Measurement-Based Probabilistic Timing Analysis for Multi-path Programs

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SEVENTH FRAMEWORK PROGRAMME

Motivation

- *Critical Real-Time Embedded (CRTE) systems*
  - Used in Space, Aerospace, Transportation,… industries
- *CRTES requirements*
  - Recurring: Reduced development and production costs
  - Emerging: Increased functional value
- *More functional value → more computational power*
  - More complex SW
  - More complex HW: multicore and caches
- *Complex HW and SW affect time analysability*
- *PROARTIS view:*
  - Simple processors hard to analyse with current analysis techniques
  - Current analysis techniques cannot keep pace with novel HW

Execution history (EH)

- *Current architectures exploit knowledge on EH*
  - To improve average-case execution time (ACET)
  - Caches: Temporal and spatial locality
- *The ACET and WCET of programs heavily* ***depend on EH***
- ***Current analysis techniques require info about EH***
- ***Limitations*** *&* ***increasing effort*** *in acquiring EH info*
  - Complex processor architectures (IP protected)
  - Incomplete and/or inaccurate documentation
  - Program information may be unknown at analysis time
- *Reduction of available knowledge about HW/SW → pessimistic assumptions → degradation of the tightness of the WCET*

Execution history (EH)

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- *The ACET and WCET of programs heavily* ***depend on EH***

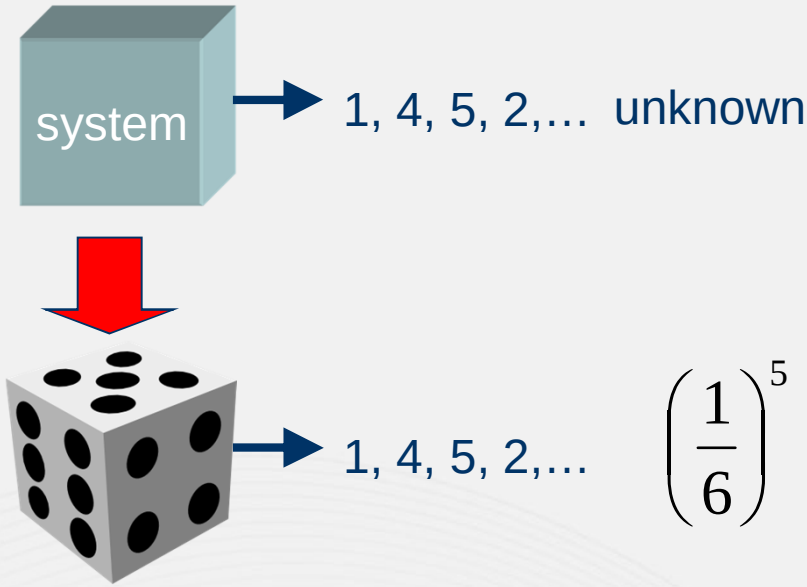
- Design HW and SW whose execution time behaviour does not depend on execution history
  - Without removing performance-improving hardware!
  - The functional behaviour is left unchanged
- Provide new **probabilistic timing analysis** techniques

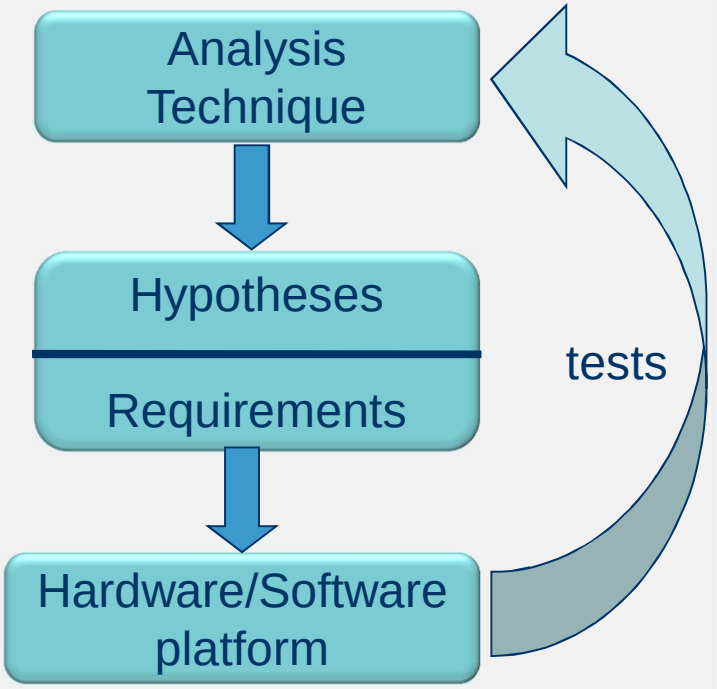
pessimistic assumptions →
degradation of the tightness of the WCET

Probabilistically **A**nalysable **R**eal-**Ti**me **S**ystems

- Probability of appearance of an event *is not equal to its* frequency of appearance within a finite time interval

Probability of 1, 1, 1, 1, 1?





Probabilistic nature of the system

- pWCET estimations for high integrity systems
  - Counter intuitive
- Probabilistic modeling is in close match with actual nature of the system
  - Mechanical parts → designed with a probability of failure in mind
  - Hardware → affected by radiation, temperature, ...

    Probability of failure
  - Failure rate for airborne applications → 10^{-9} per hour of operation
- The system as a whole has a distinct **prob. of failure**
- PTA: upperbounds the execution time of programs with an attached probability of exceedance
  - Time Failures can be considered just another type of failure

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F. J. Cazorla, E. Quinones, T. Vardanega, L. Cucu, B. Triquet, G. Bernat, E. Berger, J. Abella, F. Wartel, M. Houston, L. Santinelli, L. Kosmidis, C. Lo, D. Maxim.
PROARTIS: Probabilistically Analysable Real-Time Systems.
In *ACM Transactions on Embedded Computing Systems. Special issue on Probabilistic Computing.*

WWW.PROARTIS-PROJECT.EU

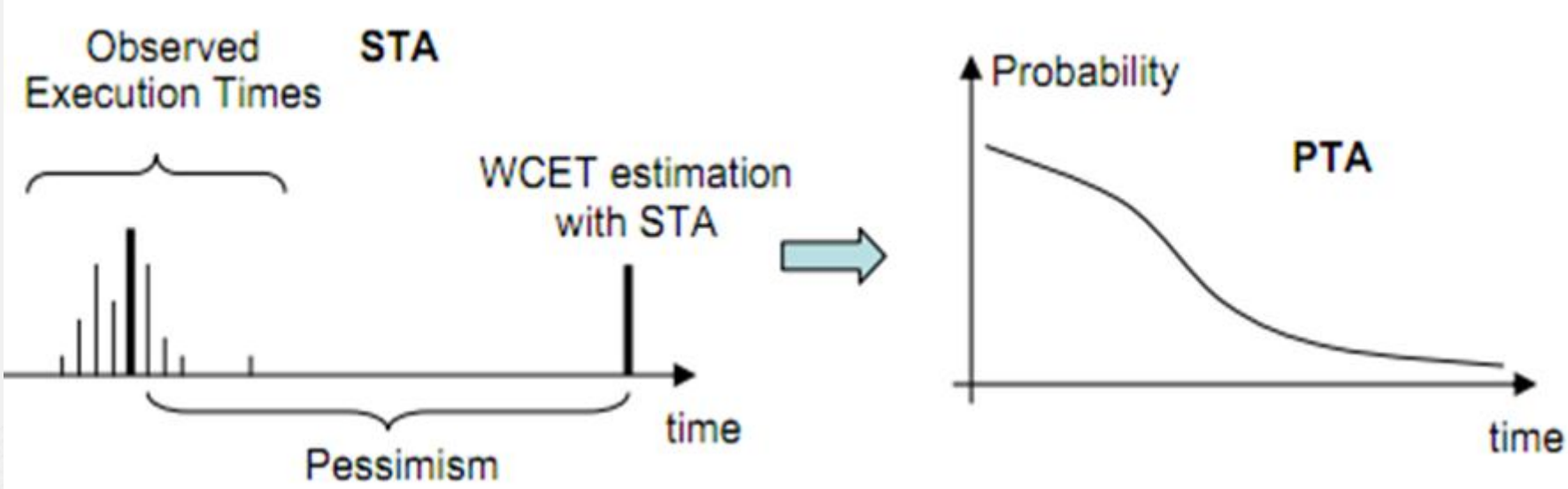
attached probability of exceedance
  - Time Failures can be considered just another type of failure

Outline

- *Probabilistic Worst-Case Execution Time*
  - Definition
  - Extreme Value Theory
- *Measurement-based approach for single-path programs*
- *Measurement-based approach for multi-path programs*
- *Experiments*
- *Conclusions and ongoing work*

Probabilistic Timing Analysis

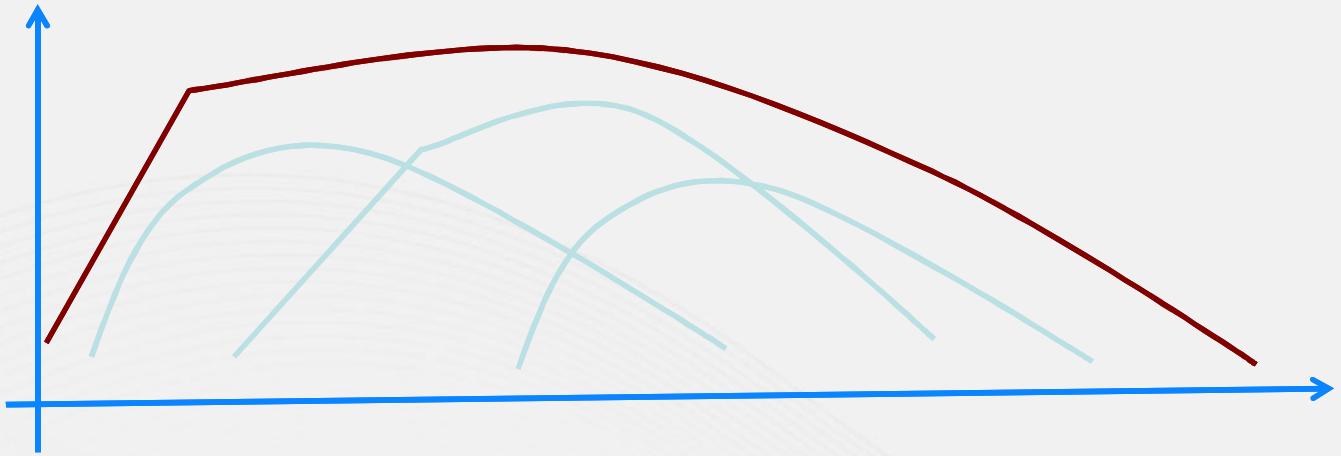
- *PTA allows cutting the WCET bound tail at the level of probability suited for the system (e.g. 10^{-16} per hour of operation)*
  - Probability of failure of the program **x** execution rate per hour



What is Extreme Value Theory?

- *Measurement Based Probabilistic Timing Analysis*
- *The pWCET estimate is obtained by applying Extreme Value Theory*

Let $\{\mathcal{X}_1, \mathcal{X}_2, \ldots, \mathcal{X}_n\}$ *be a sequence of i.i.d. random variables and let* $\mathcal{M}_n = max\{\mathcal{X}_1, \mathcal{X}_2, \ldots, \mathcal{X}_n\}$. *If* F *is a non degenerate distribution function and there exists a sequence of pairs of real numbers* (a_n, b_n) *such that* $a_n \geq 0$ *and* $lim_{n\to\infty} P(\frac{\mathcal{M}_n - b_n}{a_n} \leq x) = F(x)$, *then* F *belongs to either the Gumbel, the Frechet or the Weibull family.*

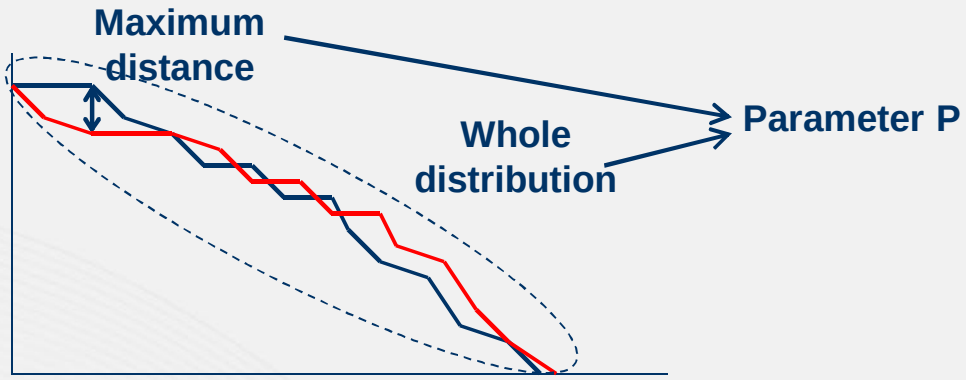


I.i.d. random variables

- *Independent random variables*
  - Random variables that describe events which are not related
  - “Event A: my laptop died” and “Event B: the beamer does not like my laptop”
- *Identically distributed random variables*
  - Random variables that have the same distribution function
  - “Event A: arrival of a client in a bank” and “Event B: arrival of a car at a gas station”
- *Both properties checked through statistical tests*

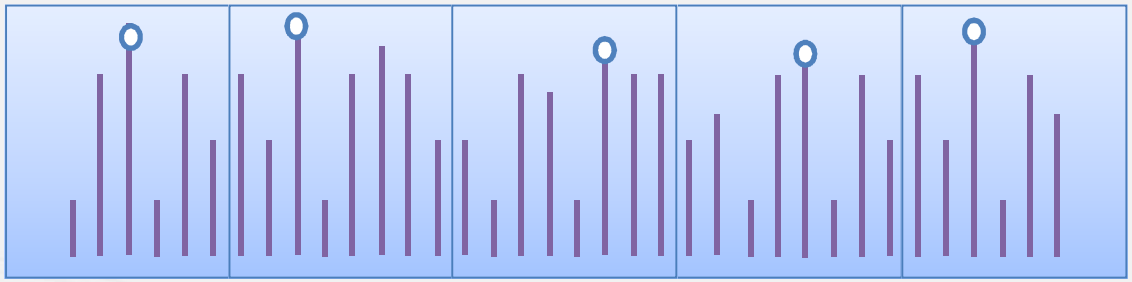
Required properties: identical distribution

- *Data must be identically distributed*
  - Hypothesis testing with *Kolmogorov-Smirnov* test
    - Two subsets of data randomly obtained from the trace
    - Distributions are compared looking at the maximum distance P between the data sets
    - If P is above a given threshold, data are identically distributed
      - Threshold (0.05) is chosen based on experience/common practice



Applying Extreme Value Theory

- *Measurement Based Probabilistic Timing Analysis*
- *First sound utilisation of EVT to pWCET estimating*
  - The hypothesis of independence and identical distribution is checked before any EVT utilisation
  - Continuous function: block maxima applied with a proper definition of minimum number of runs



  - Utilisation of a (proven) correct statistical test to check that data belong to the Gumbel domain

Required properties: Gumbel

- *Data must fit a Gumbel distribution*
  - Hypothesis testing with *exponential tail* test
    - A parameter P is obtained for the actual data
    - A confidence interval CI is obtained for the actual data assuming it fits a Gumbel distribution
    - If P belongs to CI then the data fit a Gumbel distribution

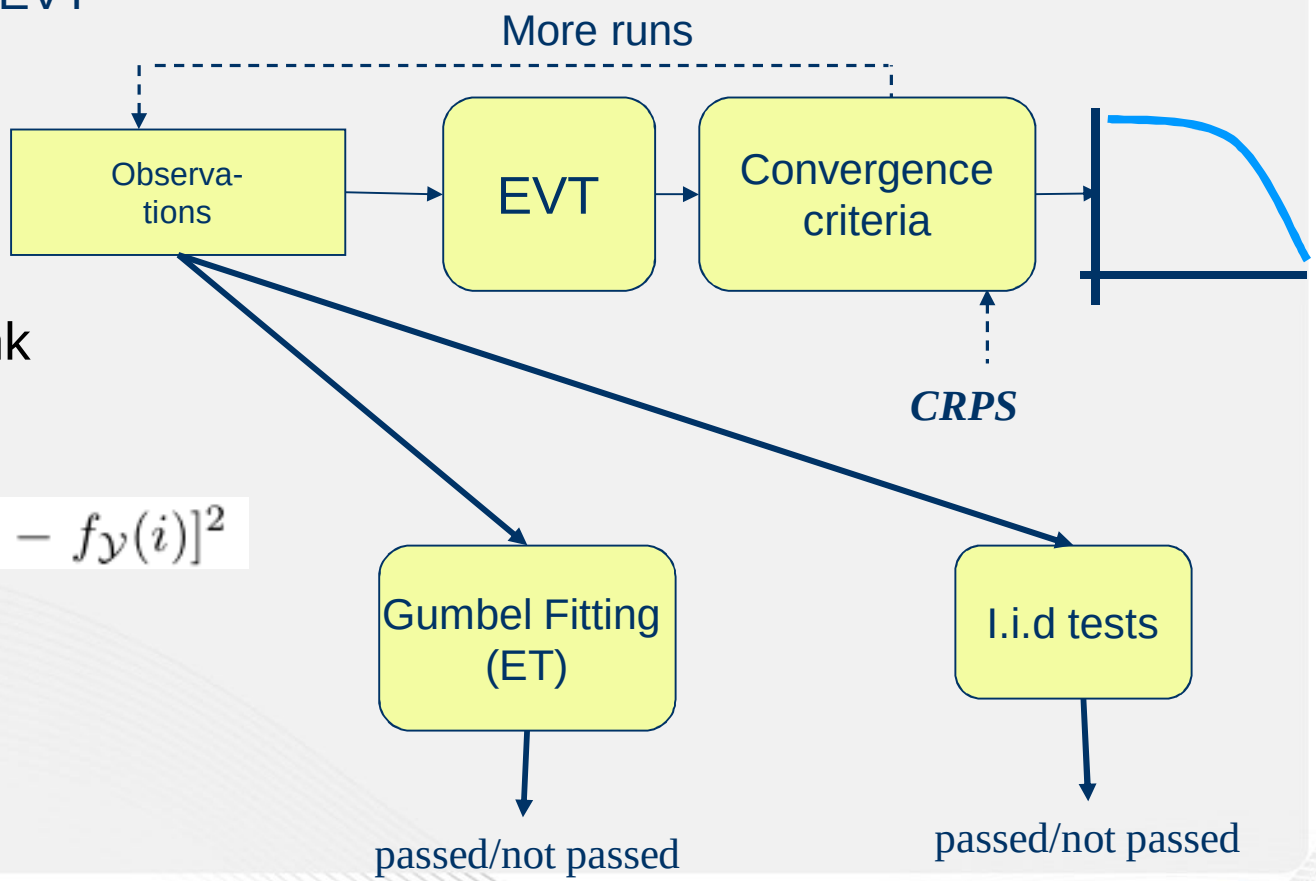
Steps of applying EVT (single-path programs)

- Observations
- Grouping
- Fitting
- Comparison
- Tail extension

EVT

- *Convergence*
  - Continuous rank probability score

$$CRPS = \sum_{i=0}^{+\infty} [f_X(i) - f_Y(i)]^2$$



What about multi-path programs?

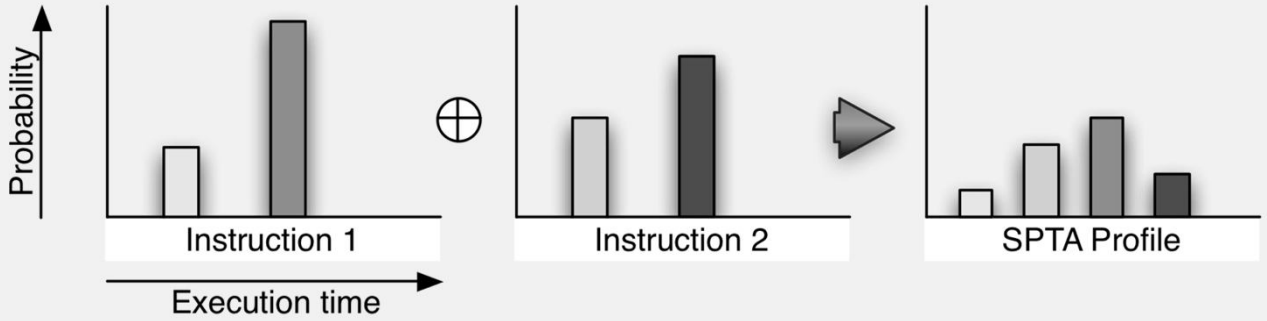
- *Measurement Based Probabilistic Timing Analysis*
- *Multi-path programs*
  - Independent and identical distributions
    - Identical distributions ensured by the convergence process
  - Minimum number of observations
    - Each path must be observed a minimum number of times and it is ensured by the convergence process
  - Path coverage
    - pWCET estimate is obtained for the observed paths

Experiments /1

- *All experiments run on a modified version of the SoCLib processor simulator*
- *Benchmarks*
  - Eight of the EEMBC Autobench (single-path programs)
  - Seven of the Mälardarlen benchmarks (multi-path programs)
  - *Our synthetic benchmark for which we know*
    - *Different paths of the program*
    - *Different input set that exercise each path*
    - *The longest path*

SPTA*

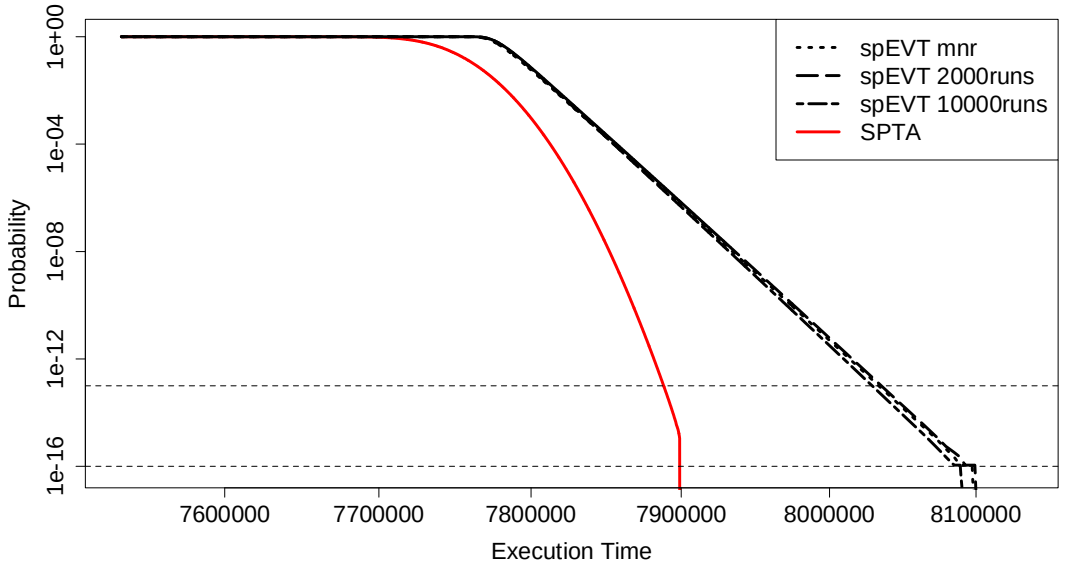
- *Static Probabilistic Timing Analysis*
- *The pWCET estimate is obtaining by convolving the random variables describing the execution time of each instruction*



$$\begin{pmatrix} 1 & 2 \\ 0.7 & 0.3 \end{pmatrix} \otimes \begin{pmatrix} 7 \\ 1 \end{pmatrix} = \begin{pmatrix} 1+7 & 2+7 \\ 1 \cdot 0.7 & 1 \cdot 0.3 \end{pmatrix} = \begin{pmatrix} 8 & 9 \\ 0.7 & 0.3 \end{pmatrix}$$

*ACM TECS 2012 – « Probabilistically analysable real-time systems»

Experiments /2 (single-path programs)



Aifirf (EEMBC)

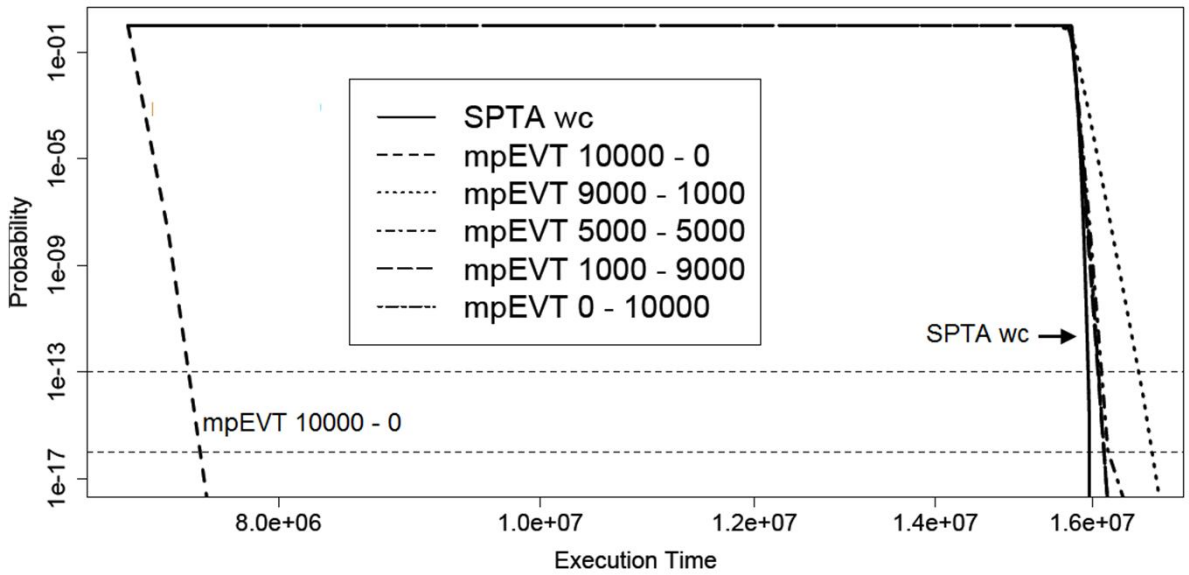
Minimum number of runs

AT	AI	CA	CN	PU	RS	TB	TT
300	650	400	450	500	300	500	300

probability	AI	AT	CA	CN	PU	RS	TB	TT
10^{-13}	9%	5%	6%	5%	5%	2%	2%	6%
10^{-16}	15%	7%	8%	7%	7%	3%	3%	9%

MBPTA versus wrt SPTA

Experiments /3 (multi-path programs)



Synthetic benchmark

MBPTA versus SPTA (Mälardarlen benchmark)

probability	BS	CNT	COM	CRC	INS	QSO	SEL
10^{-13}	7%	2%	4%	1%	9%	7%	5%
10^{-16}	8%	2%	5%	1%	11%	8%	6%

Conclusions and ongoing work

- *Proven that MBPTA is a sound utilisation of EVT*
  - But value of pWCET bound is limited to the path coverage achieved in the observations
  - Proof of the limited pessimism of EVT application

- *Defining relevant test input data*
- *Proposing a hybrid probabilistic timing analysis*

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