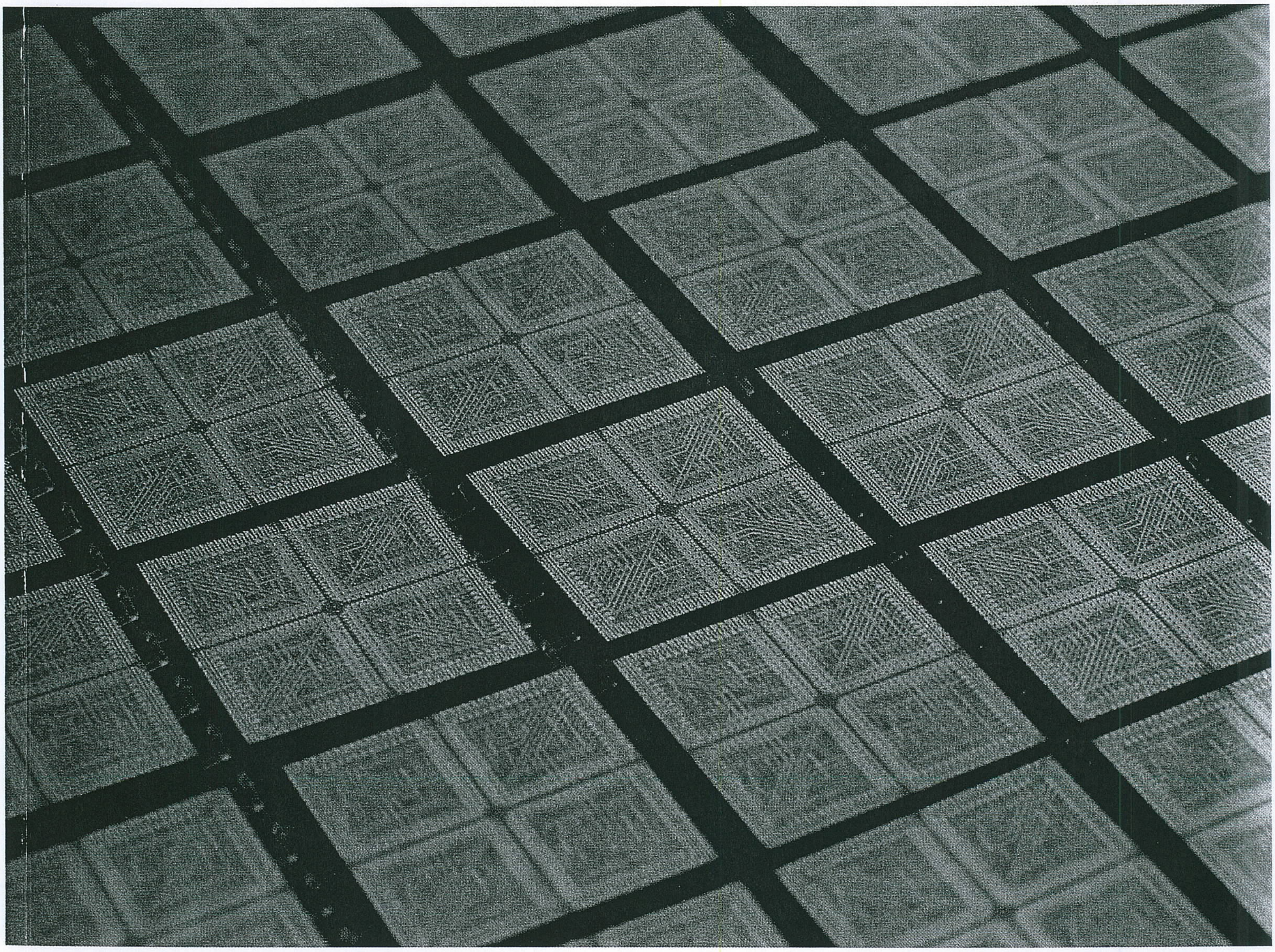
Schriftenreihe
Nr. 56

OVE

Tagungsband zur

Informationstagung
Mikroelektronik 10



Herausgeber:
Erich Gornik, Christoph Grimm,
Bernhard Jakoby, Karl Riedling,
Erwin Schoitsch

IEEE
AUSTRIA SECTION

Tagungsprogramm

Mittwoch, 7. April 2010	
09:30	Registrierung
09:45	Eröffnung
10:00	**Nanoelectronics** **Begrüßung, Eröffnung** *Erich Gornik / Karl Riedling*
	Geladener Vortrag **Prospects of Semiconductor Nanowires for Nanoelectronics** *Lars Samuelson, Semiconductor Electronics, Lund University, Sweden*
	UV-imprint lithography for advanced micro – and nanostructuring *Elisabeth Lausecker*
	La_2O_3/ZrO_2 – A gate dielectric stack for the 22 nm node and beyond? *Stephan Abermann*
11:20	Kaffeepause
11:40	**3D systems integration and its importance for the European microelectronics industry** *Martin Schrems*
	Integration of laser-annealed junctions in a low-temperature metal-gate MISFET process *Lis Nanver*
12:40	Mittagsbuffet, Postersession (Posterliste siehe Anhang)
14:30	**Industrielle Elektronik und Sensorik** **Begrüßung, Eröffnung** *Bernhard Jakoby*
14:35	Keynote Speaker **Highly-Integrated Multi-Channel Radar Transceivers with Electronic Beamsteering Capabilities in SiGe Technology** *Andreas Stelzer, Johannes Kepler Universität*
15:15	**Posterpräsentationen**
	Density sensor for application in a gas phase polymerization process based on quartz crystal resonators *J. K. Sell et.al.*
	Optimization of an EWOD Platform for 2D Droplet Translations utilizing - Cross-Reference Electrodes *Thomas Lederer et.al.*
	Charakterisierung und Regelung eines MOEMS Translationsaktuators *Martin Lenzhofer, et. al.*
	Energieautonomer Funknetzwerkknoten für Luftfahrzeuge *Dominik Samson, et. al.*
	12-Bit Digital-Analog Konverter mit kombiniertem Kapazitäts- undWiderstandsnetzwerk *Milos Davidovic, et. al.*
	CO_2 Measurement with a Simple Designed Bolometer *Johann Mayrwöger, et. al.*
	Modelling of a micro–rheometer in the spectral domain *Thomas Voglhuber–Brunnmaier, et. al.*
	Ein präziser unterabtastender Impedanzanalysator für resonante Sensoren *Alexander O. Niedermayer, et. al.*
	Q-foil – a new large area 2d position sensitive photodetector technology *R. Koeppe, et. al.*
	Design of BioMEMS for HIV/AIDS Detection *Ioanna Giouroudi et. al.*
	Remote Contactless Photoacoustic Imaging *Armin Hochreiner, et. al.*
	Computerunterstützte Entwicklung einer auf Strömungssensoren basierenden PC-Maus *M. Forstner, et. al.*
	Verfahren zur zerstörungsfreien messtechnischen Ermittlung der Belastungsgrenzen von DMOS Leistungstransistoren *Klaus Hörmaier*
	Laser ultrasonic measurements of metal thickness using a photorefractive crystal *Saeid Zamiri, et. al.*
	Impact of Doping on the Selectivity Performance of Tin Oxide Nano Gas Sensors *Alexandra Zima, et. al.*
	OPTIX: Optical Technologies for the Identification of Explosives *Bernhard Zachhuber, et. al.*
	FEM-basiertes Design eines miniaturisierten TOF-Strömungs-sensors *S. Čerimović, et. al.*
	Analyse der Dämpfung in Mikrostrukturen mit kleinen Dämpfergeometrien *M. Sachse, et. al.*
	Systematische Studie der Druck- und Geometrieabhängigkeit des Gütefaktors von mikromechanischen Cantilevern *Michael Stifter, et. al.*

	Broadband Baseband Amplifier for a Direct Conversion Measurement Receiver *Michael E. Gadringer, et. al.*
	Improved multi-lamination micromixer with wedge shaped channel inlets for time resolved FTIR spectroscopy *Wolfgang Buchegger, et. al.*
	Energieautarke drahtlose Sensornetzwerke für landwirtschaftliche Maschinen *Gerhard Müller, et. al.*
	Position Control of a Microfluidic Sample Stream *Nicola Ladisa, et. al.*
	Contact Imaging for Microfluidic Applications *Nicola Moscelli, et. al.*
	Stationäre und transiente Analyse miniaturisierter Strömungssensoren mit sehr niedriger Leistungsaufnahme *A. Talić, et. al.*
16:30	Kaffeepause
16:45	**Poster Session**
17:45	**Schlussworte** *Bernhard Jakoby*
19:00	**Conference Dinner im Melker Stiftskeller** Dinner Talk: *Malcolm Matson, The OPLAN Foundation*
Donnerstag, 8. April 2010	
09:00	**Embedded Systems** **Begrüßung, Eröffnung** *Erwin Schoitsch / Christoph Grimm*
09:05	Keynote-Talk **Design Methodologies in the Era of Embedded Systems** *Daniel Gajski (UC Irvine, USA)*
09:50	Kaffee
10:00	**Session 1** **Towards Generation of Efficient Test Cases from UML/OCL Models for Complex Safety-Critical Systems** *Wolfgang Herzner, Rupert Schlick, Harald Brandl, Willibald Krenn*
	Towards Fault Injection Based Minimal Cut Sets Generation *Rickard Svenningsson, Jonny Vinter, Henrik Eriksson, Martin Törngren*
	Sequential Design of Experiments for Effective Model-based Validation of Electronic Control Units *Monica Rafaila, Christian Decker, Georg Pelz, Christoph Grimm*
	A range based method for Noise Analysis of mixed A/D Communication Systems *Kangseok Lee, Florian Schupfer, Christoph Grimm*
	Identifikation, Authentifizierung und Schlüsselgenerierung mittels Physical Unclonable Functions (Poster mit Short Presentation) *Maximilian Hofer, Christoph Böhm, Holger Bock*
11:30	Kaffee, Poster (siehe Anhang)
12:00	**Session 2** **Functional Safety: The new standards of IEC 61508 Ed. 2 and ISO 26262 (Automotive) - a comparison and new features** *Erwin Schoitsch*
	A Novel Reconfigurable Architecture for Wireless Sensor Network Nodes *Johann Glaser, Jan Haase, Markus Damm, Christoph Grimm*
	Formale Verifikation von Embedded Systems Software *Thomas Reinbacher, Martin Horauer*
	A Common Design Architecture Approach to Vehicle to Vehicle, Vehicle to Infrastructure Communication Systems *Ömer Karacan*
	System-Testumgebung für die verteilte Automobilelektronik (Poster mit Short Presentation) *Oliver Praprotnik, Martin Zauner*
	Model-Based Design und Automatische Codegenerierung in der Industrieautomation (Poster mit Short Presentation) *Philipp H.F. Wallner*
13:30	**Abschlusssession** (Best Paper Award pro Themenfeld: Nanoelectronics, Elektronik und Sensorik, Embedded Systems)
13:50	Quick Lunch
15:30	Ende der Veranstaltung

A range based method for Noise Analysis of mixed A/D Communication Systems

Kangseok Lee, Florian Schupfer, Christoph Grimm
Institute of Computer Technology, Vienna University of Technology
{lee, schupfer, grimm}@ict.tuwien.ac.at

Abstract

Noise, which has influence on performance, reliability and durability of systems, is a fundamental system property. Especially, in cases of mixed Analog and Digital (A/D) communication systems, effects of noise can cause erratic behavior such as missed processor operations or imprecise signal representations. However, unfortunately it is impossible to avoid noise in practical systems completely. Therefore system designers need to consider carefully its impact on the system prior developing it, to guarantee the correct operation and performance of the system. Recently, various articles and studies about methods for noise analysis have been released. The result of a noise analysis and simulation can be a criterion to decide specific system properties. However, improvements are needed to support the analysis, modeling and simulation of noise. In this paper, we provide a range based method for a noise analysis which models and simulates noise of a simple example system by using affine arithmetic in conjunction with the simulation environment SystemC AMS. [1]

1 Introduction

By using microcontrollers, additional sources for noise, such as quantization, round-off and truncation errors are typically introduced. However, although unwanted no possibility to completely remove noise from the system exists. In fact, it follows the same path than the input data and consequently is amplified and attenuated according the algorithmic process of the system. This can cause erratic behavior when the noise influences the system in a way that the output violates the expected signal ranges or that weaker system signals are overlaid by the noise signal. Especially, in cases of mixed Analog and Digital (A/D) communication systems, effects of quantization noise can be the cause of critical faults such as missed processor operations when influencing control relevant signals. That is one of the reasons to analyze the effect of noise on the system before actually developing it.

In recent time, studies about reducing system noise and generally analyzing its influence are evolving. Especially there is a significant research effort about modeling the various aspects of noise to make it analyze able. One approach to model, verify and optimize the bit width of a system to reduce quantization noise is to use the concept of affine arithmetic (AA) [1],[7]. Also, symbolic analysis [2] or even formal verification [3] can provide more insight and reliable results for the analysis of system noise.

One of the main objectives of system designers is, to find the optimum system parameters. For example, to find optimization statements about the relationship between analog to digital converter (ADC) resolution and the noise caused by the quantization error on the system. High resolution ADCs will reduce this contribution, but will stress the project budget by its higher costs. An ADC converts analog signals to its digital counterparts for using them in algorithms or control loops of digital processors such as microcontrollers. Converting analog signals to digital signals generates additional quantization noise. Dynamic parameters which estimate the level of noise contributionss are Signal-to-Noise Ratio (SNR), Signal-to-Noise-and-Distortion (SINAD), Total Harmonic Distortion (THD) and Spurious-Free Dynamic Range (SFDR), respectively.

In this paper we simulated the effects of quantization noise on the system behavior, by tracking the SNR of the system, caused by the quantization error of the signal converter, through some simple digital filter examples.

We modeled and simulated the digital filter system which represents a possible signal processing design by using SystemC AMS. Additionally the quantization error of the signal converter part is modeled by using affine arithmetic in the SystemC AMS environment.

The main contributions of this paper are as follows:

- To model, simulate and track the impact of noise on the system with affine arithmetic and SystemC AMS.
- To find an optimum system property, for our example a signal resolution, by analyzing the results of the simulation and the tracking of the noise.

2 Specification and Modeling with Affine Arithmetic

Affine Arithmetic (AA) [5] which is an improvement of the standard Interval Arithmetic (IA) [11] is a method

[1] This research project is funded by “Wiener Wissenschafts-Forschungs und Technologiefonds - WWTF”.

that allows modeling for a self-validated numerical analysis. IA often yields an interval that is much wider than the exact range of the computed function, which is called an over-approximation. That means it widens the signal interval at every computation point due to the uncorrelated nature of the interval representatives even when subtracting identical intervals.

AA deals with that so called dependency problem of IA as mentioned above, by labeling the single ranges with identifiers. This allows correlated computations of the ranges which deliver also reduced resulting intervals when performing subtractions of correlated ranges.

In each affine expression, $\hat{x}$ is represented as a sum of an 'ideal' or central value x_0 and a sum of partial deviation terms $x_i\varepsilon_i$. The ε_i are unknown values from the interval [-1, 1], and the partial deviations x_i scale the sources of uncertainty. One symbol ε_i may contribute to the uncertainty of two or more quantities in the system. The sharing of symbols ε_i among two affine forms $\hat{x}$, $\hat{y}$ indicates some partial dependency in the corresponding quantities. As a result, the basic AA and its mathematical operations are defined as given below

The basic AA form is defined by:

$$\hat{x} = x_0 + \sum_{i=1}^{n} x_i\varepsilon_i\,, \qquad \varepsilon_i \in [-1,1]$$

Basic mathematical operations are defined by:

$$\hat{x} \pm \hat{y} = (x_0 \pm y_0) + \sum_{i=1}^{n} (x_i \pm y_i)\varepsilon_i$$

and

$$c\hat{x} = cx_0 + \sum_{i=1}^{n} cx_i\varepsilon_i$$

We get formally precise limits with no additional over-approximation as results of the above affine operations. Non affine operations, one which differ from the above operations, can be principally defined and are formally precise, but usually introduce over-approximation to safely include the resulting quantity. Such over-approximations present a limitation of the system simulation expressiveness and must therefore carefully be considered.

3 Modeling and Implementation of Uncertainties

In this paragraph, methods for modeling typical uncertainties and deviations are discussed and presented. Effects of mixed-signal systems, which typically contain analog and digital signal processing components as well as signal converters parts, are considered [4],[6],[10].

All these effects are modeled by summarizing ranges to affine terms which represent uncertainties to a signal as following:

$$\hat{y} = y_0 + \sum_{i=0}^{m} y_i\varepsilon_i$$

Herein we will refer to the actual quantities with the letter *y*, to distinguish it to the formal definition of an affine form which we earlier denoted as *x*. Static uncertainties such as tolerances as well as dynamic uncertainties such as noise can be described by its ideal value and additional deviations. In the case of static uncertainties, they can be represented by adding one constant deviation to an ideal signal. Contrary, in the case of dynamic uncertainties, they are modeled by adding a range value to the ideal signal at every simulation time. In this case, $\varepsilon[n]$ are extended with an index to access the noise symbols at a given point in time *n*.

In the following section we discuss methods for modeling typical uncertainties of a non-ideal implementation by adding affine terms to a signal $\hat{y}$.

Production tolerances: Analog implementations often have a static deviation $\pm e$ from the ideal behavior. It can be modeled by adding a term $e\varepsilon_{m+1}$:

$$\text{tol}\,(\hat{y}, e) = \hat{y} + e\varepsilon_{m+1}$$

Quantization: Quantization can be expressed by adding a noise symbol ε_{m+1} with a partial deviation of a half quantization unit $Q/2$ which represents the model of the worst case deviation. Also truncation of numerical operations, found in multiplications can be handled in the same way.

$$\text{quant}\,(\hat{y}, Q) = \hat{y} + \frac{Q}{2}\varepsilon_{m+1}[n]$$

Noise: Noise is a dynamic uncertainty. We can express the noise term by using the standard deviation as partial deviation of γ_i. A simple model for white noise is modeled with a sequence of statistical independent values with standard deviation σ as follows:

$$(\hat{y}, \sigma) = \hat{y} + \gamma_1[n]\sigma$$

Colored noise can be also expressed as form of filtered white noise by using a FIR filter as follows:

$$\hat{y}[n] = y_0[n] + \sum_{i=0}^{m-1} \gamma_1[n-i]c_i y_1[n-i]$$

Note that each past value of y_1 has its own noise symbol $\gamma_1[n-i]$.

The above effects are just examples or simple templates of uncertainties provided by our framework. In this paper, we modeled some simple digital filters such as IIR and FIR filters, which introduce quantization errors by using above models.

4 SystemC AMS for Semi-Symbolic Simulation

The idea of semi-symbolic block diagram simulation is as follows: We replace numerical operations by their affine arithmetic counterparts, which are mentioned in Section 3 to allow their use in an existing simulation environment. Thereby, the typical numeric representation is extended by an initially undefined symbol, the ε_i which resides by definition in the interval [-1, 1] and which is finally assigned the actual deviation to evaluate the specific behavior.

By using affine arithmetic and its defined operations, we finally get a framework to formally model uncertainties of a system. Therefore, we introduce the ideal behavior of the system quantity which is described by the central value y_0 and add the potential deviations which are modeled by a sum of y_i.

To implement a semi-symbolic simulation we performed a data flow based transient simulation, where data types such as floating point numbers are replaced by affine expressions. This can be implemented as following:

- To use a simulator that is available in source code that supports templates and that can simulate a given model.
- To add an abstract data type ‘affine expression’ which provides an efficient internal representation and which defines operations used in a given model.

SystemC AMS [9],[8] is a promising candidate for this purpose. We combine a SystemC AMS prototype as simulator with an affine arithmetic library [12] which provides an ‘AAF’ (affine arithmetic form) class in C++. The AAF class symbolically handles affine terms and provides overloaded operations such as ‘+’.

For example, designers can declare signals, and apply arithmetic operations, or add uncertainties as following:

```
AAF Signal_A, Signal_B, Signal_C;
Signal_C = Signal_A +
           quant(Signal_B,5) + noise(3);
```

Figure 2. Example composition of an Affine expression

SystemC AMS is a C++ library, and therefore allows designers to use templates. For example, most of the syntax of SystemC AMS is identical or similar to that of C++ and SystemC AMS ports and signals of a model are instantiations of certain classes.

As a result, the combination of SystemC AMS and the affine arithmetic library allows us to describe and calculate operations on affine expressions in the SystemC AMS integrated simulation environment. Figure 3 shows an example implementation of an IIR filter. The input and output ports are of type AAF, and

```
SCA_MODULE(iir_filter)
{
    sca_in<AAF> input;
    sca_out<AAF> output;
    AAF output_old;
    void iir_filter::sig_proc()
    {
        output=(GAIN_1 * input)
               + (GAIN_2 * output_old);
        output_old = output;
    }
}
```

Figure 3. Example of an IIR filter

consequently the inner class variable “output_old” also represents an affine arithmetic form. The operations ‘+’ and ‘*’ are overloaded versions, defined in the AAF class library.

5 Example and Experimental Results

In this paper, we simulated the effects of quantization errors on three example systems. The assumption for the simulation is that there is just one source of uncertainty, namely the quantization error at the input converter stage. All other error sources are neglected for this consideration.

As example system, a digital filter has been chosen which is implemented as FIR as well as an IIR variant. We modeled the digital filter, which represents digital signal processing parts as given in Figure 4 by using SystemC AMS. The quantization error of the signal converter part has been modeled by affine arithmetic as previously explained. MATLAB has been used for processing the experimental data and for a visualization of the results.

5.1 System Evaluation

For a proof of concept we simulate three digital filters with uncertainties, modeled by a symbolic term at the input port as shown in Figure 4.

The ideal value of a sine wave and the additional quantization error caused by a signal converter are combined in an affine arithmetic form, as depicted in Figure 4. The following digital filter part is chosen as computation process to evaluate and analyze the influence of finite signal resolutions on an overall system behavior.

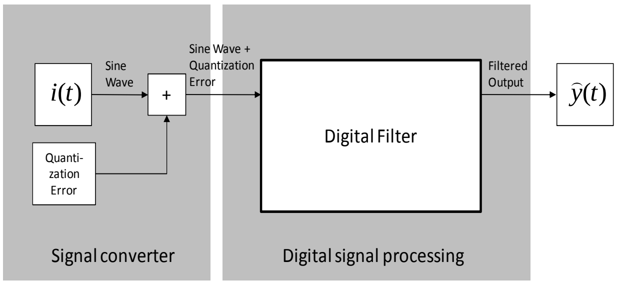


Figure 4. Block Diagram of the example system

We designed 3 types of digital filters as examples:

• FIR filter (with 10bit resolution for input signal)

• IIR filter (with 10bit resolution for input signal)

• IIR filter (with 8bit resolution for input signal)

The properties of these digital filters are the same, especially the cutoff frequency (20KHz) and the sampling frequency (1MHz) were designed identically.

By analyzing the filtering results of these 3 digital filters, we could compare the effects of different input signal resolutions and its impact on the system noise floor. Also we were able to compare the influence of variations of the feedback loop on the overall quantization error.

The simulation input signal consists of two superimposed sine waves of 5 kHz and 50 kHz, respectively as shown in Figure 5.

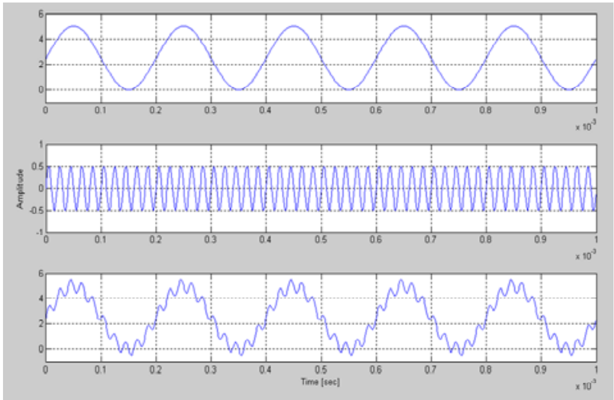


Figure 5. Input Signal

The filter cut off frequency has been designed to be 20 kHz. As a result of filtering, the output signal would be simply the 5 kHz sine wave without the 50 kHz contribution.

5.2 Simulation Results

Figure 6 shows the filtering result of the IIR filter which has an 8bit resolution for the input signal. Figure 7 shows a detailed view of the output signal, giving the nominal result and the quantization error as superimposed band.

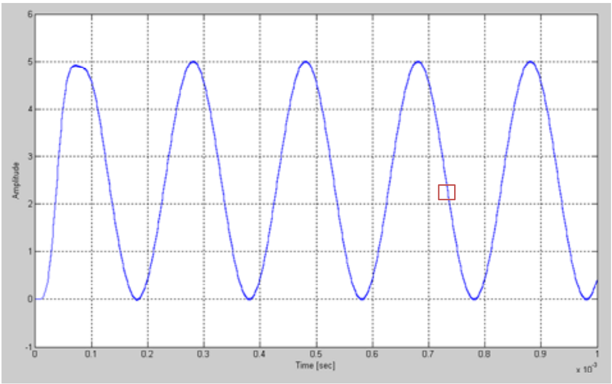


Figure 6. Output signal of the IIR filter (8bit resolution)

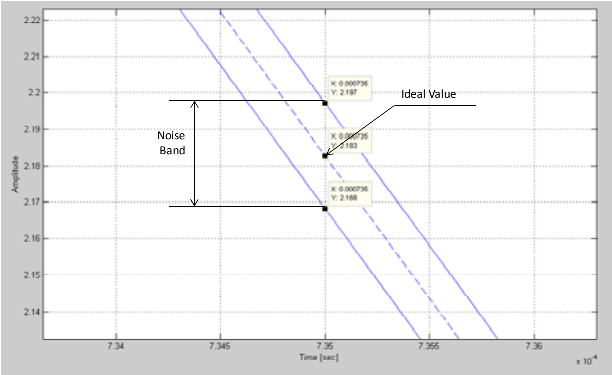


Figure 7. Detailed output signal of the IIR filter (8bit resolution)

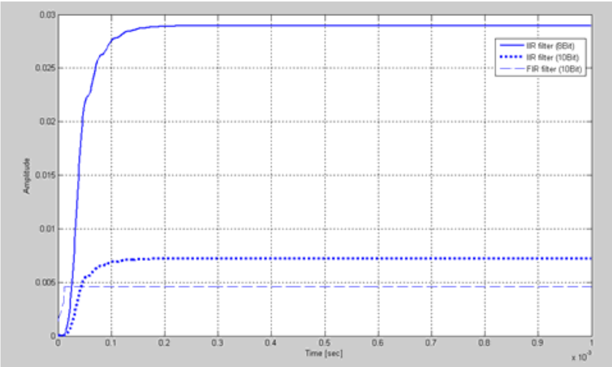


Figure 8. Quantization noise over time

In Figure 8, we can see that noise, caused by the quantization error of the input signal converter, is different according to the different underlying calculation operations and the different signal resolutions in all three digital filter examples.

When comparing the example digital filters in this paper, the IIR filter has a more complex structure and has more computations than the FIR filter. Therefore, comparing an IIR and a FIR filter which have the same input signal resolution shows, that the noise and its effect on the resulting signal is different according to the different filter structures. When using the same structure of the digital filter, that means systems which have the same computational procedures, the noise difference simply reflects the contributions of the signal resolution. For such a comparison we modeled a 10bit and a 8bit IIR filter to evaluate the quantization noise and its system effect. This implies that noise, caused by a quantization error, is reduced when moving towards higher resolutions of the input signal in a system.

In Figure 8, quantization noise is relatively small at the beginning of the simulation. Though, it increases while the simulation time advances. This is caused by the delayed loops which recursively contribute to the resulting signal. When the structure is completely filled with previous samples, the quantization noise converges to its maximum value. Following this observation it becomes clear that the quantization noise is influenced by the system characteristics such as its structure and its input signal resolution. In this example, the noise is increased proportional to the number of filter taps given by the order of the digital filter. After the quantization error has traversed the whole computation structure, the system quantization error converges to its final value.

Despite absolute noise factors and variations of noise there are some dynamic parameters to estimate its effect on systems which can be defined as following:

- Signal-to-noise ratio (SNR)
- Signal-to-noise and distortion ratio (SINAD)
- Effective number of bits (ENOB)
- Total harmonic distortion (THD)

In this paper, we used the Signal-to-noise ratio (SNR) definition to estimate the effect of quantization errors on the systems.

Signal-to-noise ratio (SNR) : SNR is the ratio of an rms (root mean square) full-scaled analog input to its rms quantization error for an analog signal reconstructed from its digital samples. The rms value of a sine wave is its peak value divided by $\sqrt{2}$, and the quantization error is the difference between the ideal analog signal and its digitally reconstructed value.

The SNR for a sinusoidal input signal can be described as follows:

$$SNR_{dB} = 20 \cdot \log_{10}(A_{SIGNAL}[rms] / A_{NOISE}[rms])$$

Where $A_{SIGNAL}[rms]$ represents the rms amplitude for the analog input signal, and $A_{NOISE}[rms]$ is the rms sum of all noise sources. The SNR of the analyzed example systems is shown in Table 1.

System	FIR 10bit	IIR 10bit	IIR 8bit
SNR	128.79dB	121.52dB	93.75dB

Table 1. SNR of the example systems

Additionally we calculated the SNR for each simulation time point and its variation over time by using the peak value of the output signal, not the rms value as used in Table 1. This result can be seen in Figure 9.

In the case of IIR filters, there are some SNR values that are lower than 0 dB. This means the noise is stronger than the ideal input signal. This can cause critical problems in system behaviors.

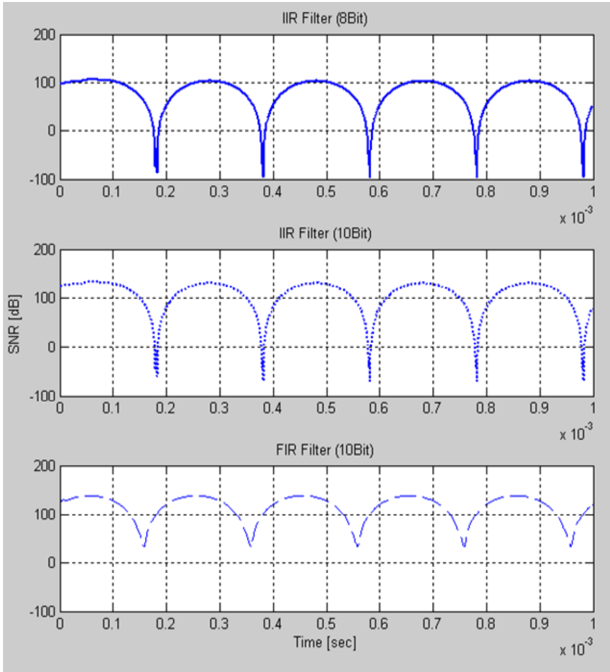


Figure 9. Signal-to-Noise Ratio

6 Discussion and Future work

In this paper, we modeled and simulated the quantization error of mixed analog/digital systems with affine arithmetic and SystemC AMS. This has been performed to calculate and analyze the quantization error and its effect on the system behavior. We implemented and simulated three digital filters as example systems.

Via simulation and tracking of the noise quantities, we showed that the noise which is caused by the quantization error is changed by the system characteristic and the input signal resolution.

As previously mentioned, using microcontrollers in electronic systems introduce noise contributions caused by quantization, round-off, and truncation error. Especially, in cases of mixed Analog and Digital (A/D) communication systems, effects of noise can be the cause of erratic behavior such as missed operations. That is one of the reasons to carefully consider and simulate the effects of noise, before developing systems.

To find an optimum system property which is sufficient for the objective of the system, noise estimation is an important aid for system designers. This article describes a method to simulate and track the noise quantities caused by the finite signal resolutions. For example, we illustrated the SNR of FIR and IIR filters with different signal resolutions in this paper with the results shown in Table 1 and Figure 9. The SNR of the maximum values, given in Table 1, indicates no problems. But when considering the noise SNR evolving over simulation time we could find some remarkable points in the SNR for some simulation time points as can be seen in Figure 9. In IIR Filters, the SNR is lower than 0 at some points and therefore critical system behavior can be expected during operation. Thus, the FIR filter with a 10 bit input signal resolution is the most reliable system.

We combined a SystemC AMS prototype as modeling and simulation environment with an affine arithmetic library, which provides an AAF class in C++. The AAF class symbolically handles affine terms and provides overloaded operations. Therefore designers can declare signals, and apply arithmetic operations, or add uncertainties when necessary.

Only quantization errors which are caused by converting analog to digital signals are considered in this paper. Additionally other variations of noise contributions to systems, like offset error, round-off or truncation error could be modeled, simulated and tracked with affine arithmetic and SystemC AMS as demonstrated in this paper. Future work will, therefore, extend the error model by round-off and truncation error also typically for digital signal processing systems. Furthermore, advanced methodologies for estimating necessary signal resolutions to obtain requested noise levels should be created.

References

[1] D. Lee; A Gaffar; O Mencer; W Luk : MiniBit: Bit-Width Optimization via Affine Arithmetic, Design Automation Conference, 2005

[2] G. Gielen; P. Wambacq; W. Sansen : Symbolic Analysis Methods and Application for Analog Circuits: A Tutorial Overview, Proceedings of the IEEE, Feb 1994

[3] L. Hedrich; E. Barke : A formal approach to verification of linear analog circuits with parameter tolerances" in Proceedings Design, Automation and Test in Europe (DATE). IEEE Computer Society Press, Paris, France, Feb 1998

[4] C. Grimm : Modeling and Refinement of Mixed Signal Systems with SystemC. In SystemC – Methodologies and Applications. Kluwer Academic Publisher (KAP), June 2003

[5] M. Andrade; J. Comba; J. Stolfi : Affine Arithmetic (Extended Abstract), In Interval '94, St. Petersburg, Russia, 1994

[6] W. Heupke; C. Grimm; K. Waldschmidt : A New Method for Modeling and Analysis of Accuracy and Tolerances in Mixed-Signal Systems. In Proceddings of the Forum on Specification and Design Languages (FDL '03), Frankfurt, Germeany, Sept 2003

[7] A. Lemke; L. Hedrich; E. Barke : Analog Circuit Sizing Based on Formal Methods Using Affine Arithmetic. In ICCAD 2002, 2002

[8] J. Romberg; C. Grimm : Refinement of Hybrid Systems from HyCharts to SystemC-AMS. In Proceedings of the Forum on Specification and Design Language (FDL '03), Frankfurt, Germany, 2003

[9] A. Vachoux; C. Grimm; K. Einwich : SystemC-AMS Requirements, Design Objectives and Rationale. In Design, Automation and Test in Europe 2003 (DATE 2003), Munich, Germany, 2003

[10] C. Grimm; W. Heupke; K. Waldschmidt : Refinement of Mixed-Signal Systems with Affine Arithmetic, IEEE Transactions on Computers-Aided Design of Integrated Circuits and Systems, Vol. 24, No. 1, Jan 2005

[11] R.E.Moore: "Interval Analysis". *Prentice-Hall*, Englewood Cliffs, NJ, 1966.

[12] O.Gay: "Libaa-C++ Affine Arithmetic Library for GNU/Linux". *http://savannah.nongnu.org/projects/libaa*, 2003.