The algorithm for pWCET estimation can be safely applied

[1] J. Gustafsson, A. Betts, A. Ermedahl, and B. Lisper, The Mälardalen WCET Benchmarks – Past, Present and Future, WCET2010, 2010.

[2] https://forge.onera.fr/projects/schedmcore

[3] P. Fournier, M. Desnoyer, and M. R. Dagenais, Combined Tracing of the Kernel and Applications with LTTng, Linux Symposium, 2009.

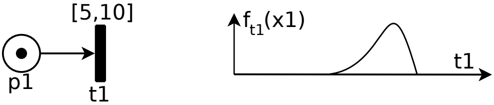
Task model



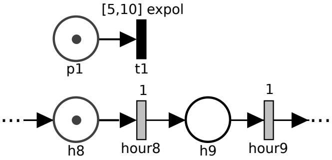
- Single-processor real-time system
- Fixed-priority non-preemptive scheduling policy
  - A higher number corresponds to a higher priority level
- Periodic real-time tasks
  - each associated with a relative deadline
  - each having either a *deterministic* or a *probabilistic* execution time (specified by a *non-Markovian* probability distribution function)
- A job is discarded as soon as its deadline is missed
- Jobs do not use mutex semaphores to synchronize
- A job cannot self-suspend before its completion

Modeling through stochastic Time Petri Nets

- A class of non-Markovian Stochastic Petri Nets (NMSPN) [4]
  - Encompass concurrent GEN transitions with bounded support
  - State = marking + remaining times of GEN transitions



- Extended with enabling functions, flush functions, and priorities
  - Change the enabling condition of transitions and the token moves
  - Neither restrict the model expressivity nor impact on the analysis

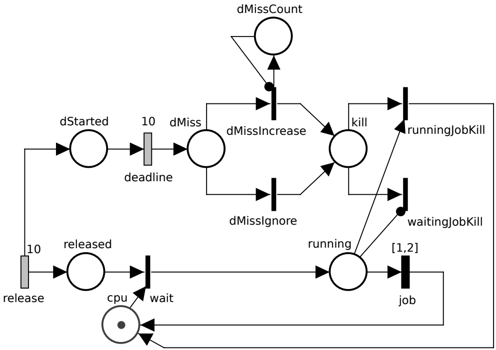


Transition	Enabling function	Flush function	Prio
t1	h9 == 1	{ p4, p5 }	-
hour8	-	-	10
hour9	-	-	10

[4] E. Vicario, L. Sassoli, L. Carnevali. "Using Stochastic State Classes in Quantitative Evaluation of Dense-Time Reactive Systems". IEEE Transactions on Software Engineering, Vol. 35, No. 5, September/October 2009.

Stochastic model of a task

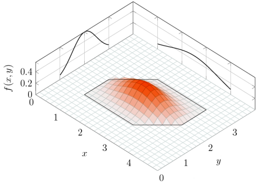
- The underlying process is a Markov Regenerative Process (MRP) including multiple concurrent generally distributed (GEN) timers
  - Regeneration point: the future is independent from the past
  - The model regenerates at each hyper-period
- Example: period=10; deadline=10; execution time supported over $[1, 2]$

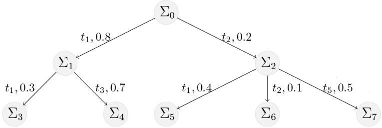


Transition	Enabling function	Flush function	Priority
deadline	-	-	9
release	-	-	8
wait	-	-	3
job	-	{*dStarted*}	-
...	...	...	...

Solution technique: the method of stochastic state classes

- A *stochastic state class* is a tuple $\langle m, D, f \rangle$
  - $m : P \to \mathbb{N}$ is a marking
  - $D \subseteq \mathbb{R}^n_{\geq 0}$ is a set of values for times-to-fire $\vec{\tau}$
  - $f : D \to [0, 1]$ is the PDF of the random vector $\vec{\tau}$ over D
- The successor $\Sigma' = \langle m', D', f' \rangle$ of Σ through transition t holds all the possible states after the firing of t in Σ and their joint PDF
  - D is a Difference Bounds Matrix zone (DBM zone)
  - f is a continuous function (piecewise over DBM subdomains)
- Symbolic calculus implemented in ORIS for expolynomials
- Classes allow to derive kernels of the underlying MRP [5] [6]
  - The transient probability of reachable markings is derived through numerical solution of generalized Markov renewal equations

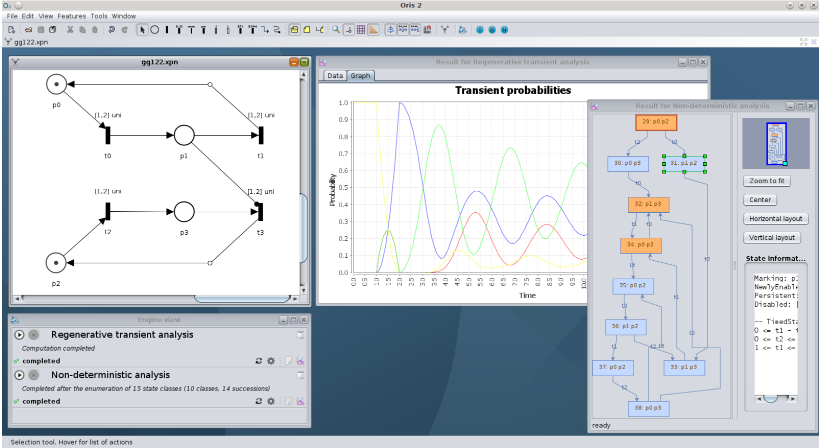




5 V. G. Kulkarni, Modeling and analysis of stochastic systems, CRC Press, 1996

6 A. Horváth, M. Paolieri, L. Ridi, E. Vicario. “Transient analysis of non-Markovian models using stochastic state classes”. Performance Evaluation, Vol. 69, No. 7, pp. 315â335, July 2012.

The ORIS Tool



- Graphical Petri net editor
- Transient analysis of non-Markovian stochastic Petri nets
- Full Java implementation (cross-platform)
- Available at `http://oris-tool.org`

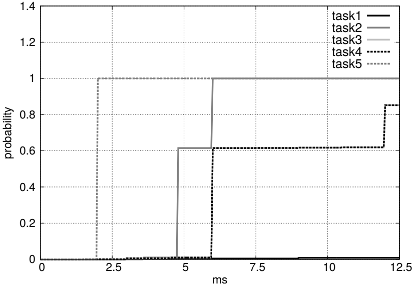
Experimental setting

- A task-set made of 5 periodic tasks
  - 2 tasks have a *deterministic* WCET
  - 3 tasks have a *probabilistic* WCET

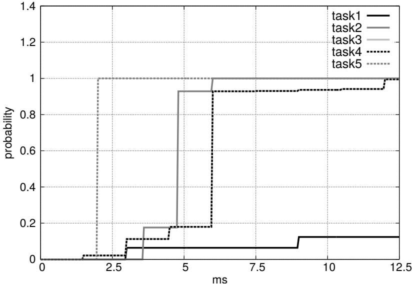
Task	Period	Priority	Execution time	Benchmark
tsk_1	1.0	5	DET(0.2)	-
tsk_2	1.2	4	DET(0.4)	-
tsk_3	1.5	3	Erlang(3, 120.19)	*ns*
tsk_4	2.0	2	Erlang(3, 40.27)	*cnt_isol*
tsk_5	3.0	1	Erlang(4, 59.50)	*cnt_mc*

- Analysis repeated for different distributions of tsk_3 execution time
  - Erlang(2, 50.05), *ns* benchmark
  - Erlang(2, 28.70), *cnt_mc* benchmark
  - Erlang(2, 18.95), *cnt_isol* benchmark
  - Erlang(2, 10.67), *edn* benchmark
- $\sim$15” to enumerate state-space, $\sim$30’ to solve renewal equations

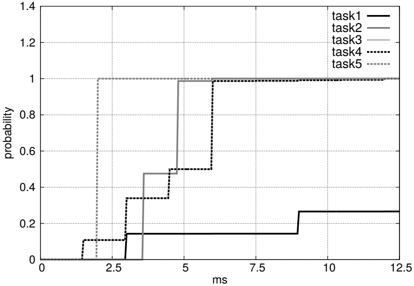
Experimental results: deadline miss probability within time t



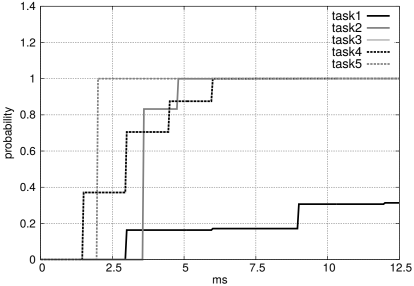
(a) tsk_3 **pWCET: Erlang(2, 50.05)**



(b) tsk_3 **pWCET: Erlang(2, 28.70)**



(c) tsk_3 **pWCET: Erlang(2, 18.95)**



(d) tsk_3 **pWCET: Erlang(2, 10.67)**

Concluding remarks

- A probabilistic approach for the analysis of real-time systems
  - Estimation of pWCETs through the Extreme Value Theory
  - Probabilistic analysis through the method of stochastic classes
  - Experiments with pWCETs derived from real benchmarks
- Future issues
  - How do guarantees of pWCETs reflect on schedulability results?
  - What is the accuracy attained by schedulability results if different distributions are used in pWCET estimation?
  - Can other scheduling policies be encompassed in the approach?