Hardware-Software Codesign

10. Performance Analysis of Distributed Embedded Systems

Lothar Thiele
System Design

- Specification
- System Synthesis
- Estimation
- SW-Compilation
- Instruction Set
- HW-Synthesis
- Intellectual Prop. Code
- Instruction Set
- Net lists
- Machine Code
- Intellectual Prop. Block
Contents

- Overview
- Real-Time Calculus
- Modular Performance Analysis
- Examples
Formal Analysis vs. Simulation

e.g. delay

Worst-Case

Best-Case

Real System  Simulation  Formal analysis

upper bound

lower bound
Embedded System = Computation + Communication + Resource Interaction

Analysis:
Infer system properties from subsystem properties.

Design:
Build a system from subsystems while meeting requirements.
Modular Performance Analysis

Task graphs → Application → Mapping Scheduling → System Model → Performance Model → Analysis → Analysis Results

Data sheets → Load Model (Environment)

Measurements → Performance Model

Service Model (Resources) → Input traces

Architecture diagrams → Architecture

Component simulation →Processing Model (HW/SW)

Formal specification
Abstract Models for Performance Analysis

- Input Stream
- Concrete Instance
- Abstract Representation

Flowchart:
- Processor
  - Task
  - Service Model
  - Processing Model
  - Load Model
Modular System Composition

- CPU
  - RM
- BUS
  - TDMA
- DSP

\[ \beta_{CPU} \]
\[ \beta_{BUS} \]
\[ \beta_{DSP} \]
Overview

- Modular Performance Analysis (MPA)
- Real-Time Calculus (RTC)
- Min-Plus Calculus, Max-Plus Calculus
Contents

- Overview

- Real-Time Calculus

- Modular Performance Analysis

- Examples
Real-Time Calculus can be regarded as a \textit{worst-case/best-case variant of classical queuing theory}. It is a formal method for the analysis of distributed real-time embedded systems.

\textbf{Related Work:}
Comparison of Algebraic Structures

**Algebraic structure**
- set of elements $S$
- one or more operators defined on elements of this set

**Algebraic structures with two operators $\oplus$, $\otimes$**
- plus-times: $(S, \oplus, \otimes) = (\mathbb{R}, +, \times)$
- min-plus: $(S, \oplus, \otimes) = (\mathbb{R} \cup \{+\infty\}, \inf, +)$

**Infimum**:  
- The infimum of a subset of some set is the greatest element, not necessarily in the subset, that is less than or equal to all other elements of the subset.
- $\inf\{[3, 4]\} = 3$, $\inf\{(3, 4]\} = 3$
- $\min\{[3, 4]\} = 3$, $\min\{(3, 4]\}$ not defined
Comparison of Algebraic Structures

**Joint properties**: □

- Closure of □: \( a \uplus b \in S \)
- Associativity of □: \( a \uplus (b \uplus c) = (a \uplus b) \uplus c \)
- Commutativity of □: \( a \uplus b = b \uplus a \)
- Existence of identity element for □: \( \exists \nu: a \uplus \nu = a \)
- Existence of negative element for □: \( \exists a^{-1}: a \uplus a^{-1} = \nu \)
- Identity element of \( \uplus \) absorbing for □: \( a \uplus \varepsilon = \varepsilon \)
- Distributivity of □ w.r.t. \( \uplus \): \( a \uplus (b \uplus c) = (a \uplus b) \uplus (a \uplus c) \)

**Example**:

- plus-times: \( a \times (b + c) = a \times b + a \times c \)
- min-plus: \( a + \inf\{b, c\} = \inf\{a + b, a + c\} \)
Comparison of Algebraic Structures

- **Joint properties**: 

  Closure of $\boxplus$: $a \boxplus b \in S$

  Associativity of $\boxplus$: $a \boxplus (b \boxplus c) = (a \boxplus b) \boxplus c$

  Commutativity of $\boxplus$: $a \boxplus b = b \boxplus a$

  Existence of identity element for $\boxplus$: $\exists \varepsilon : a \boxplus \varepsilon = a$

- **Differences** $\boxplus$:
  - **plus-times**: Existence of a negative element for $\boxplus$: $\exists (-a) : a \boxplus (-a) = \varepsilon$
  - **min-plus**: Idempotency of $\boxplus$: $a \boxplus a = a$
Comparison of System Theories

- **Plus-times system theory**
  - signals, impulse response, convolution, time-domain
  
  \[ h(t) = (f \ast g)(t) = \int_0^t f(t - s) \cdot g(s) \, ds \]

- **Min-plus system theory**
  - streams, variability curves, time-interval domain, convolution

  \[ R'(t) \geq (R \otimes g)(t) = \inf_{0 \leq \lambda \leq t} \{ R(t - \lambda) + g(\lambda) \} \]
Abstract Models for Performance Analysis

Concrete Instance

Abstract Representation

Load Model

Load Model

Service Model

Processor \( C(t) \)

Processing Model

\( \alpha(\Delta) \)

\( \beta(\Delta) \)

\( R(t) \)

\( R'(t) \)
From Streams to Cumulative Functions

- **Data streams**: $R(t) = \text{number of events in } [0, t)$
- **Resource stream**: $C(t) = \text{available resource in } [0, t)$

![Graph showing R(t) and C(t)]
From Event Streams to Arrival Curves

Event Stream

number of events in
in $t=[0 \ldots 2.5]$ ms

Arrival Curves $\alpha = [\alpha^l, \alpha^u]$

maximum / minimum
arriving events in *any interval* of length 2.5 ms
From Resources to Service Curves

Resource Availability

available service in \( t=[0 .. 2.5] \) ms

Service Curves \( \beta = [\beta_l, \beta_u] \)

maximum/minimum available service in any interval of length 2.5 ms
Example 1: Periodic with Jitter

A common event pattern that is used in literature can be specified by the parameter triple \((p, j, d)\), where \(p\) denotes the period, \(j\) the jitter, and \(d\) the minimum inter-arrival distance of events in the modeled stream.
Example 1: Periodic with Jitter

periodic

periodic with jitter
Example 1: Periodic with Jitter

Arrival curves:

\[ \alpha^l(\Delta) = \left\lfloor \frac{\Delta - j}{p} \right\rfloor \]

\[ \alpha^u(\Delta) = \min \left\{ \left\lceil \frac{\Delta + j}{p} \right\rceil, \left\lfloor \frac{\Delta}{d} \right\rfloor \right\} \]
Example 2: TDMA Resource

- Consider a real-time system consisting of $n$ applications that are executed on a resource with bandwidth $B$ that controls resource access using a **TDMA policy**.

- Analogously, we could consider a distributed system with $n$ communicating nodes, that communicate via a shared bus with bandwidth $B$, with a bus arbitrator that implements a TDMA policy.

- **TDMA policy**: In every TDMA cycle of length $\bar{c}$, one single resource slot of length $s_i$ is assigned to application $i$. 

- Diagram showing the allocation of resources over time.
Example 2: TDMA Resource

**Service curves** available to the applications / node $i$:

\[ \beta_i^l(\Delta) = B \max \left\{ \left[ \frac{\Delta}{\bar{c}} \right] s_i, \Delta - \left[ \frac{\Delta}{\bar{c}} \right] (\bar{c} - s_i) \right\} \]

\[ \beta_i^u(\Delta) = B \min \left\{ \left[ \frac{\Delta}{\bar{c}} \right] s_i, \Delta - \left[ \frac{\Delta}{\bar{c}} \right] (\bar{c} - s_i) \right\} \]
**Greedy Processing Component (GPC)**

- **Examples:**
  - computation (event – task instance, resource – computing resource [tasks/second])
  - communication (event – data packet, resource – bandwidth [packets/second])
Greedy Processing Component

Behavioral Description

- Component is triggered by incoming events.
- A fully preemptable task is instantiated at every event arrival to process the incoming event.
- Active tasks are processed in a greedy fashion in FIFO order.
- Processing is restricted by the availability of resources.
Greedy Processing Component (GPC)

If the resource and event streams describe available and requested units of processing or communication, then

\[
\begin{align*}
C(t) &= C'(t) + R'(t) \\
B(t) &= R(t) - R'(t)
\end{align*}
\]

\[
R'(t) = \inf_{0 \leq u \leq t} \{ R(u) + C(t) - C(u) \}
\]

Conservation Laws
Greedy Processing

- For all times $u \leq t$ we have $R'(u) \leq R(u)$ (conservation law).
- We also have $R'(t) \leq R'(u) + C(t) - C(u)$ as the output can not be larger than the available resources.
- Combining both statements yields $R'(t) \leq R(u) + C(t) - C(u)$.
- Let us suppose that $u^*$ is the last time before $t$ with an empty buffer. We have $R(u^*) = R'(u^*)$ at $u^*$ and also $R'(t) = R'(u^*) + C(t) - C(u^*)$ as all available resources are used to produce output. Therefore, $R'(t) = R(u^*) + C(t) - C(u^*)$.
- As a result, we obtain

$$R'(t) = \inf_{0 \leq u \leq t} \{ R(u) + C(t) - C(u) \}$$
Abstract Models for Performance Analysis

Concrete Instance

Abstract Representation

Input Stream $R(t)$ to Task $C(t)$

Service Model $\beta(\Delta)$

Load Model $\alpha(\Delta)$

Processing Model
Abstraction

\[ R(t) \xrightarrow{\text{GPC}} R'(t) \xrightarrow{} C'(t) \]

\[ \alpha(\Delta) \xrightarrow{\text{GPC}} \alpha'(\Delta) \xrightarrow{} \beta'(\Delta) \]

- time domain cumulative functions
- time-interval domain variability curves
Some Definitions and Relations

- $f \otimes g$ is called **min-plus convolution**
  \[(f \otimes g)(t) = \inf_{0 \leq u \leq t} \{f(t - u) + g(u)\}\]

- $f \ominus g$ is called **min-plus de-convolution**
  \[(f \ominus g)(t) = \sup_{u \geq 0} \{f(t + u) - g(u)\}\]

- For **max-plus convolution and de-convolution**:  
  \[(f \overline{\otimes} g)(t) = \sup_{0 \leq u \leq t} \{f(t - u) + g(u)\}\]
  \[(f \overline{\ominus} g)(t) = \inf_{u \geq 0} \{f(t + u) - g(u)\}\]

- Relation between convolution and deconvolution
  \[f \leq g \otimes h \iff f \ominus h \leq g\]
Arrival and Service Curve

The arrival and service curves provide bounds on event and resource functions as follows:

\[ \alpha^l(t - s) \leq R(t) - R(s) \leq \alpha^u(t - s) \quad \forall s \leq t \]

\[ \beta^l(t - s) \leq C(t) - C(s) \leq \beta^u(t - s) \quad \forall s \leq t \]

We can determine valid variability curves from cumulative functions as follows:

\[ \alpha^u = R \ominus R; \quad \alpha^l = R \ominus R; \quad \beta^u = C \ominus C; \quad \beta^l = C \ominus C \]

One proof:

\[ \alpha^u = R \ominus R \Rightarrow \alpha^u(\Delta) = \sup_{u \geq 0} \{ R(\Delta + u) - R(u) \} \Rightarrow \]

\[ \alpha^u(\Delta) = \sup_{s \geq 0} \{ R(\Delta + s) - R(s) \} \Rightarrow \alpha^u(t - s) \geq R(t) - R(s) \quad \forall t \geq s \]
Abstraction

GPC

$R(t)$  $R'(t)$

$C(t)$  $C'(t)$

time domain
cumulative functions

GPC

$\alpha(\Delta)$  $\alpha'(\Delta)$

$\beta(\Delta)$  $\beta'(\Delta)$

time-interval domain
variability curves
The Most Simple Relations

- The output stream of a component satisfies:
  \[ R'(t) \geq (R \otimes \beta^l)(t) \]

- The output upper arrival curve of a component satisfies:
  \[ \alpha^{u'} = (\alpha^u \otimes \beta^l) \]

- The remaining lower service curve of a component satisfies:
  \[ \beta^{l'}(\Delta) = \sup_{0 \leq \lambda \leq \Delta} (\beta^l(\lambda) - \alpha^u(\lambda)) \]
Two Sample Proofs

\[ R'(t) = \inf_{0 \leq u \leq t} \{ R(u) + C(t) - C(u) \} \geq \inf_{0 \leq u \leq t} \{ R(u) + \beta^l(t - u) \} = (R \otimes \beta^l)(t) \]

\[ C'(t) - C'(s) = \sup_{0 \leq a \leq t} \{ C(a) - R(a) \} - \sup_{0 \leq b \leq s} \{ C(b) - R(b) \} = \inf_{0 \leq b \leq s} \{ \sup_{0 \leq a \leq t} \{ (C(a) - C(b)) - (R(a) - R(b)) \} \} \]

\[ = \inf_{0 \leq b \leq s} \{ \sup_{0 \leq a - b \leq t - b} \{ (C(a) - C(b)) - (R(a) - R(b)) \} \} \geq \inf_{0 \leq b \leq s} \{ \sup_{0 \leq \lambda \leq t - b} \{ \beta^l(\lambda) - \alpha^u(\lambda) \} \} \geq \sup_{0 \leq \lambda \leq t - s} \{ \beta^l(\lambda) - \alpha^u(\lambda) \} \]
Tighter Bounds

The greedy processing component transforms the variability curves as follows:

\[
\alpha^{u'} = [(\alpha^u \otimes \beta^u) \otimes \beta^l] \land \beta^u
\]
\[
\alpha^{l'} = [(\alpha^l \otimes \beta^u) \otimes \beta^l] \land \beta^l
\]
\[
\beta^{u'} = (\beta^u - \alpha^l) \ominus 0
\]
\[
\beta^{l'} = (\beta^l - \alpha^u) \ominus 0
\]

Without proof … .
Delay and Backlog

\[ B = \sup_{t \geq 0} \{ R(t) - R'(t) \} \leq \sup_{\lambda \geq 0} \{ \alpha^u(\lambda) - \beta^l(\lambda) \} \]

\[ D = \sup_{t \geq 0} \{ \inf \{ \tau \geq 0 : R(t) \leq R'(t + \tau) \} \} = \sup_{\Delta \geq 0} \{ \inf \{ \tau \geq 0 : \alpha^u(\Delta) \leq \beta^l(\Delta + \tau) \} \} \]
Proof of Backlog Bound

\[ B(t) = R(t) - R'(t) = R(t) - \inf_{0 \leq u \leq t} \{ R(u) + C(t) - C(u) \} \]

\[ = \sup_{0 \leq u \leq t} \{(R(t) - R(u)) - (C(t) - C(u))\} \]

\[ \leq \sup_{0 \leq u \leq t} \{\alpha^u(t - u) - \beta^l(t - u)\} \]

\[ \leq \sup_{0 \leq \lambda} \{\alpha^u(\lambda) - \beta^l(\lambda)\} \]
Contents

- Overview

- Real-Time Calculus

- Modular Performance Analysis

- Examples
System Composition

How to interconnect service?

Scheduling!

β_{CPU}

β_{BUS}

β_{DSP}

α

GPC

GPC

GPC

GPC

GPC

GPC

α'
Scheduling and Arbitration

FP/RM

\( \beta \)

\( \alpha_A \rightarrow \alpha'_A \)

\( \alpha_B \rightarrow \alpha'_B \)

GPC

EDF

\( \beta \)

\( \alpha_A \rightarrow \alpha'_A \)

\( \alpha_B \rightarrow \alpha'_B \)

GPC

RR

\( \beta \)

\( \alpha_A \rightarrow \alpha'_A \)

\( \alpha_B \rightarrow \alpha'_B \)

GPC

GPS

\( \beta' \)

\( \alpha_A \rightarrow \alpha'_A \)

\( \alpha_B \rightarrow \alpha'_B \)

GPC

share

sum

TDMA

\( \beta' \)

\( \beta' \)

\( \alpha_A \rightarrow \alpha'_A \)

\( \alpha_B \rightarrow \alpha'_B \)

GPC

TDMA

\( \beta'_s \)

\( \beta'_s \)
Complete System Composition

**Diagram:**

- **CPU:**
  - Input: \( \alpha \)
  - Output: \( \beta_{CPU} \)
  - GPC
  - GPC
  - GPC

- **BUS:**
  - TDMA
  - Input: \( \beta_{BUS} \)
  - GPC
  - GPC

- **DSP:**
  - Input: \( \beta_{DSP} \)
  - GPC

- **Connections:**
  - \( \alpha \) to GPC in CPU
  - \( \beta_{CPU} \) to GPC in CPU
  - TDMA in BUS
  - \( \beta_{BUS} \) to GPC in BUS
  - \( \beta_{DSP} \) to GPC in DSP

- **Symbols:**
  - \( \alpha \), \( \alpha' \)
  - \( \beta_{CPU} \), \( \beta_{BUS} \), \( \beta_{DSP} \)
Extending the Framework

- New HW behavior
- New SW behavior
- New scheduling scheme
- ...

Find new relations:

\[ \alpha'(\Delta) = f_\alpha(\alpha, \beta) \]
\[ \beta'(\Delta) = f_\beta(\alpha, \beta) \]

This is the hard part…!
Contents

- Overview
- Real-Time Calculus
- Modular Performance Analysis
- Examples
Case Study

6 Real-Time Input Streams
- with jitter
- with bursts
- deadline > period

3 ECU’s with own CC’s

13 Tasks & 7 Messages
- with different WCED

2 Scheduling Policies
- Earliest Deadline First (ECU’s)
- Fixed Priority (ECU’s & CC’s)

Hierarchical Scheduling
- Static & Dynamic Polling Servers

Bus with TDMA
- 4 time slots with different lengths
  (#1,#3 for CC1, #2 for CC3, #4 for CC3)

Total Utilization:
- ECU1 59 %
- ECU2 87 %
- ECU3 67 %
- BUS 56 %
# Specification Data

<table>
<thead>
<tr>
<th>Stream</th>
<th>(p,j,d) [ms]</th>
<th>D [s]</th>
<th>Task Chain</th>
</tr>
</thead>
<tbody>
<tr>
<td>S1</td>
<td>(1000, 2000, 25)</td>
<td>8.0</td>
<td>T1.1 → C1.1 → T1.2 → C1.2 → T1.3</td>
</tr>
<tr>
<td>S2</td>
<td>(400, 1500, 50)</td>
<td>1.8</td>
<td>T2.1 → C2.1 → T2.2</td>
</tr>
<tr>
<td>S3</td>
<td>(600, 0, -)</td>
<td>6.0</td>
<td>T3.1 → C3.1 → T3.2 → C3.2 → T3.3</td>
</tr>
<tr>
<td>S4</td>
<td>(20, 5, -)</td>
<td>0.5</td>
<td>T4.1 → C4.1 → T4.2</td>
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<tr>
<td>S5</td>
<td>(30, 0, -)</td>
<td>0.7</td>
<td>T4.1 → C4.1 → T4.2</td>
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<tr>
<td>S6</td>
<td>(1500, 4000, 100)</td>
<td>3.0</td>
<td>T6.1</td>
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## Task

<table>
<thead>
<tr>
<th>Task</th>
<th>e</th>
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<tr>
<td>T1.1</td>
<td>200</td>
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<td>T1.2</td>
<td>300</td>
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<tr>
<td>T1.3</td>
<td>30</td>
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<td>T2.1</td>
<td>75</td>
</tr>
<tr>
<td>T2.2</td>
<td>25</td>
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<tr>
<td>T3.1</td>
<td>60</td>
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<td>T3.2</td>
<td>60</td>
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<td>T3.3</td>
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<td>T4.2</td>
<td>2</td>
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<tr>
<td>T5.1</td>
<td>8</td>
</tr>
<tr>
<td>T5.2</td>
<td>3</td>
</tr>
<tr>
<td>T6.1</td>
<td>100</td>
</tr>
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</table>

## Message

<table>
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<th>e</th>
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<tbody>
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<td>C1.1</td>
<td>100</td>
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<tr>
<td>C1.2</td>
<td>80</td>
</tr>
<tr>
<td>C2.1</td>
<td>40</td>
</tr>
<tr>
<td>C3.1</td>
<td>25</td>
</tr>
<tr>
<td>C3.2</td>
<td>10</td>
</tr>
<tr>
<td>C4.1</td>
<td>3</td>
</tr>
<tr>
<td>C5.1</td>
<td>2</td>
</tr>
</tbody>
</table>

## Periodic Server

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<thead>
<tr>
<th>Server</th>
<th>p</th>
<th>e</th>
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<tbody>
<tr>
<td>SPS_{ECU_1}</td>
<td>500</td>
<td>200</td>
</tr>
<tr>
<td>SPS_{ECU_3}</td>
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<td>250</td>
</tr>
<tr>
<td>DPS_{ECU_3}</td>
<td>600</td>
<td>120</td>
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## TDMA

<table>
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<tbody>
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<td>Cycle</td>
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<tr>
<td>Slot_{CC_{1a}}</td>
<td>20</td>
</tr>
<tr>
<td>Slot_{CC_{1b}}</td>
<td>25</td>
</tr>
<tr>
<td>Slot_{CC_2}</td>
<td>25</td>
</tr>
<tr>
<td>Slot_{CC_3}</td>
<td>30</td>
</tr>
</tbody>
</table>
The Distributed Embedded System...
... and its MPA Model
Available & Remaining Service of ECU1
Input of Stream 3
Output of Stream 3
Automated Design Space Exploration

We use evolutionary algorithms for multi-objective optimization!
Network Processor Task Model
EXPO

Implementation Nr. 60641 (EXPO, Institute TIK, ETH Zurich)

Scenario: Scen2
Optimal Scaling Factor: 0.530
Total Memory: 8.295

- DSP: Utilization: 70%
- CheckSum: Utilization: 4%
- LookUp: Utilization: 7%

Flow: RTSend
Priority: 5
Acc. Waiting Time in Queue: 0.000
- RTPtx
- VoiceEnc
- LinkTx
- Schedule
- ProcessIP
- IPModify
- LinkRx
- Schedule
- Decrypt
- AHVerify
- Classify
- LinkRx

Flow: NRTDecrypt
Priority: 4
Acc. Waiting Time in Queue: 0.000
- ESPDescaps
- ProcessIP
- IPModify
- LinkTx
- Schedule
- Decrypt
- AHVerify
- Classify
- LinkRx

Flow: RTRecv
Priority: 1
Acc. Waiting Time in Queue: 0.000
- Dejitter
- VoiceDec
- ProcessIP
- RTPtx
- Classify
- LinkRx

Flow: NRTForward
Priority: 3
Acc. Waiting Time in Queue: 23.098
- ProcessIP
- Var2UDP
- ARPLU
Results

Performance for encryption/decryption

Performance for RT voice processing

- **DSP**
  - NRT: 64%
  - RT: 39%

- **Cipher**
  - NRT: 71%
  - RT: 0%

- **LookUp**
  - NRT: 15%
  - RT: 6%

- **Classifier**
  - NRT: 27%
  - RT: 11%

- **DSP**
  - NRT: 35%
  - RT: 39%

- **LookUp**
  - NRT: 1%
  - RT: 6%

- **Classifier**
  - NRT: 1%
  - RT: 11%
Analysis vs. Simulation

- Simulation
- Analytical Method

Utilization [%]

Packet Size [Bytes]

250 Mbps
200 Mbps
150 Mbps
100 Mbps

Utilization [%]

100Mbps 150Mbps 200Mbps 250Mbps 300Mbps 350Mbps 400Mbps

OPB
PLB read
PLB write
load
Design Space Exploration

- Determine mapping
- Determine performance network
- Solve system of equations
- Determine important parameters (end-to-end delay, throughput, buffer space, output jitter, ...)
- Give feedback to optimization
RTC Toolbox

Modular Performance Analysis with Real-Time Calculus

Real-Time Calculus Toolbox

Overview

The Real-Time Calculus (RTC) Toolbox is a free Matlab toolbox for system-level performance analysis of distributed real-time and embedded systems.

Citation Information

If you use the RTC Toolbox for research purposes, we would be happy to hear about it and mention it in the manual. Please drop us a line at rtc@tik.ee.ethz.ch.

BibTeX entry for citation:

```bibtex
@misc{rtc,
  author = {Ernesto Wandel and Lothar Thiel},
  title = {Real-Time Calculus (RTC) Toolbox},
  url = {http://www.mpa.ethz.ch/rtctoolbox},
  howpublished = {\tt http://www.mpa.ethz.ch/rtctoolbox},
  year = {2006},
}
```

www.mpa.ethz.ch/rtctoolbox