TOOL CHAIN FOR HARVESTING, SIMULATION AND MANAGEMENT OF ENERGY IN SENSORIAL MATERIALS

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ABSTRACT

The continuing decrease in size and energy demand of electronic sensor circuits allows endowing engineering structures and, to an increasing degree, materials with integrated sensing and data processing capabilities. Materials that adhere to this description, we designate sensorial materials. Their development is multi-disciplinary and requires knowledge beyond materials science in fields like sensor science, computer science, energy harvesting, microsystems technology, low power electronics, energy management, and communication. Development of such materials will benefit from systematic support for bridging research area boundaries. The present article introduces the backbone of an easy-to-use toolbox for layout of the energy supply of smart sensor nodes within a sensorial material. The fundamental approach is transferred from rapid control development, where a comparable Matlab/Simulink tool chain is already in use. The main goal is to manage limited power resources without unacceptably compromising functionality in a given application scenario. The toolbox allows analysis of the modelled system in terms of energy and power and allows analyzing factors such as energy harvesting, use of predictive power estimation, power saving (e.g. sleep modes), model-based cognitive data reduction methods and energy aware algorithm switching. It is linked to a simulation environment allowing analysis of energy demand and production in a specific application scenario. Its initial version presented here supports single self-powered sensor nodes. A broad set of application cases is used to develop scenario dependant solutions with minimum energy needs and thus demonstrate the use of the toolbox and the associated development process. The initial test case is a large scale sensor network with optical fibre based data and energy transmission, for which optimization of energy consumption is attempted. The toolbox can be used to improve the power-aware design of sensor nodes on digital hardware level using advanced high-level synthesis approaches and provides input for sensor node and sensor network level.

Key words: self-powered sensor nodes, energy harvesting, Energy Simulation, toolbox, smart energy management, sensor network, optical sensor network, sensorial materials.

1. INTRODUCTION

In recent years, microsystems technology and microelectronics have continuously shrunk the size of sensor network components. This development has led to concepts like Smart Dust, a vision of dust particle sized autonomous sensor nodes or motes incorporating communication devices and able to organize themselves in sensor networks when distributed in the environment – effectively, cubic-millimetre size was reached in 2001 (Warneke et al., 2001). Our own vision is about similar motes embedded in materials, thus endowing them with the ability to “feel”: We define a Sensorial Material as the combination of host material and motes (Lang et.al. 2011a, 2011b). There are multiple application scenarios for such materials, ranging from ambient intelligence to structural monitoring, the latter discussed e. g. by Renton in the same year that Warneke et al. published their work (Renton, 2001). One of the central issues that need to be solved both for Smart Dust and Sensorial Materials is energy and power supply. In a way, this challenge is more complex for the latter, as for Smart Dust, each mote usually has to be capable of coping with lack or excess of energy individually. In contrast, for Sensorial Materials, the problem can be addressed on different levels, e. g. in terms of local energy management on the one and network-wide energy management and distribution on the other hand. The example already illustrates the many similarities to sensor network energy supply in general. However, there are major discrepancies, too. For example, material-embedded sensor networks imply that there is little room to remedy a faulty design, as the system will not be accessible for addition of, say, the extra battery later found out to be necessary. Thus Sensorial Materials require comprehensive development tools to analyze their energetic situation throughout their life cycle, and under all conceivable service conditions.

Sketching the development and evaluation of a dedicated toolbox which combines all aspects of energy supply as backbone of such a development, and at the same time as optimization environment, is the main concern of this study. This integrative approach responds to a major need, as is underlined e.g. by the 2011 IDTechEx report on energy harvesting markets, which predicts a considerable market growth, while at the same time lamenting that “there is exciting enabling technology but many component suppliers sell horizontally when users want solutions, not components” (Das, 2011). Our approach is to adapt rapid control prototyping methodologies established in measurement system layout for this purpose.

Every designer of measurement systems dealing with battery- or self-powered systems has to consider the energy behavior. Most classic measuring devices were designed to work on constant power supply. Future methods for Sensorial Materials are varying from low power design, adapting power consumption and energy management to self-organisation, self-localisation, fault tolerance, cognition, and grid intelligence. These options, however, are very often discussed on an individual basis (Mathuna et al., 2008), while the basis for a comprehensive methodology including all of them and specifically also their interdependencies in relation to a realistic application scenario is completely missing.

A typical approach in system development is to calculate the system’s power behavior and to assure that the supply will never drop below the needed power of the loads. This is often done by evaluating worst case scenarios, like a dark cloudy day for solar powered devices. Adding safety factors will ensure there is always a surplus of power, but at the cost of greatly oversizing the system for the specific application. In borderline cases feasibility is often judged negatively by such calculations. In these cases, adapting the measurement task to available power using energy based scheduling, adjustment of sample rate, or more sophisticated adaptive calculation algorithms for leveled data processing is preferable. Simulations of energy flows then have to show that the systems will not fail in a realistic environment. These simulation results are often used to adjust the layout parameters of the system.

Experienced system designers will claim that an optimal solution depends on the special circumstances of the individual measurement task. Thus for self-powered measurement nodes the system design cannot be transferred directly from one application to another.

Thus the toolbox represents a major support to the layout of Sensorial Materials. It will consist of a simulation toolkit for energy flows and a tool for designing modular sensor systems with an emphasis on self-powered systems.

The aim is to support the layout of interconnected and interacting energy supply, conversion, storage and consumer components (including data processing). To this end, the toolbox contains generic component blocks implemented in Matlab/Simulink. They should be easy to use for a measurement systems designer to layout single sensor nodes as well as sensor meshes and networks of autonomous sensor nodes.

Advanced methods and technologies like

- adaptive data processing
- energy management
- and generation of specific hardware design

will be added at a later stage to complete the features of the toolbox. The basic algorithms are developed on state-of-the-art low-power microprocessor architectures. The development road map of the toolbox ranges from microcontrollers to programmable logic (FPGA) and later on to special custom chips (ASIC) (see Figure 1).

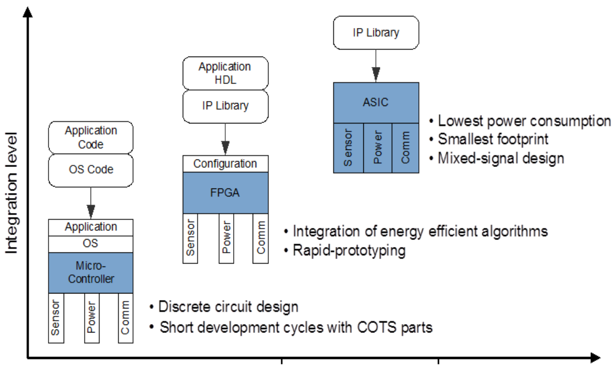

Figure 1 Toolbox development plan

There are many possible scenarios for self-powered sensor applications (Bartholmai M and Köppe E, 2010; Moser C, 2009; Budelmann C and Krieg-Brückner B, 2011). Some potential scenarios that could be analysed and parameterized by the use of the proposed toolbox are discussed in the following sections.

2. SENSOR NODES

In the context of this paper sensorial abilities should be integrated in a single sensor node. A sensor node could realize one or more measurements and could be supplied by single or multiple sources.

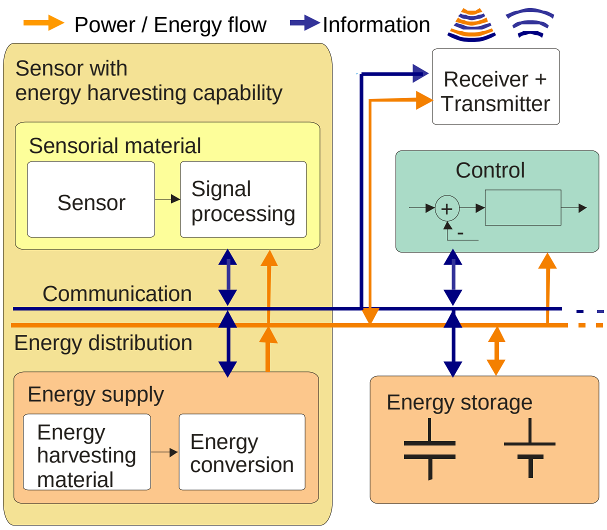

Figure 2 Example setup for a sensor node as a part of a sensorial material

Figure 2 shows an example for implementing Sensor nodes. The model of a sensor node can be divided into the parts data (acquisition, processing and communication) and energy (supply, storage, consume). Though the research activities also focus on the optimisation of data processing and communication with respect to energy consumption, this paper will concentrate on modelling, simulation and analysis of the energy branch.

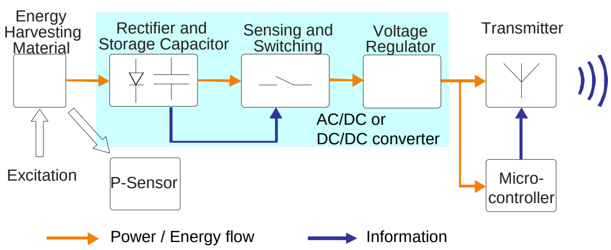

Figure 3 Example for a radio based sensor node with devices for energy harvesting and sensing

For most self-powered applications the energy provided by the energy harvesting device has to be converted. In Figure 3 a more detailed view of a power system for a sensor node is displayed. Power flow from the triggered harvester is converted to higher voltage levels and normally charges a small capacitor. When a certain voltage level is reached the following circuit activates the main functions of the sensor node. A voltage regulator is used to provide constant conditions for the parts of the node like measurement unit, processor/micro controller and if needed a radio transmitter.

3. TOOLBOX

The structure of the toolbox is in accordance with the node scheme depicted in Figure 2 and ordered from the energy's point of view (Figure 4).

Energy Sources
- + Batteries
- + Ideal Sources
- + Inductive/Magnetic
- + Mechanical
- + Piezo Electric
- + Photo Electric
- + Thermal Electric
- + Transformators

Energy Converters
- + AC/DC
- + DC/DC
- + Voltage Regulators
- + PWM
- + Amplifier

Energy Storage
- + Accumulators
- + Capacitors

Energy Consumers
- + Actuators
- + Microcontrollers
- + Sensors
- + Radio Modules
- + Illuminants

Figure 4 Structure of toolbox

For each element there are generic blocks in the structure to cover the main functionality. Special parts can be derived and added to the Library.

A mask in Simulink can be provided as a GUI for setting parameter values comfortably, which is then connected to constant variables inside the block model implemented in Simulink. (Mathworks, 2010)

All blocks of this toolbox are masked for convenience e.g. to parameterize the block according to the data sheet (see Figure 6).

In the next chapters some exemplary implementations are described to show the basic structure of the toolbox.

3.1. **Energy Sources**

The energy sources group covers the different possibilities for providing energy to the sensor system. In conventional design there is a constant source always providing enough power. This tool enables the user to tailor the ratings for average and maximum use. For the possibility of environment-dependant energy sources the blocks have the ability to be controlled by environmental conditions, e.g. solar radiation to a photovoltaic cell.

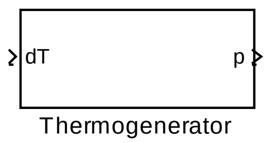

Figure 5 Thermoelectric generator block

Another scenario uses a thermoelectric generator (see Figure 5) which converts temperature differences directly into electrical energy using the thermoelectric effect.

It is modelled as an ideal module, neglecting contact resistances (Figure 6).

The power output is calculated as:

$$P = \left(\frac{\alpha \cdot \Delta T}{R_i + R_L} \right)^2 \cdot R_L$$

(Yadav, A., Pipe, K.P. and Shtein, M., 2008)

with:

- α the Seebeck coefficient/thermo-power
- ΔT the temperature difference between the two sides
- R_i the internal resistance
- R_L the external resistance

For quick approximation there is also the option of calculating the generated energy as:

$$P = \frac{P_{ref}}{\Delta T_{ref}^2} \cdot \Delta T^2$$

(Mastbergen, D. and Willson, B., 2005)

This can be applied when there is a reference power output given at a reference temperature difference.

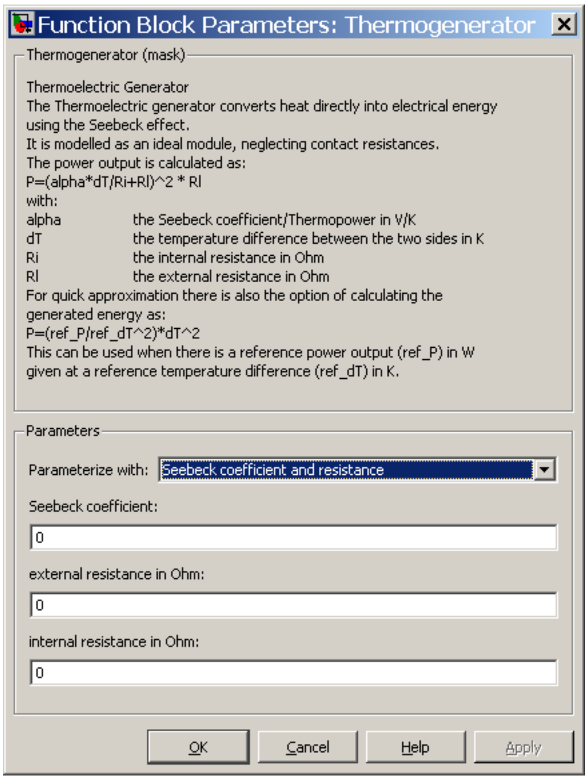

Figure 6 Block parameters thermogenerator block

3.2. **Energy Converters**

Components for converting and regulating energy flows are technically mandatory. Focussing on the energy the most important fact is that these devices have losses and so the loss of power has to be calculated. Most modern devices like DC/DC converters etc. use switched power operation. A generic approach for calculating losses without implementing the real operation is sufficient at the level of systems definition and could be recalculated when the hardware layout is fixed.

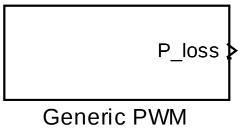

Figure 7 Generic PWM

The generic PWM (pulse width modulation) block models the power consumption due to the electrical resistance of the switch when in "on" position and switching losses.

The power consumed is calculated as

$P_{loss} = t_{switch} \cdot f_{pwm} \cdot U \cdot I + \overline{I}^2 \cdot R_{on}$ (Graovac D and Pürschel M, 2009)

with:

- t_{switch} time needed to switch between on and off
- f_{pwm} switching frequency
- U voltage of the power source
- I current at maximum voltage
- $\overline{I}$ average current
- R_{on} ohmic resistance of the switch when in "on" position

The output port provides information on power consumption.

3.3. **Energy Storage**

The generic capacitor block contains a simple model of a capacitor. The equivalent circuit is shown in Figure 8.

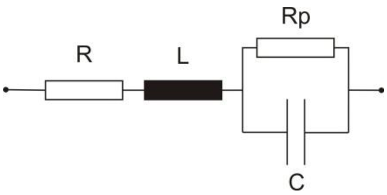

Figure 8 Equivalent circuit of a generic capacitor

The series resistance *R* represents effects of dielectric losses and conductor resistance. The capacitor inductance is represented by the series inductance *L*. The parallel resistance *Rp* models leakage current flow and self-discharge.

These values have to be entered into the block's input mask. If the value of the series resistance is unknown, the dissipation factor $\tan \delta$ and the corresponding frequency can be entered instead.

Note that the time needed for self-discharge is approximately *5RC*. An initial voltage across the capacitor can be entered in the mask.

3.4. **Energy Consumers**

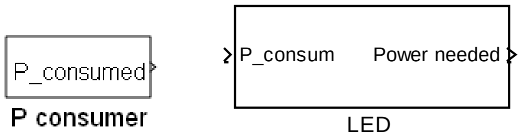

Figure 9 Consumer and LED block

The block consumer (Figure 9) provides generic constant power consumption. It is a good way to estimate the component's energy demand by using datasheet's values. It is useful for modelling components which have not been modelled in detail yet.

The LED block models a generic light emitting diode. The input signal specifies the power provided to the LED. The "output port" signal carries the information on power consumption of the LED to glow with the desired intensity.

4. TOOL CHAIN APPLICATION SCENARIO

A first field test is aimed at optimizing the energy management of small sensor nodes within the SMaLL project developed by the DFKI and other partners at the University of Bremen (Budelmann, C. and Krieg-Brückner, B. 2011). The electronic sensor nodes are interconnected only by an optical fiber which is used for data exchange and energy transfer. Local energy supply or storage is not necessary, making the sensor nodes completely maintenance-free and ideal for the integration into materials.

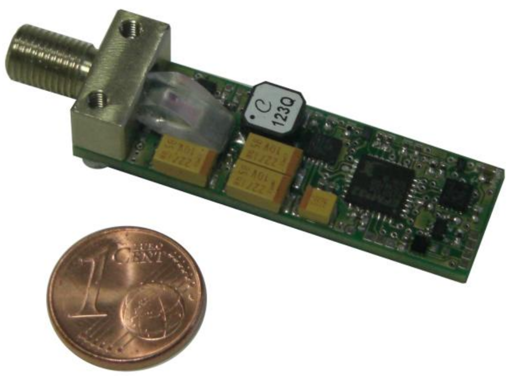

Figure 10 Prototype of the SMaLL sensor node

Figure 10 shows the first prototype of the SMaLL sensor node, which has several sensor units onboard to explore the range of applications. It already offers reduced power consumption by using low power hardware and advanced energy saving sleep modes.

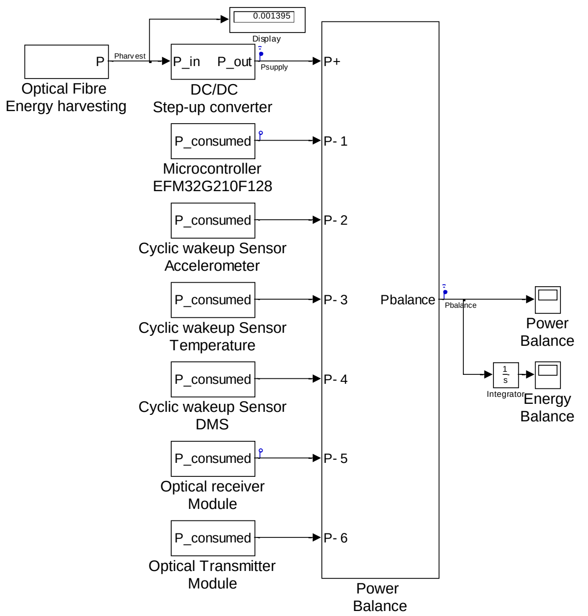

Figure 11 Power model of a multi sensor node

Most of the modelled components are dominated by a sleep schedule executing a cyclic wake up reducing energy demand by an estimated duty cycle of 1:100.

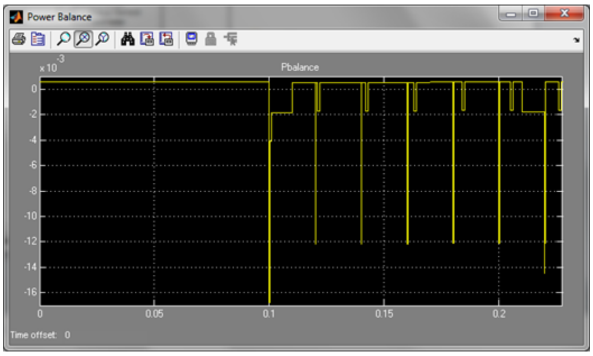

Figure 12 Power balance

When in operation the sensor node's power balance is strictly negative. In order to drive the system directly, a 17 times (see Figure 12 at graph minimum) stronger light harvester would be needed to match the short term power demand.

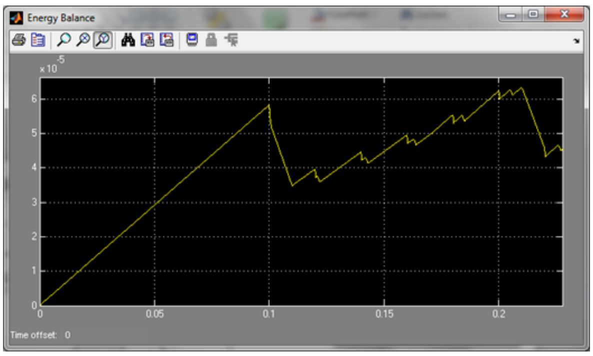

Figure 13 Energy trajectory

When introducing an energy storage device, the overall energy trend is positive, proving that the original power supply is sufficient.

The application of the analysis tool has supplied valuable information about the layout of the sensor node's power system by showing the dynamic energy flows of the different components.

5. ENERGY MANAGEMENT ON ALGORITHMIC AND CHIP LEVEL

Typically, energy management is performed by a central controller in which a program is implemented (Lagorse 2010), with limited fault tolerance and the requirement of a well-known environment world model for energy sources, sinks, and storage. Energy management in a network can additionally involve the transfer of energy between network nodes.

System-on-Chip hardware design using advanced high-level synthesis approaches on higher algorithmic level can improve energy management and power efficiency based on results from toolbox analysis. Models and model parameters provided by the toolbox can be used for algorithm design and hardware synthesis.

5.1. Energy Management on Node and Micro-chip Level

Energy management can be performed firstly at runtime and secondly at design time by using application-specific System-On-Chip (SoC) design methodologies, contributing to low-power systems on both algorithmic and technology level. The proposed tool chain offers advanced capabilities for energy management on algorithmic level by analyzing algorithms regarding to their impact to power consumption. Smart energy management can be performed spatially at runtime by a behaviour-based or state-action-driven selection from a set of different (implemented) algorithms classified by their demand of computation power and different quality-of-service, and temporally by varying data processing rates.

Signal and control processing is modelled on abstract algorithmic level using signal flow diagrams, shown in figure 12. These signal flow graphs derived from the toolbox can be mapped to Petri Nets to enable direct high-level synthesis of digital SoC circuits using a multi-processing architecture with the Communicating-Sequential-Process model on execution level and the high-level synthesis framework ConPro (Bosse, 2011).

Power analysis using simulation techniques on gate-level provides input for the algorithmic selection during runtime and improvement of energy management of the system at design time leading to a closed-loop design flow. Additionally, the signal-flow approach enables power management by varying the signal flow rate parameters.

The signal flow diagram is first transformed into a S/T Petri Net representation. Functional blocks are mapped to transitions, and states represent data which is exchanged between those functional blocks. The partitioning of functional blocks to transitions of the net can be performed at different composition and complexity levels. The signal flow diagram is partitioned using complex blocks (merging low-level blocks like multipliers and adders) to reduce communication complexity (and data processing latency).

Sensor data (I) is acquired periodically and passed to the data processing system. A token of the Petri Net is equal to a data set of one computation processed by the functional blocks in the signal flow. Functional blocks can be placed in concurrent paths of the net.

The Petri Net is then used firstly to derive the communication architecture, and secondly to determine an initial configuration for the communication network. Functional blocks with a feedback path require the injection of initial tokens in the appropriate states (not required in the example).

States of the net are mapped to buffered communication channels and transitions are mapped to concurrently executing processes - each with sequential instruction processing - using the ConPro programming language (Bosse 2011).

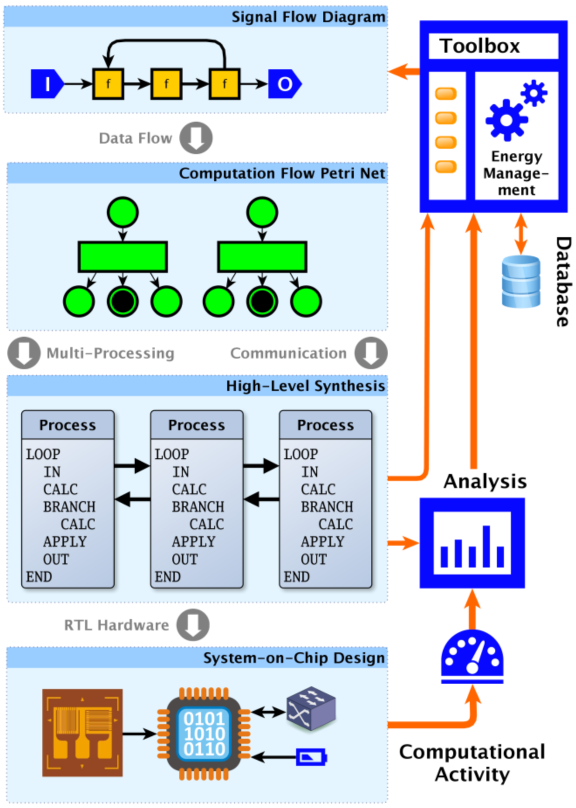

Figure 12 Power efficient System-on-Chip hardware design using high-level synthesis and smart energy management on node level using the tool chain in a feedback loop.

Energy Forked states indicate concurrency in the Petri Net flow. Exploring concurrency in signal flow diagrams using Petri Nets reduces latency for the computation of one data set. Also pipelining can decrease latency of a data set stream significantly, derived again from the Petri Net representation.

The derived multi-process programming model is finally synthesized to a digital logic SoC using the high-level synthesis, shown in figure 12. For simulation, gate-level synthesis is performed with a standard logic cell technology library. The resulting net-list is analyzed with an event-driven simulator, calculating the overall cell activity for each time unit, defined by terms of cell output changes, enabling power optimization on algorithmic level.

Methods from artificial intelligence (AI) can be used to manage energy at runtime with dynamic parameter adaptation and algorithmic selection based on results from previous algorithm analysis. AI methods differ in complexity, thus only few are suitable to be embedded in microchips, like decision trees (Bosse 2012B).

5.2. **Management on Network Level**

In a sensor network energy management can take place locally on each sensor node and globally covering the sensor network in whole. Locally energy consumption is minimized, but globally energy can be transferred between nodes to increase system stability. Again, AI methods can be used to manage energy globally in the sensor network. Having the technical abilities to transfer energy between nodes using communication channels (for example optically, like in the SMaLL sensor node), it is possible to use active messaging to transfer energy from good nodes having enough energy towards bad nodes, requiring energy.

Initially, the sensor network is a collection of independent computing nodes. Interaction between nodes can be implemented by using agents to manage and distribute information and energy. Agents are capable of being implemented on micro-chip level (Bosse 2012A), shown in figure 13.

An agent can be sent by a bad node to explore and exploit the near neighbourhood. The agent examines sensor nodes during path travel or passing a region of interest (perception) and decides to send agents holding additional energy back to the original requesting node (action). Additionally, a sensor node is represented by a node agent, too. The node and the energy management agents must negotiate the energy request.

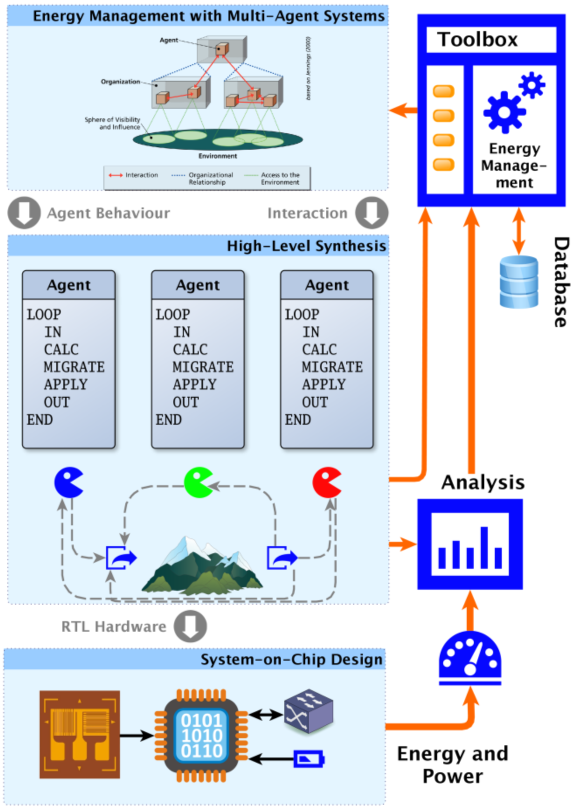

Figure 13 Design of smart energy management algorithms with Multi-Agent Systems on network level using the tool chain in a feedback loop.

The toolkit analysis can provide required input for the global energy management strategy performed by multi-agent systems, for example retrieved by machine learning methods based on analysis and experimental results.

6. CONCLUSION

The described tool chain is now capable of simulating and analyzing simple scenarios for the parameterisation of self-powered sensor nodes. As it is meant as a tool for a measurement systems designer outlining new scenarios for measurement applications, its usage is deliberately kept simple and generic. For a full simulation of e.g. the electric circuit (SPICE) or communication issues over wide spread wireless sensor networks other tools are more powerful and accurate. But these tools are limited in scope, requiring e. g. a defined hardware or an exact specification. The toolbox can contribute to the process of defining and designing the right hardware configuration. The specific focus on energy harvesting principles enables the process of exploring the area of self-powered sensors and sensorial materials. The tool chain can improve and support the hardware design of sensor nodes and the design of energy management algorithms including smart energy managements strategies on sensor node and network level.

7. OUTLOOK

As next step, the fundamentals of the realization of the tool chain will be published together with tutorials and comprehensive sample scenarios. In parallel, a platform for scientific discussion on performance and implementation of the modules will be set up. This will provide the basis for future versions incorporating contributions from the scientific community. The final aim is a powerful, yet living tool for the measurement systems and sensorial materials designer alike, who may be experienced either in materials science, power systems, energy management, computer science and communications, but usually not an expert in all of them and will thus profit from contributions of experts in complementary fields. Additionally, the tool chain will cover data processing, energy management and low level communication on micro-chip level. From this basis, automated generation of code for microcontrollers and configurable hardware will enable rapid sensor system prototyping following a development process similar to rapid control prototyping. The tool chain will then span the full range of energy-related system components and functions from sensor signal capture and conditioning via data evaluation and energy harvesting to communication, and it will allow testing of various combinations under realistic conditions as well as finding optimum solutions for given boundary conditions.

8. ACKNOWLEDGEMENTS

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