Improving Accuracy of Timing Models: From CPA to CPA+

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Motivation

Verification of real-time systems and networks

ONERA, Toulouse
Network Calculus (NC)

TU Braunschweig
Compositional performance analysis (CPA)

• Formal timing analysis provides **safe but pessimistic bounds on real-time properties for complex embedded computing systems**.
• In industrial practice, formal analysis is often replaced by simulation and test.

➡ **Unsatisfactory situation**
Potential causes of pessimism?

Comparison of NC and CPA

• One interesting observation:
  • NC is good at analyzing workload-dependent scheduling scenarios
  • CPA is good at analyzing event-dependent scheduling scenarios

• Underlying reasons:
  • Different system modeling

Can we find a common input model of NC and CPA?


What does it mean to integrate this common input model in CPA?

• This paper at DATE 2019, leading to CPA+.
• Input models of CPA and NC
  • Input model of CPA
  • Input model of NC
  • Common input model for CPA and NC [ETFA 2016]
  • Related work

• Introducing CPA+
  • CPA principle
  • Impact of new input model: interfaces, composition, analysis
  • Use cases

• Conclusion
Outline

• Input models of CPA and NC
  • Input model of CPA
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Informal model of a packet stream in NC / CPA

### Packet stream

- **40 bit**
- **32 bit**
- **5 packets in Δt**
- **48 bit**

### Amount of data sent over time
- 136 bits in Δt

### Number of packets over time
- 5 packets in Δt

### Characterizing the packet stream

<table>
<thead>
<tr>
<th>NC</th>
<th>CPA</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Amount of data sent over</strong></td>
<td><strong>Number of packets over</strong></td>
</tr>
<tr>
<td>time</td>
<td>time</td>
</tr>
<tr>
<td>136 bits in Δt</td>
<td>5 packets in Δt</td>
</tr>
</tbody>
</table>

### Variance of packet length

- **Decreasing**
## Formal model of a packet stream in NC / CPA

<table>
<thead>
<tr>
<th>Trace (also: flow)</th>
<th>NC (workload-based model)</th>
<th>CPA (event-based model)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Data flow $A(t)$</td>
<td>$\eta(\Delta t)$</td>
<td></td>
</tr>
<tr>
<td>Event flow $E(t)$</td>
<td>$\tilde{\eta}(\Delta t)$</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Interval Bounding Pair (IBP)</th>
<th>Workload curves</th>
<th>Event curves</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\alpha(\Delta t)$</td>
<td>$\eta(\Delta t)$</td>
<td></td>
</tr>
<tr>
<td>$\bar{\alpha}(\Delta t)$</td>
<td>$\tilde{\eta}(\Delta t)$</td>
<td></td>
</tr>
</tbody>
</table>
Common input model for NC/CPA

- Addition of a **packet function** $P$: number of packets in the first $x$ bits of the data flow
- Interval bounding pair for $P$: **packet curves** $(\pi, \overline{\pi})$

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**NC [ETFA 2016]**

- Workload curves $(\alpha, \overline{\alpha})$
  bounding data flow $A(t)$
- Packet curves $(\pi, \overline{\pi})$
  bounding packet function $P$
- Event curves $(\eta, \overline{\eta})$
  bounding event flow $E(t)$ are implicit.

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**CPA [ETFA 2016]**

- Workload curves $(\alpha, \overline{\alpha})$
  bounding data flow $A(t)$ are implicit.
- Packet curves $(\pi, \overline{\pi})$
  bounding packet function $P$
- Event curves $(\eta, \overline{\eta})$
  bounding event flow $E(t)$

**compatibility**
What is the benefit of the common input model?

- **NC** needs to infer information on events during analysis.
- **CPA** needs to infer information on workload during analysis.

**NC: From workload to events**

Simple transformation
\[
\eta(\Delta t) = \frac{\alpha(\Delta t)}{p^+}
\]
\[
\bar{\eta}(\Delta t) = \frac{\bar{\alpha}(\Delta t)}{p^-}
\]

Transformation [ETFA 2016]
\[
\eta(\Delta t) = (\pi \circ \alpha)(\Delta t)
\]
\[
\bar{\eta}(\Delta t) = (\pi \circ \bar{\alpha})(\Delta t)
\]

**CPA: From events to workload**

Simple transformation
\[
\alpha(\Delta t) = p^- \cdot \eta(\Delta t)
\]
\[
\bar{\alpha}(\Delta t) = p^+ \cdot \bar{\eta}(\Delta t)
\]

Transformation [ETFA 2016]
\[
\alpha(\Delta t) = (\pi^{-1} \circ \eta)(\Delta t)
\]
\[
\bar{\alpha}(\Delta t) = (\pi^{-1} \circ \bar{\eta})(\Delta t)
\]

**lossless**

**bit arrival rates are lost**
**Related work**

**Component**
- Add variation in packet sizes
  - *Mok et al. 1997*
  - *Quinton et al. 2012*
- Add information on events
  - *Wandeler et al. 2005*
  - *Bouillard et al. 2011 + 2012*
- Compatible input model for NC/CPA
  - *Boyer et al. 2016*

**Composition of components**
- **NC**
  - *Wandeler et al. 2005*
  - *Bouillard et al. 2011 + 2012*
- **CPA**
  - *Boyer et al. 2016*

**Related work**
- Boyer et al. 2016
- Wandeler et al. 2005
- Bouillard et al. 2011 + 2012
- Quinton et al. 2012

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Compositional approach:

- **Global analysis problem** is decomposed into dependent local analysis problems.
- Dependencies are represented by event streams.

New input model will change interfaces of local analysis problems.

Composition of local analysis problems?

Internals of local analysis problems?
Lossy event-to-workload transformation at the input
Composition allows lossy chained transformations
Interface issues

Lossy event-to-workload transformation at the input

\[ (\eta, \bar{\eta}) \]

\[ (\pi^{-1}, \bar{\pi}^{-1}) \]

\[ (\alpha, \bar{\alpha}) \]

2 primary inputs: events + packet sizes

1 implicit input: workload

Better:

\[ (\eta, \bar{\eta}) \]

\[ (\pi^{-1}, \bar{\pi}^{-1}) \]

\[ (\alpha, \bar{\alpha}) \]

\[ \text{min/max} \]

3 primary inputs: Events, workload and packets
Composition issues

Chained transformations in the naïve composition

Example:

\[(\eta, \bar{\eta})\] = \[(\pi^{-1}, \pi^{-1})\] = \[(\alpha, \bar{\alpha})\]

Identity transformation
- zero response jitter
- No change in packet sizes

\[\min/\max\] \rightarrow \[(\pi^{-1}', \pi^{-1}')\] = \[min/\max\] \rightarrow \[(\alpha', \bar{\alpha}')\]

Identity transformation
- zero response jitter
- No change in packet sizes
Follow an analysis path

Composition issues

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\[ \pi^{-1}, \pi^{-1}, \alpha', \alpha', \eta', \eta \]

\[ \eta, \eta \]

\[ (\pi^{-1}, \pi^{-1}) \]

\[ (\alpha, \alpha) \]

1st transf.: event-to-workload

\[ \alpha_{out}(\Delta t) = (\pi^{-1} \circ \eta)(\Delta t) \]

Maximum workload = largest packets combined with maximum event number

\[ (\pi, \pi) \]

\[ \min/\max \]

2nd transf.: workload-to-event

\[ \eta'(\Delta t) = (\pi \circ \alpha_{out})(\Delta t) \]

Maximum number of events = smallest packets combined with maximum workload

\[ (\alpha', \alpha') \]

\[ (\pi^{-1}, \pi^{-1}) \]

\[ \min/\max \]

\[ \eta'(\Delta t) = (\pi \circ \pi^{-1} \circ \eta)(\Delta t) \Rightarrow \eta'(\Delta t) > \eta(\Delta t) \]

Identity transformation

- zero response jitter
- No change in packet sizes
Three primary inputs

Elimination of chained transformations:
only event-to-workload transformations are allowed.
Impact on the local analysis problem

\[(\eta, \bar{\eta}) \quad \xrightarrow{\pi^{-1}, \bar{\pi}^{-1}} \quad \text{Response time analysis} \]

\[(\alpha, \bar{\alpha}) \quad \xrightarrow{\min/\max} \quad \text{NEW: response time analysis uses now both inputs} \Rightarrow \text{Theorem 2} \]

\[(\eta', \bar{\eta}') \quad \xrightarrow{\text{Computation of output event curves}} \]

\[(\alpha', \bar{\alpha}') \quad \xrightarrow{\text{Computation of output workload curves}} \]

NEW: response time analysis uses now both inputs

\[\Rightarrow \text{Theorem 2} \]

\[\Rightarrow \text{Theorem 3} \]
Multi-component system with complex schedulers

- **event-centered scheduler**, e.g., round robin
  - Distinction of individual packets (events) is important!

- **workload-centered scheduler**, e.g., budget-based scheduling
  - Sent data over time is important (workload), not number of packets!

- **scheduler depending on events and workload**, e.g., packetizer
  - Packet dispatch on time-out, buffer-full, high-priority event, ...

- **Multi-component system with different service specifications**
  - **per-event service specification**, e.g., decoder
  - **per-workload service specification**, e.g., processor
Use Cases for Event-Workload-Dualism in NC and CPA

- Computation of buffer filling
  - per-packet (event-based)
  - per-byte (workload-based)
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Problem:
• Apply a dual (event-workload) input model to CPA

Solution: CPA+
• Define and compute a dual (event-workload) output model for CPA components
• Define new composition rules for CPA components
• Update response-time analysis within CPA components.

Benefits:
• Accurate system model and analysis for complex systems
• Compatibility of NC and CPA+

Future work:
• Joint tool of NC and CPA+