# Refinement of EmbeddedAnalog/Mixed-Signal Systems with SystemC-AMS

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# Warning!

## This tutorial

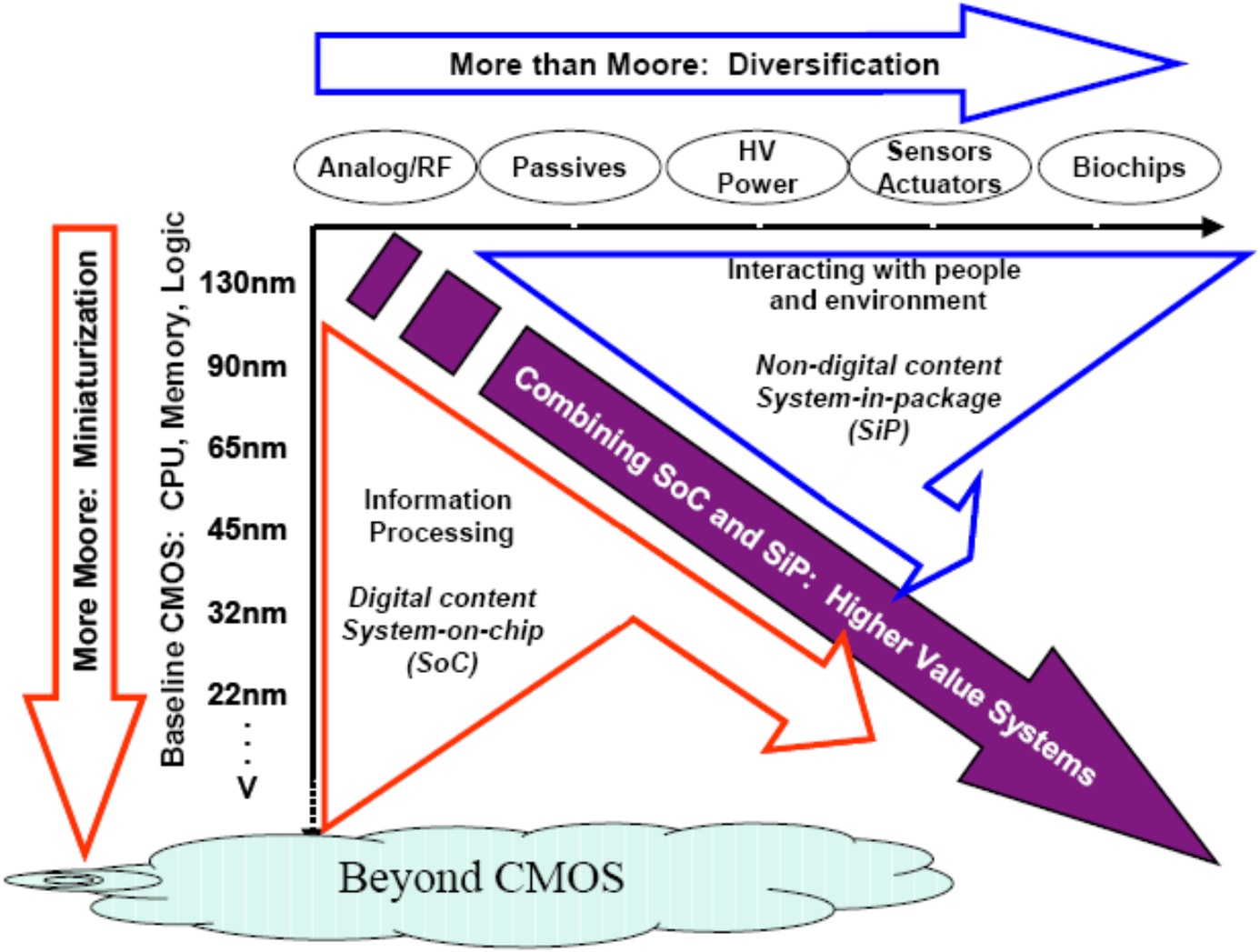
- does not teach you syntax of SystemC AMS extensions.
- it does not even want to teach it!
- SystemC-AMS syntax will change – standardization is in progress!

## But this tutorial wants to

- describe problems SystemC AMS extensions will solve
- explain underlying motivation and semantics
- teach a methodology for productive use of SystemC AMS extensions!

Not a warning, but - many thanks to *Karsten Einwich, Alain Vachoux* and *Martin Barnasconi* who contributed to AMS extensions and this tutorial!

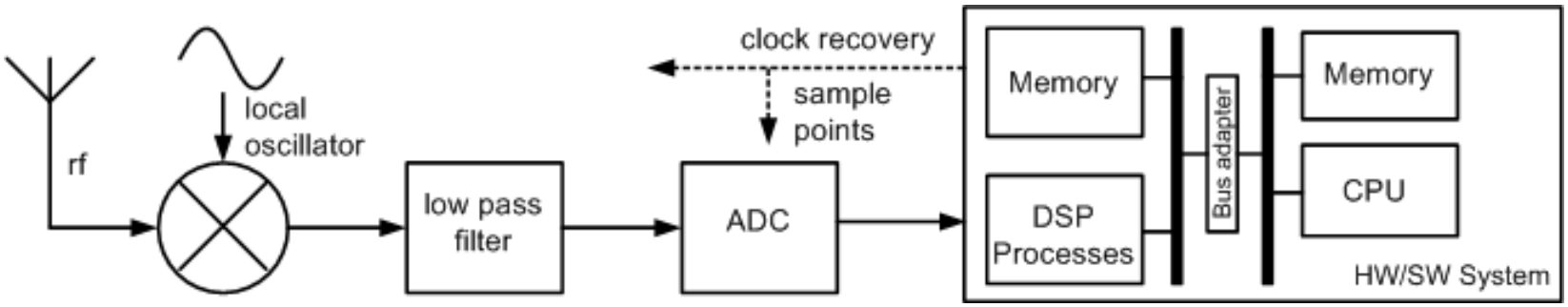
# Motivation: More than Moore!



# Refinement of Embedded Analog/Mixed-Signal Systems with SystemC-AMS

- **Embedded Analog/Mixed-Signal Systems**
- **SystemC-AMS Overview**
- **Refinement methodology**
- **Outlook**

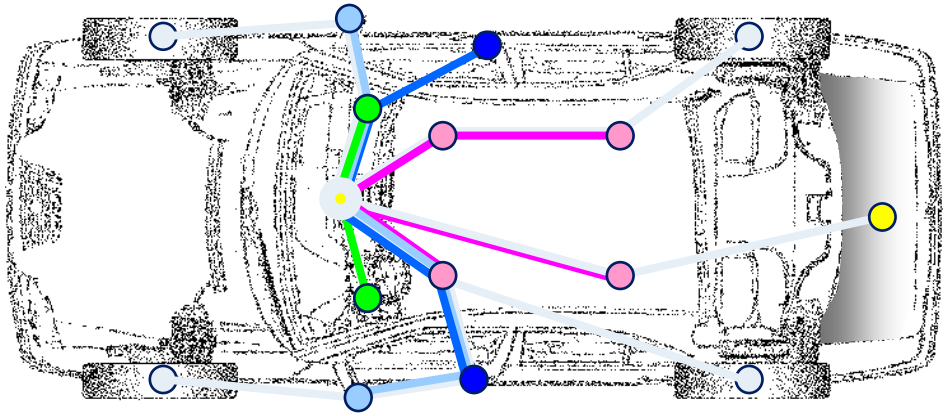
# Example 1: Cognitive Radio




**Software Defined Radio, Cognitive Radio**

- HW/SW System tightly interwoven with AMS
- Ideal Partitioning SW-FPGA-HW-Analog/RF?
- Required for system design: HW/SW **+ AMS**

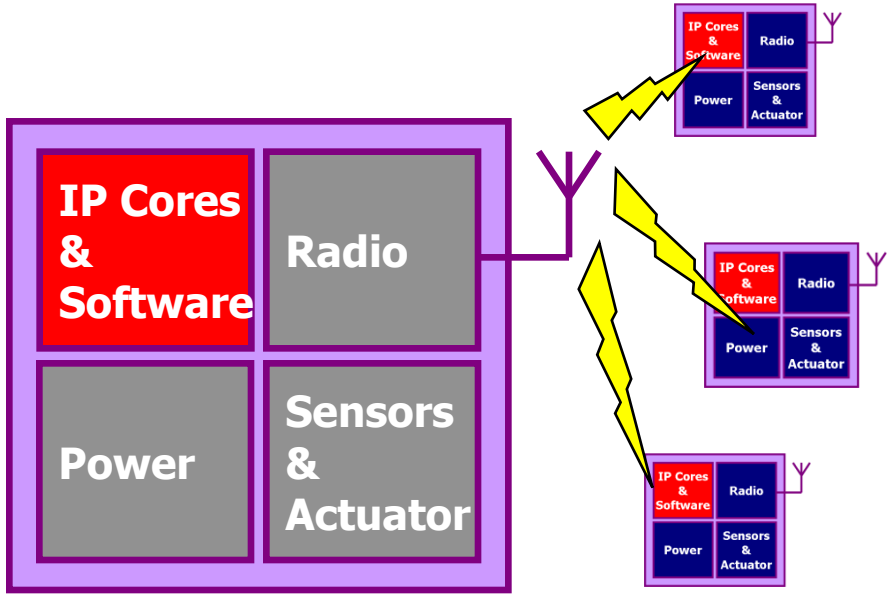
# Example 2: Wireless Sensor Net



**Wireless, energy-self sufficient sensor net**

- Sensor node = AMS+RF+Processor
- Average power consumption < limit ?
- Power consumption depends onn
  - AMS+RF hardware,
  - protocol, routing, …

# In general: E-AMS




- **Embedded Analog/Mixed-Signal (E-AMS) system**
- ***Analog circuits* functionally interwoven with *HW/SW system***
- **Functionality/architecture can only be understood as a whole**

# MoC in E-AMS

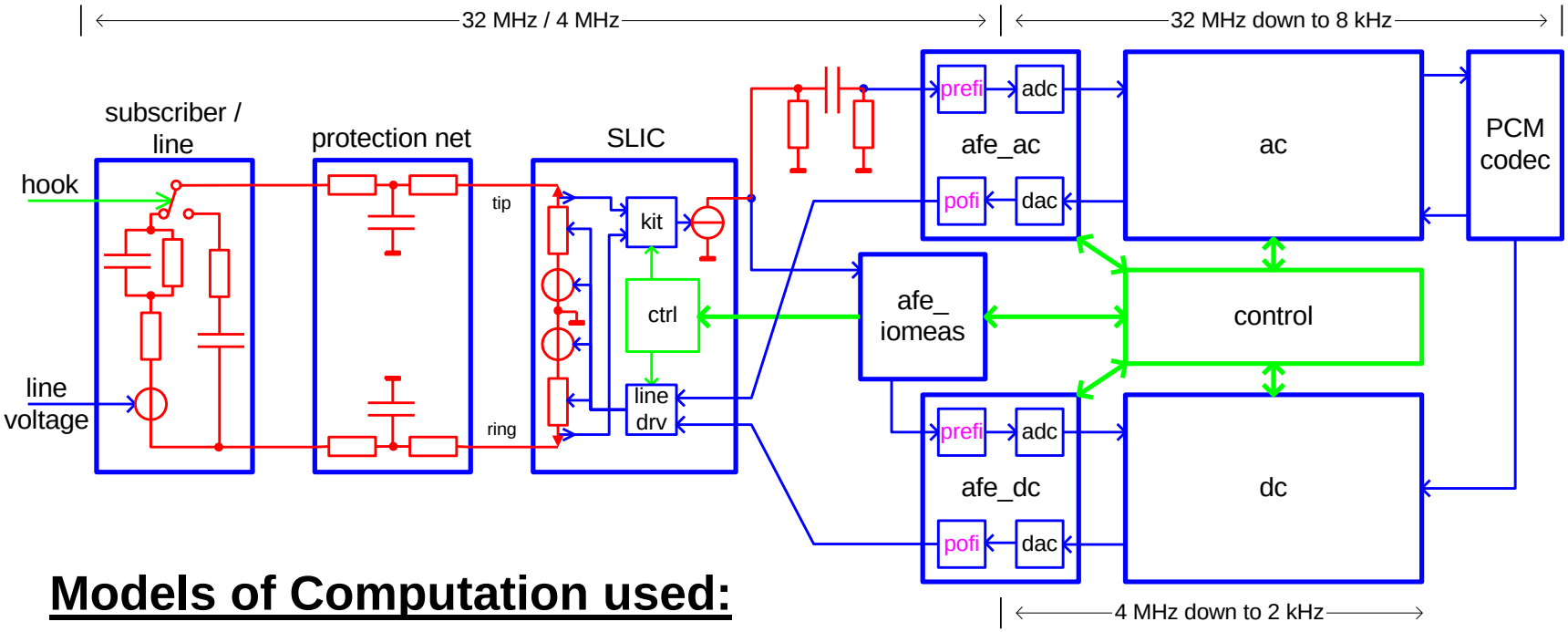



Figure: Karsten Einwich, FhG-IIS/EAS Dresden

**Models of Computation used:**

Discrete Event

Data/signal flow

Differential equations

Electrical network

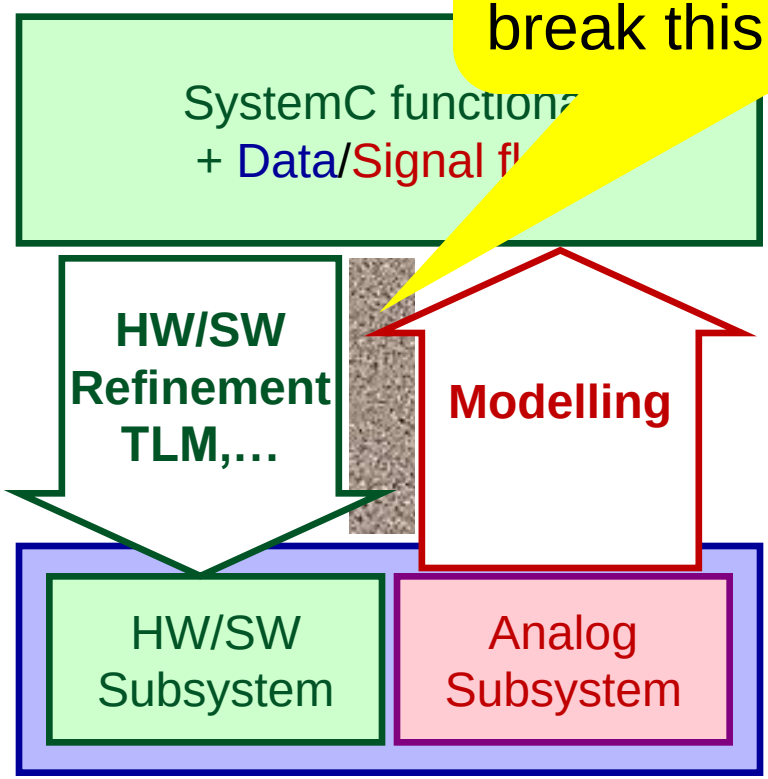
# Design of E-AMS

For real **Analog/Digital Co-Design** we have to break this wall!

Functional Level

**Architecture Level**

Subsystem Level




**A/D Partitioning**

**(DSP) Algorithm design,**

**Bit widths, …**

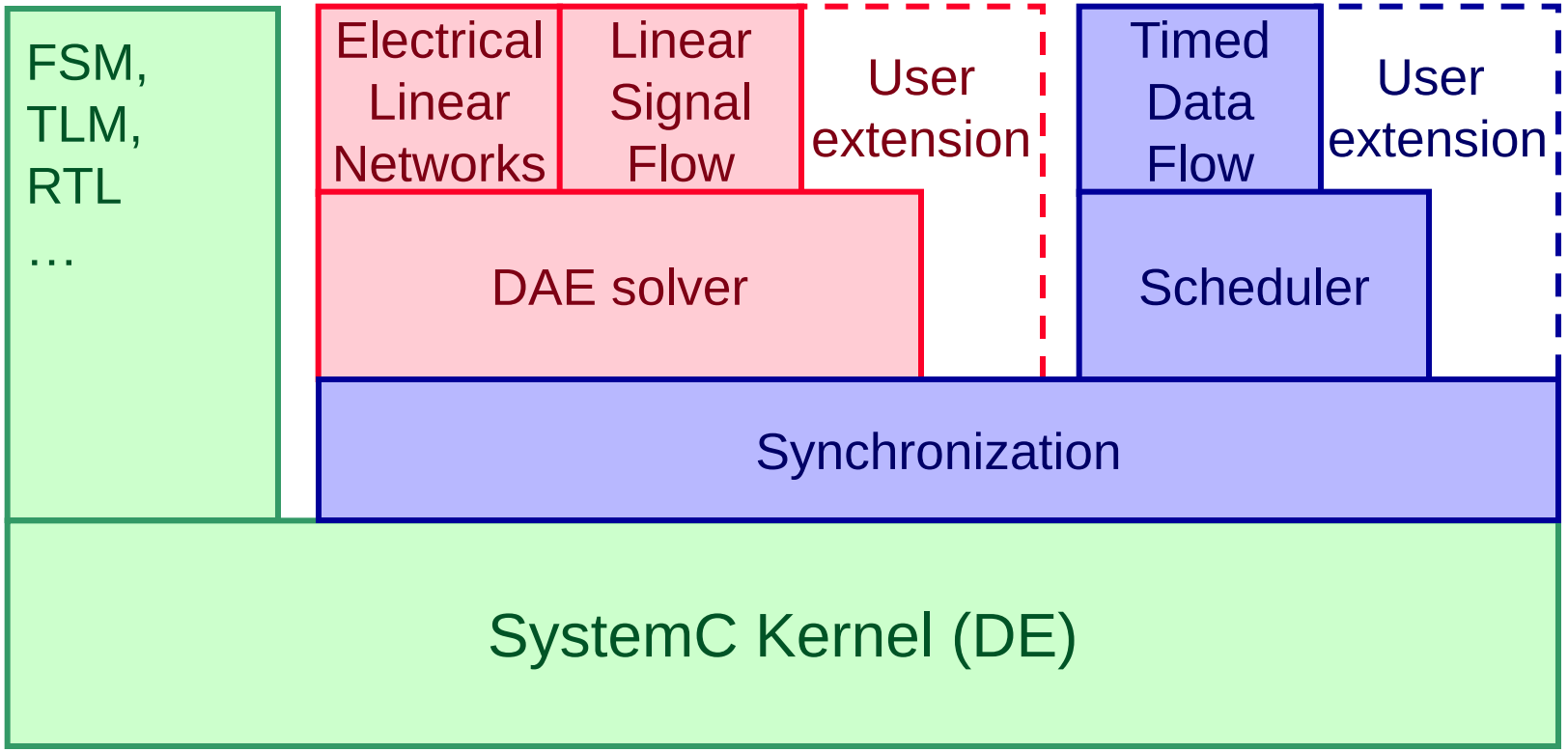
# Refinement of Embedded Analog/Mixed-Signal Systems with SystemC-AMS

- Embedded Analog/Mixed-Signal Systems
- SystemC AMS Extensions Overview
- Refinement methodology
- Outlook

# SystemC-AMS Requirements

- **Very high simulation performance**
  - **Virtual prototyping, overall system simulation, …**
  - **Tradeoff vs. reduced accuracy acceptable**
- **Extensible approach**
  - **Data flow, timed**
  - **Signal flow**
  - **Electrical network**
  - **Transfer functions**
  - **Extensions from EDA vendors, …**
    - Methodology specific support
    - Integration of simulators, e.g. SPICE!

# Layered Approach for Extensibility



# Continuous Time Systems

- **Analog behavior = Blockdiagrams with …**
  - Static nonlinear functions
    example: y=a*b
  - Dynamic linear functions
    example: Linear DAEs, Transfer functions, …
- **Analog circuits**
  - linear (R,L,C, …)
  - switched linear
  - linear + nonlinear: Transistors, Diodes, …

Focus of SystemC AMS extensions

# Electrical Linear Networks (ELN)

**Electrical nodes connect network primitives**

```
// Language primitives:
sca_eln::sca_node n1;
```

**Each network needs one connection with reference node of class `sca_eln::sca_ref`**

```
sca_eln::sca_ref gnd;
```

**Hierarchical structure by using ports of the class `sca_eln::sca_port`**

```
sca_eln::sca_port p1;
```

**Network elements can be instanciated and connected like other modules …**

```
sca_eln::sca_r r1("r1");
  r1.value = 2e3; // 2kOhm
  r1.p(w_it);
  r1.n(gnd);
```

# Electrical Networks - Converter Modules

**TDF controlled sources**

```
sca_tdf::sca_tdf2i i1("i1", <gain>);
    i1.p(w1);
    i1.n(w2);
    i1.ctrl(tdf_signal);
    // tdf_signal is of type
    // double

sca_tdf::sca_tdf2v v1("v1", <gain>);
```

**DE (sc_signal<double>) controlled source**

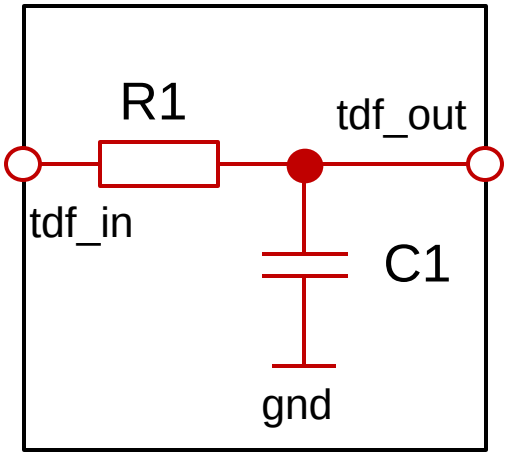
```
sca_tdf::sca_sc2i i1("i1", <gain>);

sca_tdf::sca_sc2v v1("v1", <gain>);
```

**Conversion of physical sizes to DE and TDF**

```
sca_tdf::sca_i2tdf iconv1(„iconv1");

sca_tdf::sca_v2tdf iconv1("vconv1");
…
```

# ELN Example: RC low pass filter

```
SC_MODULE(lp_filter_eln) {
   sca_tdf::sca_in<double>   tdf_in;
   sca_tdf::sca_out<doublbe> tdf_out;

   sca_eln::sca_node in, out; // node
   sca_eln::sca_ref gnd;      // reference
   sca_eln::sca_r *r1;        // resistor
   sca_eln::sca_c *c1;        // capacitor
   sca_eln::sca_tdf2v *v_in;  // converter TDF -> U(t)
   sca_eln::sca_v2tdf *v_out; // converter U(t) -> TDF

   SCA_CTOR(lp_filter_eln) {
     v_in = new sca_eln::sca_tdf2v("v_in", 1.0);// scale factor 1.0
       v_in->ctrl(tdf_in);                      // TDF input
       v_in->p(in); v_in->n(gnd);               // converted to voltage

     r1 = new sca_r("r1", 10000.0);             // 10kOhm resistor
       r1->p(in); r1->n(out);

     c1 = new sca_c("c1", 0.0001);              // 100uF capacitor
       c1.p(out); c1.n(gnd);

    v_out = new sca_eln::sca_v2tdf("v_out", 1.0); // scale factor 1.0
       v_out1->p(out); v_out1->n(gnd);          // filter output
       v_out->ctrl(tdf_out);                    // converted to TDF
} }
```



# Linear Signal Flow Models (LSF)

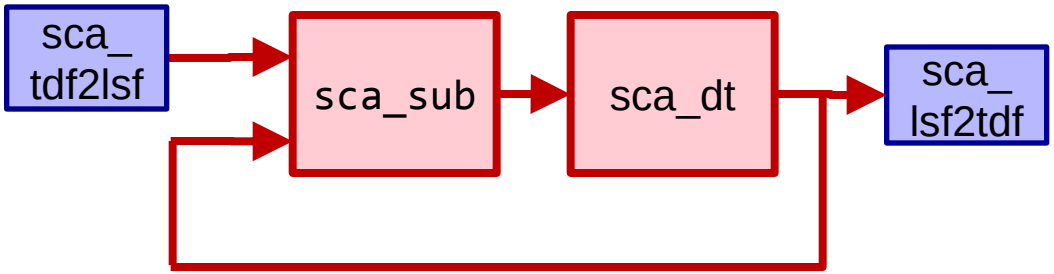
**Linear Signal Flow**

- **Continuous time**
- **Directed signals**
- **Loops allowed are equations that are solved numerically**

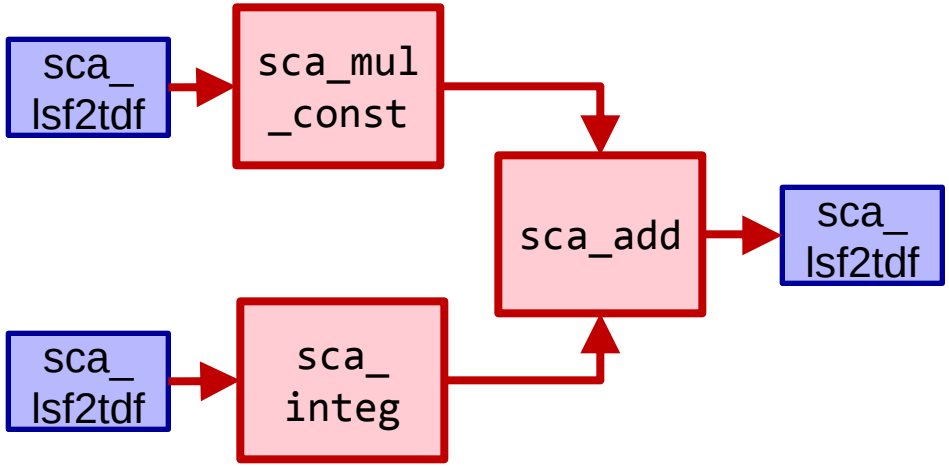
- **Predefined blocks in AMS extensions:**
  - **Transfer functions**
  - **add, sub, integ, dt**
  - **…**

# Linear Signal Flow Models (LSF)

## LSF low pass filter structure




## LSF PI controller structure



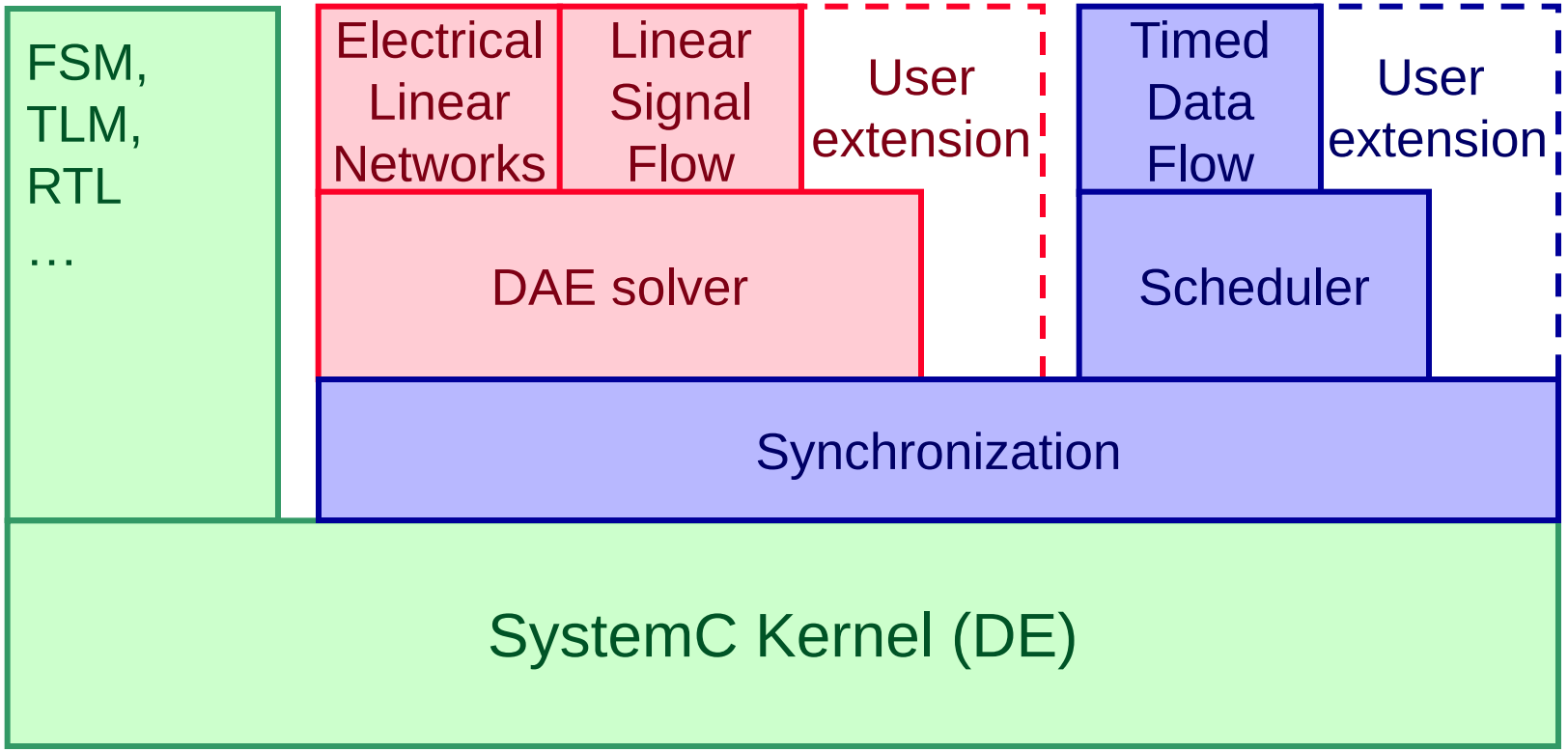
# Some limitations of prototype (may change!)

- No step width control
- Only linear components publicly available
- Syntax not yet in line with LRM proposal

… certainly some bugs …

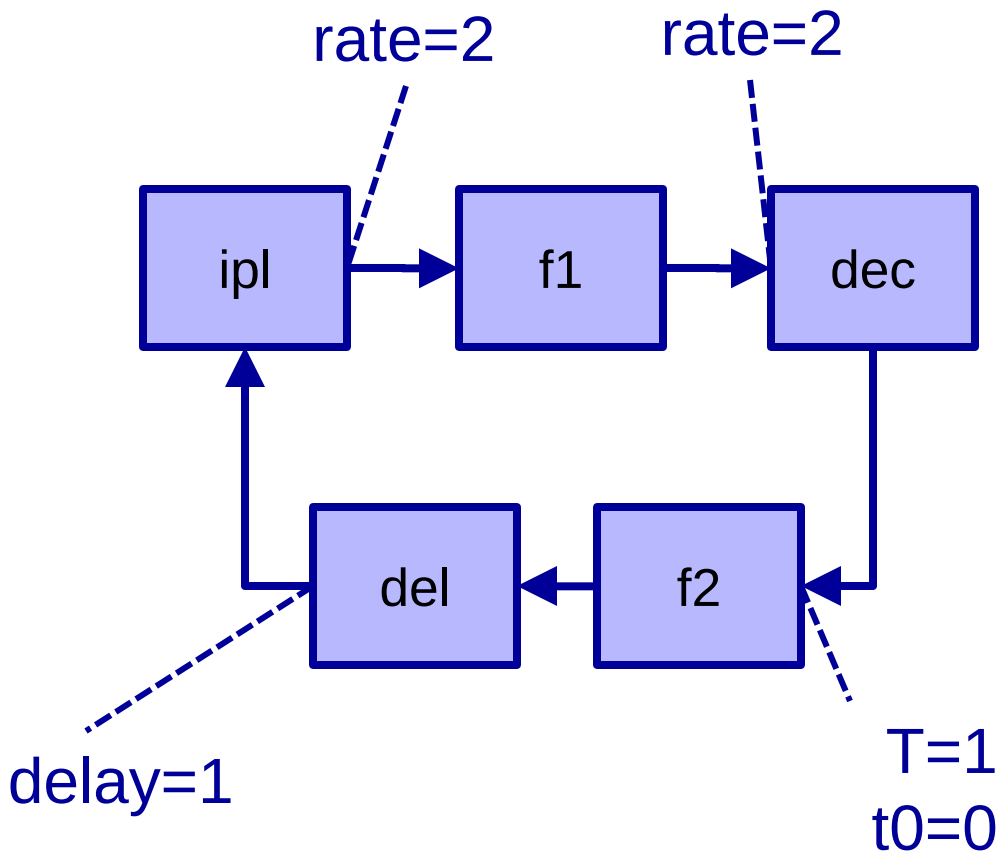
*Wait and see …*

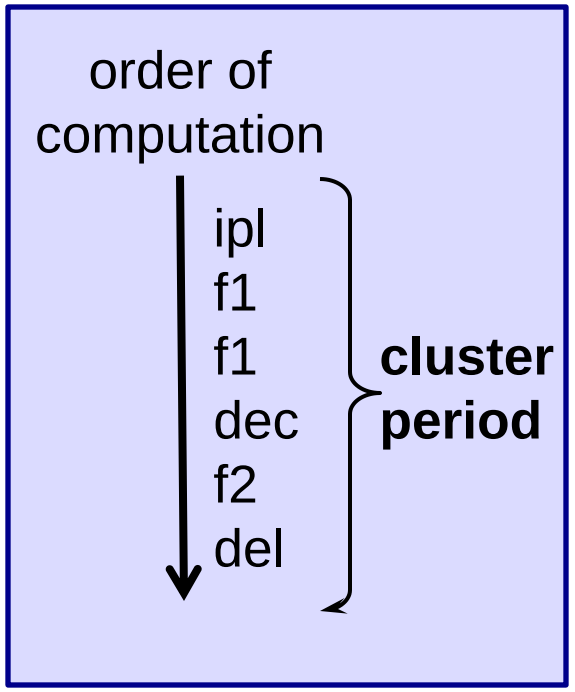
# Layered Approach for Extensibility



# Timed Data Flow (TDF)

**„cluster“** := set of connected TDF modules



# Timed Data Flow – Code snippet

**TDF Module:**
**no hierarchy!**

```
SCA_TDF_MODULE(par2ser)
{
  sca_tdf::sca_in<sc_bv<8> > in;
  sca_tdf::sca_out<bool>     out;
```

**Attributes specify timed semantics**

```
  void set_attributes()
  { out.set_rate(8);
    out.set_delay(1);
    out.set_timestep(1, SC_MS);}
```

**processing()**
**describes computation**

```
  void processing()
  {
    for (int i=7; i >= 0 ; i-- )
      out.write(in.get_bit(i), i);
  }
  SCA_CTOR(par2ser)
}
```

# Data flow MoC – Converter ports

**Converter ports towards discrete event domain**

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

**Note: Time in TDF may run ahead DE time!**

```
sc_time sca_get_time()
```

# TDF example: Mixer model

```
SCA_TDF_MODULE(mixer) // TDF primitive module definition
{
  sca_tdf::sca_in<double>  in1, in2; // TDF in ports
  sca_tdf::sca_out<double> out;      // TDF out ports
  void set_attributes()
  {
    set_module_timestep(1.0, SC_US); // time between activations
  }
  void processing()                  // executed at each activation
  {
    out.write(in1.read() * in2.read());
  }
  SCA_CTOR(mixer) {}
};
```

# TDF example 2: CT Low pass filter

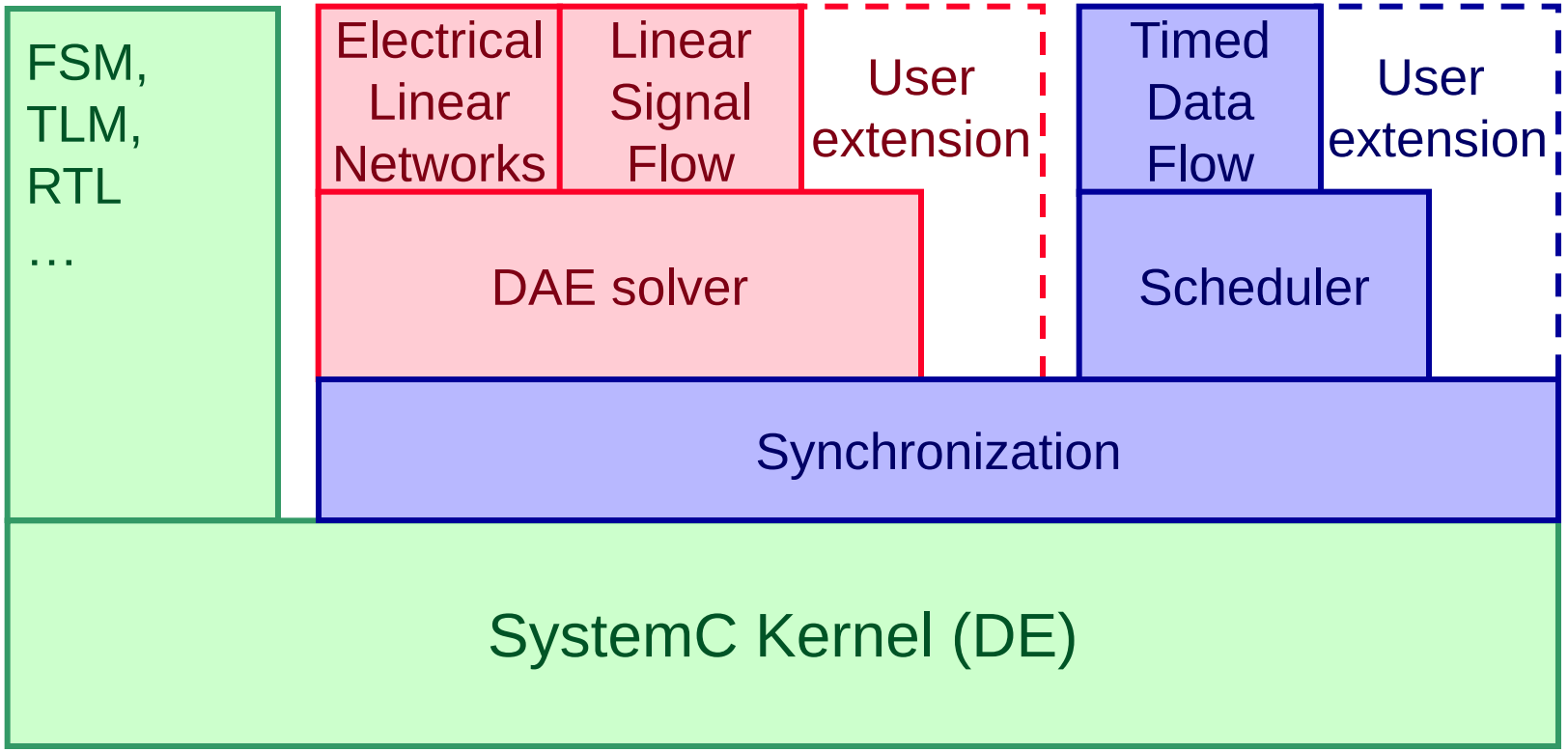
```
SCA_TDF_MODULE(lp_filter_ltf)
{
  sca_tdf::sca_in<double>  in;
  sca_tdf::sca_out<double> out;
  sca_tdf::sca_ltf_nd ltf;                  // computes transfer function
  sca_utio::sca_vector<double> num, den; // coefficients
  void initialize()
  {
    num(0) = 1.0;
    den(0) = 1.0; den(1) = 1.0/(2.0*M_PI*1.0e4); // M_PI=3.1415
  }
  void processing()
  {
    out.write( ltf(num, den, in.read() ) );
  }
  SCA_CTOR(lp_filter_ltf) {}
};
```

# Current limitations of prototype (may change!)

- **Syntax of prototype (0.16) does not yet match LRM proposal (as used in this tutorial)**
- **activation currently at constant time steps.**

***Wait and see …***

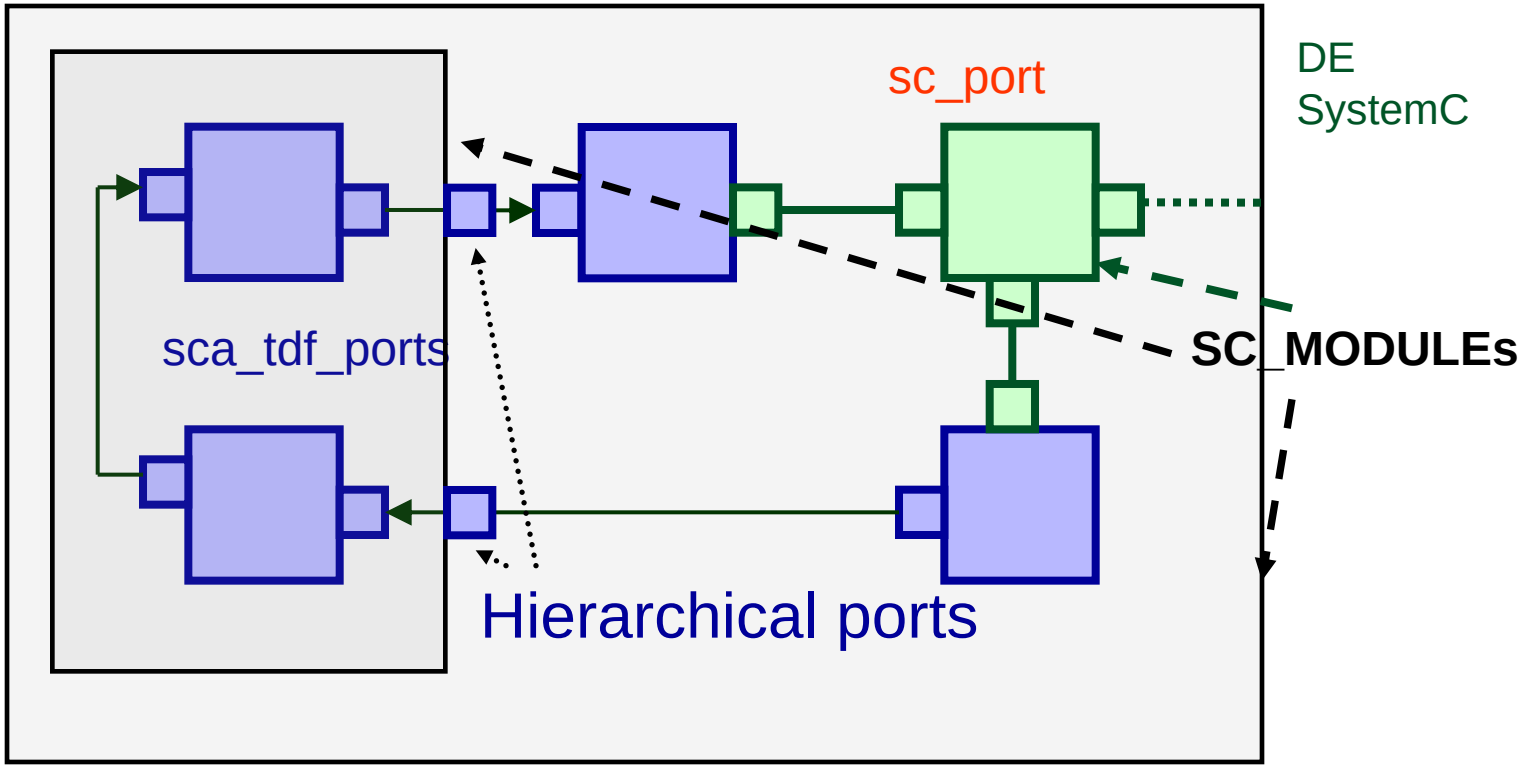
# Layered Approach for Extensibility



# Support for hierarchy

**SC_MODULEs are used for structuring design hierarchically**

- **SCA_*** modules primitives for data flow and signal flow modeling**
- **Use same port classes – but no converter ports allowed**



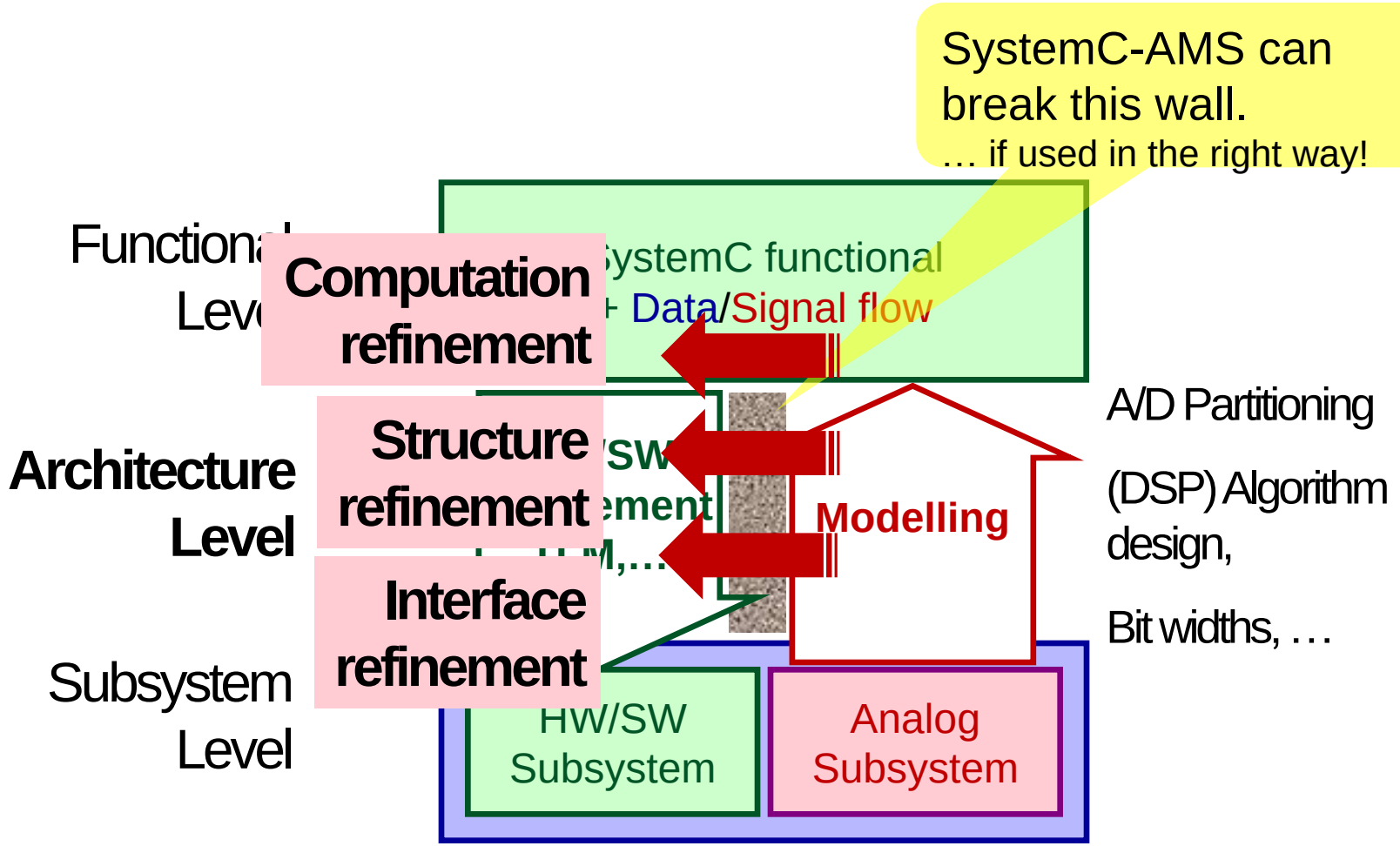
# Hierarchy example: RF frontend

```
SC_MODULE(frontend)  // SC_MODULES used for hierarchical structure
{
  sca_tdf::sca_out<double> if_out;     // use TDF ports to connect with
  sca_tdf::sca_in<double> rf, loc_osc; // TDF ports/signals in hierarchy
  sca_tdf::sca_signal<double> if_sig;  //
  mixer*    mixer1;
  low_pass* lp1;
  adc*      adc1;
  SCA_CTOR(frontend)
          {
    mixer1 = new mixer("mixer1");
      mixer1->in1(rf);
      mixer1->in2(loc_osc);
      mixer1->out(if);
    lpf1 = new lp_filter_ltf("lpf1");
      lpf1->in(if_sig);
      lp1f->out(if_out);
  }
}
```

# Refinement of Embedded Analog/Mixed-Signal Systems with SystemC-AMS

- Embedded Analog/Mixed-Signal Systems
- SystemC-AMS Overview
- Refinement methodology
- Outlook

# Refinement of E-AMS

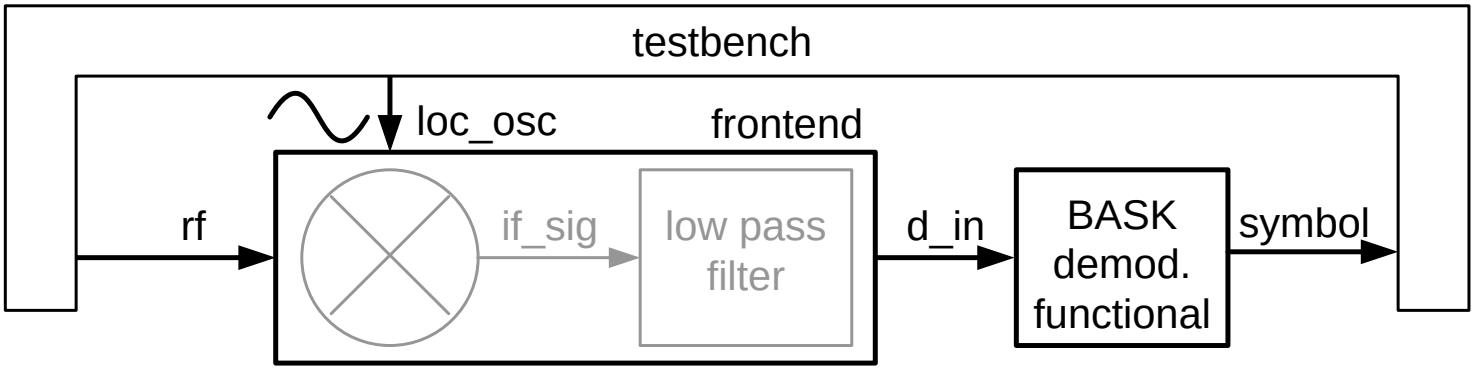


# Executable specification at functional level

**Executable specification**

- Check understanding of spec
- Adapt executable spec to match architecture!
- Data flow, signal flow MoC, double numbers

- **Example: BASK receiver (simple …)**



# Example: BASK receiver

**Frontend: code hierarchy example!**
**Very simple demodulator could be written as follows:**

```
SCA_TDF_MODULE(bask_demodulator)
{
  sca_tdf::sca_in<double>  in;
  sca_tdf::sca_out<bool>   out;
  void attributes()
  {
    in.set_rate(20000);            // port in has 20000 samples/timestep
    in.set_timestep(0.1, SC_MS);
    out.set_delay(1);              // port out is delayed by one timestep
  }
  void processing()                // Maps 20000 samples to 1 symbol
  {
    double val = 0.0;
    for (int i = 0; i < in.get_rate(); i++)
      val += abs( in.read(i) );
    if ( val>THRESHOLD ) out.write( false ); // THRESHOLD in header
    else out.write( true );
  }
  SCA_CTOR(bask_demodulator) {}
}
```

# Computation refinement (functional level)

1. **Successively add most important non-ideal effects**
   - Adapt model of computation to system partitioning (CT/DT)
   - Add noise, distortion, quantization, accurate step widths
   - Don‘t detail the rest – unless you have much time
2. **Evaluate overall system behavior, goto (1)**

**Example for refined mixer model:**

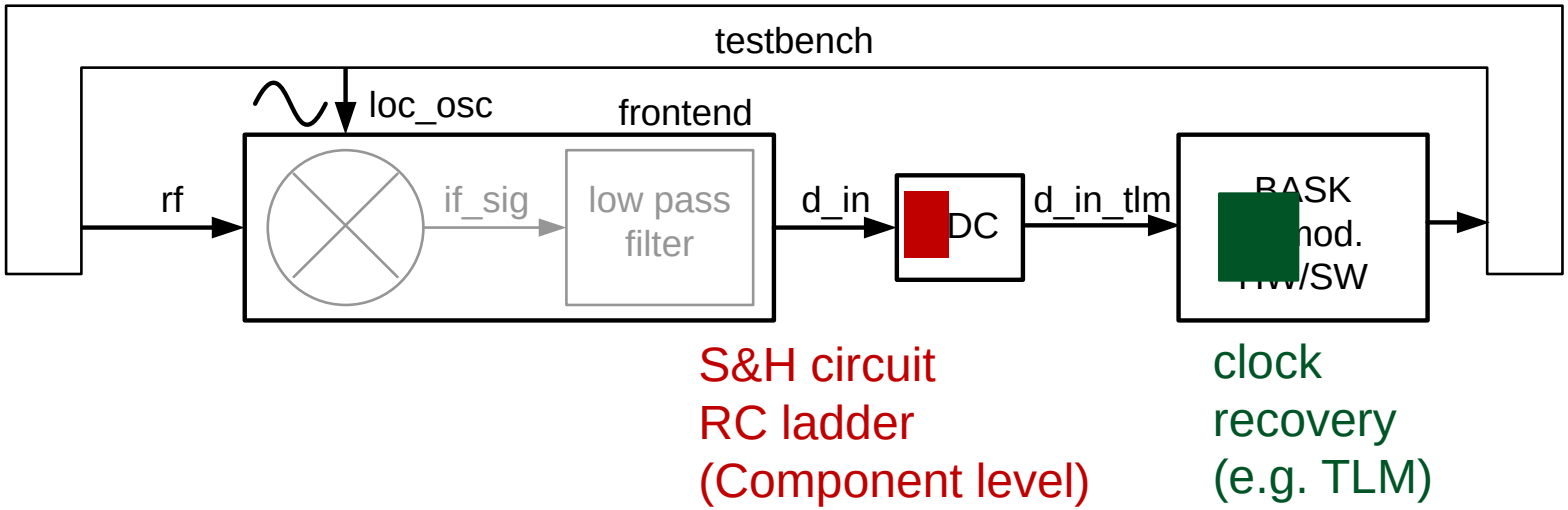
```
void processing()  // Mixer refined with distortions and noise
{
  double rf = in1.read();
  double lo = in2.read();
  double rf_dist = (alpha – gamma  * rf * rf ) * rf;  //alpha and gamma
  double mix_dist = rf_dist * lo;                     //user-defined
  if_out.write( mix_dist + my_noise() );
}
```

# Structure refinement at architecture level

**Structure refinement at architecture level:**

1. Adapt architecture to intended structure
2. Add more accurate components where critical
3. Evaluate architecture behavior, goto (1)

**Example BASK receiver:**



# Support by converter channels, adapters

- **Converter channels support structure refinement**
  - **Adaption of MoC & data types:** Encapsulate MoC/Data type converter in hierarchical channels („converter channels“)!

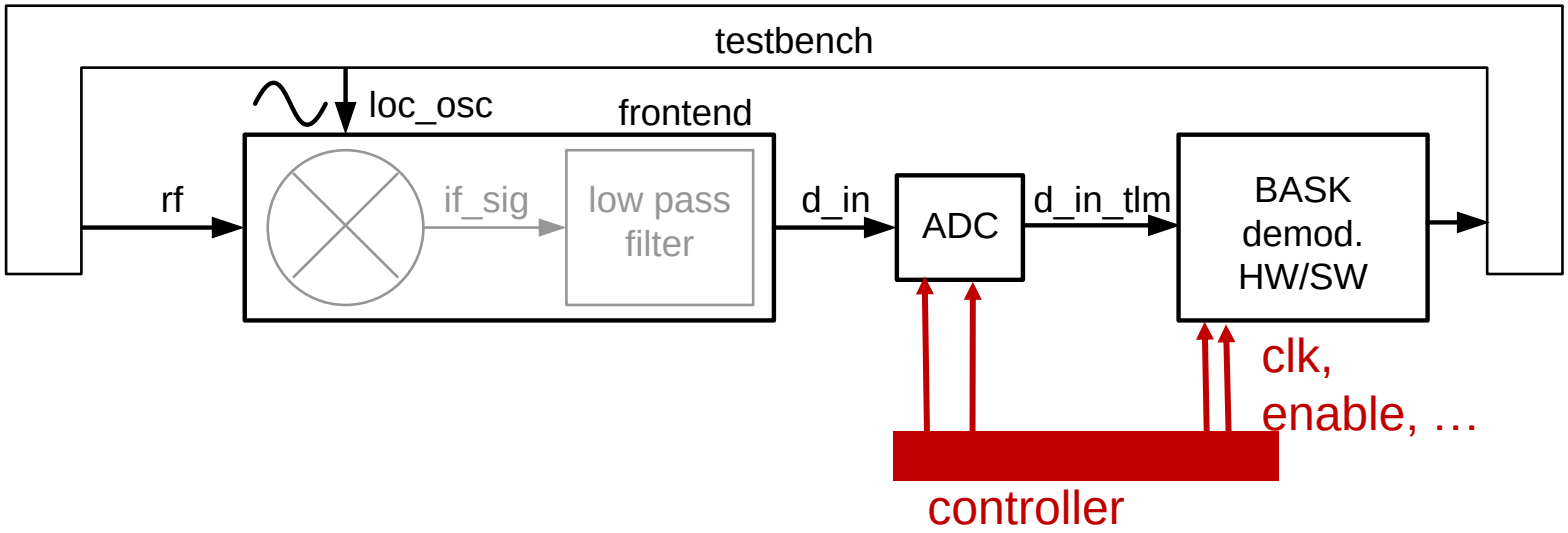

  - Also possible for TLM (not shown)

# Interface refinement at architecture level

**For design of subsystems & verification integration**

- Adapt signal types, add clk, enable, etc.
- Blocks are executable spec for subsystem design
- Model can be used for verification integration

**Example BASK receiver:**



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- **Converter channels support structure refinement**
  - **Adaption of MoC & data types:** Encapsulate MoC/Data type converter in hierarchical channels („converter channels“)!


  - Also possible for TLM (not shown)

- **Adapter translate 1-port signals to multi-port signals**

- **Adapter and converter channels can be seen as „AMS Transactors“**

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# Summary

- **SystemC-AMS supports seamless C-based flow for**
  - **executable spec**
  - **architecture exploration**
  - **integration validation**
  - **virtual prototyping**

- **Effective use requires integration of simulators for circuit design (Verilog, VHDL, SPICE,… ) → EDA vendors?**

# Outlook

- **Standardization in progress**
  - **You are invited to contribute!**
- **On agenda**
  - **RF/Baseband support**
  - **Nonlinear signal flow, nonlinear networks**
  - **physical domains**
- **At DATE:**
  - **TUESDAY 12:30-14:00 SystemC Interactive Forum**
  - **Contact**
    **Martin Barnasconi, NXP (AMS WG chair) or**
    **Christoph Grimm, TU Vienna (AMS WG vice chair)**

# Further information, References

- **www.systemc.org**
  (OSCI members only at the moment)

- **www.systemc–ams.org**

  (For information from  former SystemC-AMS SG, provides some information for the public)

- Alain Vachoux, Christoph Grimm, Karsten Einwich
  **SystemC Extensions for Heterogeneous and Mixed Discrete/Continuous Systems.**
  In: *International Symposion on Circuits and Systems 2005 (ISCAS '05)*, Kobe, Japan. IEEE, May 2005.

- Christoph Grimm: **Modeling and Refinement of Mixed Signal Systems with SystemC.** In: *SystemC: Methodologies and Applications*. Kluwer Academic Publisher (KAP), Juni 2003.