Scenario-Aware Dataflow

Bart Theelen (B.D.Theelen@tue.nl)
2 Overview

- Introduction
- Scenario-Aware Dataflow
  - MPEG-4 AVC Shape Decoder
  - MPEG-4 SP Decoder
  - Channel Equalizer
  - MP3 Decoder
- Tool Support
- Conclusions
3 Introduction

• Goal
  • Design-time performance prediction of hard & soft real-time streaming applications running on platforms with guaranteed and/or (lossless) best-effort services

• Starting point
  • Data flow models allow specifying streaming applications

• But, traditional data flow models
  • Can’t express dynamism (SDF)
  • Don’t support relevant analysis techniques (KPN)

• Current approach uses SDF to capture worst-case resource usage
  • Large overestimation of required resources
  • Inefficient use of a too expensive platform
  • Suitable for hard real-time/guaranteed services only
Scenario-Aware Dataflow (SADF)

- **SADF extends SDF with scenarios**
  - Scenarios classify behaviour based on resource requirements

- **SADF can express**
  - Parameterised numbers of communicated tokens
  - Inactive processes
  - Discrete execution time distributions
  - (Hierarchical) correlations between the above for different processes
  - Pipelined reconfiguration
  - Scenario changes do not need to follow reoccurring fixed patterns

- **SADF combines**
  - Streaming data and control
  - Hard and soft real-time
  - Design-time verification of functional correctness
  - Design-time performance analysis of worst/best case and average case
5 SADF = SDF + Execution Time Distributions

- **MPEG-4 AVC Shape Decoder**
  - 'HSDF' where execution time of A depends on block type

```
A
1 1 1 2 1 2 1
1 1 1 1 1 1 1

\begin{tabular}{|c|c|}
\hline
A & S_1 \quad 1.858ms \\
\hline
 & S_2 \quad 4.788ms \\
\hline
 & S_3 \quad 6.055ms \\
\hline
B & All \quad 0.980ms \\
\hline
C & All \quad 3.816ms \\
\hline
D & All \quad 3.816ms \\
\hline
\end{tabular}
```

- **Approach 1 - SDF for each block type**
  - Throughput for $S_1 = 0.262055$, $S_2 = 0.17337$ and $S_3 = 0.142146$

- **Approach 2 - SDF with symbolic execution time [DATE’08]**
  - Replace options with symbol $t$
  - Throughput = $1/\max(3.816, 0.98 + t)$

- **Approach 3 - SADF with only kernels**
  - Thee possible samples of distribution
  - Throughput = 0.191256

*Auto-concurrency excluded implicitly for (H)SDF*
SADF = SDF + Parameterised Rates

- MPEG-4 SP Decoder

- FD detects frame type (9 scenarios)
  - I-frame (99 macro blocks, 0 motion vectors)
  - \( P_x \)-frame (x macro blocks, x motion vectors)
  - \( P_0 \)-frame (still video)

<table>
<thead>
<tr>
<th>Rate</th>
<th>I</th>
<th>( P_0 )</th>
<th>( P_x )</th>
</tr>
</thead>
<tbody>
<tr>
<td>a</td>
<td>0</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>b</td>
<td>0</td>
<td>0</td>
<td>x</td>
</tr>
<tr>
<td>c</td>
<td>99</td>
<td>1</td>
<td>x</td>
</tr>
<tr>
<td>d</td>
<td>1</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>e</td>
<td>99</td>
<td>0</td>
<td>x</td>
</tr>
</tbody>
</table>

\( x = \{30, 40, 50, 60, 70, 80, 99\} \)

VLD and IDCT fire per macro block
FD, MC and RC fire per frame
SADF = SDF + Parameterised Rates

- MPEG-4 SP Decoder

- Worst-case resource requirements do not occur in a single scenario
  - Worst-case rates in $P_{99}$
  - Worst-case execution times in $I$ & $P_{99}$
8 SDF versus SADF

- SDF worst-case approximation is inadequate

SDF
Throughput = 0.252525

SADF
Throughput = 0.425571

Taking dynamism into account is good idea

Auto-concurrency excluded implicitly for SDF
SADF Semantics (1)

- **Kernel semantics**
  - Wait for scenario-valued control token on control inputs
  - Fix scenario and hence rates and execution time distribution
  - Finalise firing as SDF actor

- **Detectors contain automata to capture occurrences of scenarios**
  - Real-life: data-dependent control behaviour (normal state machine)
  - Worst/best case only model: non-deterministic state machine
  - Worst/best case and average case model: Markov chain

![Non-deterministic state machine](image1)

![Markov chain](image2)
SADF Semantics (2)

- Detector semantics
  - Wait for scenario-valued control token on control inputs
  - Fix scenario (select automaton corresponding to control tokens values)
  - Fix subscenario based on next state of selected automaton
    - Subscenario gives rates and execution time distribution
  - Finalise firing as SDF actor
    - Tokens produced to control channels are scenario valued

- MPEG-4 SP Decoder
  - Scenario occurrences captured with fully connected 9-state Markov chain

<table>
<thead>
<tr>
<th>State</th>
<th>SubScenario</th>
</tr>
</thead>
<tbody>
<tr>
<td>X</td>
<td>S₁</td>
</tr>
<tr>
<td>Y</td>
<td>S₂</td>
</tr>
<tr>
<td>Z</td>
<td>S₂</td>
</tr>
</tbody>
</table>

Captures sequences
- S₂, S₂, S₁ with probability 1/3
- S₂, S₁ with probability 2/3
SADF includes CSDF

- Channel Equalizer

- $p = [1, 7*0]$ and $q = [8*1]$
- Weakly consistent
- Throughput = 0.000162443

<table>
<thead>
<tr>
<th>load</th>
<th>[8*224]</th>
</tr>
</thead>
<tbody>
<tr>
<td>absx</td>
<td>114</td>
</tr>
<tr>
<td>avg</td>
<td>[704, 7*416]</td>
</tr>
<tr>
<td>log</td>
<td>114</td>
</tr>
<tr>
<td>lvl</td>
<td>[440, 7*24]</td>
</tr>
<tr>
<td>norm</td>
<td>328</td>
</tr>
<tr>
<td>cu</td>
<td>[4944, 7648, 6*4966]</td>
</tr>
<tr>
<td>fir</td>
<td>114</td>
</tr>
<tr>
<td>cf</td>
<td>328</td>
</tr>
<tr>
<td>absy</td>
<td>114</td>
</tr>
</tbody>
</table>

Auto-concurrency excluded implicitly for CSDF
SADF includes CSDF

- Channel Equalizer

<table>
<thead>
<tr>
<th></th>
<th>PO</th>
<th>P1-7</th>
</tr>
</thead>
<tbody>
<tr>
<td>p</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>r</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Variable</th>
<th>Default</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>load</td>
<td>All</td>
<td>224</td>
</tr>
<tr>
<td>absx</td>
<td>Default</td>
<td>114</td>
</tr>
<tr>
<td>avg</td>
<td>P0</td>
<td>704</td>
</tr>
<tr>
<td>log</td>
<td>Default</td>
<td>114</td>
</tr>
<tr>
<td>lvl</td>
<td>P0</td>
<td>440</td>
</tr>
<tr>
<td>norm</td>
<td>Default</td>
<td>328</td>
</tr>
<tr>
<td>cu</td>
<td>P2-7</td>
<td>4966</td>
</tr>
<tr>
<td>fir</td>
<td>Default</td>
<td>114</td>
</tr>
<tr>
<td>cf</td>
<td>Default</td>
<td>328</td>
</tr>
<tr>
<td>absy</td>
<td>Default</td>
<td>114</td>
</tr>
</tbody>
</table>

- Scenarios PO, P1, P2-7
  - Control tokens to avg and lvl are valued P1-7 in scenario P1 and P2-7

- Throughput = 0.000162443

TU/e Electronic Systems
13 SADF > Similar SDF Graphs

- MP3 Decoder

- 3 Frame types for each granule of both channels
  - Short frame = 96 short blocks (6 frequency components)
  - Long frame = 32 long blocks (18 frequency components)
  - Mixed frame = 2 long blocks succeeded by 90 short blocks

- 5 Scenarios LL, SS, LS, SL, M
SADF > Similar SDF Graphs

- **MP3 Decoder**

<table>
<thead>
<tr>
<th></th>
<th>LL</th>
<th>SS</th>
<th>LS</th>
<th>SL</th>
<th>M</th>
</tr>
</thead>
<tbody>
<tr>
<td>e</td>
<td>0</td>
<td>576</td>
<td>0</td>
<td>576</td>
<td>540</td>
</tr>
<tr>
<td>f</td>
<td>576</td>
<td>0</td>
<td>576</td>
<td>0</td>
<td>36</td>
</tr>
<tr>
<td>g</td>
<td>0</td>
<td>576</td>
<td>576</td>
<td>0</td>
<td>36</td>
</tr>
<tr>
<td>h</td>
<td>576</td>
<td>0</td>
<td>0</td>
<td>576</td>
<td>540</td>
</tr>
<tr>
<td>x</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>2</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>L</th>
<th>S</th>
<th>M</th>
</tr>
</thead>
<tbody>
<tr>
<td>a, c</td>
<td>576</td>
<td>0</td>
</tr>
<tr>
<td>b, d</td>
<td>0</td>
<td>576</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>BL</th>
<th>BS</th>
</tr>
</thead>
<tbody>
<tr>
<td>i, j</td>
<td>18</td>
</tr>
<tr>
<td>k, m</td>
<td>0</td>
</tr>
<tr>
<td>l, n</td>
<td>18</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>LBL</th>
<th>SBS</th>
<th>MBL</th>
<th>MBS</th>
</tr>
</thead>
<tbody>
<tr>
<td>y, z</td>
<td>32</td>
<td>96</td>
<td>2</td>
</tr>
</tbody>
</table>

- FD contains fully connected 5-state Markov chain
- Control tokens to RQ, RO are values L, S, M
- Control tokens to AR, IMDCT, FI are valued BL, BS
- Throughput = 2.68096e-07
SADF > Similar SDF Graphs

- **MP3 Decoder**
  - Scenario LL

- **Scenario SS**

Auto-concurrency excluded implicitly for SDF
SADF > Similar SDF Graphs

- MP3 Decoder
  - Scenario M

- Markov chain of BD for scenario M captures order of blocks
SADF > Similar SDF Graphs

- **MP3 Decoder**
  - Scenario M

- Structure is unintuitive
  - Duplicates & artefacts

- Structure SADF graph matches structure of code
  - Weakly consistent

Auto-concurrency excluded implicitly for SDF
Expressiveness

- SDF and CSDF are subsets of SADF
  - Even with execution time distributions

- SADF is suitable to model for example
  - PSDF, SSDF, HDF, CDDF, BDF, ICDF, KPN, CTG, DDF, RPN

  by capturing dynamism with detectors
  - Scheduling settings of environment (SSDF)
  - Data-dependent functional implementation details (all except SSDF)
  - Continuous control as abstraction of reactive control (RPN)

- SADF is design-time analysable
Performance Analysis

- Model checking techniques in SDF$^3$
  - Take probabilities into account for state-space exploration when needed
  - Probabilities capture relative occurrence of scenarios and execution times

- Worst/best case metrics (probabilities irrelevant)
  - min/max response delay
  - max buffer occupancy
  - min/max inter-firing latency

- Expected/probabilistic reachability metrics (probabilities relevant)
  - expected response delay
  - response delay deadline miss probability

- Long-run metrics (probabilities relevant)
  - throughput
  - av/var inter-firing latency
  - periodic deadline miss probability
  - av/var buffer occupancy

- May suffer from state-space explosion
  - Simulation-based estimation offered as alternative
Conclusions & Future

• SADF extends SDF with scenarios
• SADF is fully analysable at design-time
• SDF$^3$ implements analysis techniques for SADF

• More efficient analysis techniques
  • Compositional per scenario approach instead of whole at once
  • Both for verification of correctness and performance analysis
• Extension with parametric execution times

www.es.ele.tue.nl/sadf