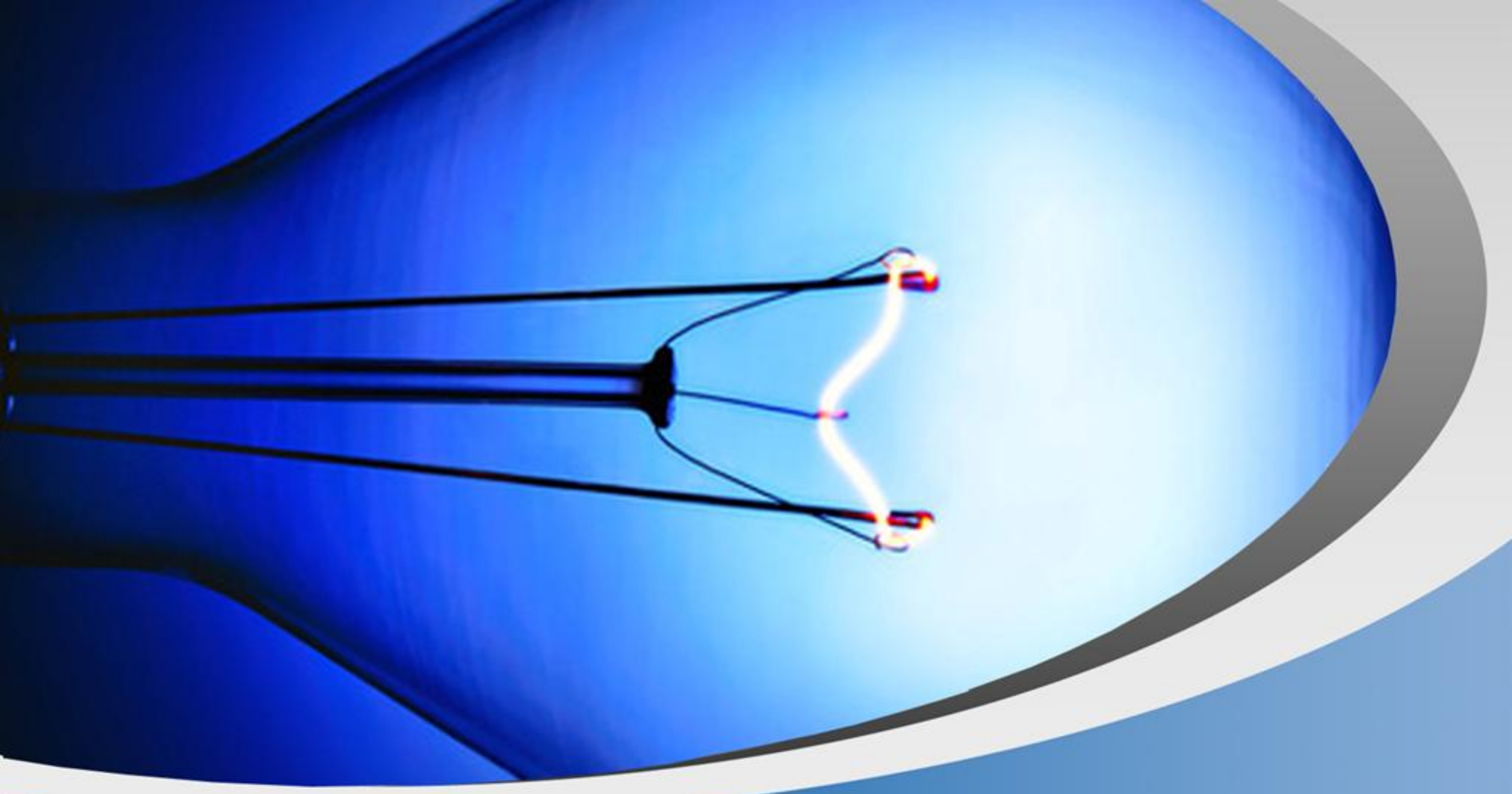

Introduction to SystemC AMS

Martin Barnasconi, AMSWG chair

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Outline

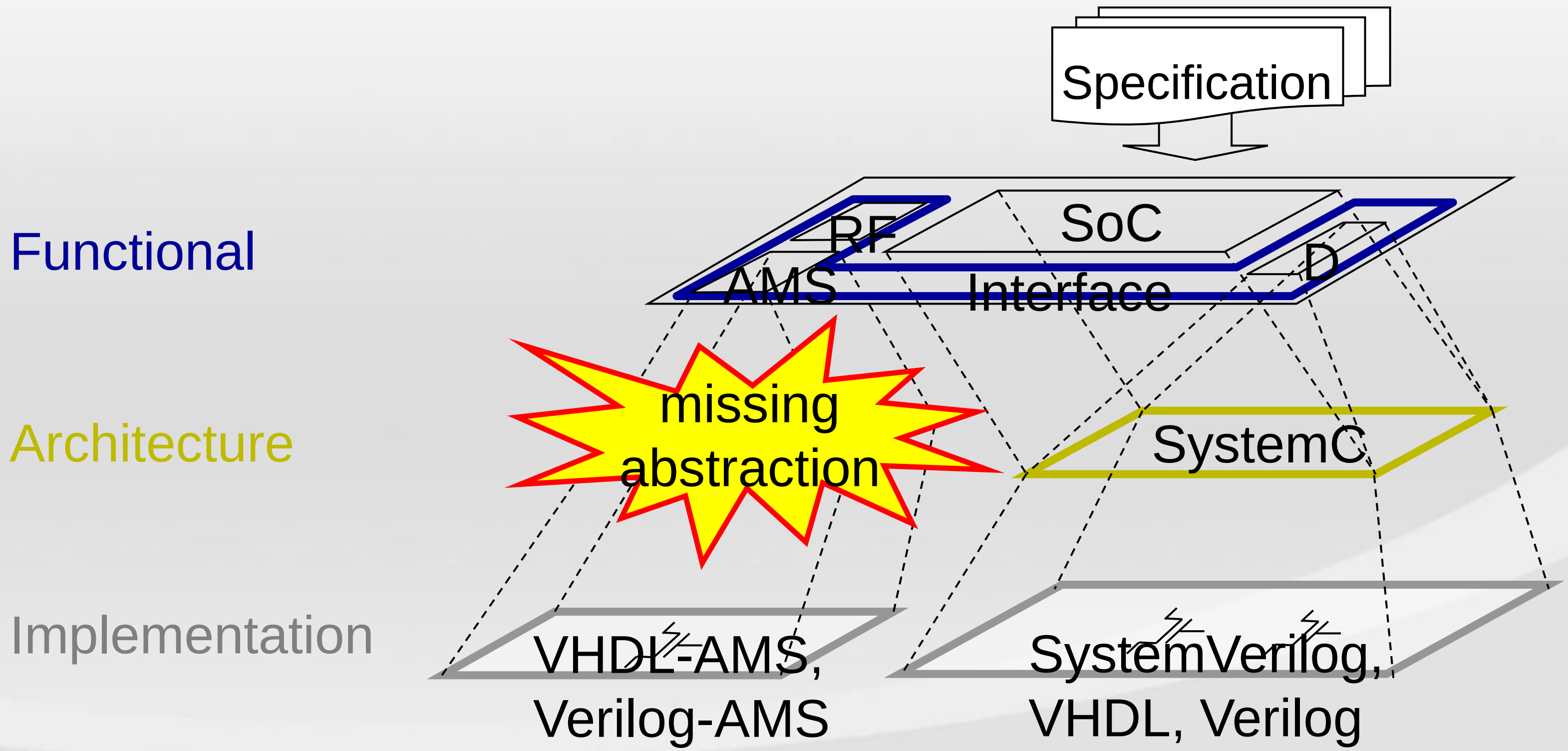
- Introduction to SystemC AMS extensions
- SystemC AMS 1.0 standard – language features
- SystemC AMS 2.0 standard – language extensions
- Summary and outlook

Introduction to SystemC AMS extensions

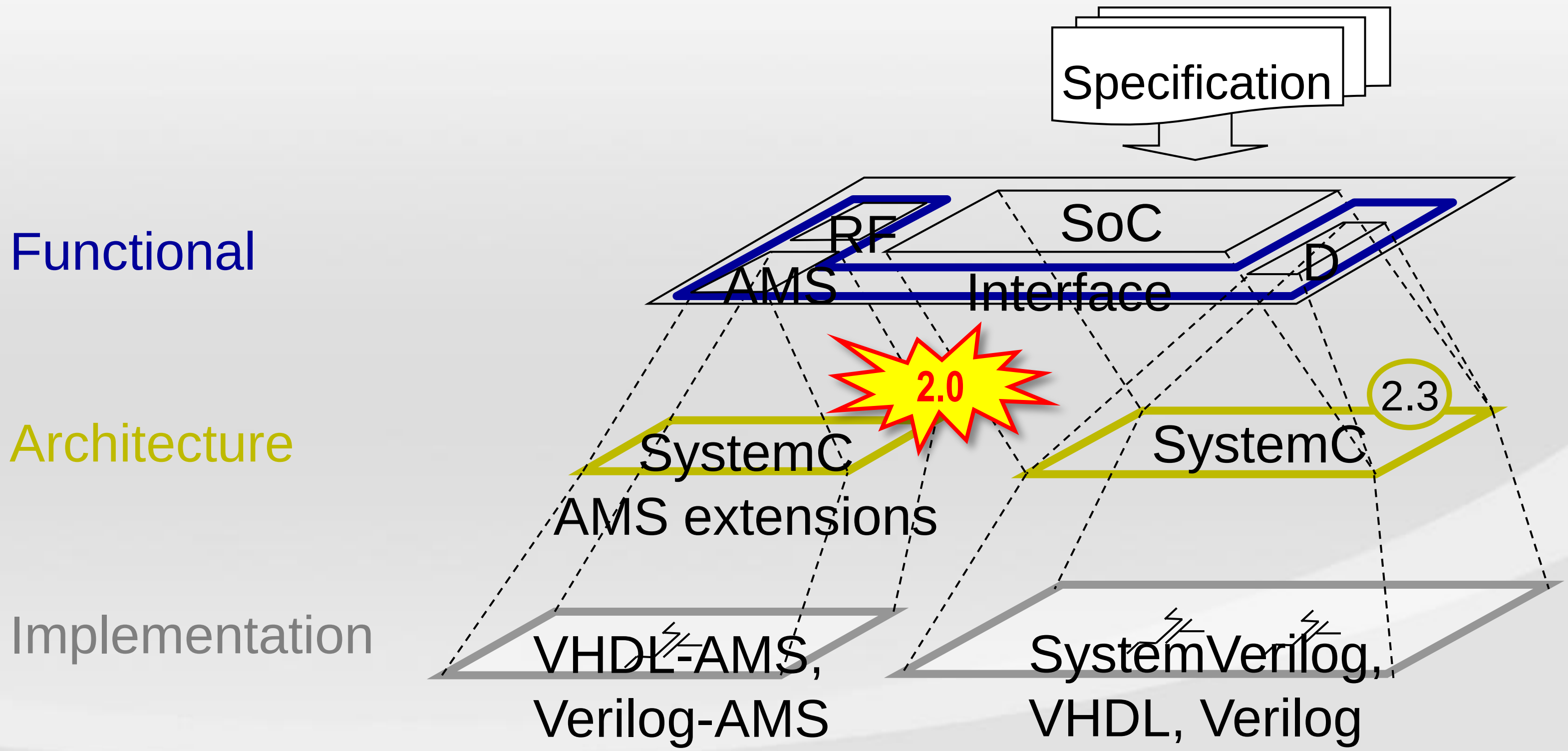
Introduction SystemC AMS extensions

- **Objectives of having a SystemC AMS language standard**
  - Unified and **standardized modeling language** to design and verify embedded AMS systems
  - **Abstract AMS model descriptions** supporting a design refinement methodology, from functional specification to implementation
  - AMS language constructs and semantics defined as **C++ class library** built on top of IEEE Std 1666-2011 (SystemC LRM)
  - Providing a **modeling framework** for development and exchange of AMS intellectual property
  - Foundation for development of **AMS system level design** tools
- **SystemC AMS extensions scope**
  - **System-level language** for analog and digital signal processing
  - Integration of abstract AMS/RF subsystems in **mixed-signal virtual prototypes**

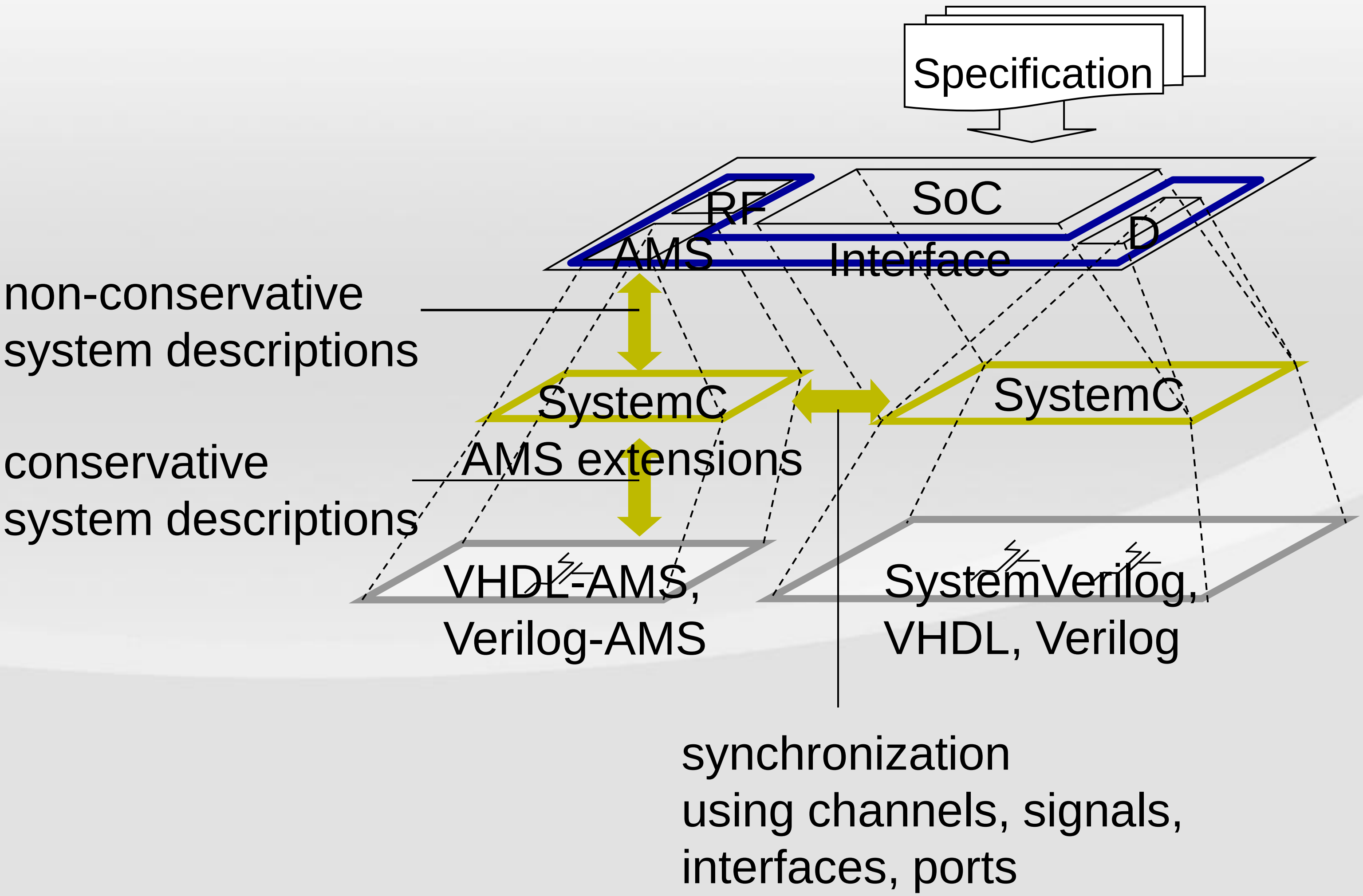
SystemC and AMS extensions



SystemC and AMS extensions



SystemC and AMS extensions



SystemC AMS – history of >10 years!

1999

- **1999: Open SystemC Initiative (OSCI) announced**
- **2000: SystemC 1.0 released (sourceforge.net)**
- **2002: OSCI SystemC 1.0.2**
- **2005: IEEE Std 1666-2005 LRM**
- **2005: SystemC Transaction level modeling (TLM) 1.0 released**
- **2007: SystemC 2.2 released**
- **2009: SystemC TLM 2.0 standard**
- **2009: SystemC Synthesizable Subset Draft 1.3**
- **2011: IEEE Std 1666-2011 LRM**
- **2012: SystemC 2.3**

- **~2000: First C-based AMS initiatives (AVSL, MixSigC)**
- **2002: SystemC-AMS study group started**
- **2005: First SystemC-AMS PoC released by Fraunhofer**
- **2006: OSCI AMSWG installed**
- **2008: SystemC AMS Draft 1 LRM**
- **2010: SystemC AMS 1.0 standard**
- **2010: SystemC AMS 1.0 PoC released by Fraunhofer**
- **2012: SystemC AMS 2.0 draft standard**

today

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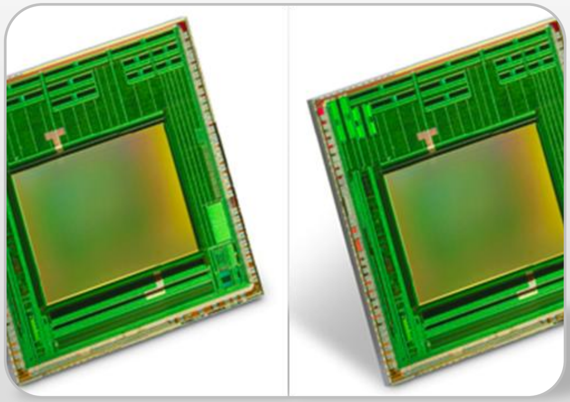
SystemC AMS application focus

Communication systems

Image courtesy of STMicroelectronics



Imaging systems

Automotive systems

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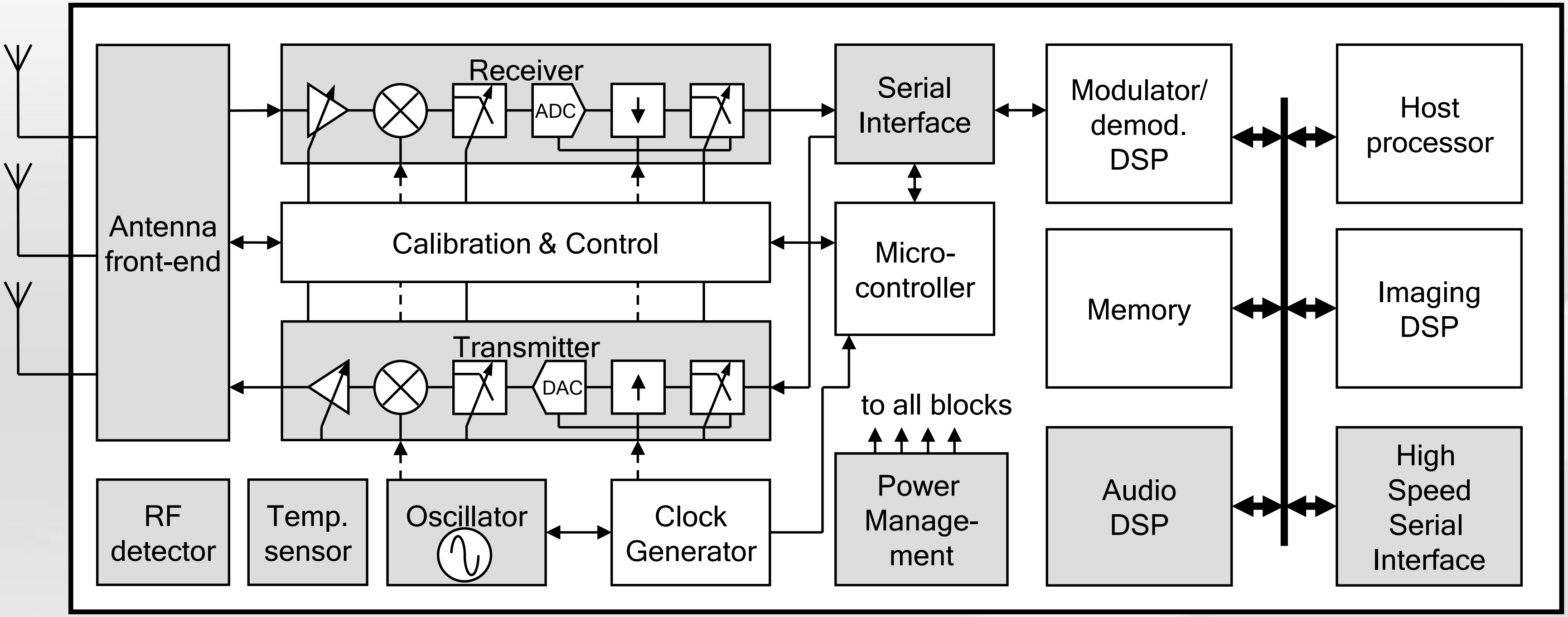
Example: Communication System



- ***Tight interaction*** **between digital HW/SW and AMS sub-systems**
  - Signal path: Communication protocol stack – modeling including PHY layer
  - Control path: more and more HW/SW calibration and control of analog blocks

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Industry requirements and needs

- **Design of True Heterogeneous Systems-on-a-chip**
  - Analog, Mixed-signal, RF, digital HW/SW (processor) interaction
  - Multi-domain, high frequencies, high bandwidth, configurable AMS components
- **Support different levels of design abstraction**
  - Functional modeling, architecture design, (abstract) circuit representations
- **Support different use cases – also for AMS!**
  - Executable specification, architecture exploration, virtual prototyping, integration validation

Need for Virtual Prototype Environments which enable inclusion of **digital HW/SW** and **abstract AMS/RF** system-level representations

SystemC AMS advantages

- **SystemC, thus C++ based**
  - The power of C++
  - Object oriented – modular and easy extendable
  - AMS class libraries available for basic building blocks (analog primitives)
  - Tool independent / EDA-vendor neutral
- **Modeling in multiple abstractions using one simulator**
  - No need for complex multi-kernel/co-simulation
  - No difficult APIs
  - Converter models and ports are part of the language
  - Allows abstraction along four axis
    - structure, behavior, communication and time/frequency
- **Transparent modeling platform**
  - Access to simulation kernel to ease debugging and introspection

Model abstraction and formalisms

Use cases

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

Model abstractions

- **Discrete-time** static non-linear
- **Continuous-time** dynamic linear
- **Non-conservative behavior**
- **Conservative behavior**

Modeling formalism

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

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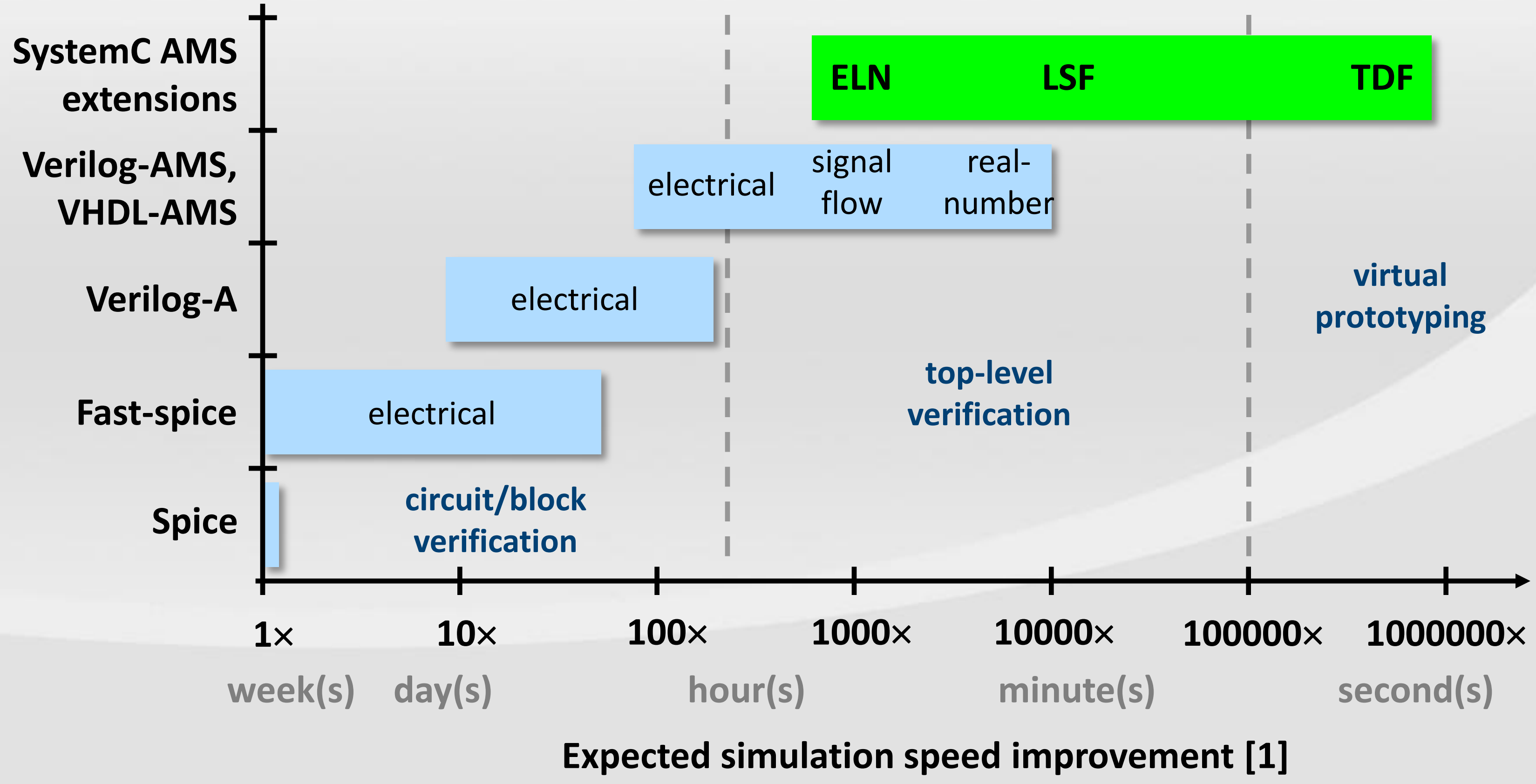
AMS models in Virtual Prototypes realistic?

Yes, as long as you use the right language and abstraction method



[1] M. Barnasconi, *SystemC AMS Extensions: Solving the Need for Speed*, http://www.accellera.org/community/articles/amsspeed/

SystemC AMS extensions LRM

- **Language Reference Manual defines the standard of the SystemC AMS extensions**
- **Contents**
  - Overview
  - Terminology and conventions
  - Core language definitions
  - Predefined models of computation
  - Predefined analyses
  - Utility definitions
  - Introduction to the SystemC AMS extensions (Informative)
  - Glossary (Informative)
  - Deprecated features (Informative)
  - Changes between SystemC AMS 1.0 and 2.0 standard (Informative)

13 March 2012

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Draft Standard SystemC® AMS extensions 2.0 Language Reference Manual

Abstract

This is the SystemC Analog Mixed Signal (AMS) extensions Language Reference Manual, version 2.0

Keywords

Accellera Systems Initiative, SystemC, Analog Mixed Signal, Hardware Description Language, Heterogeneous Modeling and Simulation

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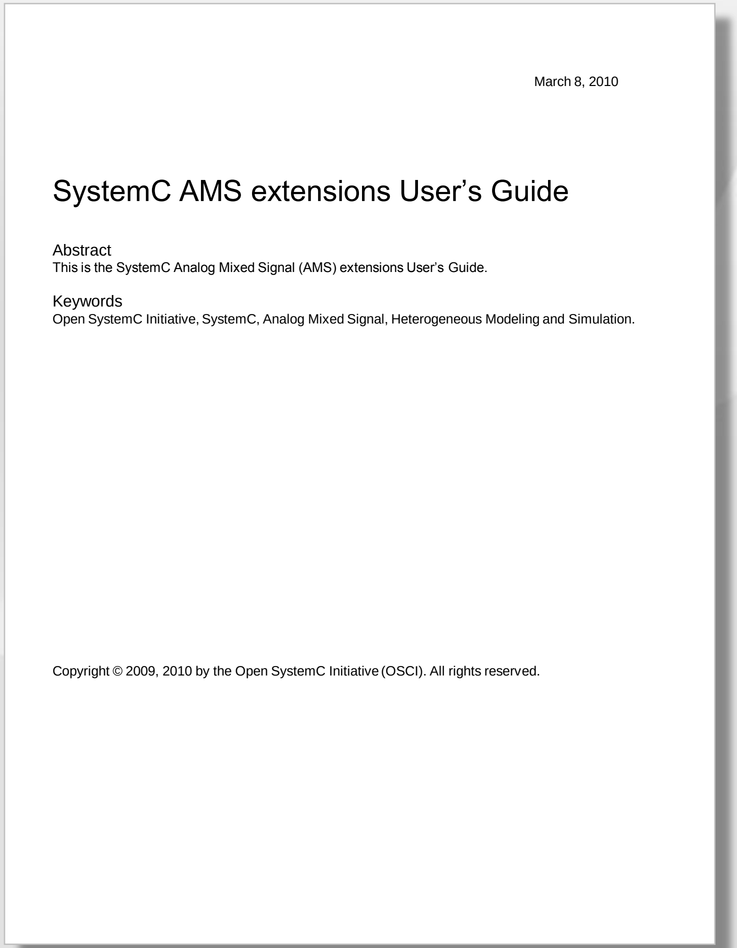
SystemC AMS User's Guide

- **Comprehensive guide explaining the basics of the AMS extensions**
  - TDF, LSF and ELN modeling
  - Small-signal frequency-domain modeling
  - Simulation and tracing
  - Modeling strategy and refinement methodology
- **Many code examples**
- **Application examples**
  - Binary Amplitude Shift Keying (BASK)
  - Plain-Old-Telephone-System (POTS)
  - Analog filters and networks
- **Has proven it's value: reference guide for many new users**


March 8, 2010

SystemC AMS extensions User's Guide

Abstract
This is the SystemC Analog Mixed Signal (AMS) extensions User's Guide.

Keywords
Open SystemC Initiative, SystemC, Analog Mixed Signal, Heterogeneous Modeling and Simulation.

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SystemC AMS 1.0 standard language features

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SystemC AMS language features

Mixed-Signal Virtual Prototypes
written by the end user

SystemC methodology-specific elements
Transaction-level modeling (TLM), Cycle/Bit-accurate modeling, etc.

AMS methodology-specific elements
elements for AMS design refinement, etc.

Timed Data Flow (TDF)
modules
ports
signals

Linear Signal Flow (LSF)
modules
ports
signals

Electrical Linear Networks (ELN)
modules
terminals
nodes

Scheduler

Linear DAE solver

Time-domain and small-signal frequency-domain simulation infrastructure (synchronization layer)

SystemC Language Standard (IEEE Std. 1666-2011)

SystemC AMS methodology elements

- **Support design refinement using different models of computation**
  - Timed Data Flow (TDF) - efficient simulation of discrete-time behavior
  - Linear Signal Flow (LSF) - simulation of continuous-time behavior
  - Electrical Linear Networks (ELN) - simulation of network topology & primitives
- **Using namespaces**
  - Clearly identify the used model of computation
  - Unified and common set of predefined classes, (converter) ports and signals
- **Examples**

- Module	`sca_tdf::sca_module`	`sca_lsf::sca_module`
- Input port	`sca_tdf::sca_in`	`sca_lsf::sca_in`
- Output port	`sca_tdf::sca_out`	`sca_lsf::sca_out`
- Signals	`sca_tdf::sca_signal`	`sca_lsf::sca_signal`
- Nodes (electrical only)		`sca_eln::sca_node`
- Terminal (in/output port, electrical only)		`sca_eln::sca_terminal`

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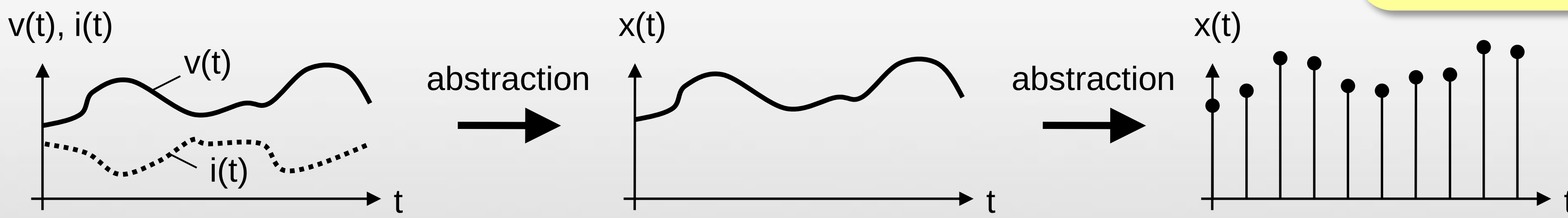
Abstraction of analog signals

TDF is the preferred modeling style!



Electrical Linear Networks (ELN)

- Conservative description represented by two dependent quantities, being the voltage v(t) and the current i(t)
- Continuous in time and value
- Analog (linear) solver will resolve the *Kirchhoff's Laws*

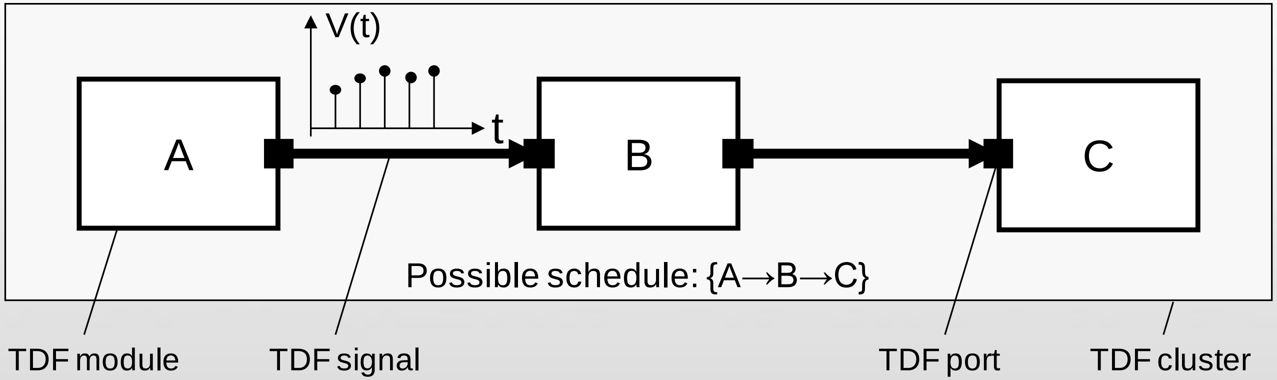
Linear Signal Flow (LSF)

- Non-conservative description represented by single quantity x(t), to represent e.g. the voltage or current (not both)
- Continuous in time and value

Timed Data Flow (TDF)

- Non-conservative description represented by single quantity x(t), to represent e.g. the voltage or current (not both)
- Discrete-time samples only, can hold any arbitrary data type

Timed Data Flow (TDF) basics



- **TDF is based on synchronous dataflow**
  - A module is executed if enough samples are available at its input ports
  - The number of read/written samples are constant for each module activation
  - The scheduling order follows the signal flow direction
- **The function of a TDF module is performed by**
  - reading from the input ports (thus consuming samples)
  - processing the calculations
  - writing the results to the output ports
- **The TDF model of computation is a discrete-time modeling style**

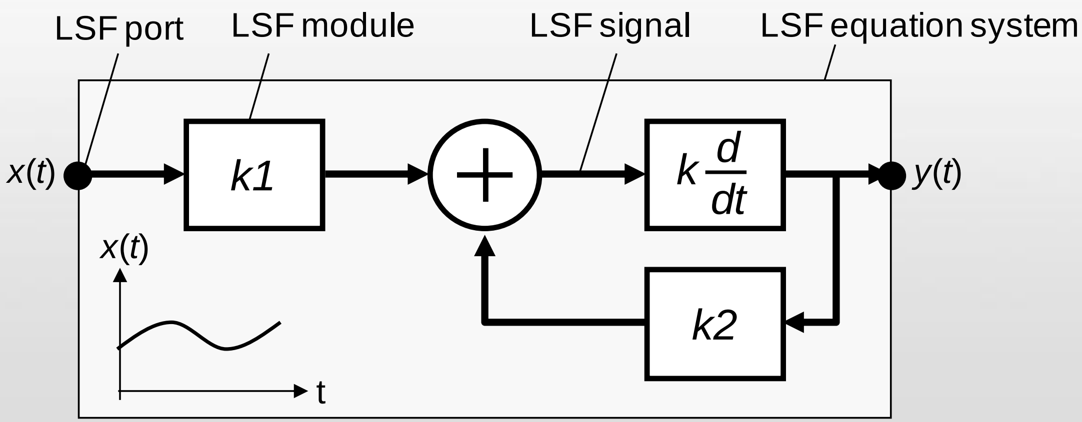
TDF language constructs

- **Predefined classes**
  - sca_tdf::sca_module
  - sca_tdf::sca_signal_if
  - sca_tdf::sca_signal
  - sca_tdf::sca_in
  - sca_tdf::sca_out
  - sca_tdf::sca_de::sc_in (sca_tdf::sc_in)
  - sca_tdf::sca_de::sc_out (sca_tdf::sc_out)
  - …
- **member functions**
  - set_delay, get_delay
  - set_rate, get_rate
  - set_timestep, get_timestep
  - read, write
  - kind
  - set_attributes
  - initialize
  - processing
  - ac_processing
  - …

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. time step between module activations
  }

  void initialize()
  {
    // put your initial values here
  }

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

  SCA_CTOR(mytdfmodel) {}
};
```

Linear Signal Flow (LSF) basics



- **Continuous-time behavior described in the form of *block diagrams***
  - LSF primitives describe relations between variables of a set of linear algebraic equations
- **Only a single quantity is used to represent the signal**
  - There is no dependency between flow (e.g. current) and potential (e.g. voltage) quantities
  - Uses directed real-valued signals, resulting in a non-conservative system description

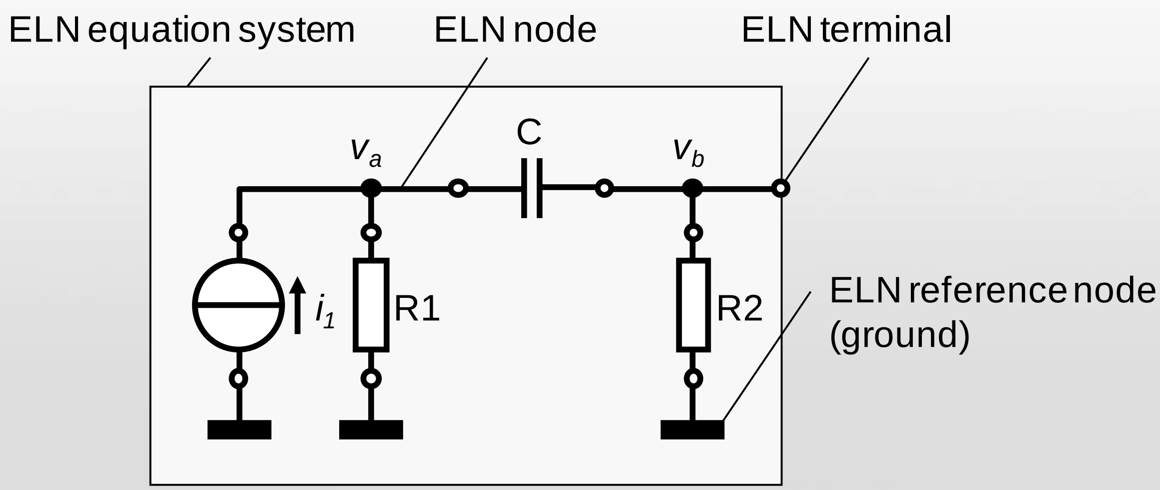
LSF language constructs

- **Predefined classes**
  - sca_lsf::sca_in
  - sca_lsf::sca_out
  - sca_lsf::sca_signal
  - 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
- **Predefined classes (cont.)**
  - sca_lsf::sca_ss
  - sca_lsf::sca_tdf::sca_source
  - sca_lsf::sca_tdf::sca_gain
  - sca_lsf::sca_tdf::sca_mux
  - sca_lsf::sca_tdf::sca_demux
  - sca_lsf::sca_tdf::sca_sink
  - sca_lsf::sca_de::sca_source
  - sca_lsf::sca_de::sca_gain
  - sca_lsf::sca_de::sca_mux
  - sca_lsf::sca_de::sca_demux
  - sca_lsf::sca_de::sca_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

  mylsfmodel( sc_module_name nm, 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);
  }

};
```

Electrical Linear Networks (ELN) basics



- **ELN modeling style allows the instantiation of *electrical primitives***
  - Connected ELN primitive modules will form an electrical network
- **The electrical network is represented by a set of differential algebraic equations**
  - following Kirchhoff's voltage law (KVL) and Kirchhoff's current law (KCL)
- **ELN captures conservative, continuous-time behavior**

ELN language constructs

- **Predefined classes**
  - sca_eln::sca_terminal
  - sca_eln::sca_node
  - sca_eln::sca_node_ref
  - 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
  - ...
- **Predefined classes (cont.)**
  - sca_eln::sca_vsource
  - sca_eln::sca_vsink
  - sca_eln::sca_tdf::sca_vsource
  - sca_eln::sca_tdf::sca_isource
  - sca_eln::sca_de::sca_vsource
  - sca_eln::sca_de::sca_isource
  - sca_eln::sca_tdf::sca_r
  - sca_eln::sca_tdf::sca_l
  - sca_eln::sca_tdf::sca_c
  - sca_eln::sca_de::sca_r
  - sca_eln::sca_de::sca_l
  - sca_eln::sca_de::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_ref gnd;     // ELN reference node

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

    c1 = new sca_eln::sca_c("c1", 100e-6);
    c1->p(out);
    c1->n(gnd);
  }

};
```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Real-number modeling vs. SystemC AMS

- **Real-number modeling (RNM) discretizes analog signals in time and represents a single quantity by a floating-point (real) data type**
- **RNM using 'plain' SystemC:** `sc_in<double>`
- **However, RNM in 'plain' SystemC is very inefficient**
  - Inefficient event generators needed to sample signals and process the samples
  - Each sample to be processed requires (or causes) one or more events
  - No capabilities to combine discrete-time signals with continuous-time functions
- **SystemC AMS is very computation efficient**
  - Time step can be naturally specified as module or port attribute
  - The Timed Data Flow model of computation is not event-driven, but data-driven
    - This significantly reduces the number of events, resulting in very fast simulations
  - Enables easy combination with analog / continuous-time functions (e.g. Laplace transfer functions)

SystemC AMS 2.0 standard language extensions

Additional use cases and requirements

- **Abstract modelling of sporadically changing signals**
  - E.g. power management that switches on/off AMS subsystems
- **Abstract description of reactive behaviour**
  - AMS computations driven by events or transactions
- **Capture behaviour where frequencies (and time steps) change dynamically**
  - Often the case for clock recovery circuits or capturing jitter
- **Modelling systems with varying (data) rates**
  - E.g. multi-standard / software-defined radio (SDR) systems

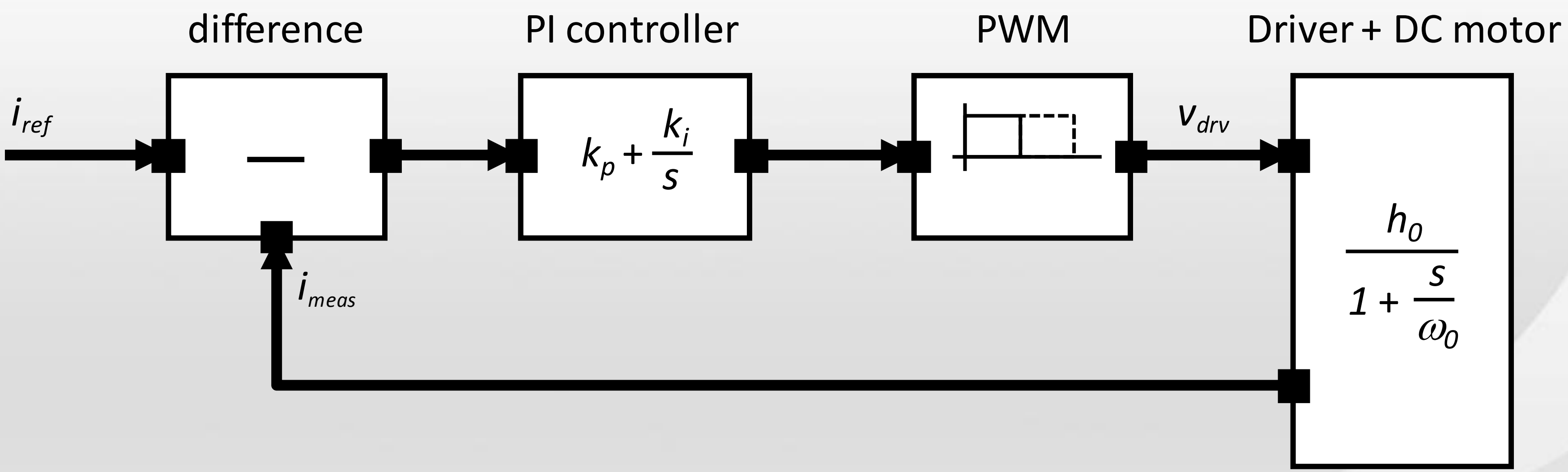
This requires a *dynamic* and *reactive* Timed Data Flow modeling style

- Basically introduce variable time step instead of fixed/constant time step

Use cases and requirements overview

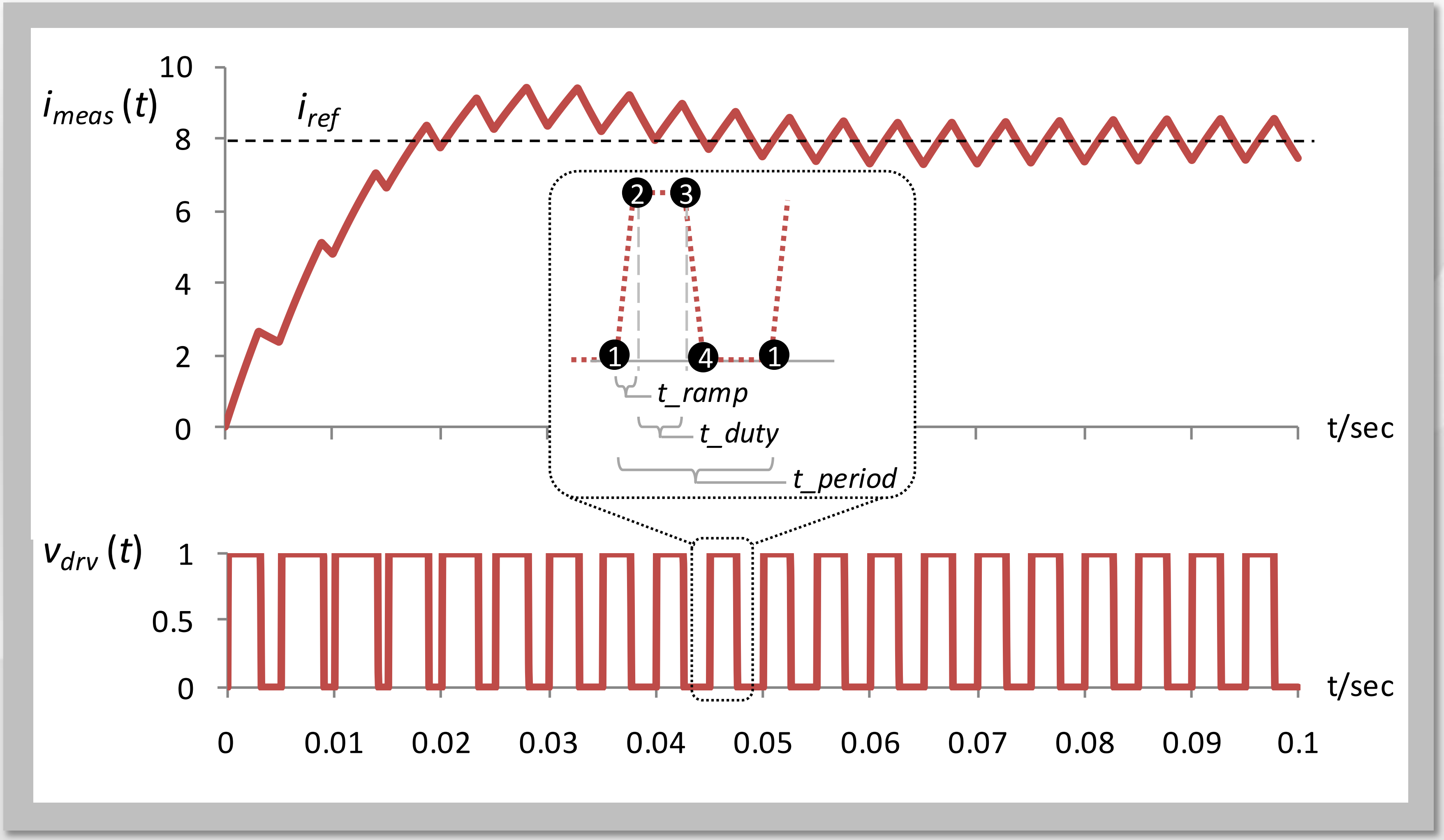
Use cases	Requirements	Application examples
Abstraction of sporadically changing signals	Switch on/off AMS computations	Power management unit
Abstract description of reactive behavior	Detect analog zero- or threshold crossing	Sensor circuits; alarm mode of systems
	Request and response caused by digital event or transaction	AMS embedded in digital HW/SW virtual prototype
Capture behavior where frequencies (and time steps) change dynamically	Changeable time step of AMS computations	VCO, PLL, PWM, Clock recovery circuits
Modeling systems with varying (data) rates	Changeable time step and/or data rate	Communication systems, multi-standard radio interfaces (e.g. cognitive radios)

Example: DC motor control



- **Functional model in the Laplace domain modelled in SystemC AMS**
- **To achieve high accuracy, many module activations are necessary when using fixed time steps (AMS 1.0)**
- **Introducing *Dynamic TDF* to only compute when necessary, due to dynamic time step mechanism (AMS 2.0)**

DC motor control loop behavior



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Dynamic TDF features in AMS 2.0

New callback and member functions to support Dynamic TDF:

- **change_attributes()**
  - callback provides a context, in which the time step, rate, or delay attributes of a TDF cluster may be changed
- **request_next_activation(…)**
  - member function to request a next cluster activation at a given time step, event, or event-list
- **does_attribute_changes(), does_no_attribute_changes()**
  - member functions to mark a TDF module to allow or disallow making attribute changes itself, respectively
- **accept_attribute_changes(), reject_attribute_changes()**
  - member functions to mark a TDF module to accept or reject attribute changes caused by other TDF modules, respectively

Example of Pulse Width Modulator (1)

```
// pwm_dynamic.h

#include <cmath>
#include <systemc-ams>

SCA_TDF_MODULE(pwm) // for dynamic TDF, we can use the same helper macro to define the module class
{
  sca_tdf::sca_in<double> in;
  sca_tdf::sca_out<double> out;

  pwm( sc_core::sc_module_name nm, ... )
  : in("in"), out("out") {}

  void set_attributes()
  {
    does_attribute_changes();              // module allowed to make changes to TDF attributes
    accept_attribute_changes();            // module allows attribute changes made by other modules
  }

  void change_attributes()                 // new callback to change attributes during simulation
  {
    double t = get_time().to_seconds();    // current time
    double t_pos = std::fmod( t, t_period); // time position inside pulse period
    ...
```

Dynamic TDF features indicated in red

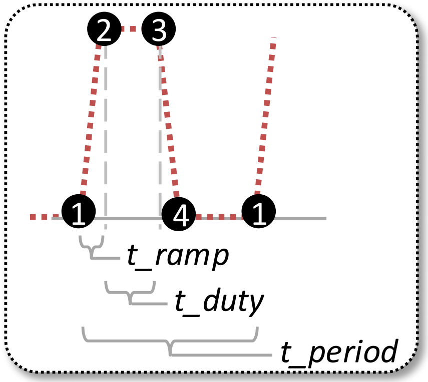
Example of Pulse Width Modulator (2)

```
if ( t_pos < t_ramp ) {
      // rising edge
      request_next_activation( t_ramp - t_pos, sc_core::SC_SEC );❶
    } else if ( t_pos < t_ramp + t_duty ) {
      // plateau
      request_next_activation( ( t_ramp + t_duty ) - t_pos, sc_core::SC_SEC );❷
    } else if ( t_pos < t_ramp + t_duty + t_ramp ) {
      // falling edge
      request_next_activation( ( t_ramp + t_duty + t_ramp ) - t_pos, sc_core::SC_SEC );❸
    } else {
      // return to initial value
      request_next_activation( t_period - t_pos, sc_core::SC_SEC );❹
    }
  }

  void processing()
  {
     ... // PWM behavior
  }

 private:
  ...    // member variables
};
```

Dynamic TDF features indicated in red



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TDF vs. Dynamic TDF comparison

TDF model of computation variant	*t_step* (ms)	*t_ramp* (ms)	*t_period* (ms)	Time accuracy (ms)	#activations per period
Conventional TDF	0.01 (fixed)	0.05	5.0	0.01 (= *t_step*)	500
Dynamic TDF	variable	0.05	5.0	defined by **`sc_set_time_resolution()`**	4

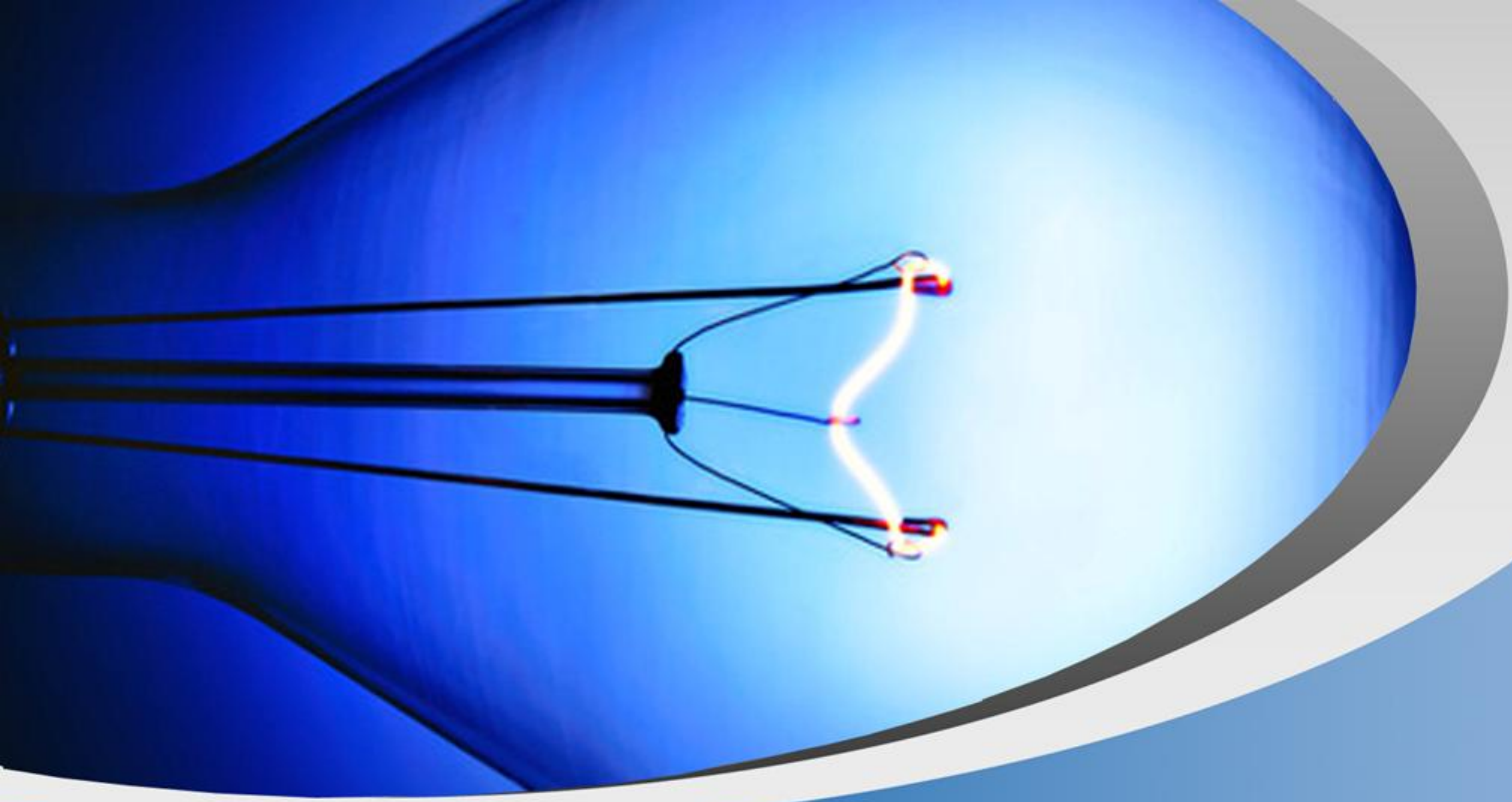
- **Comparison of the two variants of the TDF model of computation**
  - Conventional PWM TDF model uses a fixed time step that triggers too many unnecessary computations
  - When using Dynamic TDF, the PWM model is only activated if necessary.

Summary and outlook

- **SystemC AMS developments are fully driven and supported by European industry: NXP, ST, Infineon, and Continental**
- **SystemC AMS 1.0 standard was released in March 2010**
- **SystemC AMS 2.0 standard released in March 2013**
  - Introducing Dynamic Timed Data Flow to facilitate a more reactive and dynamic behavior for AMS computations
- **Third party Proof-of-Concept implementation for SystemC AMS 1.0 available under Apache 2.0 license**
  - Thanks to Fraunhofer IIS/EAS Dresden
- **Discussions ongoing with EDA vendors for commercial tool support**

More information

- www.accellera.org
- www.accellera.org/downloads/standards/systemc/ams
- www.accellera.org/community/articles/amsspeed
- www.accellera.org/community/articles/amsdynamictdf
- www.systemc-ams.org



Thank you

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Back-up

Simple code example: Top-level RF frontend module

Top-level RF frontend module

```
SC_MODULE(rf_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");
    mixer1->rf_in(rf);
    mixer1->lo_in(loc_osc);
    mixer1->if_out(if_sig);

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

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

SC_MODULE is used for hierarchical structure

usage of TDF signals and SystemC signals

Abstract mixer model (TDF module)

Low pass filter at implementation level (ELN module)

easy to combine with normal SystemC modules!

Abstract mixer function in TDF

```
SCA_TDF_MODULE(mixer)
{
  sca_tdf::sca_in<double>  rf_in, lo_in;
  sca_tdf::sca_out<double> if_out;

  void set_attributes()
  {
    set_timestep(1.0, SC_US); // time between activations
  }

  void processing()
  {
    if_out.write( rf_in.read() * lo_in.read() );
  }

  SCA_CTOR(mixer) {}
};
```

TDF primitive module: no hierarchy

TDF input and output ports

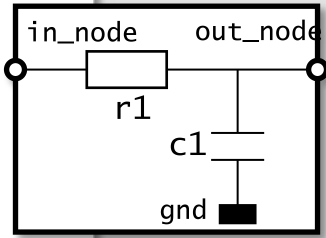
Attributes specify timed semantics

processing() function is executed at each activation

AMS module constructor

Low-pass filter in ELN

```
SC_MODULE(lp_filter_eln)
{
  sca_tdf::sca_in<double> in;
  sca_tdf::sca_out<double> out;

  sca_eln::sca_node in_node, out_node;
  sca_eln::sca_node_ref gnd;

  sca_eln::sca_r *r1;
  sca_eln::sca_c *c1;
  sca_eln::sca_tdf_vsource *v_in;
  sca_eln::sca_tdf_vsink   *v_out;

  SC_CTOR(lp_filter_eln)
  {
    v_in = new sca_eln::sca_tdf_vsource("v_in", 1.0);
    v_in->inp(in);
    v_in->p(in_node);
    v_in->n(gnd);

    r1 = new sca_eln::sca_r("r1", 10e3);  // 10kOhm resistor
    r1->p(in_node);
    r1->n(out_node);
    c1 = new sca_eln::sca_c("c1", 100e-6);// 100uF capacitor
    c1->p(out_node);
    c1->n(gnd);

    v_out = new sca_eln::sca_tdf_vsink("v_out", 1.0);
    v_out->p(out_node);
    v_out->n(gnd);
    v_out->outp(out);
  }
};
```



SC_MODULE is used for hierarchical structure

nodes to connect to electrical components

network primitives: resistor and capacitor

Converter modules to connect electrical domain to TDF domain

Electrical network topology is specified here