# Introduction to the SystemC AMS DRAFT Standard


| | |
|---|---|
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| **Karsten Einwich** | **Fraunhofer IIS/EAS Dresden** |




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# The Fraunhofer-Gesellschaft – at a Glance

The Fraunhofer-Gesellschaft undertakes **applied research** of direct utility to private and public enterprise and of wide benefit to society.


- Founded in 1949 and named by Joseph von Fraunhofer (1787-1826) – a scientist (Fraunhofer lines), inventor (methods of making lenses) and businessmen (managing of a glassworks)
- 57 institutes across Germany with a total staff of 15,000
- Total budget €1.4 billion with approx. 60% of income generated from contract research and government-sponsored projects

**Research areas:**

- **Information and Communication Technology**
- Life Sciences
- **Microelectronics**
- Surface Technology and Photonics
- Production
- Materials and Components
- Defense and Security





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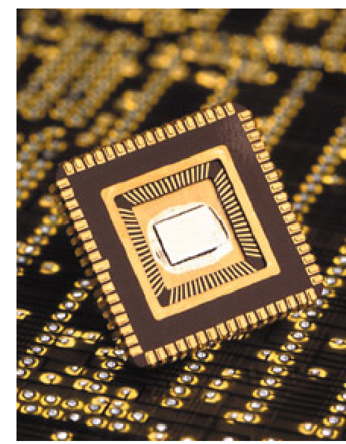
# The Fraunhofer Institute for Integrated Circuits IIS

- Founded in 1985
- Approx. 585 staff
- Budget: approx. € 72 million
- Revenue sources:
  > 80% income from projects
  < 20% public funding
- Locations in Erlangen (Headquarter), Fürth, Nuremberg, **Dresden**, Ilmenau

**Business areas:**

- Audio und multimedia technologies
- Imaging systems
- Digital broadcasting systems
- Embedded communication
- IC design and **design automation**
- Communication networks
- Navigation
- Logistics
- Medical technology
- Optical inspection systems
- X-ray technology





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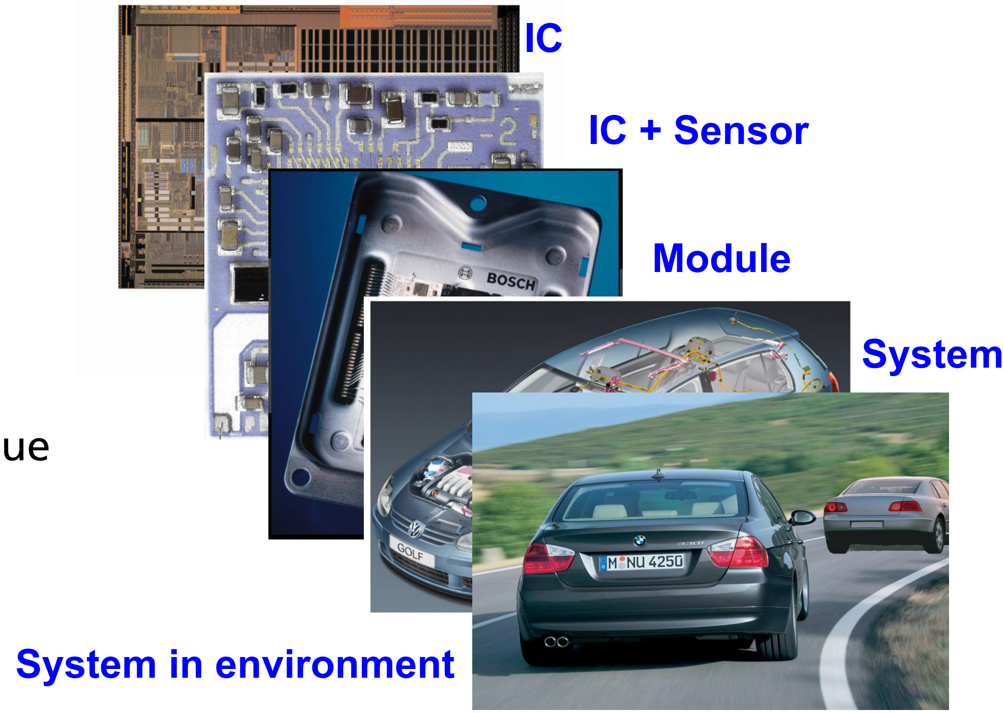
# Design Automation Division EAS, Dresden

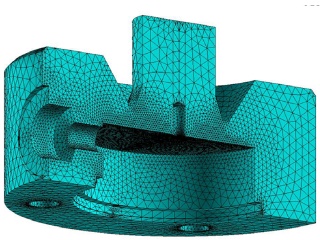
Founded in 1993

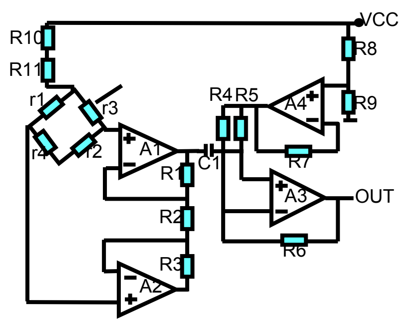
Approx. 80 staff

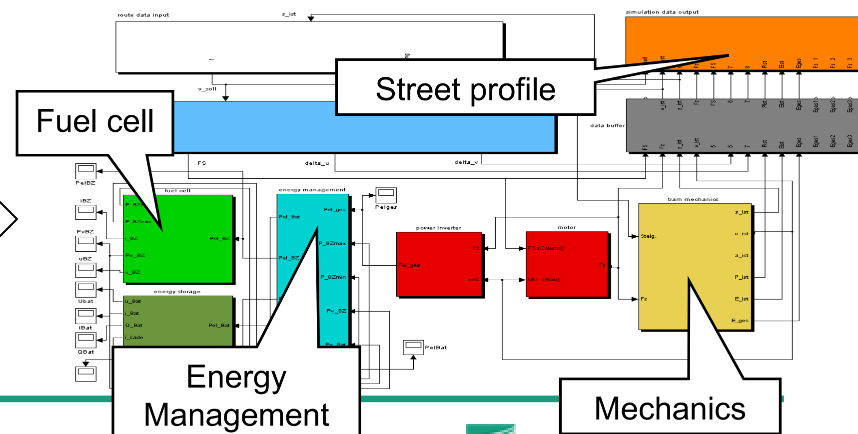
Budget: approx. € 6 million

- Development of methods and tools for computer-aided design of electronic circuits and systems for the complete value chain
- Main areas of work Modeling, simulation, synthesis, optimization, verification and testing







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# Outline

Introduction

SystemC AMS Basics

Introduction to SystemC AMS DRAFT 1

Application Examples

# SystemC AMS is …

- an extension of **SystemC** which permits modeling of analog mixed-signal behavior

# SystemC is …

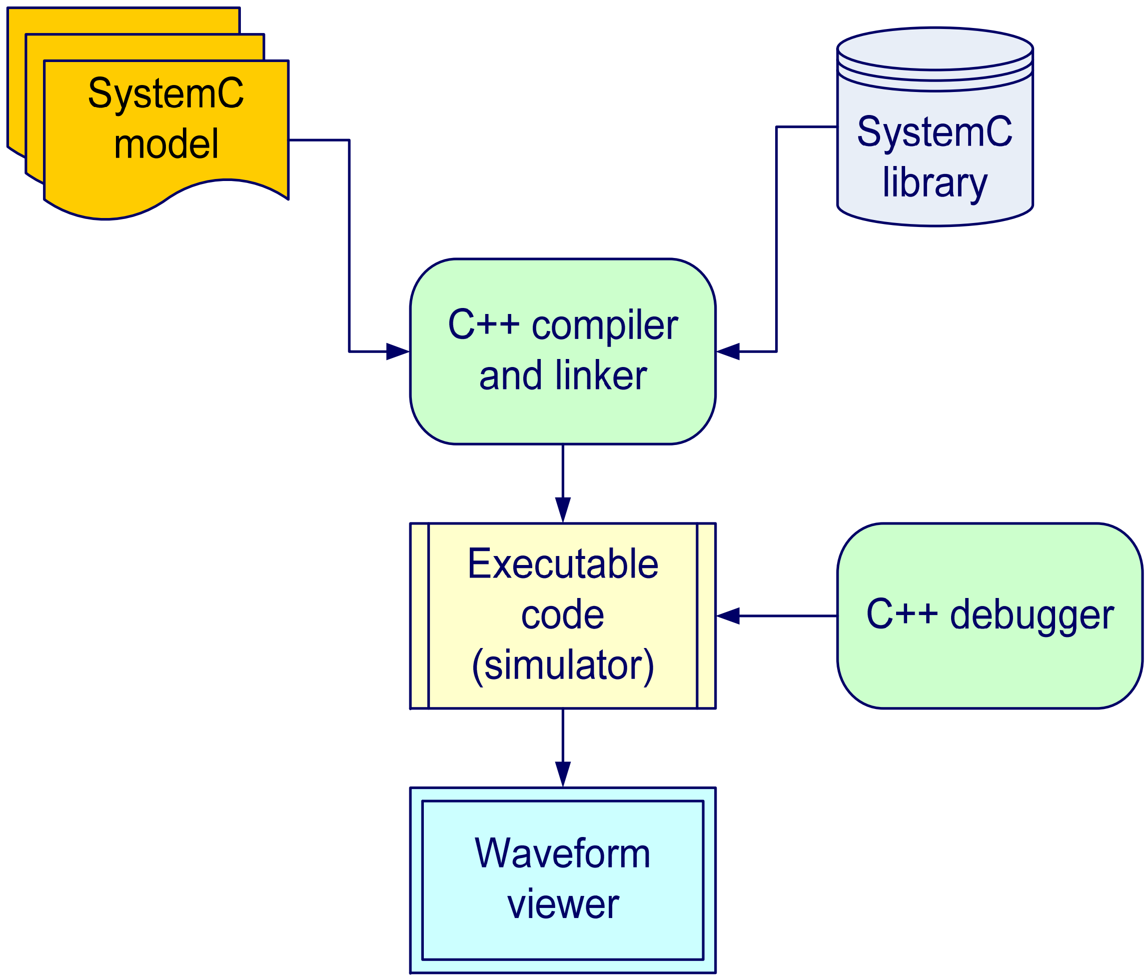
a **definition of C++ language constructs** for the description of complex digital hardware systems on different abstraction levels, using different Models of Computation (MoC)

Definition of classes for modeling:

- Time
- De-composition, Hierarchy
- Concurrency (processes)
- Reactivity
- Signals
- Generic communication channels
- Datatypes

SystemC – models can be simulated using a reference implementation of the C++ class library

# SystemC Use Flow



# SystemC – Yet another VHDL or Verilog ?

- Based on the programming language C++
- Generic Model of Computation
- Layered approach enables extensibility

- Best suited for higher abstraction levels like system level design and architectural level exploration
- Easy integration of software

- Support of special methodologies like TLM

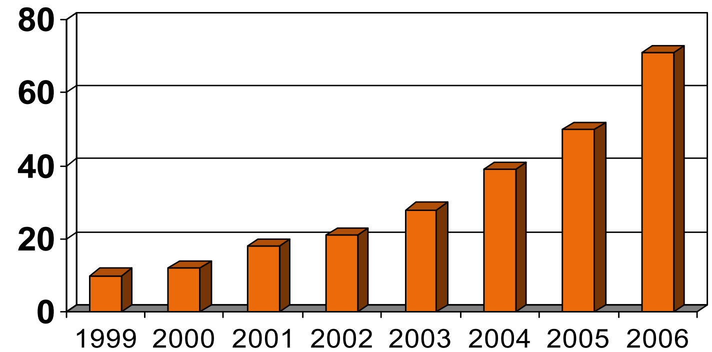
# Why AMS Extensions for SystemC ?

- It's an analog world – analog is how we interact with the real world
- Each digital system is embedded in the analogue world

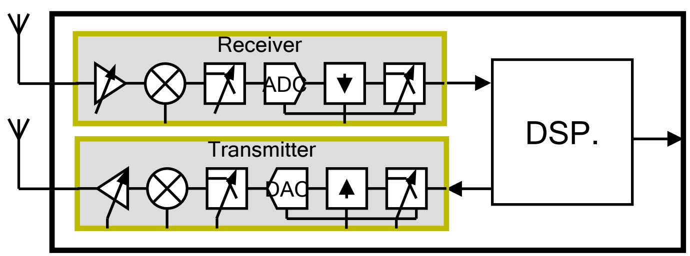
- Analog doesn't scale, the performance of the devices becomes worse, …
- -> Use digital gates to improve analog performance
- –> digital assisted analog
- -> Tight interaction (loops) between analog and digital hard- and software

**Analog's Presence in SoC**

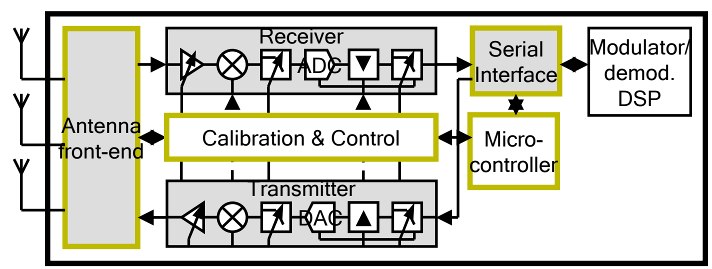
Percents of SoC with analog Elements




Source ITRS 2006




Traditional architecture




Digital assisted analog





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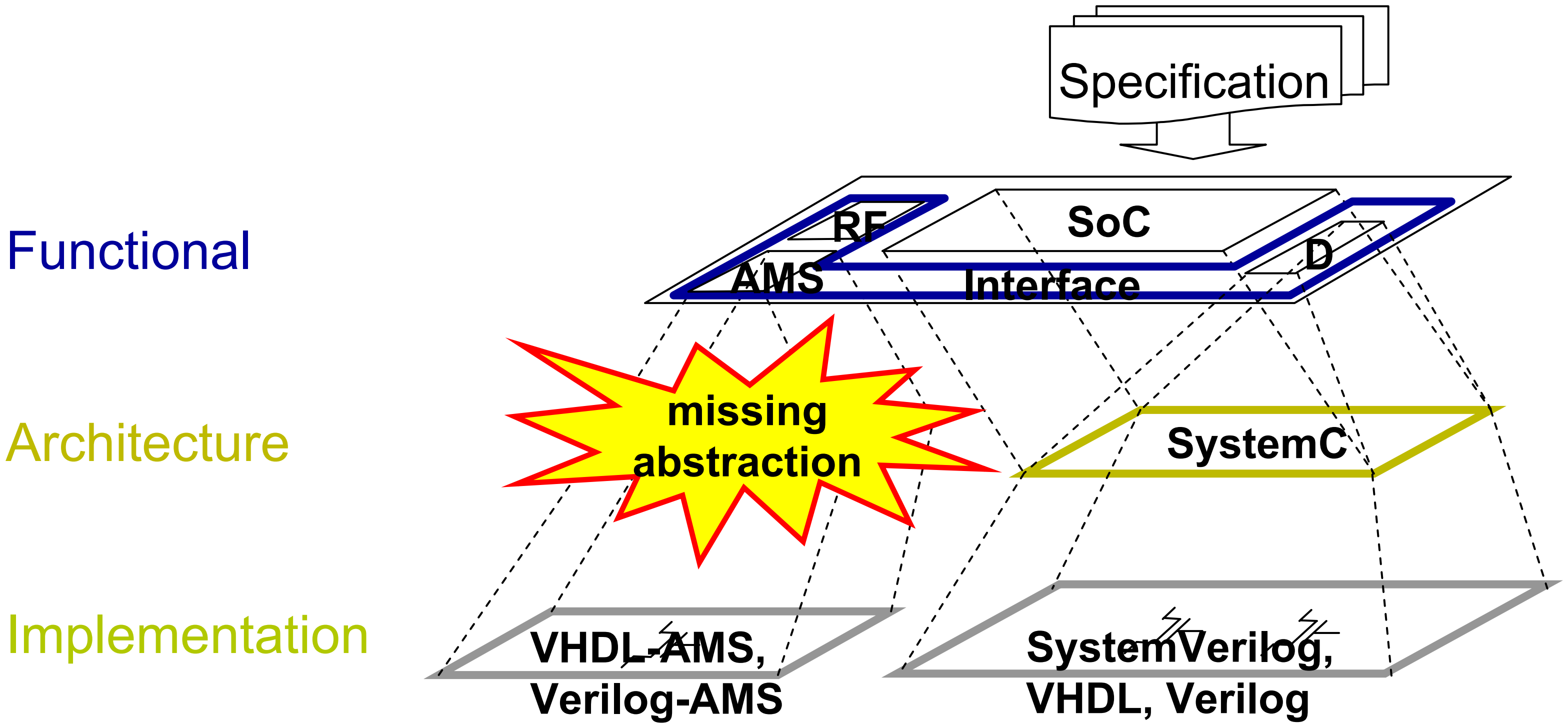
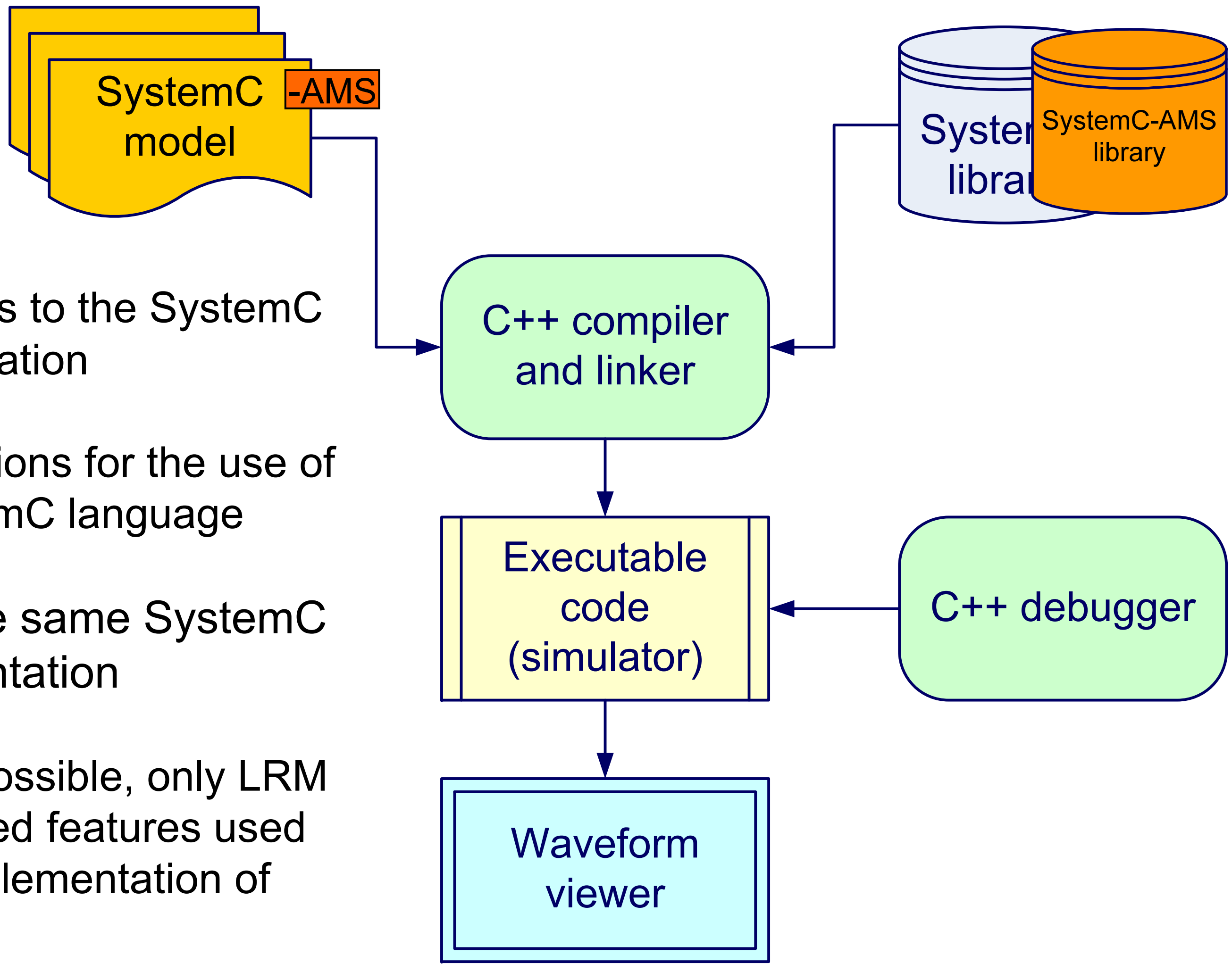
# Why AMS Extensions for SystemC ?




Analog and digital cannot further considered separately

End-to-End platform modeling becomes more and more essential

# SystemC-AMS is an extension of SystemC




- no changes to the SystemC implementation

➡ no restrictions for the use of the SystemC language

➡ use of the same SystemC implementation

- as far as possible, only LRM documented features used for the implementation of the library

# AMS Working Group

# SystemC AMS History

- **2000** Fraunhofer and Infineon developed SystemC extension library mixsigc
- 2000 University Frankfurt and Continental Teves developed AVSL
- 2001 SystemC-AMS study group founded
- Analog extensions from different universities (South Hampton, University Ancona), Dataflow implementation from Shukla
- Ca. 2002 reimplementation of mixsigc to systemc-ams -> publication as prototype of the study group
- **2006** official approval as OSCI AMSWG with Martin Barnasconi from NXP as chair
- 2008 White paper publication at DAC
- December 2008 DRAFT1 Language Reference Manual publicized





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# OSCI AMS Working Group Roster

Steady growth in AMS WG: 53 individuals from 19 organizations

- strong drive from semiconductor industry
- full support of universities and research institutes
- growing interest and participation of EDA/ESL vendors

Chair: Martin Barnasconi, NXP Semiconductors

Vice chair: Christoph Grimm, Vienna University of Technology

# AMS Working Group scope

Embedded analog/
mixed-signal systems

- Heterogeneous systems including analog, mixed-signal, RF and digital HW/SW

Application domains

- Wireless
- Wired
- Automotive
- Imaging sensors

Use cases

- Virtual prototyping for SW development
- Creating reference models for functional verification
- Architecture exploration, definition and algorithm validation

| End Product Markets | 2003 | 2004 | 2005 | 2006 | 2007 |
|---|---|---|---|---|---|
| Microprocessor/DSP | 18.9% | 16.0% | 13.1% | 10.5% | 14.7% |
| Computer, Peripheral | 22.9% | 21.6% | 18.5% | 24.2% | 19.0% |
| Wired Network | 11.2% | 5.2% | 5.8% | 4.8% | 5.2% |
| Wireless Network | 13.1% | 10.4% | 13.1% | 7.3% | 6.9% |
| Multimedia | 25.6% | 34.2% | 33.8% | 37.9% | 31.9% |
| Automotive | 1.9% | 3.0% | 3.8% | 4.0% | 4.3% |
| Others | 6.4% | 9.7% | 11.9% | 11.3% | 18.1% |

source: SystemC Trends report, April 2007

focus of AMS WG

# Planning and timing

Phase 1: Requirements study **(2006-2007)**

- Agreement of functional requirement specification
- Architecture and code review existing solutions

Phase 2: Definition and Proposal **(2007-2008)**

- Whitepaper introducing SystemC AMS Extensions
- SystemC AMS draft 1 Standard

Phase 3: Feedback and Standardization **(2008-2009)**

- Public review of SystemC AMS Language Reference Manual
- Promote SystemC AMS extensions as OSCI standard

we are here

AMS WG status and drafts will be announced via www.systemc.org





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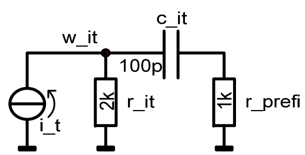
# SystemC AMS Extension Basics

# SystemC Model of Computation

- SystemC has a **generic** Model of Computation (**MoC**)
- This generic MoC is based on the communication and synchronization of parallel processes
  - -> the underlying **system behavior** is **solved "ad hoc"**
- Therefore methods and classes for process registration, events and triggering to events are existing
- Thus MoC's which assume that the system **state changes at discrete time points** can be easily mapped

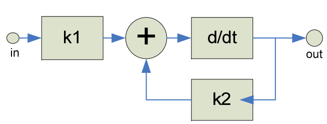
# What's different between analog and digital ?

- Analog equation cannot be solved by the communication and synchronization of processes




$$0 = i\_t + \frac{v(w\_it)}{r\_it} + c\_it \bullet \frac{d(v(w\_it) - v(w\_p))}{dt}$$

$$0 = \frac{v(w\_p)}{r\_prefi} - c\_it \bullet \frac{d(v(w\_it) - v(w\_p))}{dt}$$

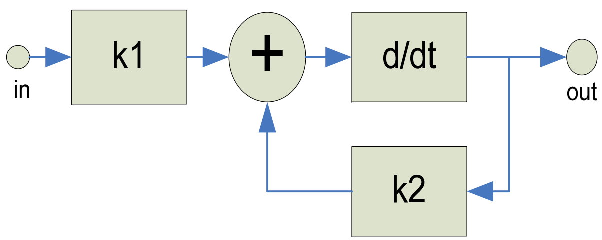


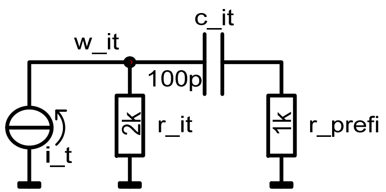

$$out = k1 \bullet \frac{din}{dt} + k2 \bullet out$$

->in general an **equation system must be setup**

- The analog system **state changes continuously**
  - the value between solution points is continuous (linear is a first order approximation only)
  - -> the value of a time point between two solution points can be estimated only after the second point has been calculated (otherwise instable extrapolation)

# Non conservative vs. Conservative




- Abstract representation of analog behavior
- The graph represents a continuous time (implicit) equation (system)

- Represents topological **structure** of the modeled system
- Nodes are characterized by two quantities – the **across** value (e.g. voltage) and the **through** value (e.g. current)
- For electrical systems, **Kirchhoff's laws** applied (KCL, KVL)
- For other **physical domains generalized** versions of Kirchhoffs's laws applied

# Why different analogue MoC's?

- Modeling on **different abstraction** / accuracy levels yields the possibility to apply specialized algorithms, which are **orders of magnitude faster** than a general approach.
- It is possible to **reduce** the **solvability problem** significantly.
- Due to the **encapsulation** of analogue MoC / solvers SystemC-AMS models are very well **scalable** – very large models can be handled.
- Examples for specialized analogue Models of Computations:
  - Dataflow solver for non-conservative / Signalflow Descriptions
  - Linear Networks / Differential-Algebraic Equation (DAE) systems
  - Non-linear Networks / DAE systems
  - Switched Capacitor Networks (leads to simple algebraic equation)





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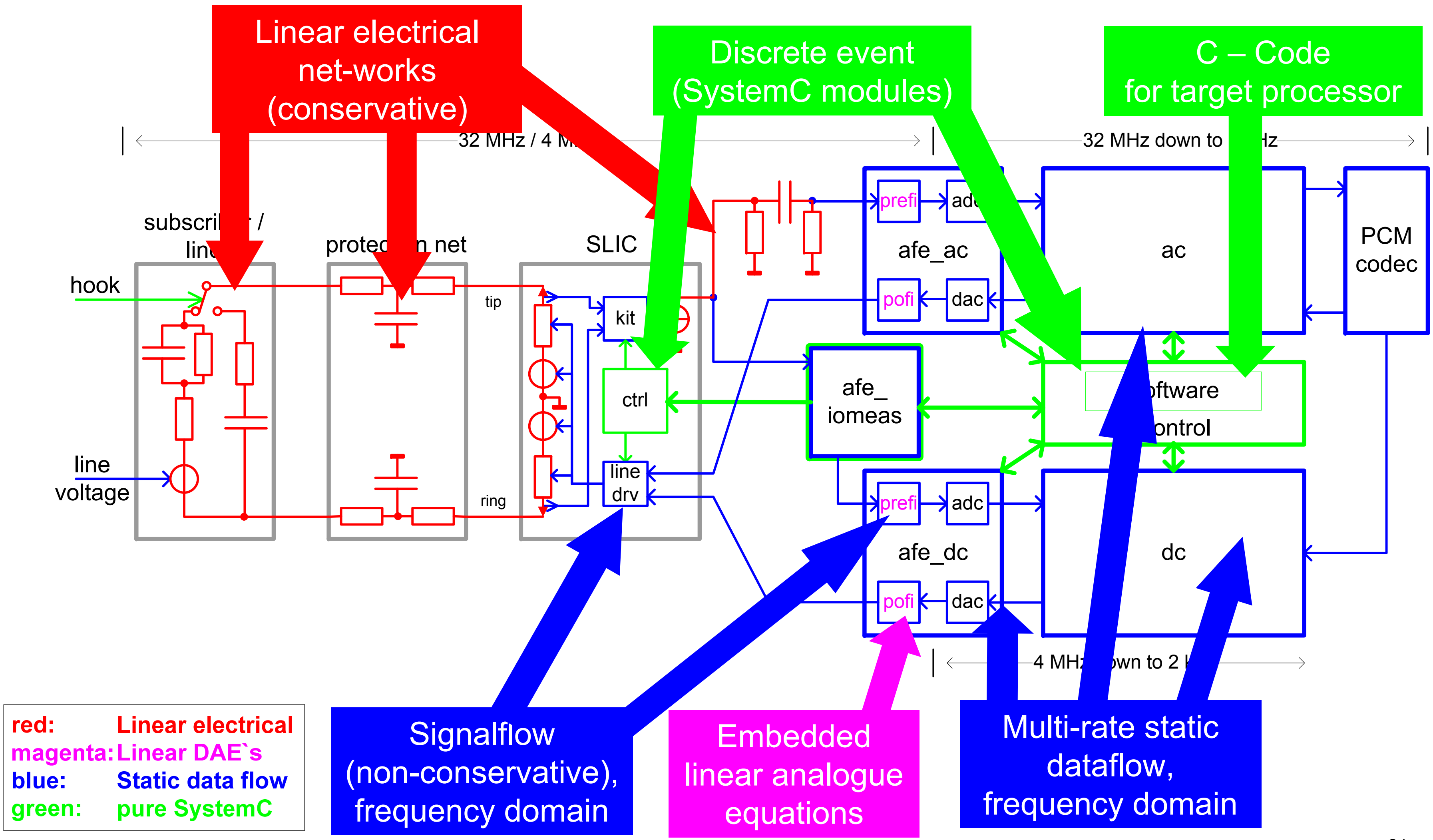
# Modeling with multiple MoC





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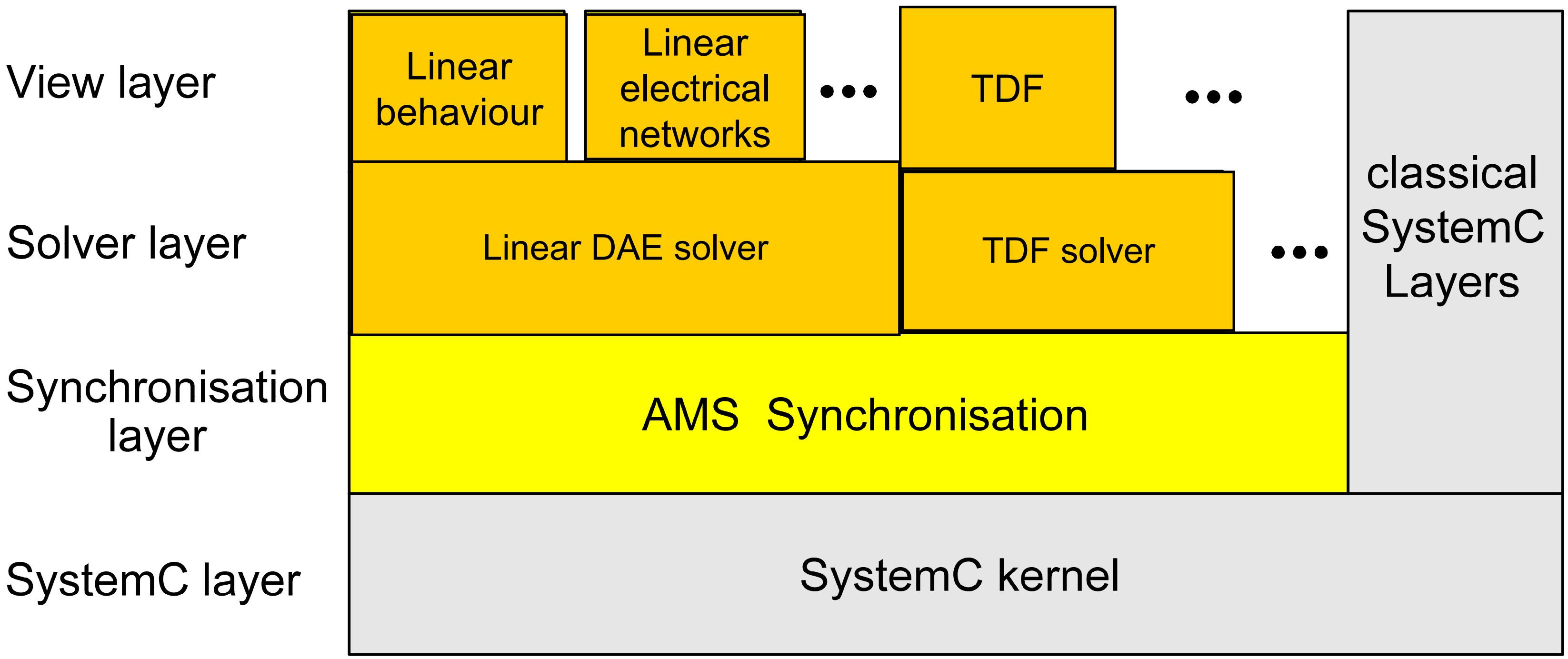
# SystemC-AMS Generic Concept





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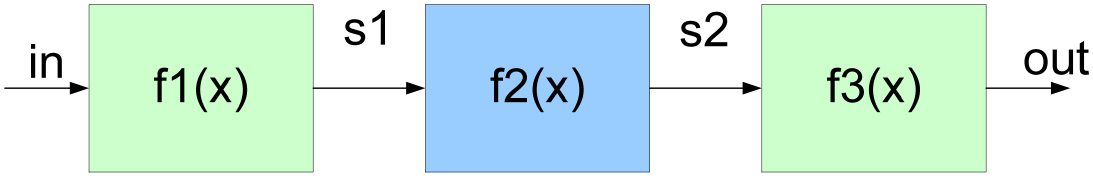
# SystemC-AMS MoC

- Public version supports modeling of:
  - Non-conservative systems
  - Multi rate synchronous dataflow (SDF now called TDF)
  - Linear electrical networks
  - Linear behavioral functions (linear transfer function numerator/denumerator and pole zero, state space),
  - Frequency domain simulation
  - Powerful trace functionality

- Experimental extensions available at Fraunhofer: Switched Capacitor solver, Nonlinear DAE solver with de-synchronization

# Dataflow MoC: Modeling non-conservative behavior



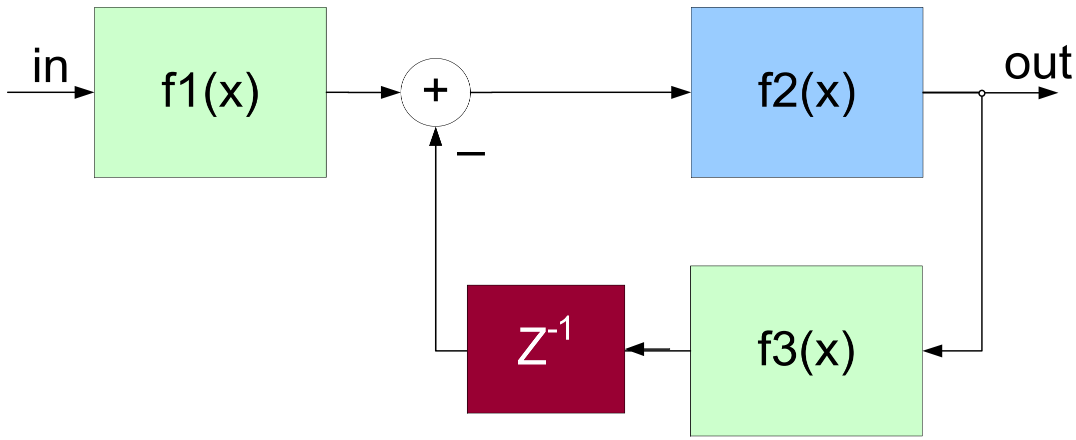

equation system:

s1 = f1(in)
s2 = f2(s1)
out = f3(s2)

out = f3( f2( f1(in) ) )

- Simple firing rule: A module is activated if enough samples are available at its input ports.
- The function of a module is performed by
  - reading from the input ports (thus consuming samples),
  - processing the calculations and
  - writing the results to the output ports.
- For synchronous dataflow (SDF) the numbers of read/written samples are constant for each module activation.
- The scheduling order follows the signalflow direction.
- One drawback is the need of having the equations in an explicit formulation. Thus, only explicit DAE systems can be described by means of the SDF.

# Loops in Synchronous Dataflow Graphs




- Simulating signalflow behaviour by synchronous dataflow MoC with algebraic loops is not possible.

- Thus, at least one delay in the loop is crucial!

$$out = f2(\ f1(in) - f3(out)\ ) \longrightarrow out = f2(\ f1(in) - f3(out)\ z^{-1}\ )$$

# Why Synchronous Dataflow?

- Due pre-scheduling very **fast execution**
- Well encapsulation -> **no solvability problem**
- No iterations required
- Well adopted for signal processing systems
- Smooth crossover to digital processing domain
- The price: **no algebraic loops** is usually acceptable for system and architectural level modeling





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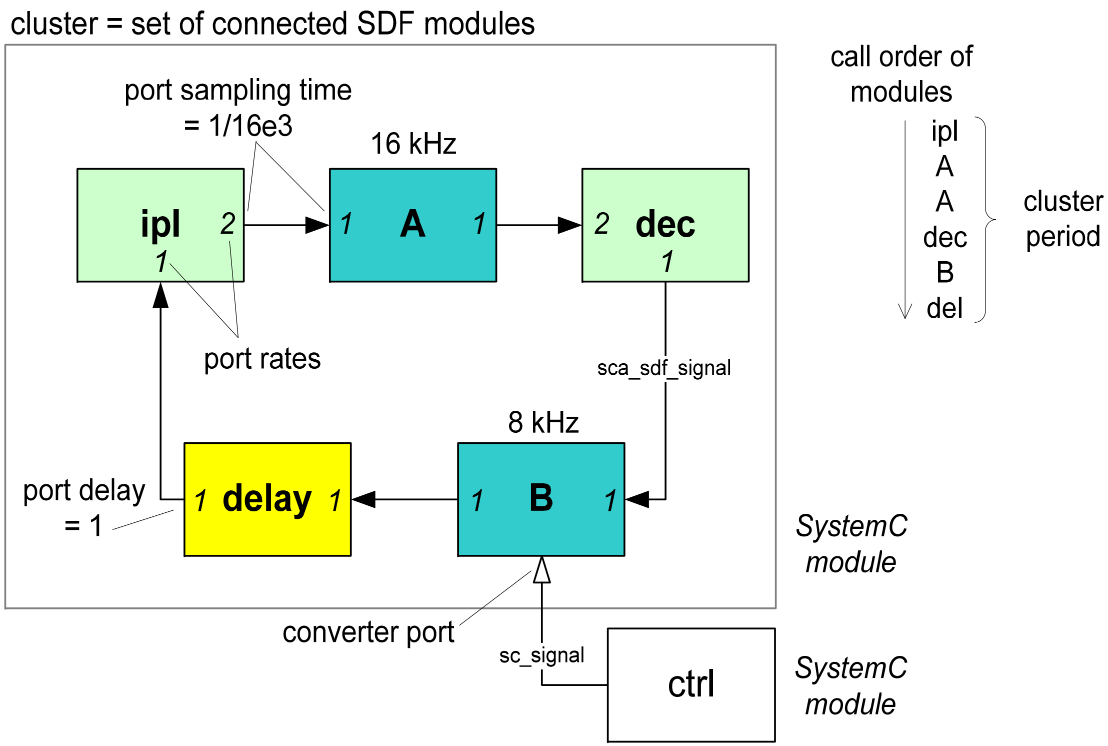
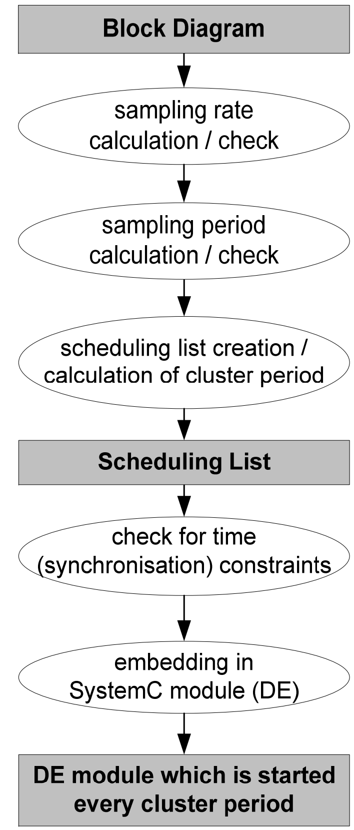
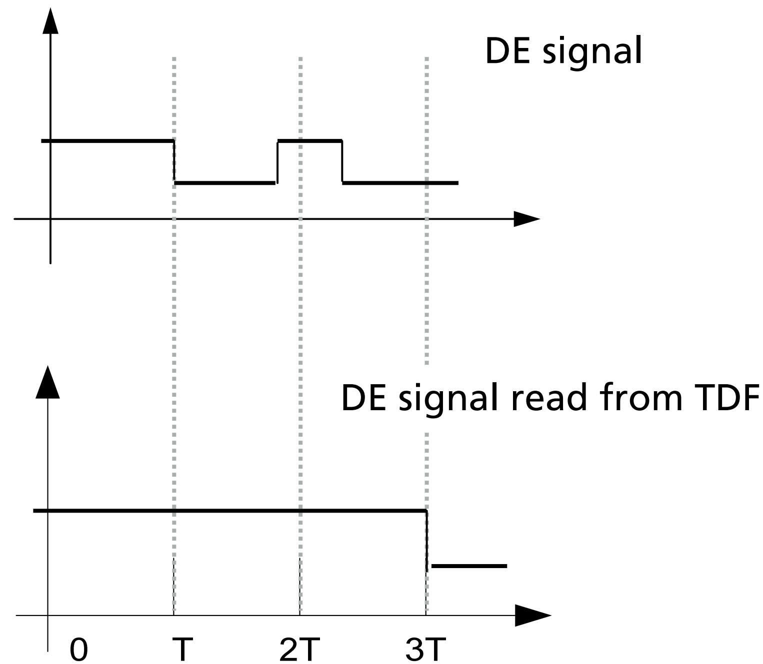
# Implementation of Multi-Rate SDF with Time (TDF) in SystemC-AMS



# Synchronization between TDF and DE

- TDF samples are mapped to sc_time.
- SystemC (DE) signals are sampled at Δ=0 of the specified sampling period. SDF samples are scheduled at Δ=0 as well (and thus valid at least at Δ=1).
- The sampling period T is specified as port attribute and propagated along the TDF signals of the cluster.
- That is why the sampling period must be specified at least for one port of a module in every TDF cluster – are ≥ 2 sampling periods given, the simulator performs a consistency check.



# AMS Draft 1 Standard



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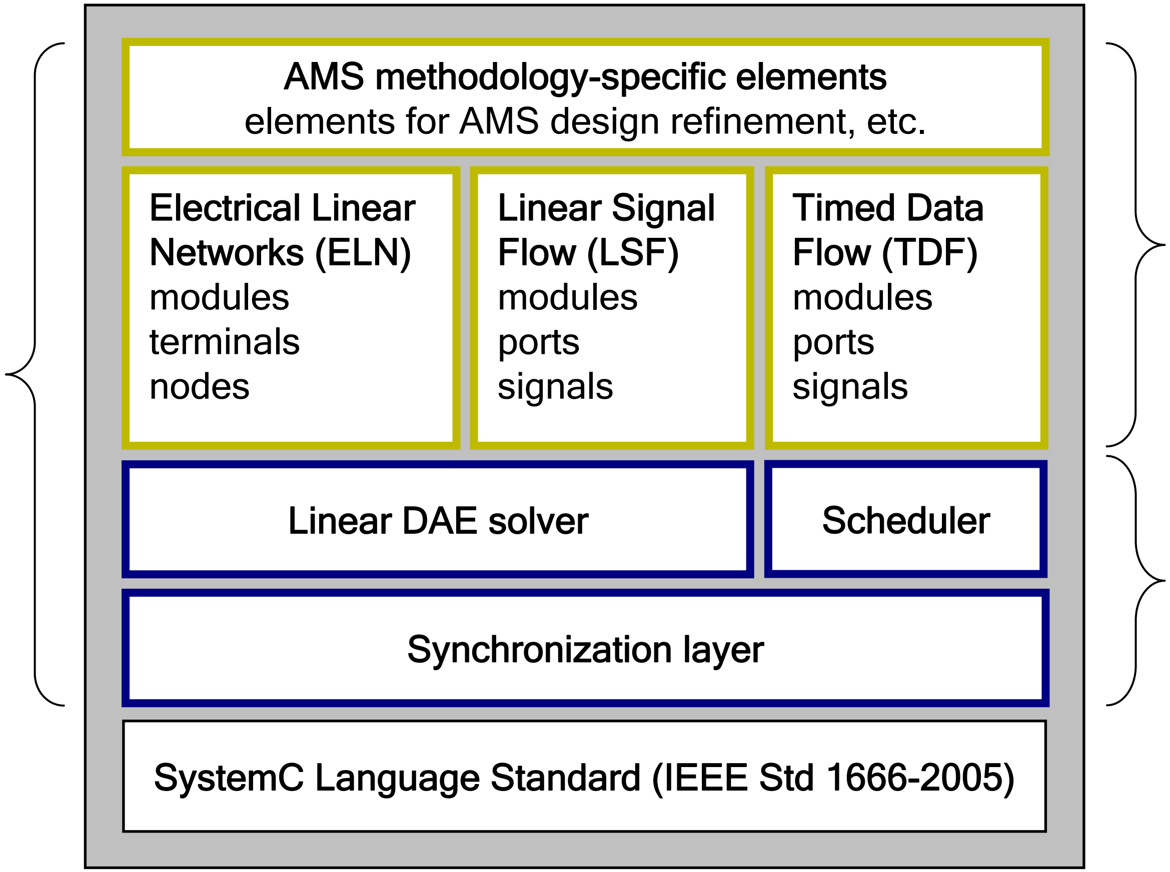
# AMS Draft 1 standard – kit contents

- Draft Standard SystemC AMS extensions Language Reference Manual
- Requirements specification for SystemC AMS extensions
- Whitepaper “An Introduction to Modeling Embedded Analog/Mixed-Signal Systems using SystemC AMS extensions”
- Code example SystemC AMS extensions

# SystemC AMS extensions LRM Draft 1

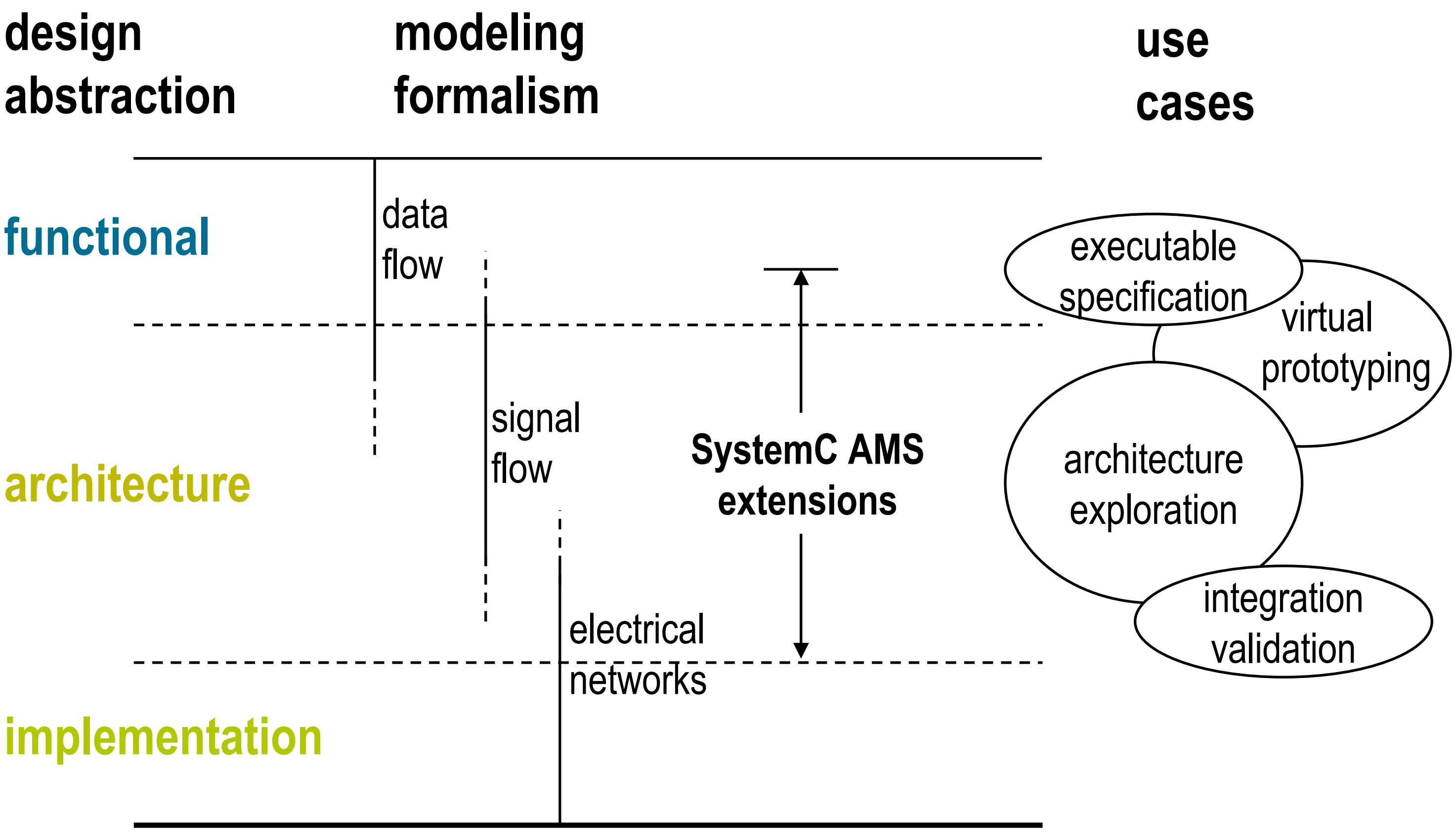
**Semantics** defined in AMS LRM Draft 1




**User features:** Classes and interfaces defined in AMS LRM Draft 1

**Enabling technology:** Classes and interfaces not defined in AMS LRM Draft 1

# Modeling formalisms and use cases



# Model abstraction and formalisms

*Use cases*

- Executable specification
- Virtual prototyping
- Architecture exploration
- Integration validation

*Model abstractions*

| Discrete-time<br>static non-linear | Continuous-time<br>dynamic linear | |
|---|---|---|
| Non-conservative behavior | | Conservative behavior |

*Modeling formalism*

| Timed Data Flow (TDF) | Linear Signal Flow (LSF) | Electrical Linear Networks (ELN) |
|---|---|---|

# SystemC AMS DRAFT 1

Modeling formalisms and language constructs

# SystemC AMS extensions - concept

- AMS modeling formalisms based on known *models of computation* (MoC)
  - Data flow - abstract modeling of non-conservative linear/non-linear
  - Signal flow - linear non-conservative modeling
  - Electrical networks – linear conservative modelling

- AMS models of computation are not based on communication / synchronization of processes
  - instead, AMS descriptions represent an *equation system*

- An AMS primitive module represents a set of equation, which has to be contributed to the overall equation system
- An AMS interface / channel represents a node in a conservative system or a variable in a non-conservative system

# SystemC AMS extensions – elements 1/2

- **Timed Data Flow** - efficient simulation of discrete-time behavior
  - Data flow simulation accelerated using static scheduling
  - Schedule is activated in discrete time steps, introducing timed semantics
  - Support of static non-linear behavior
- **Linear Signal Flow** - simulation of continuous-time behavior
  - Differential and Algebraic Equations solved numerically at appropriate time steps
  - Primitive modules defined for adders, integrators, differentiators, transfer functions, etc.
- **Electrical Linear Networks** - simulation of network primitives
  - Network topology results in equation system which is solved numerically
  - Primitive modules defined for linear components (e.g. resistors, capacitors) and switches



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# SystemC AMS extensions – elements 2/2

- AMS methodology-specific elements
  - Unified design refinement methodology to support different use cases
  - Time domain simulation and Small-signal frequency-domain AC and noise analysis
- User-defined AMS extensions
  - Additional simulators and solvers can be linked in a C++ manner
  - Using the synchronization layer for the communication with SystemC
- Synchronization with SystemC
  - Fixed time-step synchronization with SystemC
  - Predefined converter ports and converter modules/primitives to synchronize between TDF, LSF and/or ELN and SystemC
- Each model of computation has its own namespace
  - Timed Data Flow: sca_tdf
  - Linear Signal Flow: sca_lsf
  - Electrical Linear Networks: sca_eln

# SystemC AMS Language Definition Issues

- A Module represents a contribution of equations to a certain MoC
  - -> primitives of each MoC must be derived from a MoC specific base class

- The concept shall be extensible to an arbitrary number of MoC
  - -> how to handle the naming confusion / convention
  - -> Solution: Only a few base elements are defined, the assignment to the specific MoC is done by the namespace

# SystemC AMS extensions - module types

- AMS modules are derived from sca_core::sca_module which is derived from sc_core::sc_module
  - note: not all sc_core::sc_module member functions can be used

- **AMS modules are always primitive modules**
  - an AMS module can not contain other modules and/or channels
- Hierarchical descriptions still use sc_coree::sc_module (or SC_MODULE macro)

- Depending on the MoC, AMS modules are pre-defined or user- defined
- Language constructs
  - sca_*MoC*::sca_module (or SCA_*MoC*_MODULE macro)
  - e.g. sca_tdf::sca_module (or SCA_TDF_MODULE macro)

# SystemC AMS extensions - channel types

- AMS channels are derived from sca_core::sca_interface which is derived from sc_core:sc_interface
- AMS channels for Time Data Flow and Linear Signal Flow
  - based on directed connection
  - used for non-conservative AMS model of computation
  - Language constructs
    - sca_*MoC*::sca_signal
    - e.g. sca_lsf::sca_signal, sca_tdf::sca_signal<T>
- AMS channels for Electrical Linear Networks
  - conservative, non-directed connection
  - characterized by an across (voltage) and through (current) value
  - Language constructs
    - sca_*MoC*::sca_node / sca_*MoC*::sca_node_ref
    - e.g. sca_eln::sca_node, sca_eln::sca_node_ref

# SystemC AMS base Language Element Composition

- sca_module – base class for SystemC AMS primitive
- sca_in / sca_out – non-conservative (directed in/outport)
- sca_terminal – conservative terminal
- sca_signal – non-conservative (directed) signal
- sca_node / sca_node_ref – conservative node

- The MoC is assigned by the namespace e.g.:
  - sca_tdf::sca:module - base class for timed dataflow primitives modules
  - sca_lsf::sca_in - a linear signalflow inport
  - sca_tdf:sca_in<int> - a TDF inport
  - sca_eln::sca_terminal - an electrical linear network terminal
  - sca_eln::sca_node - an electrical linear network node





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# SystemC AMS Language Element Composition - Converter

- Converter elements are composed by the namespaces of booth domains:
  - **sca_tdf::sc_core::sca_in**<int>  - is a port of a TDF primitive module, which can be connected to an sc_core::sc_signal<int> or to a sc_core::sc_in<int>
    - Abbreviation: **sca_tdf::sc_in**
  - **sca_eln::sca_tdf::sca_voltage** – is a voltage source which is controlled by a TDF input
    - Abbreviation: **sca_eln::sca_tdf_voltage**
  - **sca_lsf::sc_core::sca_source** – is a linear signal flow source controlled by a SystemC signal ( sc_core::sc_signal<double>)
    - Abbreviation: **sca_lsf::sca_sc_source**

# Timed Data Flow (TDF) Modeling Constructs (selection)

- Module declaration macros

```
SCA_TDF_MODULE(<name>)
struct <name> : public sca_tdf::sca_module
```

- Port declarations dataflow ports

```
sca_tdf::sca_in< <type> >,
sca_tdf_sca_out< <type> >
```

- Port declaration converter ports (for TDF primitives only)

```
sca_tdf::sc_in< <type> >,
sca_tdf::sc_out< <type> >
```

- Virtual primitive methods called by the simulation kernel – overloaded by the user tdf primitive
- 

```
void set_attributes()
void initialize()
void processing()
void ac_processing()
```

- Methods for setting module activation timestep

```
void set_timestep(const sca_time&);
```

- Method for getting current module activation time

```
sca_time get_time()
```

- Constructor macro / constructor

```
SCA_CTOR(<name>)
<name>(sc_module_name nm)
```

- Channel/signal for connecting sca_tdf::sca_in / sca_tdf::sca_out ports

```
sca_tdf::sca_signal< <type> >
```





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# TDF Port Methods (selection)

- Sets/gets number of sample delay

```
void set_delay(unsigned long nsamples)
unsigned long get_delay()
```

- Sets/gets number of samples to read/write to the port per activation

```
void set_rate(unsigned long rate)
unsigned long get_rate()
```

- Sets/gets time distance of samples

```
void set_timestep(const sca_time&)
sca_time get_time_step()
```

- Gets absolute sample time

```
sca_time get_time(unsigned long sample)
```

- Writes initial value to delay buffer

```
void initialize(const T& value,
                unsigned long sample_id=0)
```

- Reads value from inport

```
const T& read(unsigned long sample_id=0)
```

- Writes value to outport

```
void write( const T& value,
            unsigned long sample_id)
```





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# Example: TDF language constructs

```
SCA_TDF_MODULE(mytdfmodel)            // create your own TDF primitive module
{
  sca_tdf::sca_in<double>  in1, in2;  // TDF input ports
  sca_tdf::sca_out<double> out;       // TDF output port

  void set_attributes()
  {
    // placeholder for simulation attributes
    // e.g. rate: in1.set_rate(2); or delay: in1.set_delay(1);
  }

  void initialize()
  {
    // put your initial values here e.g. in1.initialize(0.0);
  }

  void processing()
  {
    // put your signal processing or algorithm here
  }

  SCA_CTOR(mytdfmodel) {}
};
```

# Linear Dynamic Behavior for TDF Models 1/2

- TDF Models can embed linear equation systems provided in the following three forms:

$$H(s)=\frac{b_n \cdot s^n + b_{n-1} \cdot s^{n-1} + \ldots + b_0}{a_m \cdot s^m + a_{m-1} \cdot s^{m-1} + \ldots + a_0}$$

- Linear transfer function in numerator / denumerator representation

$$H(s)=k \cdot \frac{(s-z_0)\cdot(s-z_1)\cdot \ldots \cdot(s-z_n)}{(s-p_0)\cdot(s-p_1)\cdot \ldots \cdot(s-p_n)}$$

- Linear transfer function in pole-zero representation

$$\begin{aligned} \dot{x} &= Ax + Bu \\ y &= Cx + Du \end{aligned}$$

- State Space equations

# Linear Dynamic Behavior for TDF Models 2/2

- The equation systems will be represented and calculated by objects:
  - **sca_tdf::sca_ltf_nd** - Numerator / denumerator representation
  - **sca_tdf::sca_ltf_zp** - Pole-zero representation
  - **sca_tdf::sca_ss** - State space equations

- The result is a continuous time signal represented by a “artificial” object (sca_tdf::sca_ltf_proxy or sca_tdf::sca_ss_proxy)
  - This object performs the time discretization (sampling) in dependency of the context – this makes the usage more comfortable and increases the accuracy
  - This mechanism permits additionally a very fast calculation for multi-rate systems





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# Linear Signalflow (LSF) Modeling

- Library of predefined elements
- Permits the description of arbitrary linear equation systems
- Several converter modules to/from TDF and SystemC (sc_core::sc_signal) available
- Models for switching behavior like mux / demux available

- LSF models are always hierarchical models

- Ports:
  - sca_lsf::sca_in - inport
  - sc_lsf::sca_out - outport
- Channel / Signal:
  - sca_lsf::sca_signal

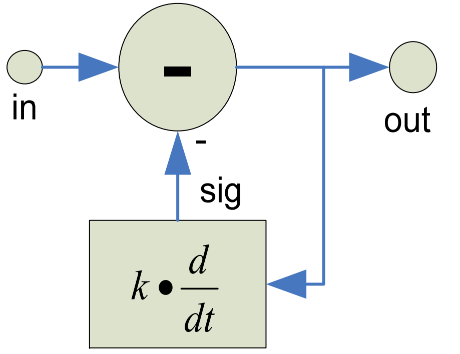
# LSF predefined modules

- sca_lsf::sca_add
- sca_lsf::sca_sub
- sca_lsf::sca_gain
- sca_lsf::sca_dot
- sca_lsf::sca_integ
- sca_lsf::sca_delay
- sca_lsf::sca_source
- sca_lsf::sca_ltf_nd
- sca_lsf::sca_ltf_zp
- sca_lsf::sca_ss

- sca_lsf::sca_tdf::sca_source (sca_lsf::sca_tdf_source)
- sca_lsf::sca_tdf::sca_gain (sca_lsf::sca_tdf_gain)
- sca_lsf::sca_tdf::sca_mux (sca_lsf::sca_tdf_mux)
- sca_lsf::sca_tdf::sca_demux (sca_lsf::sca_tdf_demux)
- sca_lsf::sca_tdf::sca_sink (sca_lsf::sca_tdf_sink)
- sca_lsf::sc_core::sca_source (sca_lsf::sca_sc_source)
- sca_lsf::sc_core::sca_gain (sca_lsf::sca_sc_gain)
- sca_lsf::sc_core::sca_mux (sca_lsf::sca_sc_mux)
- sca_lsf::sc_core::sca_demux (sca_lsf::sca_sc_demux)
- sca_lsf::sc_core::sca_sink (sca_lsf::sca_sc_sink)

# Example: LSF language constructs

```
SC_MODULE(mylsfmodel)          // create a model using LSF primitive modules
{
  sca_lsf::sca_in  in;         // LSF input port
  sca_lsf::sca_out out;        // LSF output port

  sca_lsf::sca_signal sig;     // LSF signal

  lp_filter_lsf(sc_module_name, double fc=1.0e3) // Constructor with
  {                                              // parameters

    sub1 = new sca_lsf::sca_sub("sub1");         // instantiate predefined
    sub1->x1(in);                                // primitives here
    sub1->x2(sig);
    sub1->y(out);

    dot1 = new sca_lsf::sca_dot("dot1", 1.0/(2.0*M_PI*fc) );
    dot1->x(out);
    dot1->y(sig);
  }

};
```





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# Electrical Linear Network (ELN) Modeling

- Library of predefined elements
- Permits the description of arbitrary linear electrical network
- Several converter modules to/from TDF and SystemC (sc_core::sc_signal) available
- Models for switching behavior like switches

- ELN models are always hierarchical models

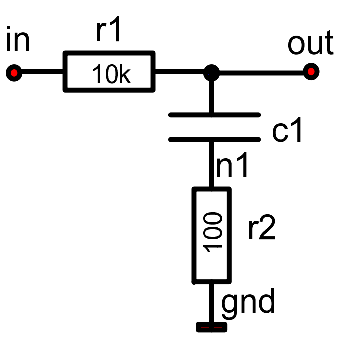
- Ports:
  - sca_eln::sca_terminal - conservative terminal
- Channel / Node:
  - sca_eln::sca_node – consevative node
  - sca_eln::sca_node_ref – reference node, node voltage is always zero

# ELN predefined elements

- sca_eln::sca_r
- sca_eln::sca_l
- sca_eln::sca_c
- sca_eln::sca_vcvs
- sca_eln::sca_vccs
- sca_eln::sca_ccvs
- sca_eln::sca_cccs
- sca_eln::sca_nullor
- sca_eln::sca_gyrator
- sca_eln::sca_ideal_transformer
- sca_eln::sca_transmission_line
- sca_eln::sca_vsource
- sca_eln::isource
- sca_eln::sca_tdf::sca_vsink
  - sca_eln::sca_tdf_vsink
- sca_eln::sca_tdf::sca_vsource
  - sca_eln::sca_tdf_vsource
- sca_eln::sca_tdf::sca_isource
  - sca_eln::sca_tdf_isource
- sca_eln::sc_core::sca_vsource
  - sca_eln::sc_vsource
- sca_eln::sc_core::sca_isource …
- sca_eln::sca_tdf::sca_r …
- sca_eln::sca_tdf::sca_l …
- sca_eln::sca_tdf::sca_c …
- sca_eln::sc_core::sca_r …
- sca_eln::sc_core::sca_l …
- sca_eln::sc_core::sca_c …
- …

# Example: ELN language constructs

```
SC_MODULE(myelnmodel)              // model using ELN primitive modules
{
  sca_eln::sca_terminal in, out; // ELN terminal (input and output)

  sca_eln::sca_node     n1;      // ELN node
  sca_eln::sca_node_ref gnd;     // ELN reference node

  sca_eln::sca_r *r1, *r2;
  sca_eln::sca_c *c1;

  SC_CTOR(myelnmodel)                // standard constructor
  {
    r1 = new sca_eln::sca_r("r1");  // instantiate predefined
    r1->p(in);                      // primitive here (resistor)
    r1->n(out);
    r1->value = 10e3;                      //named parameter association

    c1 = new sca_eln::sca_c("c1", 100e-6); //positional parameter association
    c1->p(out);
    c1->n(n1);

    r2 = new sca_eln::sca_r("r2",100.0);
    r2->p(n1);
    r2->n(gnd);
  }

};
```





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# Small Signal Frequency Domain Analysis (AC-Analysis)

- Support of two flavors:
  - “classical” AC domain setup and calculates linear complex equation system
  - AC noise domain – setup linear complex equation system and solves it for each noise source contribution (other source contributions will be neglected) – adds the results arithmetically
- ELN and LSF description are specified in the frequency domain
- TDF description must specify the linear complex transfer function of the module using the method ac_processing (otherwise they do not contribute – the out values will be assumed as zero)
- This transfer function can depend on the current time domain state (e.g. the setting of a control signal)
- Two simulation start commands:
  - sca_ac_start(double startf,double endf,unsigned long npoints, sca_ac_scale)
  - sca_ac_noise_start(…)





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# Tracing of analog Signals

- SystemC AMS has a own trace mechanism:
  - Analog / Digital timescales are not always synchronized
  - the vcd file format is in general inefficient for analog
- Traceable are:
  - all sca_signals, sca_nodes (voltage) and sc_core::sc_signals
  - Most ELN modules – the current through the module
  - for TDF a traceable variable to trace internal model states
- Two formats supported:
  - Tabular trace file format - **sca_util::sca_create_tabular_trace_file**
  - VCD trace file format - **sca_util::sca_create_vcd_trace_file**
- Features to reduce amount of trace data:
  - enable / disable tracing for certain time periods, redirect to different files
  - different trace modes like: sampling / decimation



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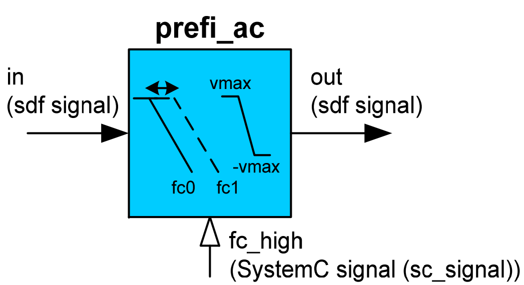
# Code example

# TDF Module – Example with LTF

```
SCA_TDF_MODULE(prefi_ac)
{
  sca_tdf::sca_in<double>    in;
  sca_tdf::sca_out<double> out;

  // control / DE signal from SystemC
  // (connected to sc_signal<bool>)
  sca_tdf::sc_in<bool>   fc_high;

   double fc0, fc1;
   double v_max;

    // filter equation objects
   sca_tdf::sca_ltf_nd ltf_0, ltf_1;
   sca_util::sca_vector<double>  a0, a1, b;
   sca_util::sca_vector<double> s;

   void initialize()
   {
     const double r2pi = M_1_PI * 0.5;
     b(0)   = 1.0;     a1(0) = a0(0) = 1.0;
     a0(1) = r2pi/fc0; a1(1) = r2pi/fc1;
   }
```

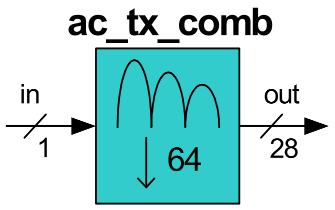
```
void processing()
{
  double tmp; // high or low cut-off freq.
  if(fc_high)  tmp = ltf_1(b, a1, s, in);
  else         tmp = ltf_0(b, a0, s, in);

  //output value limitation
  if      (tmp >  v_max)  tmp =  v_max;
  else if (tmp < -v_max)  tmp = -v_max;

    out.write(tmp);
 }

  SCA_CTOR(prefi_ac)
  {    // default parameter values
   fc0 = 1.0e3;  fc1=1.0e5;  v_max  = 1.0;
  }
};
```

$$H(s) = \frac{1}{1 + \frac{1}{2\pi f_c} s}$$



# Frequency Domain Specification

```
SCA_TDF_MODULE(ac_tx_comb)
{
  sca_tdf::sca_in<bool>          in;
  sca_tdf::sca_out<sc_int<28> > out;

  void set_attributes()
  {
    in.set_rate(64);     // 16 MHz
    out.set_rate(1);    // 256 kHz
  }

  void ac_processing()
  {
    double      k  = 64.0;
    double      n  =   3.0;

    // complex transfer function:
    sca_complex h;
    h = pow( (1.0 - sca_ac_z(-k)) /
             (1.0 - sca_ac_z(-1)),n);

      sca_ac(out) = h * sca_ac(in) ;
  }

  void processing()
  {
      int x, y, i;
      for (i=0; i<64; ++i) {
          x = in.read(i);
      …
      out.write(y);
  }

  SCA_CTOR(ac_tx_comb)
  {
      …
  }
};
```




$$H(z)=\left(\frac{1-z^{-k}}{1-z^{-1}}\right)^{n}$$

$$z=e^{j2\pi f/f_s}$$

# Code example – top-level (RF front-end)

```
SC_MODULE(frontend)
{
  sca_tdf::sca_in<double> rf, loc_osc;
  sca_tdf::sca_out<double> if_out;
  sc_core::sc_in<sc_dt::sc_bv<3> > ctrl_config;

  sca_tdf::sca_signal<double> if_sig;
  sc_core::sc_signal<double> ctrl_gain;

  mixer* mixer1;
  lp_filter_eln* lpf1;
  agc_ctrl* ctrl1;

  SC_CTOR(frontend) {
    mixer1 = new mixer("mixer1");     // TDF module
       mixer1->rf_in(rf);
       mixer1->lo_in(loc_osc);
       mixer1->if_out(if_sig);

    lpf1 = new lp_filter_eln("lpf1"); // ELN module
       lpf1->in(if_sig);
       lpf1->out(if_out);

    ctrl1 = new agc_ctrl("ctrl1");    // SystemC module
       ctrl1->out(ctrl_gain);
       ctrl1->config(ctrl_config);
  }};
```

**SC_MODULE used for hierarchical structure**

**usage of different signals**

**High-level mixer model (TDF module)**

**LPF close to implementation level (ELN module)**

**easy to combine with normal SystemC modules !**





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# SystemC AMS Testbench

```
#include <systemc-ams.h>
           :
int sc_main(int argn,char* argc)
{
  //instantiate signals, modules, …
  //from abritrary domains e.g.:

  sca_tdf::sca_signal<double>  s1;;
  sca_eln::sca_node            n1;
  sca_lsf::sca_signal         slsf1;
  sca_core::sca_signal<bool>  scsig1;
                :
  dut i_dut("i_dut");
    i_dut->inp(s1);
    u_dut->ctrl(scsig1);
           :
  //no difference/restriction to
  //"classical" SystemC
//"classical" SystemC tracing
sc_trace_file*
sctf=sc_create_vcd_trace_file("sctr");
   sc_trace(sctf,scsig1,"scsig1"); …
```

```
sca_trace_file*
satf=sca_create_tabular_trace_file("mytr.dat");
  sca_trace(satf,s1,"s1");
  sca_trace(satf,n1,"n1"); …

 //start time domain simulation for 2ms
 sc_start(2.0,SC_MS);
 satf->disable(); //stop writing
 sc_start(2.0,SC_MS); //continue 2ms
 satf->enable();     //continue writing
 sc_start(2.0,SC_MS); //continue 2ms

 //close time domain file, open ac-file
 satf->reopen("my_tr_ac.dat");
 //calculate ac behavior at current op
 sca_ac_start(1.0,1e6,1000,SCA_LOG);
 //reopen transient file, append
 satf->reopen("mytr.dat",std::ios::app);
 //sample results with 1us time distance
 satf->set_mode(sca_sampling(1.0,SC_US));
 sc_start(100.0,SC_MS); //continue
}
```

# Fraunhofer Add-on Libraries

# SystemC AMS Nonlinear Extension

- Also on system level, there are parts of the circuit which can not be modeled idealized with the required accuracy
- Especially the influence of **front/back ends** like driver stages have often a complicated not negligible dynamic non-linear behavior
- The nonlinear extension enables modeling possibilities like the languages VHDL-AMS, Verilog-AMS or Modellica
- Permits the description (and simulation) of nonlinear dynamic modules using equations and there connection via a conservative network
- Description of reactivity to events from the de-SystemC kernel
- Detection of threshold crossings and scheduling of events at crossing time





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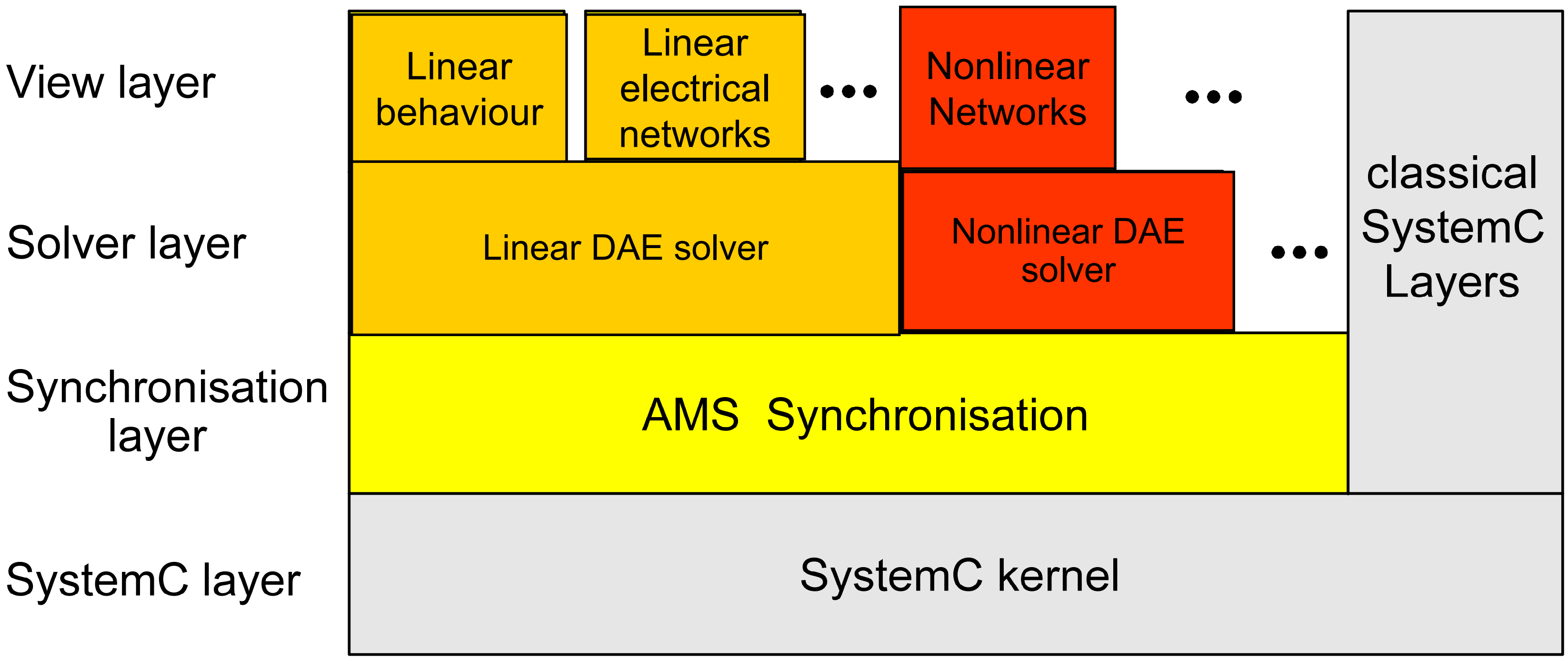
# SystemC-AMS Generic Concept





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# Outlook Nonlinear conservative MoC

```
SCA_NLN_MODULE(sca_nl_rdiode)
{
  sca_nln::sca_terminal<electric> a;
  sca_nln::sca_terminal<electric> b;

  double v_thres;
  double r_on;
  double r_off;
  double cj;

  sca_nln::sca_var  v_diode;

  void equations();

  SCA_CTOR(sca_nl_rdiode)
  {
    v_thres  = 0.7;
    r_on     = 1e-2;
    r_off    = 1e7;
    cj       = 1e-12;
  }

};
```

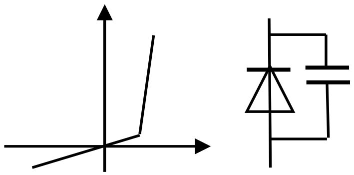
```
void sca_nl_rdiode::equations()
{
  eq(v_diode) <<
             v_diode == ( a.v() - b.v() );

  double i_diode;

  if ( v_diode.above(v_thres) )
  {
    i_diode = ( v_diode - v_thres ) / r_on
                          + v_thres / r_off;
  }
  else
  {
    i_diode = v_diode / r_off;
  }

  i_diode += cj * v_diode.dt();

   a += i_diode;
   b -= i_diode;
}
```



# SystemC-AMS Extension for Statistic Modeling

- Based on VHDL-AMS standard SAE J2748 (Society of Automotive Engineers)
- Independent from tool implementation, platform, compiler version, …
- The SAE standard includes descriptions for different distribution functions, such as:
  - UNIFORM
  - NORMAL
  - BERNOUILLI
  - PWLPDF (piecewise linear probability density function)
  - PWLCDF (piecewise linear cumulative density functions)
  - ...
- Permits the description of user defined distribution functions
- Simulation control e.g. to perform Monte Carlo available





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# Simple application example: correlated resistors

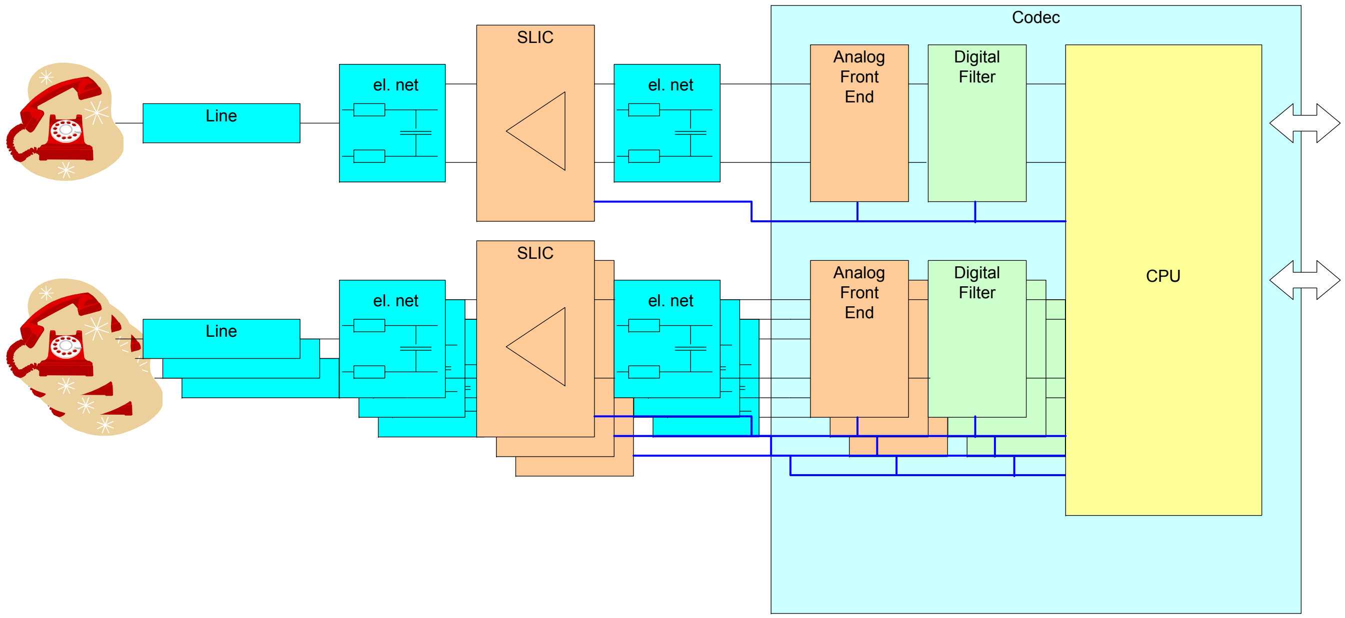
- Statistic information added while parametrizing
  - Example shows correlated resistors
  - Statistic information will be used by simulation control
  - Monte Carlo, Corner Case or more sophisticated algorithm for parameter selection possible

```
…
// definition of a reference resistance value
const double rvalue_global = normal(100.0, 0.2);

sca_r r1;
r1.p(el_node_n1);
r1.n(el_node_n2);
r1.value = uniform(5.0 * rvalue_global, 0.01);

sca_r r2;
r2.p(el_node_n3);
r2.n(el_node_n4);
r2.value = uniform(20.0 * rvalue_global, 0.003);
```

# Application Examples

# POTS System Design

- Complete System functionality modeled
- All relevant analogue effects
- Digital parts “bittrue”, original code of embedded software
- Hundreds of simulation scenarios as regression tests available
- Simulation scenarios partially re-used for silicon verification
- Embedded software debugged before silicon






Source: Gerhard Nössing LANTIQ



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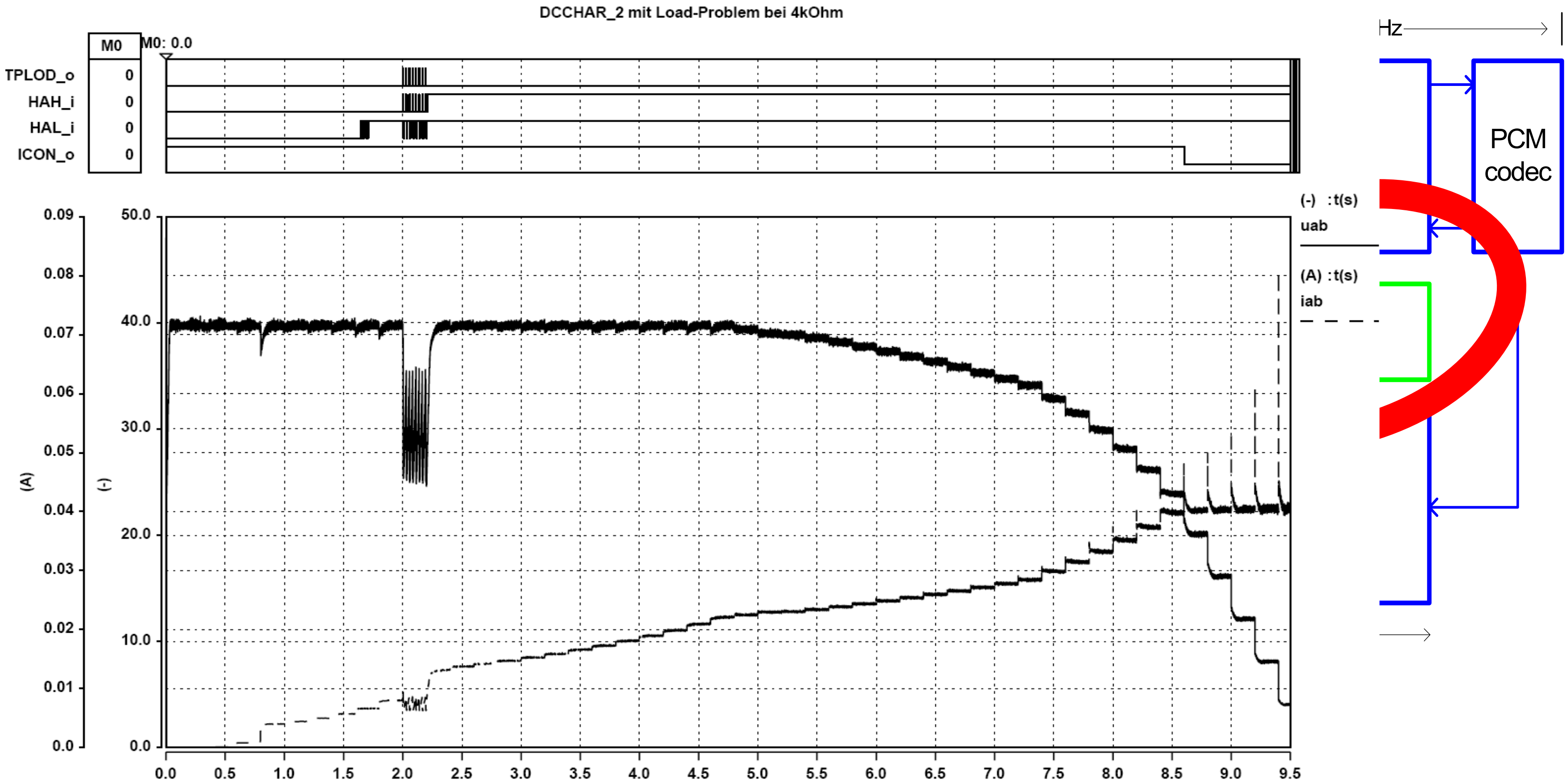
# Hardware / Software Cosimulation



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# Simulation Time for Vinetic 2CPE System

SystemC-AMS Simulation

- 1 sec realtime ➔ 1,5h simulation time

- 2 channel including: SLIC, externals, AFE, DFE, ASDSP and part of Carmel FW

VHDL RTL

- 1 sec realtime ➔ 300h simulation time

- 2 channel including: AFE, DFE, ASDSP, Carmel and Interfaces

Nano Sim (Fast CMOS simulator)

- 1 ms realtime ➔ 15h simulation time

- 2 channel including: AFE top level

Titan Simulation

- 1 ms realtime ➔ 500h simulation time

- 2 channel including: AFE top level

SystemC-AMS Simulation for FW development

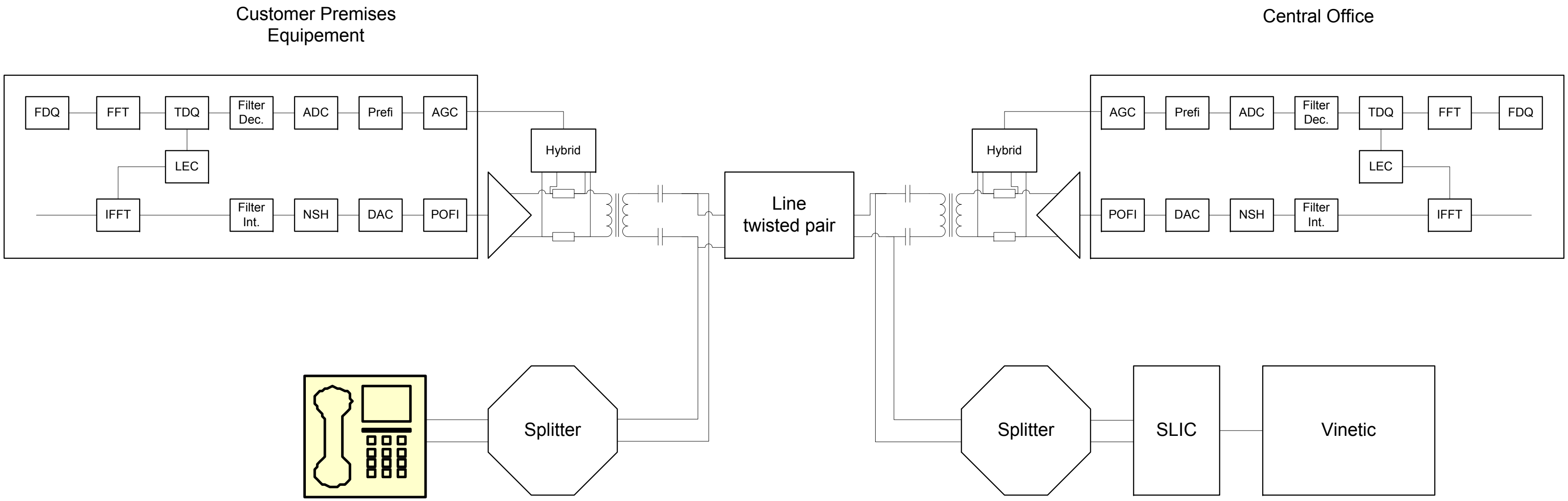
- 1sec realtime ➔ 90 sec simulation time

- only one channel
- reduce sampling rate for analog blocks

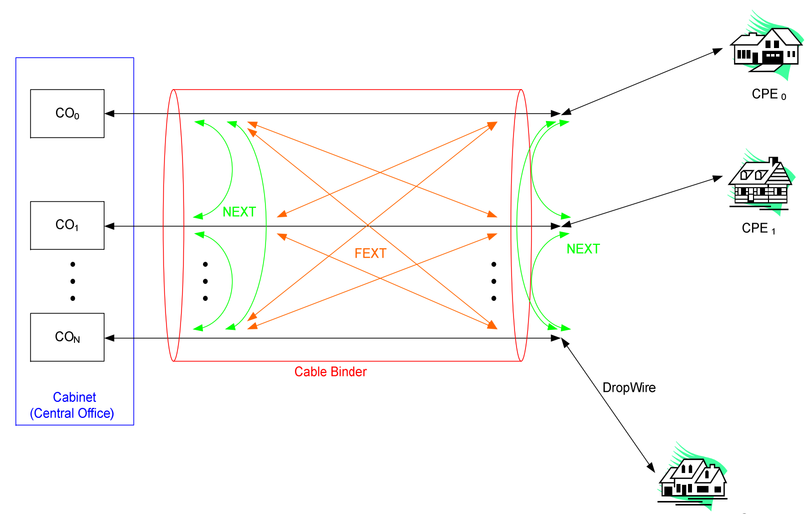


Source: Gerhard Nössing
LANTIQ

# ADSL / VDSL Systems




- Transient settling behavior
- Interaction Voice / Data transmission
- Training algorithm
- BER estimations
- Numerous of use scenarios
- Interaction of different lines
- Multi level simulation environment essential





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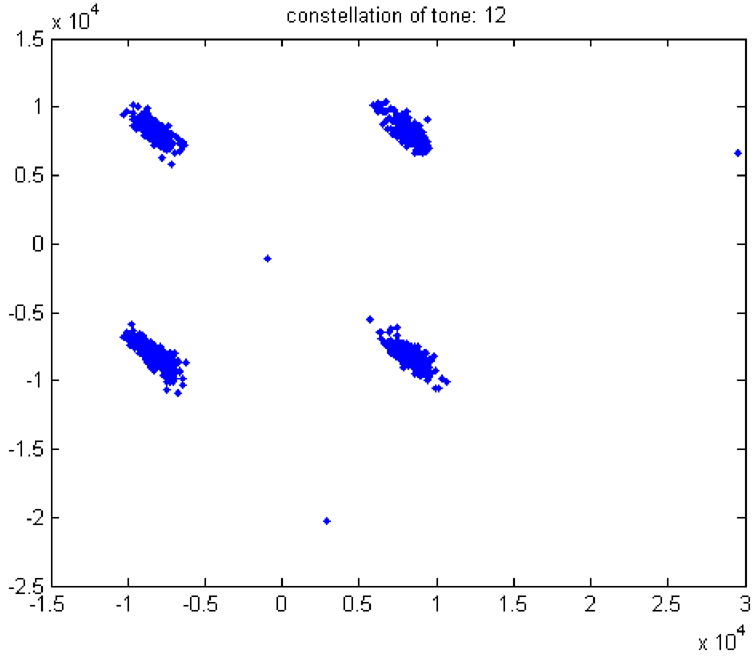
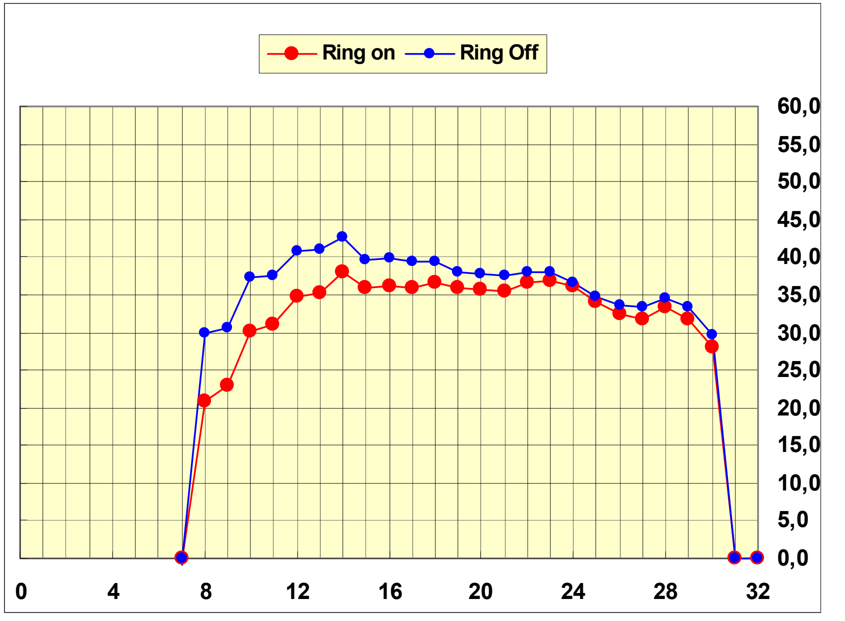
# ADSL Simulation

Backlash Voice to data path








Source: Gerhard Nössing
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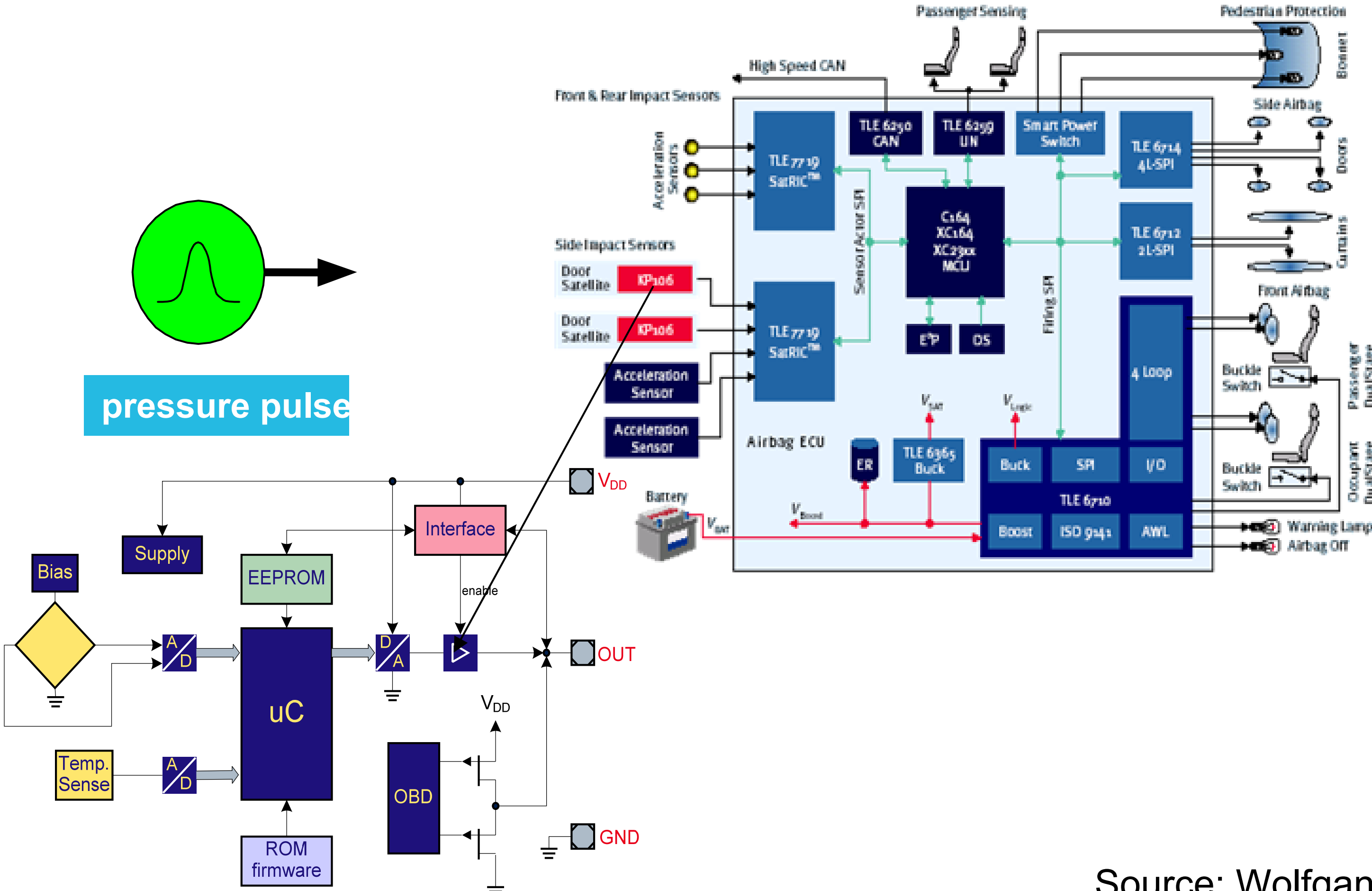
# Automotive Sensor Applications

TIER2

TIER1

OEM




Source: Wolfgang Scherr Infineon AIM





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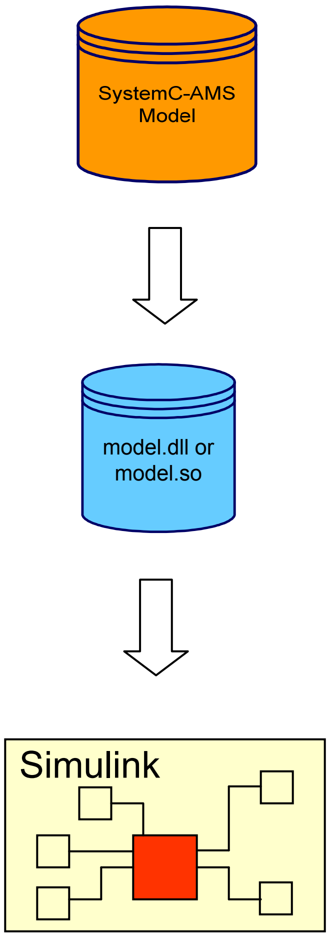
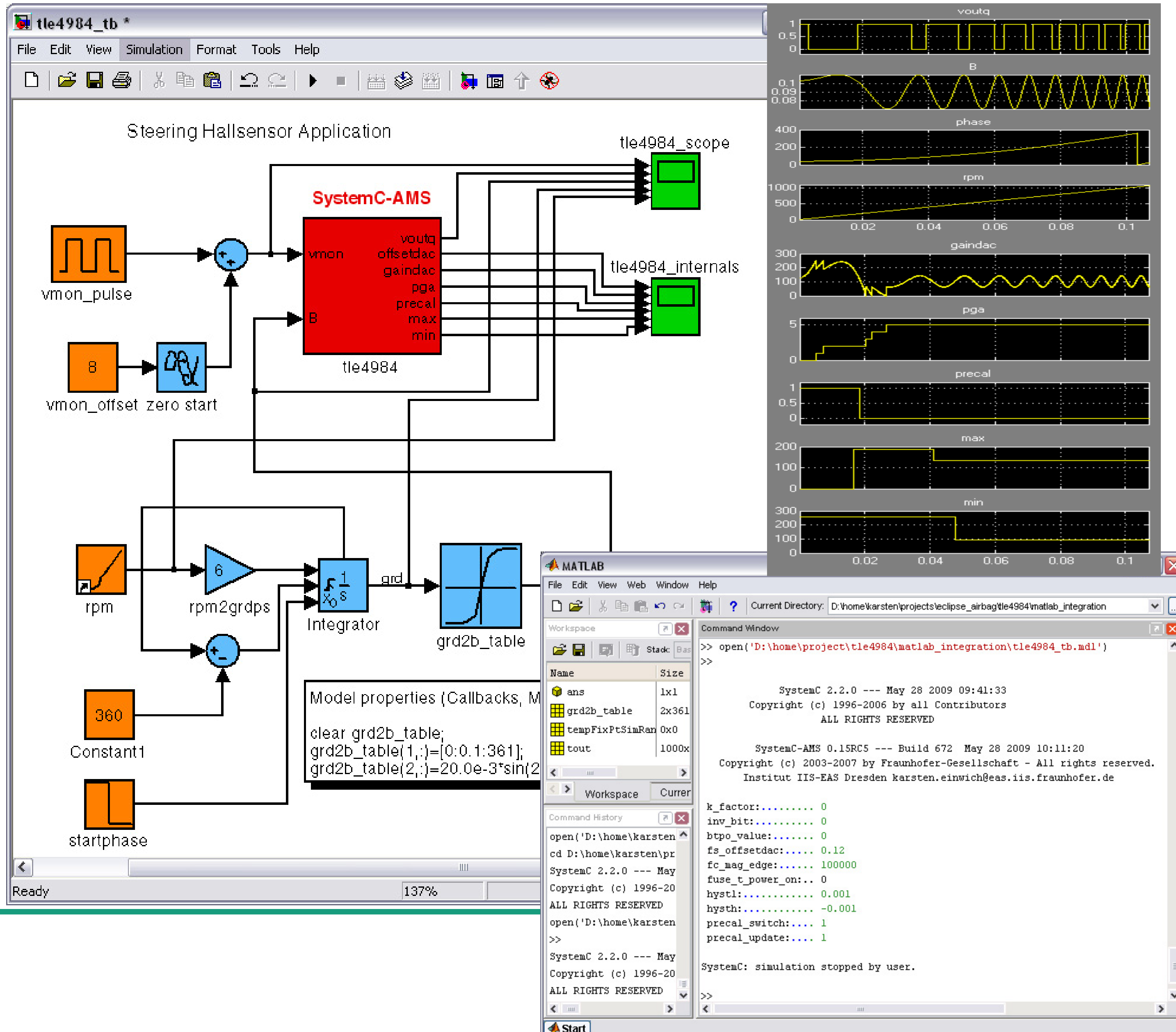
# Automotive Sensor Projects

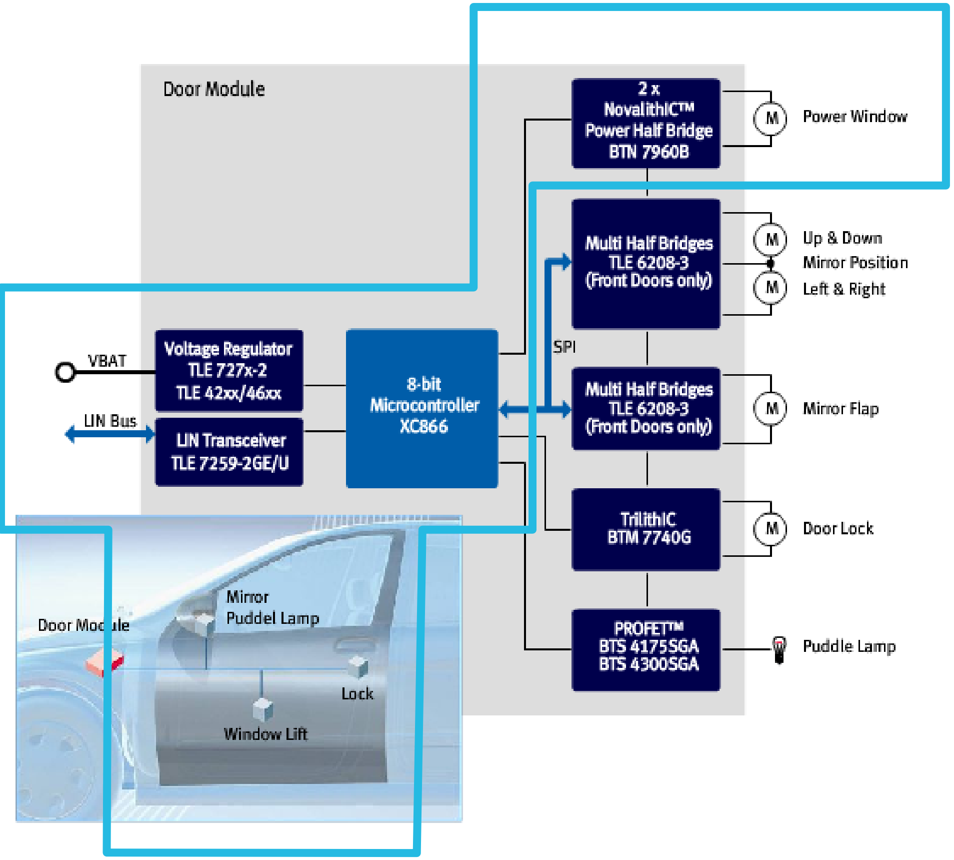
- Systemlevel model including the embedded processor on a cycle accurate level
- Switched capacitor converter
- Diagnose modes, offset calibration, temperature dependencies, noise, manchester interface, synchronization via supply voltage, ...
- Original code of embedded software
- TLM based modeling for processor communication
- IP protected customer model as Matlab/Simulink Module (mex – dll)
- Simulation performance ~ 10min /sec

# SystemC AMS Modelexchange via Simulink Integration



# Window Lifter – Substantial Subset of Door ECU




SystemC(-AMS) simulations (functional and system MC) for substantial parts of ECU on

- ECU architecture
- Chip architecture in system context
- Chip design in system context
- ECU design

This research project (AutoSUN) is supported by the German Government, Federal Ministry of Education and Research under the grant number 01M3178

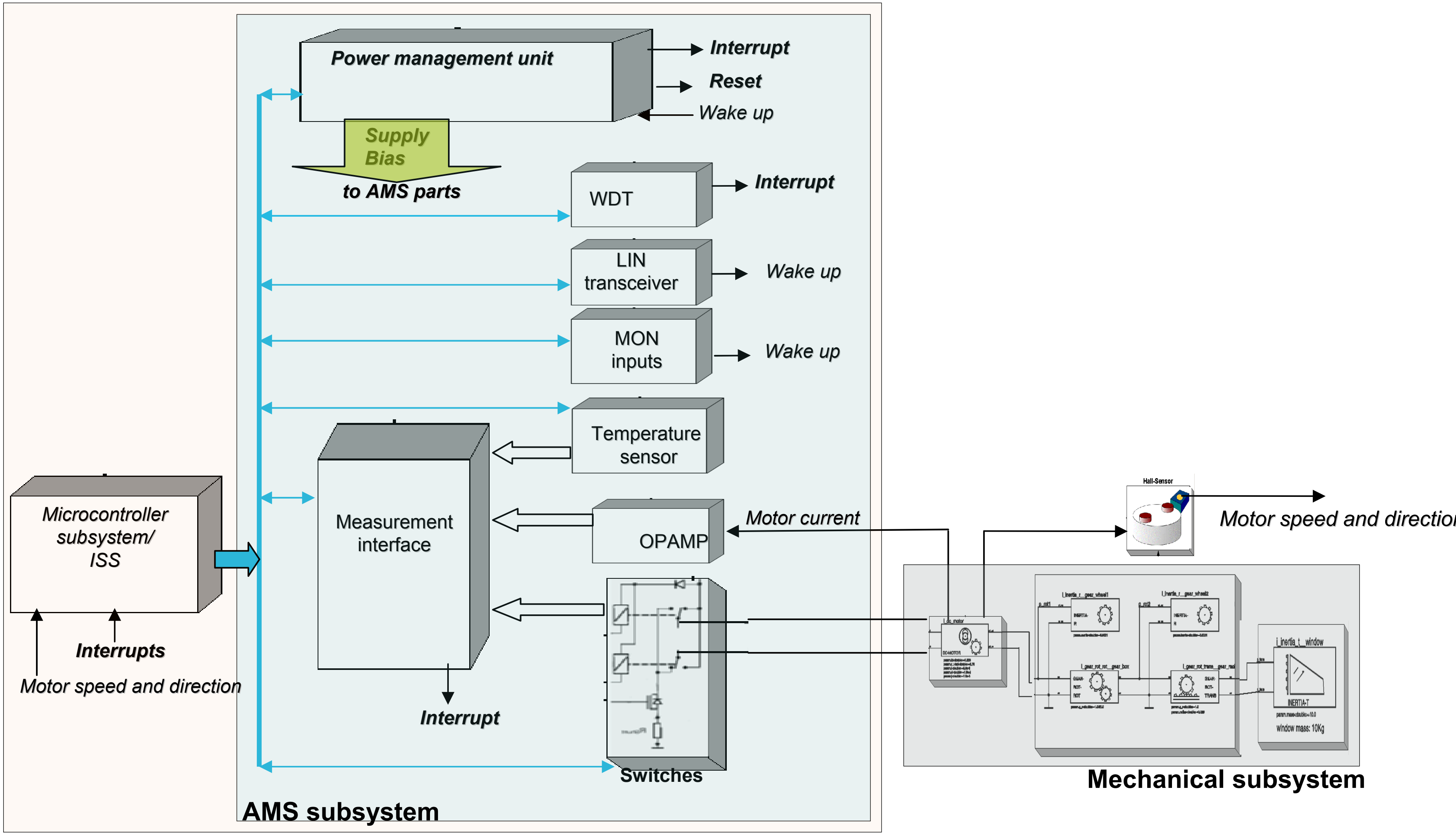
Bundesministerium
für Bildung
und Forschung





Source:
Georg Pelz Infineon Technologies

# Window Lifter Model Overview

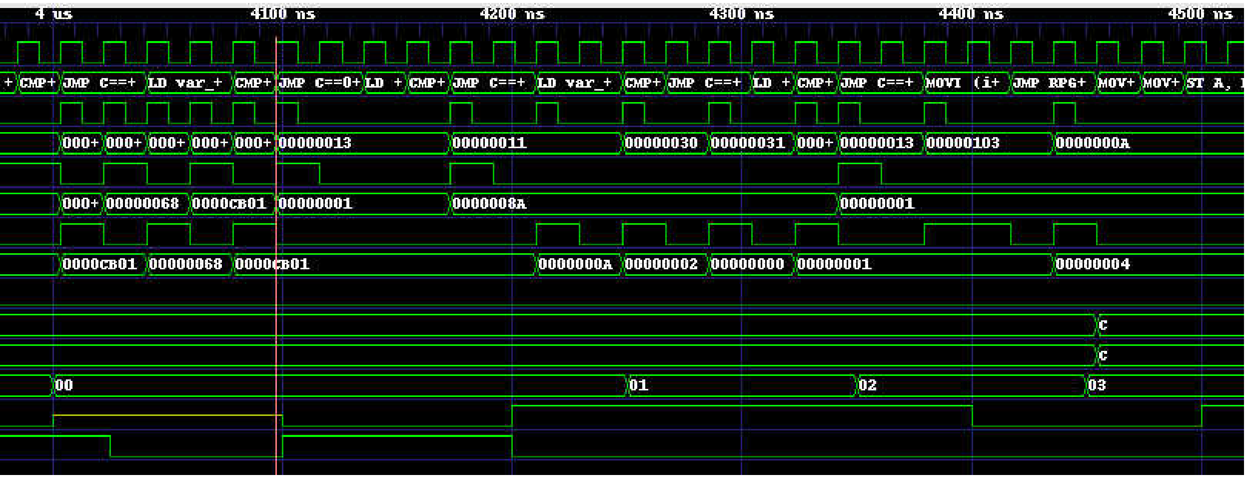




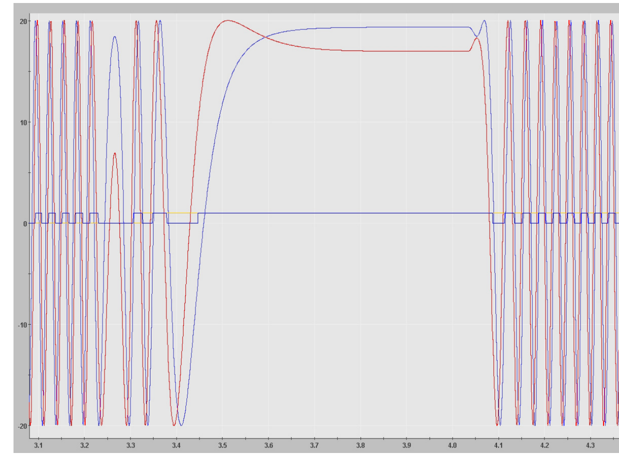



Source:
Georg Pelz, Monica Rafaila
Infineon Technologies

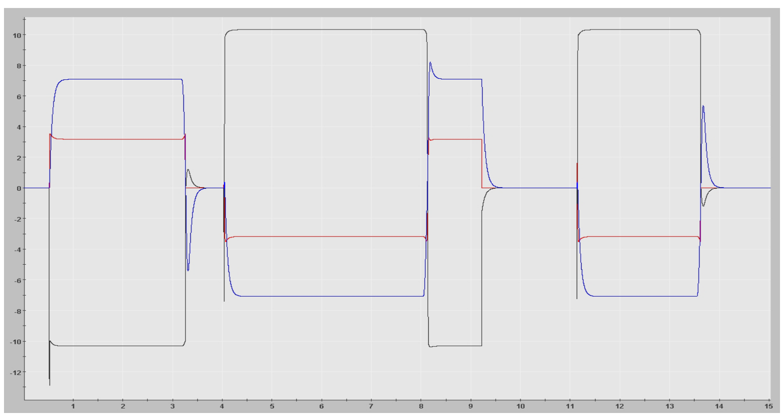
# Window Lifter Simulation Results



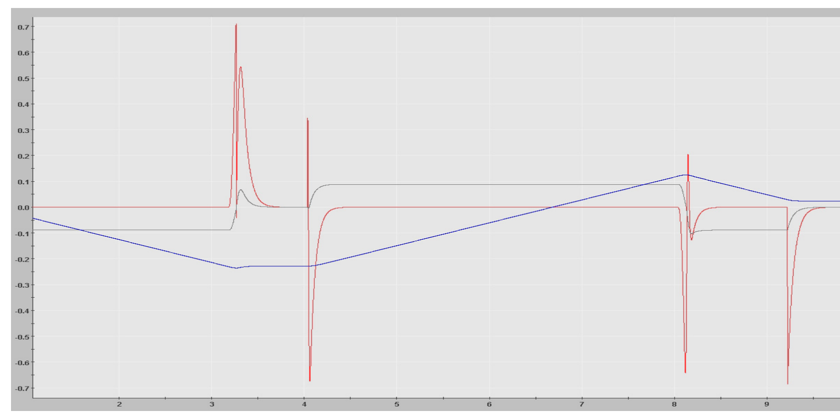

A huge amount of digital HW/SW …



Magnetic flux -> digital sensor out



Electronics: voltages/currents -> torque



Mechanics: position, torque, forces, …

# System Level Parameter Variations

Major parameters of a window lifter:

Environment

- Battery voltage
- Ambient temperature

Power bridge

- Slew-rate / on-resistance / impedance
- Over-current limits
- Over-temperature limits
- Free-wheeling behavior

Electric motor

- Armature L, R, friction, inertia
- Torque constant / backEMF Gear
- Friction, inertia

Mechanical load

- Friction, inertia
- Position of stop

→ > 20 parameters

All parameters have a distribution

Major goal of a development is cost minimization

- Resulting in even bigger spec windows for parameters
- Classical way out blocked: belt and suspenders

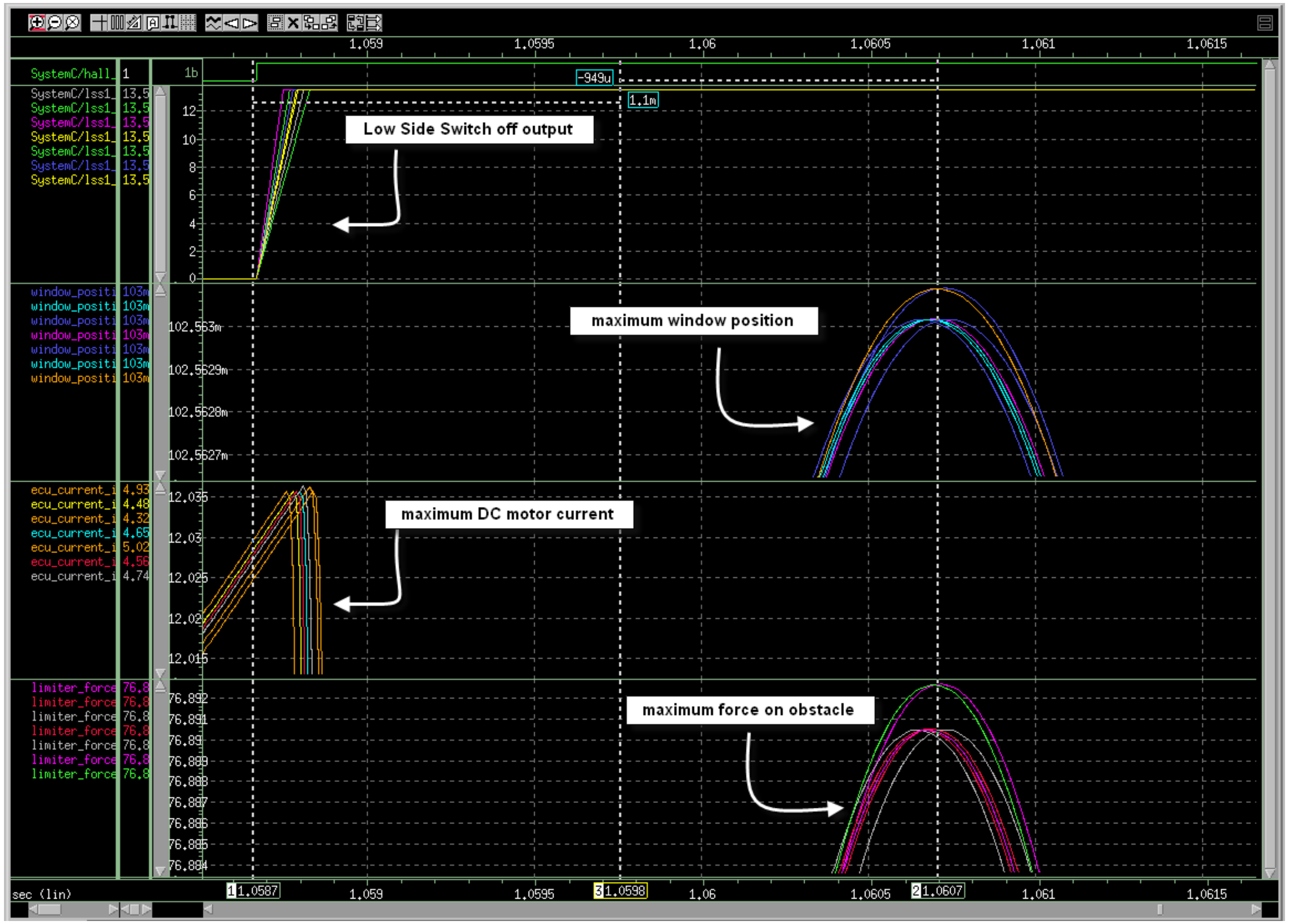
Nonetheless, function has to be proven for any choice of parameters





Source:
Georg Pelz, Monica Rafaila
Infineon Technologies

# Tons of Simulations with MC-Varied Parameters




- Tons of simulations deliver tons of data
- Here's one way to illustrate the results including the parameter and results correlations …





Source:
Georg Pelz, Monica Rafaila
Infineon Technologies

# Simulation Performance – Complete Window Lifter

How to measure simulation performance:

- Evaluate factor F:

$$F = \frac{\text{simulation time}}{\text{simulated time}}$$

**SystemC-AMS**
**Software on algorithm level**,
i.e. directly bound-in

- Factor F ≈ 5 – 100

**SystemC-AMS**
**Cycle-accurate MCU model**

- Factor F ≈ 1.000 – 5.000

**VHDL-AMS / VHDL**

- Factor F ≈ 100.000 – 1.000.000

**FastMOS (Ultrasim)**

- Factor F ≈ 1.000.000.000 – 10.000.000.00 (start-up only)

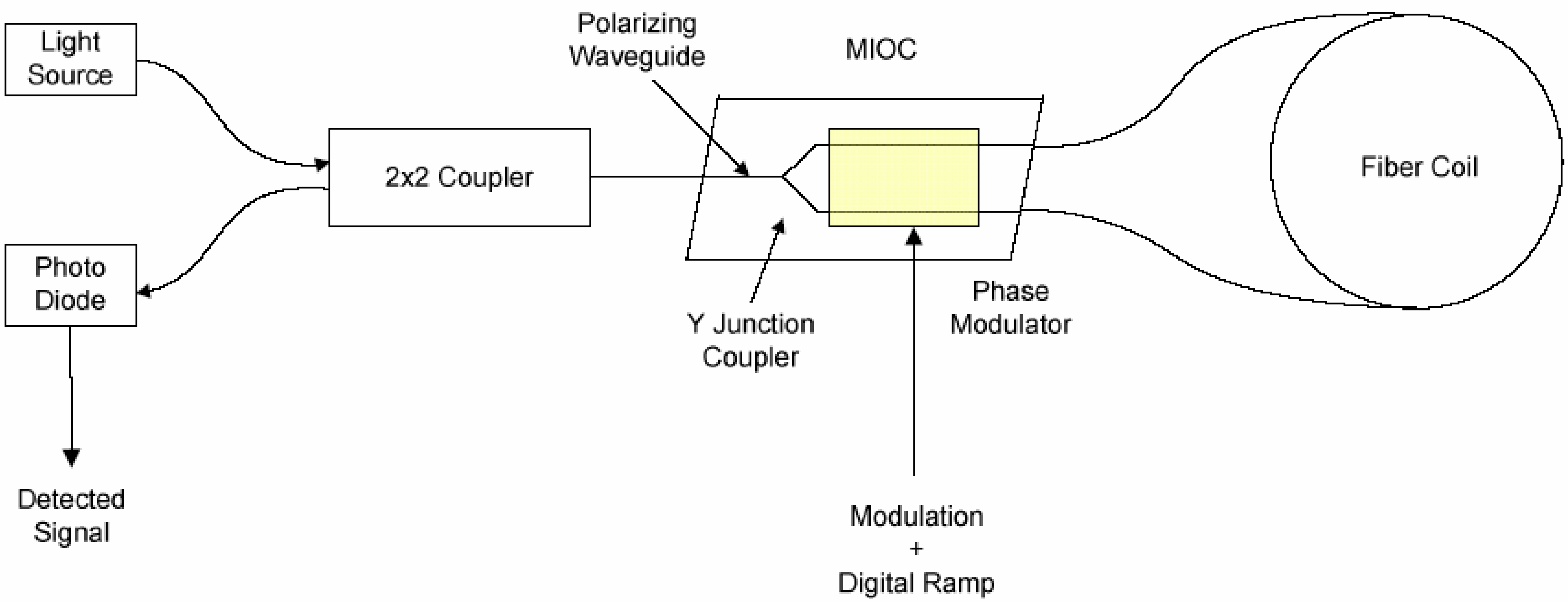
**Spice-alike (Spectre)**

- No way!



Source:
Monica Rafaila, Georg Pelz
Infineon Technologies

# Fiber optical Gyrosensor




This research project (Syena) is supported by the German Government, Federal Ministry of Education and Research under the grant number 01M3178

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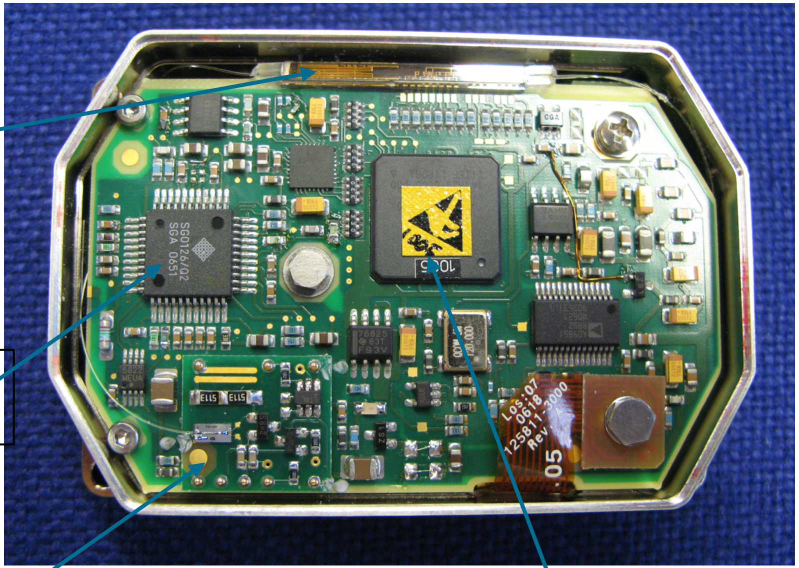
NG LITEF GmbH

Fraunhofer IIS

# Fiber optical Gyrosensor

NORTHROP GRUMMAN

**Sensor Electronic Module (SEM)**



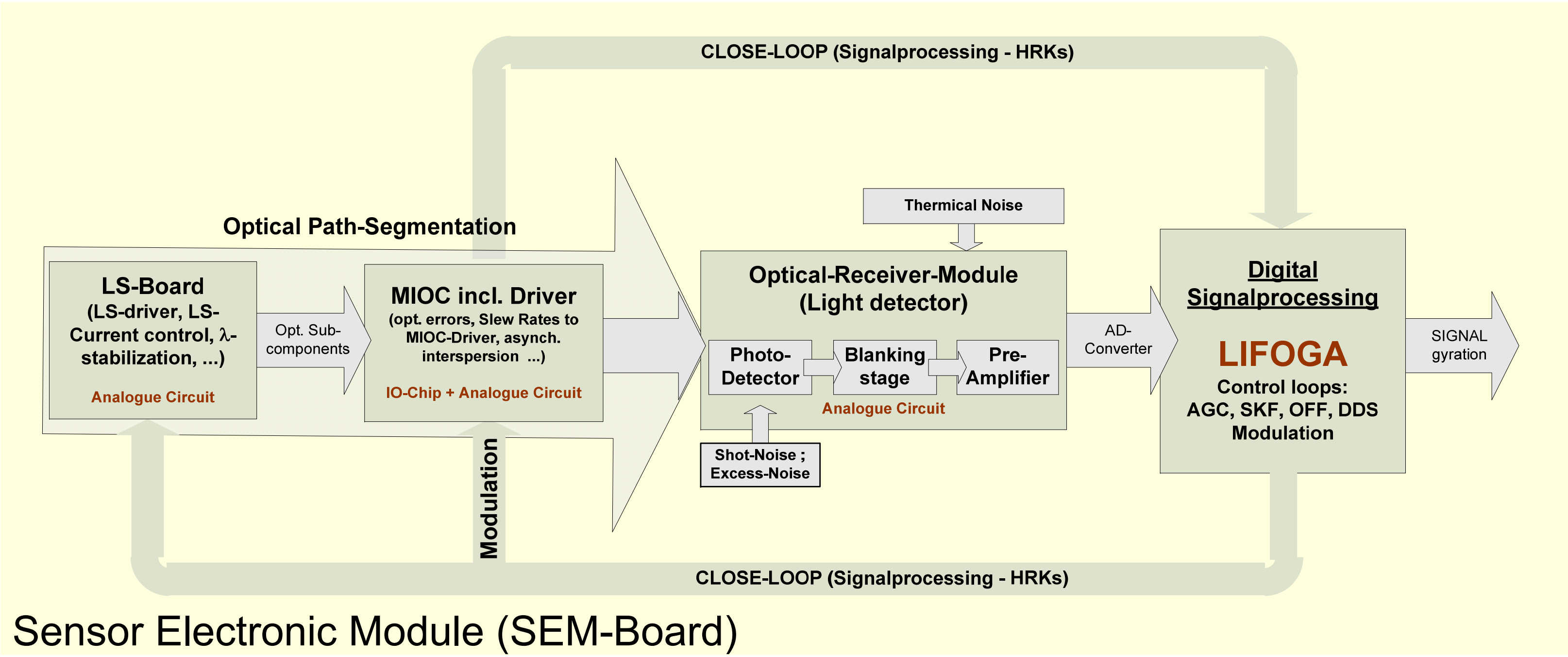

## Northrop Grumman LITEF GmbH




NG LITEF GmbH

SyEnA Fraunhofer IIS

# Fiber optical Gyrosensor




- Interconnection of different physical domains – optic, thermal and electronic
- Interconnection of digital and anlogue hard- and software

Important aspects:

- Dynamic and time resolution
- Device behavior like slew-rates, rise times , overshoots, ...
- Device - environment interaction like temperature to ADC

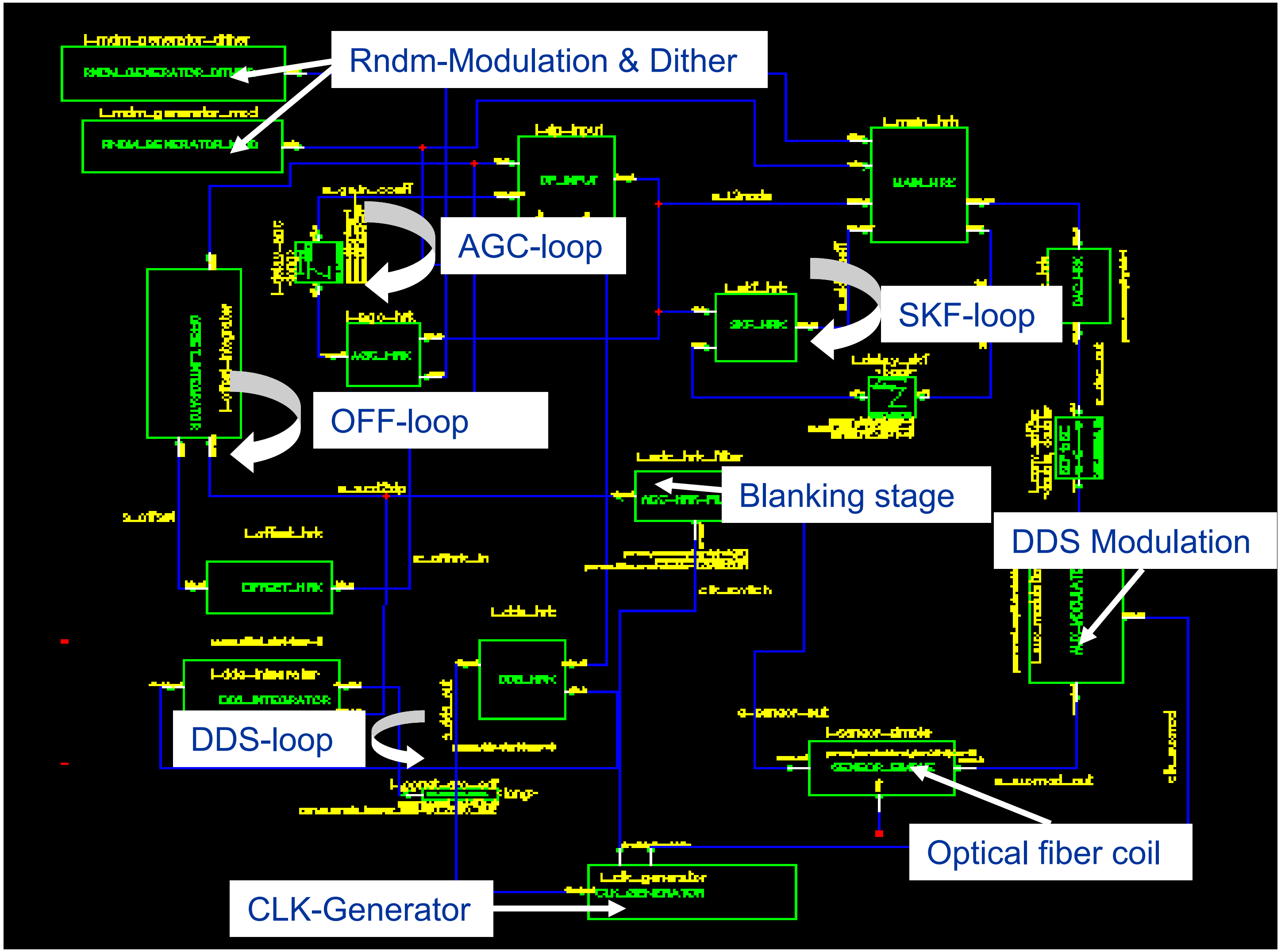
Source:
Andrea Dahlhoff
NG LITEF





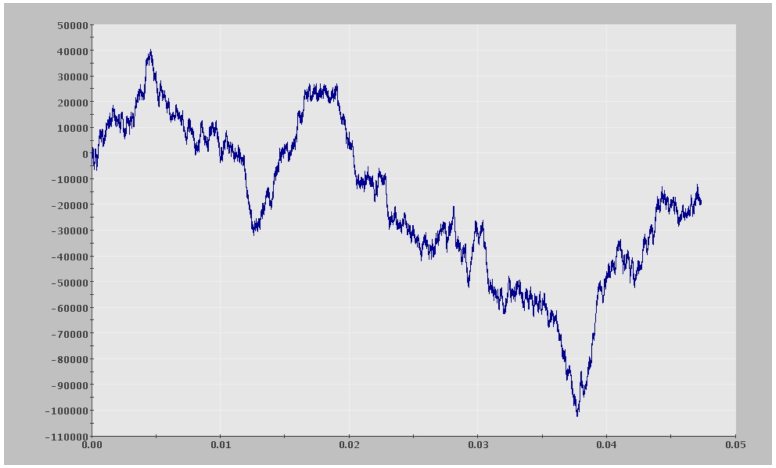
NG LITEF GmbH

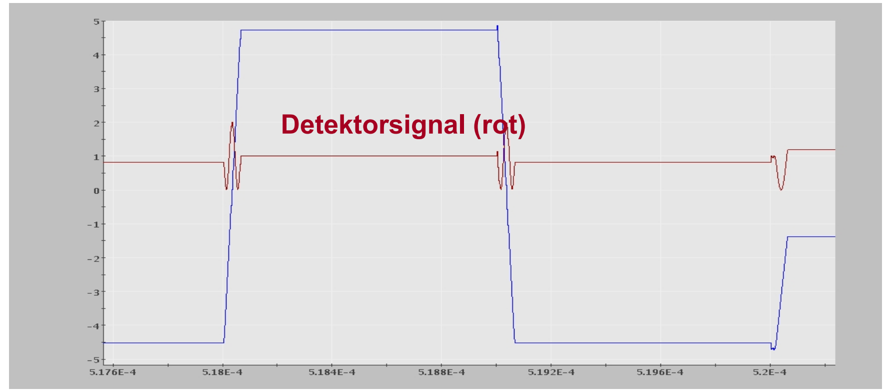
# Toplevel Blockdiagram Systemlevel Model

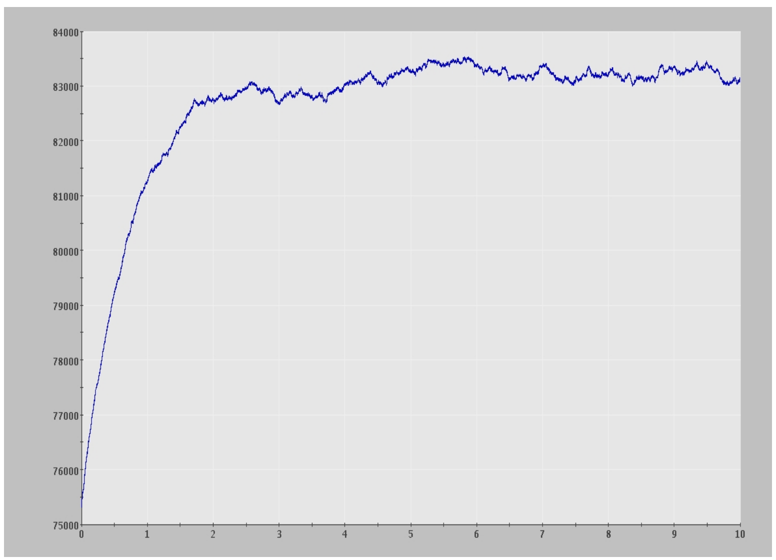


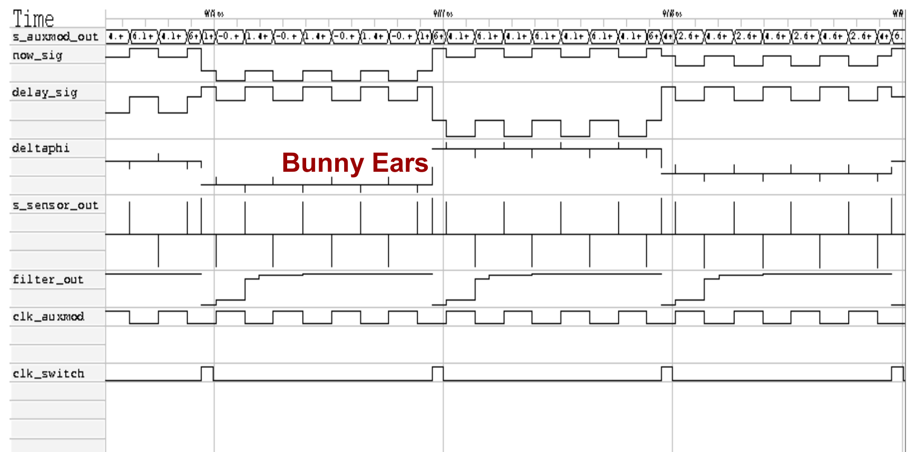

Source:
Andrea Dahlhoff
NG LITEF

# Fiber optical Gyrosensor









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# Conclusion

- SystemC together with the extension SystemC AMS is suitable for creating executable specification, virtual prototypes and architectual level models for EAMS systems
- An experimental prototype can be downloaded under: www.systemc-ams.org (not compatible with the DRAFT 1 standard)
- SystemC AMS DRAFT 1 standard is public available: www.systemc.org
- OSCI SystemC AMS 1.0 standard is expected in December 2009
- Information of the Fraunhofer SystemC AMS activities and documentation: www.systemc-ams.eas.iis.fraunhofer.de