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Edited by
Hans-Peter Bernhard
Silicon Austria Labs GmbH, 4040 Linz
Johannes Kepler University Linz, 4040 Linz

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Silicon Austria Labs (SAL)

SAL-DC

This document is an summary of abstracts to present an overview to the SAL Doctoral College (SAL-DC)

Austria, September 3, 2022

Preface

In this second edition of our SAL-DC booklet, we offer the interested reader a one page overview for each individual SAL-DC PhD thesis that shall introduce her to the respective topic on one hand, and that shall provide her with a glimpse at SAL's PhD research portfolio on the other hand. The compilation in a booklet provides a nice and colorful overview of the multi-disciplinary research conducted by SAL researchers for covering our contributions to the field of Electronic Based Systems (EBS). Some of the theses are quite elaborate and almost finished, while others are connected to our most recent activities and are thus in their early stages. But all of the theses and PhD students contribute to the active strategic research areas considered within SAL, and connect to collaborative projects with industry or basic research with national and international universities.
The PhD students whose work you can access in this booklet are employed either by SAL or by an institution working with us in partnership on specific topics or research. Thus SAL-DC members, i.e., students supervised at the universities TUG, AAU or JKU who run the SAL-DC together with SAL, and the associated students, i.e., students supervised by other faculties, contributed to this booklet and have been contributing to our SAL-DC. In this context, it is important to note that at SAL our mission is to provide all PhD students with the same support, and to integrate all of them into an active SAL-DC. For this mission, we are following a clear plan with the goal of establishing a lively community of fellow researchers providing discussions, support and social activities. We provide seasonal schools, language training, internal presentations for all sites, and local as well as SAL-wide team activities in order to foster the desired lively research environment.
Some facts by June 2022: SAL-DC has 25 full and 22 associate members who have been contributing to our research with publications and presentations according to the following table.

Type	**Number**
Journals	19
Conference publications	36
Posters	4
Others	2
Total	61

At this very point, I would like to take the chance and thank all the supervisors and partners for supporting our students in their work and providing them with the freedom and flexibility for conducting ambitious research— which means enabling, creating and following paths for the students' research, but also taking detours that are necessary for a successful completion of our students' individual theses. Of course it shall also not be left unsaid that we consider the work of our students at SAL to be remarkable; many of them contribute also to industry projects and their research often requires significant efforts that are additional or complementary to their project. Thanks!

Hans-Peter Bernhard, Linz 25.06.2022

Contents

Part I

mmWAVE - RF

Design of a sub-6GHz Receiver Using an Analog Generator

Fatemeh Abbassi, Silicon Austria Labs GmbH (SAL), Linz, Austria
SAL supervisor: Mirjana Videnovic-Misic, Silicon Austria Labs GmbH (SAL), Linz, Austria
University supervisor: Timm Ostermann, Johannes Kepler University, Linz, Austria

1 Introduction

Compared to the digital counterpart, where Electronic Design Automation (EDA) tools synthesize the final layout from a high-level description, the design and layout of analog and radio-frequency (RF) circuits is still a time-consuming and error-prone manual process. Rapidly rising number of the design rules and detrimental effect of interface parasitic and Layout-Dependent Effects (LDE) on the circuit performance in multi-patterned technologies reduces explored design space. Thus, by losing layout degrees of freedom the automated layout solutions have become even more attractive. Due to the increased interest in the design automation tools, Berkeley Analog Generator (BAG) [1]- an automated analog generator methodology, is selected for this study. BAG allows complete automatization of the design flow but also the use of generators in a combination with the custom-designed circuit representations. The framework, Fig. 1, follows the same design procedures as the standard analog design flow [2]. It has two main parts: a circuit generator that includes schematic and layout generators, and a verification framework that controls the process of the testbenches generation and simulation/measurement execution. At the highest level, the input parameters, such as device dimensions, biasing and passive component values, testbench, and simulation parameters are defined in a specification file (spec file) and fed into the circuit generators scripted by the designer. As a result, a schematic, layout, and symbol with mentioned input parameters are generated, specified simulation executed and the results reported. At the same time, the technology information is included as a specific framework layer thus enabling generator reuse across different technology nodes and circuit exploration in an agile way.

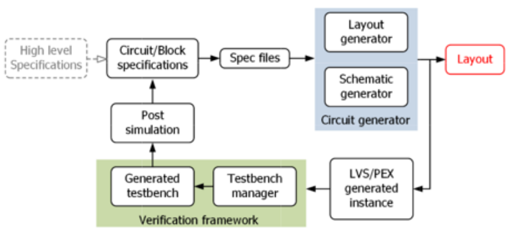


Figure 1: Bag framework overview

2 Project Overview

To achieve the final goal that is the design of a receiver using an analog generator, the project is planed into two phases as follows:

2.1 Phase I: Enabling and verifying the framework using a simple circuit Operational Transconductance Amplifier OTA

Process portable schematic, layout, and testbench generators are implemented in this framework for a conventional two-stage OTA structure shown in Fig. 2. The first OTA stage is a differential amplifier with diode-connected and positive feedback loads (negative-gm) while the second stage is a pseudo-differential common source amplifier. The topology has the following benefits: first, the large output swing; and second, common-mode feedback is only required for the second stage. The circuit is designed in TSMC 28nm CMOS technology with 1V supply in the typical corner.

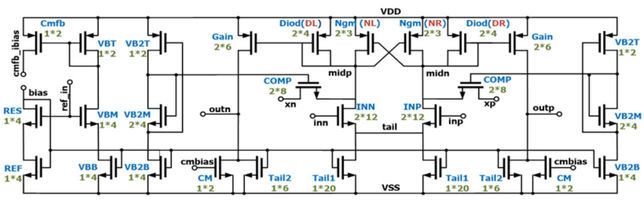


Figure 2: An NMOS input fully differential two-stage amplifier stage OTA

2.2 Phase II: Design of sub-6GHz Receiver using BAG

Considering the advantage of N-path and switch-cap structures in creating reconfigurability, also by reviewing the most recent papers in this area, it is found that full receiver chain up to ADC, can be implemented by utilizing only a few standard building blocks such as switches, capacitors, and inverter-based amplifier. Therefore, creating a general generator for these building blocks can give the capability of implementing different receiver topologies with various specifications within a shorter time.

3 Bibliography

[1] Crossley, John, et al. "BAG: A designer-oriented integrated framework for the development of AMS circuit generators." 2013 IEEE/ACM International Conference on Computer-Aided Design (ICCAD). IEEE, 2013.

[2] Chang, Eric, et al. "BAG2: A process-portable framework for generator-based AMS circuit design." 2018 IEEE Custom Integrated Circuits Conference (CICC). IEEE, 2018.

D-band Phased-Array Receiver

Samir Aziri,Silicon Austria Labs
SAL supervisor: Gernot Hueber, Silicon Austria Labs
University supervisor:

1 Introduction

The increasing demand for high-speed (multi-Gb/s) communication has driven the development of the wireless communications beyond 5G. Over the last two decades a considerable RF performance at mmWave frequencies has been achieved using low-cost CMOS technology[1-3]. Such high-speed traffic demands the large bandwidth available at D-band frequencies (110-170GHz). Some of the design challenges of such multi-Gb/s receivers lie in the limited link budget due to high free space path loss and relatively High noise figure of the LNA which in terms limit the output SNR of the receiver. Phased array is proposed as a viable solution to overcome the forementioned issues and relax the design of the receiver front end. One of the most important and challenging blocks in phased-array receiver front end is the phase shifter. Phase shifters are used in a phased-array receiver to electronically steer the antenna beam resulting a high signal to noise ratio (SNR). Phase shifters can be divided into two categories passive and active phase shifters. Passive shifters such as reflector type phase shifters (RTPS), loaded line phase shifters exhibit high Noise figure and loss which significantly degrade the performance of the array in addition to that they occupy a large die area. Active phase shifters such as vector modulator (VM) exhibit less noise figure and loss, may even exhibit some gain and occupy less area at the expenses of power and linearity.

2 Phase-Array Architecture

Figure 1 represents the block diagram of an RF phased-array receiver front end. In the first phase of the project a single channel receiver highlighted by the red box consisting of a low noise amplifier (LNA), a vector-modulator based phase shifter (PS) and a variable gain amplifier (VGA) is designed.

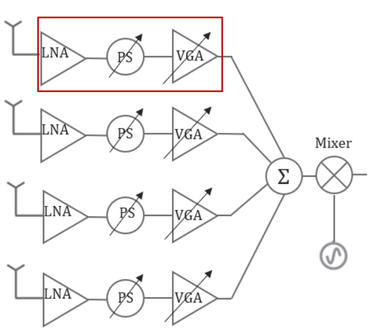


Figure 1: Block diagram of an RF phased-array receiver

2.1 D-band LNA

A 3-stage transformer-coupled differential common source LNA (Figure 2(a)) with capacitive neutralization to boost the gain is designed. In this design a new technique of simultaneous noise and power matching is employed. With the new technique the same performance as state-of-the-art LNAs is achieved with half power consumption.

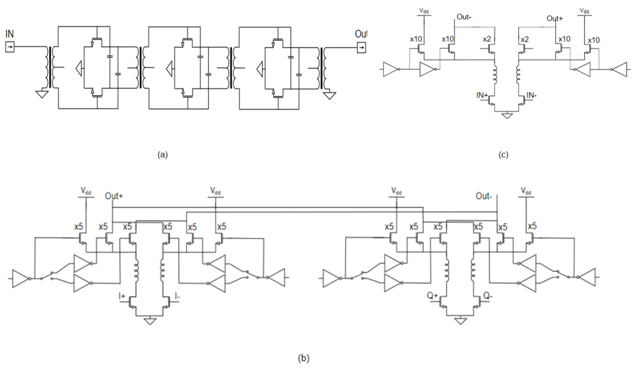


Figure 2: Schematic of (a) 3-stage LNA, (b)Vector modulator, (c)VGA

2.2 D-band Vector Modulator and VGA

Figure 2(b) and (c) shows the schematic of the digitally-controlled VM and VGA respectively. Both blocks (VM and VGA) employ a phase-invariant technique to minimize the unwanted phase variation at different gain modes[4].

3 Bibliography

[1] T. Heller, et.al."A 102–129-GHz 39-dB Gain 8.4-dB Noise Figure I/Q Receiver Frontend in 28-nm CMOS," in IEEE Transactions on Microwave Theory and Techniques, vol. 64, no. 5, pp. 1535-1543, May 2016

[2] Li, Siwei, et.al. "A 134-149 GHz IF Beamforming Phased-Array Receiver Channel with 6.4-7.5 dB NF Using CMOS 45nm RFSOI." 2020 IEEE Radio Frequency Integrated Circuits Symposium (RFIC). IEEE, 2020

[3] A. A. Farid, et.al, "A Broadband Direct Conversion Transmitter/Receiver at D-band Using CMOS 22nm FDSOI," 2019 IEEE Radio Frequency Integrated Circuits Symposium (RFIC), Boston, MA, USA, 2019, pp. 135-138

[4] Y. Yi, et.al. "A Ka-band CMOS Digital-Controlled Phase-Invariant Variable Gain Amplifier with 4-bit Tuning Range and 0.5-dB Resolution," 2018 IEEE Radio Frequency Integrated Circuits Symposium (RFIC), 2018, pp. 152-155

Sigma Delta ADC Generator

Cristian Tatu, Silicon Austria Labs GmbH
SAL supervisor: Bernd Lemaitre, Silicon Austria Labs GmbH
University supervisor: Timm Ostermann, Johannes Kepler University, Linz, Austria

1 Introduction

Analog-to-Digital Converters (ADCs) are essential building blocks in any electronic system which act as a bridge between analog signals and digital processors. Current research investigates compact circuit designs suitable for electronic equipment powered by batteries with limited storage capability while enduring long time operation under stressful conditions such as low/high temperature or external interference. This trade-off between area minimization, energy efficiency and robustness requires a careful design procedure for ADC architectures that can deal with signals in noisy environments and can convert signals with different conversion rates.

2 Motivation

Sigma Delta modulation is a popular technique used for implementing high resolution ADCs [1]. It uses oversampling along with noise shaping for the suppression of quantization noise within the band of interest. However, conventional design flow is time consuming when applying transistor level simulations and most of the time is spent on layout and post-layout verification, which limit designers' ability to explore new circuit designs. Generators are parametrized design procedures that produce schematics, layouts, and verification testbenches for a circuit with given input specifications. Generators can be used either as a concept exploration tool or as a software product which enables reuse of IP modules and process portability.

3 Methodology

The Berkeley Analog Generator (BAG) framework will be used as an interface with the Cadence environment[2]. It enables automation of simulation procedures and post-processing of data as well as writing parametrizable scripts which generate the schematics and layout, as well as running the layout-versus-schematic and post-layout extraction.

The diagram shown in Fig. 1 illustrates the 4 main steps of the generator's design flow: design synthesis (calculation of topology limitations down to circuit elements such as capacitors and operational transconductance amplifiers), design implementation (schematic implementation using look-up table based sizing), layout implementation (robust and compact layout, such that the design specifications can be satisfied) and verification.

4 Bibliography

[1] Steven R. Nosworthy, Richard. Schreier and Gabor C. Temes, "Delta-Sigma Data Converters" in Theory Design and Simulation, IEEE Press, 1997.

[2] J. Crossley et al., "BAG: A designer-oriented integrated framework for the development of AMS circuit generators," in IEEE/ACM International Conference on Computer-Aided Design (ICCAD). IEEE, Nov. 2013, pp. 74–81.

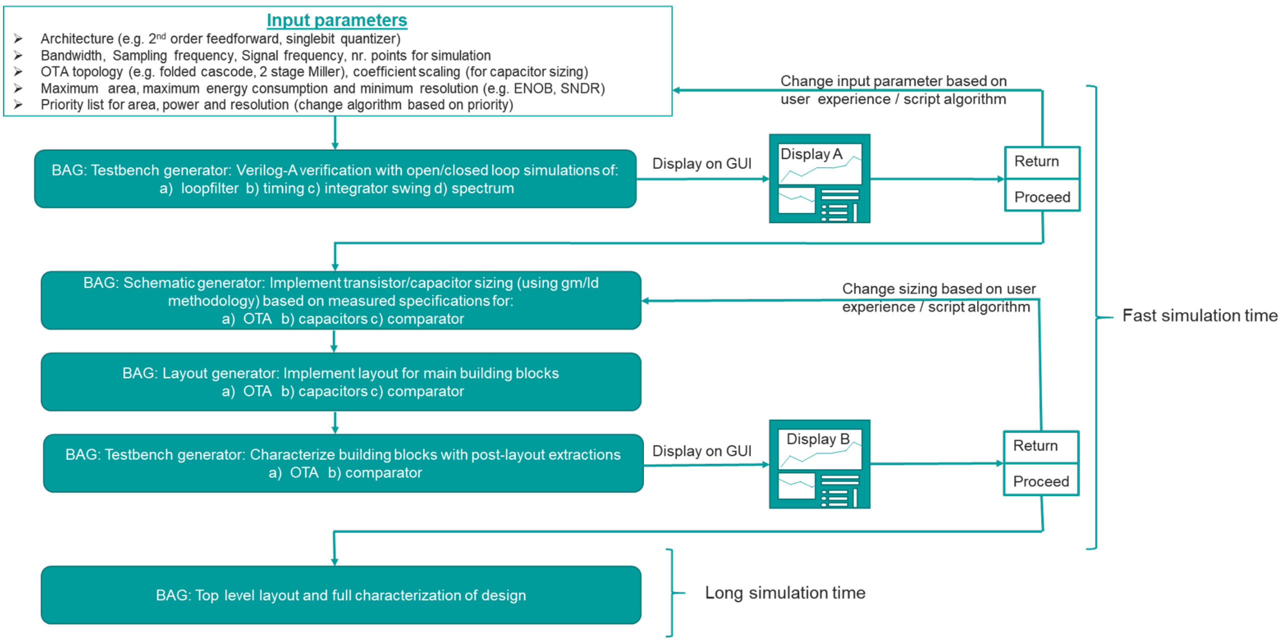


Figure 1: Flow for Sigma Delta ADC Generator

Radar Calibration for Large Aperture Radars in Antenna Test Ranges

Simon Heining, Johannes Kepler University Linz
SAL supervisor: Gernot Hueber, Silicon Austria Labs GmbH
University supervisor: Andreas Stelzer, Johannes Kepler University Linz

1 Introduction

Calibration is a substantial aspect, when it comes to nowadays MIMO radar systems. With more and more enlarging apertures the established farfield calibration is no more practical. With D being the aperture dimension and λ the wavelength, the distance where farfield can be assumed is calculated by

$$R_{Farfield} = \frac{2D^2}{\lambda}. \tag{4.1}$$

Table 4.1 shows dimensions from existing radar systems and their calculated farfield distance.

Table 4.1: Tab. I: Radar systems and their farfield distances

Radar	D/mm	λ_0/mm	$R_{Farfield}/m$
K-Band Monostatic	61.5	12.5	6.05
X-Band MIMO	400	30	10.67
W-Band MIMO	250	3.89	32.13

From the dimensions from above mentioned radar systems, we can see, that in small measurement chambers large aperture radars will never be in farfield condition.

2 Compact Antenna Test Ranges

2.1 CATR Design Aspects

To generate farfield conditions in a reasonable measurement environment, a newly designed compact antenna test range (CATR) will be developed. With its help we can generate farfield conditions on a relatively small footprint. Depending mostly on the size of the parabolic shaped mirror used, the area where farfield conditions are assumed - called quiet zone (QZ) - can be approximated by a square of half the mirror size. In this area - due to the parabolic shape of the reflector - the energy of the feedhorn will be equally distributed as a plane wave. Fig. 1 shows the general concept of such CATR with a radar placed in the quiet zone.

One challenging aspect is the quiet zone quality. It is determined by magnitude and phase imperfections resulting from scattered fields at the edges of the mirror. If we imagine a rectangular mirror shape, the edges would be responsible for a sharp boundary condition for the fields. To reduce scattered fields from this boundary condition, techniques such as rolling- or serrated edges can be used to scatter fields outside of the quiet zone. A tradeoff has to be made regarding illuminating efficiency, relative quiet zone size and quiet zone quality. In order to evaluate the quality of the fields in the QZ, a quadrartic magnitude

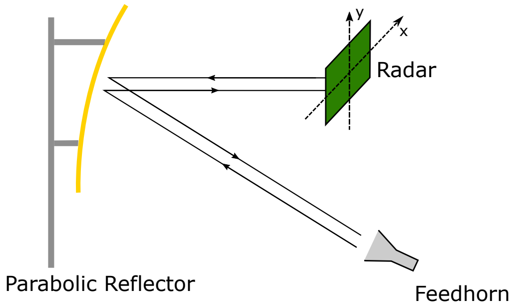


Figure 1: Setup of the proposed CATR

and phase error can be defined as shown in for the area of interest with equation (4.2). N_x and N_y are the number of discrete points in QZ domain, $\varphi(i,j)$ the phase at the respective points i and j and $\bar{\varphi}$ the mean phase in the QZ area. With this in mind, the optimization of the mirror can be performed.

$$\sigma = \frac{1}{N_x N_y} \left|\varphi(i,j) - \bar{\varphi}\right|^2 \tag{4.2}$$

2.2 Verification and Calibration

For a verification of the setup the QZ quality has to be measured. We aim, to use two different techniques to do so. The first, is a general approach widely used in literature: A Network Analyzer with extenders is moved across the QZ with a high accuracy positioner and measures the phase differences between the fixed feed and the moving probe in the QZ. The phase difference can directly be measured. From that measurement also the path loss of the system can be evaluated.

An approach developed by us uses the radar under test and a RF short on the feedhorn of the parabolic mirror system. The radar is also moving across the QZ and performs radar measurements. The short on the feedhorn appears as target in the radar measurement, where the phase can be evaluated from. This way we can also measure the QZ errors.

An algorithm detects and eliminates errors that are derived by minimal setup inaccuracies. Additionally the errors can be separated in systematic and QZ errors. With this system we want to achieve a measurement of the QZ properties combined with a full over-the-air calibration of the radar system.

Active Metamaterial for Antenna and Sensing Applications - AMASA

Christoph Kohlberger, Silicon Austria Labs GmbH
SAL supervisor: Gernot Hueber, Silicon Austria Labs GmbH
University supervisor: Andreas Stelzer, Johannes Kepleer University Linz

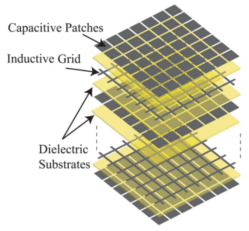
1 Motivation and State of the Art

The aim of this work is the investigation and prototyping of active metasurfaces based on inductive/capacitive grids or patch-arrays to manipulate radiation of antennas or the reflection properties of radar targets. Compared to existing works, the metasurface control shall be realized by integrable active devices as e.g. transistors or varactors.

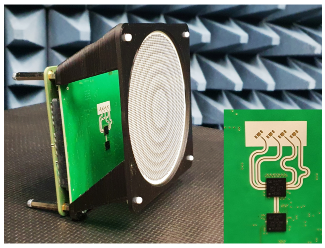
Future developments in RF technology fields as e.g. wireless communication and mobile radar will potentially require novel methods for manipulating electromagnetic waves. Especially, with increasing frequencies and for highly integrated devices, new steering, focusing and scattering techniques become important to firstly save energy and secondly avoid crosstalk. A currently popular research example would be a reconfigurable wallpaper for directive wave reflection usable in e.g. wireless communications.

Metamaterials and their two-dimensional pendants, metasurfaces, are investigated in academic research since the beginning of the 21st century auguring various novel applications as e.g. antenna cavities, perfect reflectors and absorbers or radar cloaks. Despite appealing properties, RF metasurfaces still did not find their way into mass market applications. This can be e.g. due to complex design procedures or sophisticated fabrication techniques.

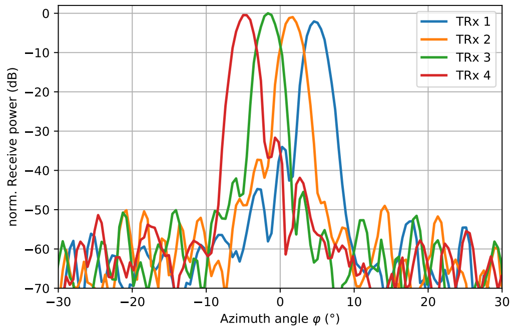
To improve the design procedure of metasurfaces, scientists developed equivalent circuit models for increasingly complex frequency selective surfaces. However, to reach the needed transmission phase shift of more than 360°, high order multilayer systems need to be fabricated. At these structures, electromagnetic effects occur, which are mostly not considered in equivalent circuit models and have to be computed via commercial full-wave simulators.



(a) Metasurface layers



(b) Radar front-end, metalens



(c) Measured radar beam pattern of the system above

Figure 1: Operating 77-GHz radar system with corresponding beam pattern when using a lens with 100 mm diameter.

2 Achievements so Far

Since metamaterial design often requires a generation of novel concepts, it is indispensable to verify the fabricated structures firstly with simulations, but more important through measurements. For this, a quasi-optical bench for over-the-air S-parameter determination was created at the beginning of the project. This setup helped to suppress unwanted scattering during structure verification.

After the creation of some example structures, the fabrication of an applicable metasurface had priority. For that, a gradient optimization procedure was applied to a metal multilayer consisting of three patch arrays and two grids shown in Fig. 1a. Thereby, design parameters of the multilayer were iteratively changed, to get an optimum frequency response, which was continuously evaluated through full-wave simulations. Resulting designs were finally combined to build metamaterial lenses operating at 24 GHz and 77 GHz. The latter was further applied to a radar front-end (Fig. 1b) resulting in high gain radar beam patterns, shown in Fig. 1c.

Especially, when it comes to research on active metasurfaces, e.g. grid structures connected to active circuit components, the evaluation through full-wave simulation becomes highly inefficient. Therefore, it was necessary to investigate electromagnetic scattering through multiple periodic metal layers and the related multi-modal equivalent network. This finally enabled quick calculation of scattering properties of simple passive and active grid arrays, which was helpful for the development of a novel active reflector concept.

3 Outlook

Currently, active components as e.g. varactors are characterized to obtain accurate device characteristics. These are essential when applying them to periodic structures. We aim to realize an active reflector operating around 28 GHz that enables firstly a tunable reflection coefficient, but further directive reflection. This will trigger new ideas for promising applications and techniques, requiring further interesting investigation.

Chiplet Based Heterogeneous Sub-THz Transceiver

Georg Zachl, Johannes Kepler University Linz
SAL supervisor: Gernot Hueber, Silicon Austria Labs GmbH
University supervisor: Harald Pretl, Johannes Kepler University Linz

1 Introduction

High datarate communication systems and microwave sensing with radars are becoming more and more integrated into our daily life. Typically, the performance of these systems (higher data rates, higher radar resolution) can be increased by more efficient use of the available spectrum and by *simply* increasing the bandwidth. This is why the LIT/SAL mmW Lab sets its research focus on integrated circuits that exploit currently unused frequencies reaching beyond 0.3 THz, but this also comes with technical challenges that need to be solved. Current semiconductor technologies need to be pushed to their limits for sub-THz applications to achieve high output power. Receivers need to have a high sensitivity to deal with large free-space path-loss. The target of our research is to implement a complete sub-THz communication system, reaching above 100 Gbit s^{-1}, based on a chiplet design strategy. The heterogeneous approach will enable us to select the best technology for each subsystem and it also allows the reusing of existing components. Figure 1 is an example block diagram for a sub-THz heterogeneous chiplet TRX.

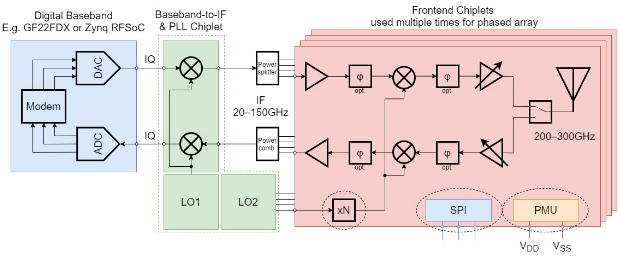


Figure 1: Proposed partitioning of a sub-THz TRX using a chiplet-based heterogeneous design. In this example, the frontend chiplets (red) are implemented in the IHP SG13G2Cu process, which are currently in the focus of our design.

2 Current Work

As a first result of the research work in the SAL/LIT mmW Lab, a chip was taped out in December 2021. It uses the IHP SG13G2 BiCMOS process technology, with an f_T/f_{max} of 350 GHz/450 GHz and a copper metal backend, that is very well suited for sub-THz applications and research.
The chip named CATX1 (an acronym for Chiplet with Antenna and Transceiver, eXperimental chip 1) incorporates a 320 GHz transmitter based on a 16x frequency multiplier chain, with the required matching and balun structures as well as a on-chip patch antenna. The design is intended to operate in physical configurations up to 2-by-2 for enhanced EIRP of the whole system. To keep the complexity of testing and usage of the chip reasonable, CATX1 has included LDOs (low drop out regulators), bias current generation and an SPI (serial peripheral interface) to configure named components.
The next step for CATX1 is now to test the silicon. This will include the verification of the basic functionality (DC, SPI, LDOs, bias generation), followed by a characterization of the RF path. Due to a relatively new process technology and a completely new tool setup on our side, this will give us an insight into the actual performance of the devices and the passive metal components.

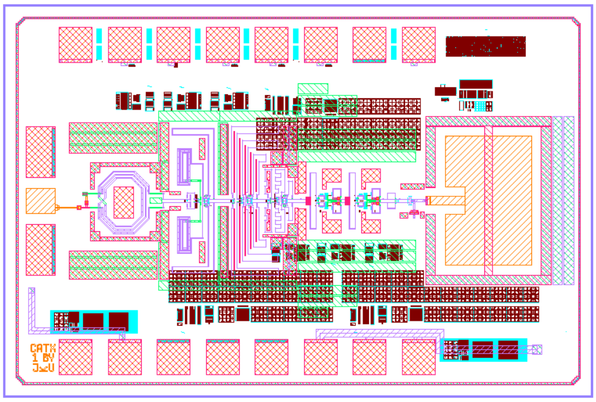


Figure 2: Layout overview of the CATX1 transmitter chip. The supply and SPI pins are on the north and south side, with the bias generation, SPI and LDOs placed around them. On the chips west side is the a single-ended GSG (ground-signal-ground) pad for the signal input, followed by a balun and the multiplier/amplifier chain up to the antenna on the east side.

3 Research Outlook

With the finalization of the silicon testing of CATX1, we will have a 320 GHz transmitter ready that is able to transmit a CW (continuous wave) signal but also simple, non-coherently modulated signals. The next step is to implement a receiver for a complete radio link. Due to the high carrier-frequency, conventional mixer-based receiver architectures suffer from low sensitivity and high power consumption, so alternative architectures are in the focus of research. Also, the switch to an even faster technology will help to increase the performance, which will also enable a further transmitter for even higher frequencies.

Sub-THz frequency synthesizers for 6G wireless wireless transceivers

Rohish Kumar Reddy. Mitta, Johannes Kepler University Linz
SAL supervisor: Gernot Hueber, Silicon Austria Labs GmbH
University supervisor: Harald Pretl, Johannes Kepler University Linz

1 Abstract

The research approach is towards frequency synthesis and integrated communication systems targetting 6G wireless applications. In most cases integrated sub-THz frequency generation is based on the harmonic frequency extraction exploiting the non-linearities of the device characteristics. By exploiting the harmonic frequencies the amplitude of the synthesized frequencies and clock diminishes at the initial stage of realization. The research approaches into the multi-pronged solution to achieve a realizable trade off to implement a robust and low power consuming sub-THz synthesizer for communication and sensing applications.

Adding to the challenges there has been a MIMO based approach involving multiple transceivers. For the MIMO applications, the frequencies synthesized must be distributed with a very robust and systematic approach to synchronize the phases of the generated frequencies with all the array-based transceivers to achieve high performance of the communication links and reach the link budget based on theoretically calculated specications.

2 Research focus

The frst stage of research work focuses on frequency synthesizers with IHP 130nm node with copper backend process.

The initial stage will start with acquiring pure clocks and references from the FBAR or SAWbased resonators which have shown generated frequencies with phase noise of -150dBc/Hz at 1kHz frequency offset. Using such sources as hard reference further high frequency sub-THz frequencies can be realized and synthesized for the intended applications. With the knowledge gained from the first implementation, the future design approaches will be realized as a heterogeneous chiplet design involving both CMOS and BiCMOS processes to realize a complete transceiver, working with data rates in excess of 100Gbit/s.

The proposed implementation of the frequency multiplier and mixer implementation is shown in the Fig. 1
Based on the implementation the architecture negates the requirement of area consuming BALUNs and realizes a full scale IP for the intended application. With real pure frequency synthesis from the SAW and FBAR based resonators. The later implementation work on low power frequency distribution system finally realizing phased array based systems for MIMO based applications.

The further Design implementation realizes the PLL based frequency synthesizers with frequency tuning for realizing an reference standard of IEEE Std 802.15.3d operating in frequency ranges from 250GHz to 350GHz Bands with further inclusion of purely Phase modulation based information mixing in these applications.

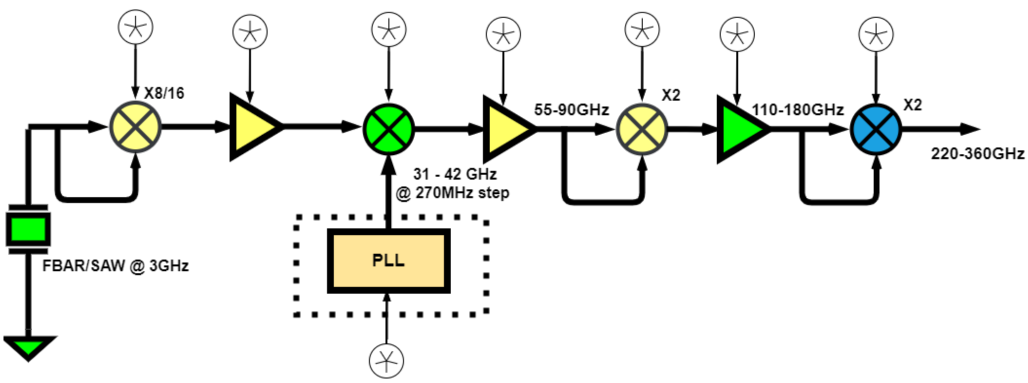


Figure 1: Proposed Block diagram for multiplier realization

mm-Wave Frequency Generation

Sarthak Sharma, Silicon Austria Labs GmbH
SAL supervisor: , Silicon Austria Labs GmbH
University supervisor:

1 Abstract

Wireless communication has seen an explosive growth in the data rate in the recent years. The trend is still continuing as more and more user applications for medical or educational purposes etc. are targeted to be performed in a wireless fashion requiring extremely high data rates. To allow for such high dates beyond 100Gbps, high network bandwidth is an absolute requirement. The mm-Wave frequencies provide a good solution for this problem because of the availability of wide and unused frequency spectrum. As a result, there is a keen interest in current research for developing transceivers working at mm-Wave frequencies. Oscillators form an integral part of the full transceiver analog front end. They are used in receivers to downconvert the incoming signal to baseband frequencies for digital processing, and in transmitters, for upconverting the signal to mm-Wave frequencies for transmission. The noise performance of oscillators, among others, determine the complexity of the digital modulation that can be supported for the transmission. The aim of the current project is to design a low phase noise mm-Wave oscillator which can be integrated inside a transceiver system and demonstrate communication at mm-Wave frequencies. The oscillator is designed in Global Foundries 22nm FDSOI CMOS technology and works at 150GHz with phase noise of -96dBc/Hz at 1MHz offset using 40mW of power with 10% tuning range.

2 Project Description

Different types of oscillator topologies can be seen in the literature. But communication systems solely use inductor capacitor (LC) oscillators due to their better phase noise performance. The LC oscillators are designed by connecting an (LC) resonator or LC tank to an active circuit with power gain so as to compensate the losses of the tank and hence sustaining oscillations. The phase noise performance of the oscillator depends on the quality factor of the LC tank. So circuit techniques needed for improving the quality factor need to be incorporated in the design. The noise performance depends also on the configuration of the active circuit used in the design. Careful circuit techniques are required to ensure that the noise performance is not deteriorated because of the active structure. A mm-Wave frequency oscillator can have two kinds of architecture, viz. fundamental and sub-harmonic. In the fundamental oscillator the LC tank is tuned directly at the output mm-Wave frequency. But this architecture suffers from low tuning range, and low quality factor of the LC tank resulting in low phase noise performance. A sub-harmonic oscillator offers better performance for both of these specifications and is usually preferred as shown in the Fig. 1.

In this work, a 50GHz Colpitts oscillator with LC tank at both the drain and the gate of the transistor is magnetically coupled with another identical Colpitts oscillator. The magnetic coupling is done in a quadrature manner so as to allow both in-phase (I) and quadrature (Q) outputs from the oscillator itself. After careful selection of the tank component values, the coupling can be performed in a way which enhances the third harmonic (150GHz) of the fundamental oscillator output. Thus resulting in a Class-F operation for the complete structure. Since the third harmonic amplitude is large, the oscillator also acts as a multiplier. And this allows the 150GHz output to be easily extracted using tuned buffers avoiding the need for extra high power multipliers. Since the IQ mismatch is also an important parameter for the quadrature oscillators, a single balanced mixer is also designed to down-convert the oscillator output to base-band frequency (100MHz). This is required because of the device limitations to measure the IQ mismatch accurately at mm-Wave frequencies.

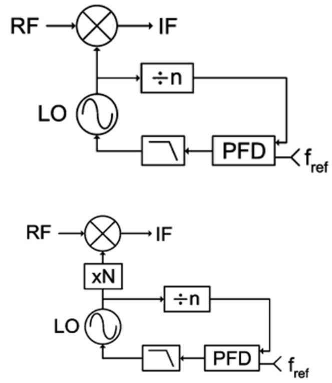


Figure 1: Oscillator architectures: Fundamental (above) vs Sub-harmonic (below)

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Sub-THz tranceiver with inbuilt synthesizer and on chip antenna for 6G wireless wireless transceivers

Rohish Kumar Reddy. Mitta
SAL supervisor: Gernot Hueber, Silicon Austria Labs GmbH
University supervisor: Harald Pretl, Johannes Kepler University Linz

1 Abstract

The research approach is towards frequency synthesis and integrated communication systems targetting 6G wireless applications. In most cases integrated sub-THz frequency generation is based on the harmonic frequency extraction exploiting the non-linearities of the device characteristics. By exploiting the harmonic frequencies the amplitude of the synthesized frequencies and clock diminishes at the initial stage of realization. The research approaches the multi-pronged solution to achieve a realizable trade to implement a robust and low power consuming sub-THz synthesizer for communication and sensing applications.
Adding to the challenges there has been a MIMO based on approach involving multiple transceivers. For the MIMO applications, the frequencies synthesized must be distributed with a very robust and systematic approach to synchronizing the phases of the generated frequencies with all the array-based transceivers to achieve high performance of the communication links and reach the link budget is based on theoretically calculated specifications

2 Research focus

The work focuses on implementing the transmitter with a frequency multiplier chain multiplying the input clock-/frequency from the reference source up to the range of maximum frequency of 320GHz catering to the bandwidth in realizing IEEE Std 802.15.3d. The realization of this transmitter is done using the SiGe SG13G2Cu process from IHP [1]. The reason for the technology choice is because of the speed of the BJT devices in the process which can easily cater to the frequencies of interest due to the ft/fmax of 350/450 GHz. Along with the device, frequencies offered the process offers a very robust metal layer to realize a very high Q passive.
The initial stage will start with acquiring pure clocks and references from the FBAR or SAW-based resonators which have shown generated frequencies with phase noise of -150dBc/Hz at 1kHz frequency offset. Using such sources as hard reference further high-frequency sub-THz frequencies can be realized and synthesized for the intended applications. With the knowledge gained from the first implementation, the future design approaches will be realized as a heterogeneous chiplet design involving both CMOS and BiCMOS processes to realize a complete transceiver, working with data rates in excess of 100Gbit/s.
The proposed implementation of the frequency multiplier and mixer implementation is shown in Fig. 1. This includes a programmable supply generator which will be inbuilt to realize the real-life solutions of plug-and-play implementations of 6G frontends.

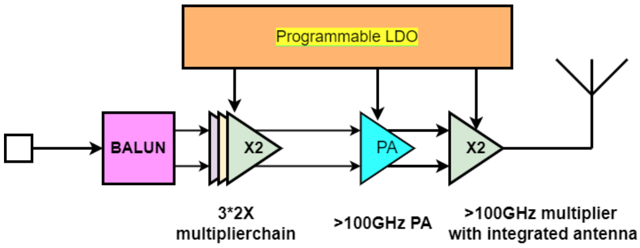

Figure 1: Proposed multiplier chain with integrated Power source and Radiating frontend

The later implementation is to realize the Local oscillator (LO) with baseband modulation schemes to realize the complete transceiver system. The further Design implementation realizes the PLL-based frequency synthesizers with frequency tuning for realizing a reference standard of IEEE Std 802.15.3d [2] operating in frequency ranges from 250GHz to 350GHz Bands with further inclusion of purely Phase modulation-based information mixing in these applications.

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Non-linear Interference Suppression System for sub-6GHz Communication Applications

Meysam Shayestehfar, Silicon Austria Labs GmbH
SAL supervisor: Hao Gao, Silicon Austria Labs GmbH, Eindhoven University of Technology, Eindhoven, the Netherlands
University supervisor:

1 Abstract

This article tries to demonstrate the functionality of a new approach for dealing with interference bottleneck in multi-radio coexistence scenarios which are recently of concern in communication systems. A non-linear interference suppressor is introduced handling complex modulated dynamic interference signal and providing more than 40dB interference cancellation. The system shows high linearity and very low complexity, power consumption and noise figure.

2 Introduction

Nowadays, due to recent tremendous growth and advancements of modern communication systems, large number of devices are sharing the environment. According to various applications, each of these devices is providing multiple communication standards. GSM, UMTS, LTE, 4G and 5G are some of the examples which almost every modern device supports. As a result, each device contains various transceivers, working at the same time.
Recently, by increase in demands for higher data rates and bandwidth for the communication system, sub-6 GHz frequency spectrum is still interesting for communication. Consequently, it is a crowded and almost fully occupied frequency band. According to the mentioned multi-radio coexistence scenarios, carrier aggregation is expected and large interference between many transmitters (Tx) or aggressor and receivers (Rx) or victims is probable which can interrupt and deteriorate the Rx performance.
There are many solutions for dealing with the multi-radio coexistence such as RF, mixed-signal and digital domain cancellation techniques, frequency filtering techniques and using nonlinear systems.

3 Nonlinear Interference Suppression Receiver

Nonlinear Interference Suppression (NIS) system uses nonlinear characteristics of RF devices to suppress interference seems promising due to low power consumption and dealing with (un-)known interference sources at RF front-end solving general multi-radio coexistence problems [1]. NIS Rx is a complex system which requires specific characterization, great precision, and various auxiliary subsystems to guarantee that the sensitive NIS system is working properly. To satisfy the system's requirements, many digital, analog and mixed-signal sub-systems are necessary.
Fully analog closed-loop NIS system is a modern version of NIS which is high-speed, adaptive, precise, low-power, low-complexity system beneficial for modern communication systems. Analog closed-loop is able to maximize the interference cancellation of the Rx in a cost-efficient way.
The novel analog closed-loop contains 3 sub-systems: Envelope tracking, amplitude misalignment adaptation and phase misalignment adaptation sub-systems. Fig. 1 shows the main core of the NIS system and an auxiliary analog closed-loop as a small part of the whole Rx.

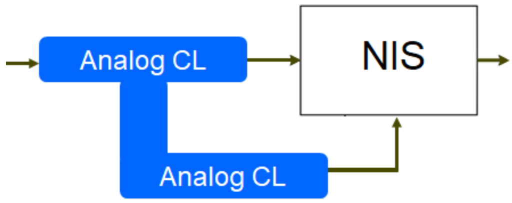

Figure 1: Analog closed˙loop and NIS system.

4 Results and Conclusions

Fig. 2 demonstrates the performance of the NIS in terms dynamic interference cancellation.

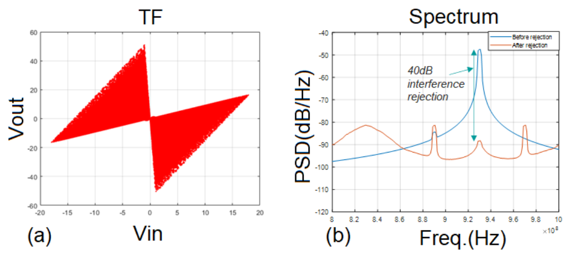

Figure 2: (a) NIS transfer function. (b) NIS suppression performance.

The results show a perfect performance for the NIS Rx dealing with multi-radio coexistence scenarios. It handles constant/varying envelope, high PAPR and wide BW signals common in modern telecommunication systems.
In conclusion, the auxiliary analog closed-loop is a noticeable solution for the adaptive NIS system which is very fast, simple, low cost, low power, accurate and supporting the NIS TF to suppress the interference more than 45dB and also amplify the small desired signal around 20dB.

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Part II

Machine Learning and Signal Processing

Event-Based low power Deep Neural Networks architectures

Diego Gigena Ivanovich, Silicon Austria Labs GmbH
SAL supervisor: Pedro Julian, Silicon Austria Labs GmbH
University supervisor: Pedro Julian, UNS Argentina

1 Introduction

IoT enables to collect information from the environment through a sensor, whether this is a single variable like temperature, pressure, flow, etc., or a more complex source of information which could be the case in a vision, acoustic or even a tactile sensor. In the former case, a good solution is often achieved by sampling the variable of interest at the lowest possible frequency and transmitting information on demand. In the latter case, which is the one we are interested in, the amount of information is larger; vision sensors are at the top followed by acoustic and tactile; and transmitting raw data becomes too expensive in terms of energy. This motivate researchers to find clues in biological systems, and the ways in which features are extracted and further communicated, producing the emergence of a new field called Neuromorphic Engineering. One of the first cases that was studied was vision, probably because it was the most data demanding problem, as already mentioned, but the concepts directly apply to other types of sensory information. Traditional artificial vision systems capture and process sequences of frames, commonly using convolution operations and linear layers that extract characteristics and combine them to produce a classification score as a result. This is a rather intensive process, both in terms of the computation and bandwidth required to feed the network with input data and parameters and propagate the information between layers, respectively. However, the brain does not operate using frames; the photoreceptors in the retina collect light, and when a certain threshold is exceeded, a spike (asynchronous) signal is sent down the nerve pathway. Inspired by this principle, several event-based (EB) image sensors have been developed, like the Dynamic Vision Sensor (DVS), which only produces an event (spike) when there is a change in the light intensity of a pixel, and in the absence of stimuli, it does not produce any output.

Another interesting approach is the Flexible Read-Out Integration Sensor (FRIS), where the output is also EB and can be selectively generated when the absolute value or the relative increment of the sensor output exceeds some programmable thresholds, but the output value is the value of the measured variable instead of a spike.

2 About this work

This work focuses in the exploration and development of event-based NN for FRIS-like events, that fully exploits the spatio-temporal sparseness along the entire network. In this regard, we have developed an algorithm to compute event-based convolutions, that takes a sequence of events and calculates the output avoiding the computation of zeros. Later on, we developed a hands-shadows event-based dataset based on an emulator that given the desired thresholds, it is capable of generate events from a video. Using this, accumulating the input events in a frame, we trained a CNN with good results, and we are studying others types of architectures like Long-Short Term Memory (LSTM), in order to develop strategies that allows us to exploit the sparseness in time, as seen in figure 1. With this in mind, we aim to implement low-power hardware engines capable of efficiently compute this types of networks.

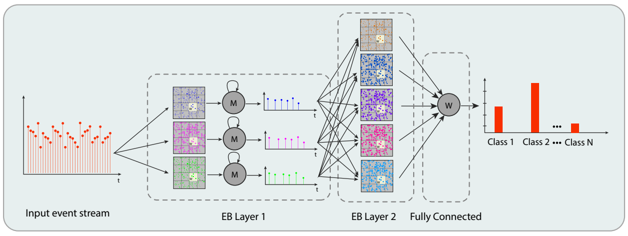

Figure 1: Event Based network with recurrent cells.

Machine Learning Approaches for Wireless Communications

Stefan Baumgartner
SAL supervisor: Pedro Julian, Silicon Austria Labs GmbH
University supervisor: Mario Huemer, Johannes Kepler University Linz

1 Abstract

Data-driven machine learning methods have become state-of-the-art for many applications in different research areas. Communications engineering, in turn, is a research field that is currently dominated by model-based signal processing methods. The goal of this thesis is the development and investigation of methods that combine the best of both data-driven and model-based approaches to enhance or substitute model-based methods for different tasks in communications engineering.

2 Introduction

Typical tasks in communications engineering such as channel and data estimation, (self-) interference cancellation, and digital pre-distortion have been accomplished with model-based estimation methods for several decades. These methods are based on well-established physical and statistical models. However, modeling errors, oversimplifications, wrong statistical assumptions, or insufficient domain knowledge might lead to severe performance degradation of model-based approaches. Furthermore, model-based methods delivering optimal performance often suffer from high computational complexity, requiring resorting to suboptimal methods in practice. Data-driven machine learning approaches can resolve some of the aforementioned issues and have been employed with incredible success in a variety of application areas in the last few years. Therefore, recent research has been conducted on the applicability of these methods, in particular, that of neural networks (NNs), to different tasks in communications engineering. The data-driven methods, however, usually require large amounts of training data, and incorporating existing model knowledge is hardly possible. The goal is to combine the best of both model-based and data-driven approaches to obtain top-performing and/or low complex methods for various tasks in communications engineering.

3 Current Work

Currently, we are developing and investigating diverse NNs for data estimation in communication systems. More specifically, these NNs are based on standard fully-connected NNs, transformers, or "model-inspired" NNs, where the structures of the networks are related to models of the communication systems. We have already applied NN-based data estimators in a communication system employing the so-called unique word orthogonal frequency division multiplexing (UW-OFDM) signaling scheme, where close to optimal bit error ratio (BER) performance has been achieved [1]. Further, we have developed a model-inspired NN called SICNN for data estimation in single carrier frequency domain equalization (SC-FDE) systems [2]. The obtained results are promising, since, as shown in Fig. 1, the developed SICNN can outperform state-of-the-art model-based data estimators like the decision-feedback equalizer (DFE) or the linear minimum mean square error (LMMSE) estimator.

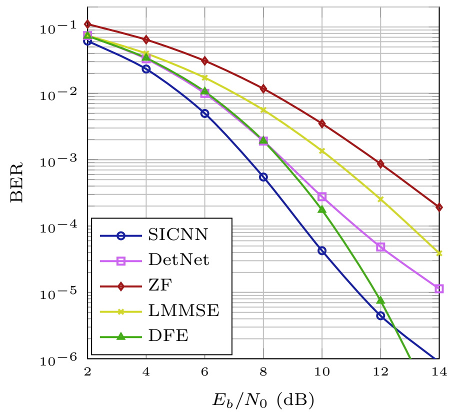

Figure 1: Bit error ratio curves of different model-based and data-driven data estimators for an SC-FDE system.

However, some problems, such as quite a high inference complexity of the NNs, have not yet been finally solved.

4 Outlook

As one of the next steps, NN-based data estimation shall also be investigated for SC-FDE systems when faster-than-Nyquist (FTN) signaling is employed. FTN signaling increases the bandwidth efficiency while introducing additional intersymbol interference, and thus more complex (nonlinear) data estimators are required. Consequently, communication systems employing FTN signaling could be an auspicious application area for NN-based data estimators.

Moreover, promising use cases of data-driven approaches for wireless communications will be selected and explored in agreement with the goals in the 6G lighthouse project of SAL.

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Sample Efficient Reinforcement Learning for protect SoC Design

Markus Hofmarcher, Johannes Kepler University, Linz
SAL supervisor: Pedro Julian, Silicon Austria Labs GmbH
University supervisor: Sepp Hochreiter, Johannes Kepler University Linz

1 Introduction

Due to the ever increasing complexity of circuits and systems, the design of System on Chips (SoC) starts at high levels of abstraction. Model-based design is a state-of-the-art design methodology which addresses this development. Here, initial drafts of the design are defined using modeling languages.
Following this early design phase several additional stages with their own set of highly complex design decisions have to be solved to finalize a chip design. One such stage is the problem of *macro placement*. The objective of this task is to place individual components of a chip (i.e. macros and standard cells) onto a canvas such that power, performance and area are optimized while adhering to constraints on density and routing congestion. Due to the large number of macros and cells (several millions) this is a highly complex task occupying experts for weeks or months. Additionally, evaluating a design candidate is a time consuming process in the order of several hours or even days.

2 Related Work

Multiple approaches including the application of meta-heuristic algorithms like *Simulated Annealing*, approaches based on *Machine Learning*, as well as *Genetic Algorithms*, or approaches based on reasoning engines have been researched in industrial and academic communities. However, these approaches require extensive tuning and adaptation for each new SoC design. Recently, it has been shown that agents trained with reinforcement learning can optimizing such designs [2].

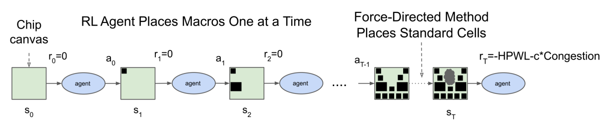

Figure 1: Schematic depiction of a placement model via reinforcement learning [2]. The chip canvas is a 2D grid with a fixed number of cells. The agent iteratively selects the position for the next component until all components are placed. Afterwards standard cells are placed in a post-processing step before evaluating the resulting design.

3 Sample Efficient Reinforcement Learning

The reward function of this problem is episodic, meaning that only when all components are placed and evaluated can the design be evaluated. Such a sparse and delayed reward makes learning an agent difficult and increases the number of required samples significantly. Recent advances in reinforcement learning, such as RUDDER [1], focus on this challenging problem by decomposing the reward given at the end into contributions of individual state-action pairs and assigning reward to those states and/or actions causing it. Doing so can significantly speed up learning and require substantially less samples, i.e. interactions with the evaluation function. However, this approach uses an LSTM model to learn the reward redistribution, which still requires a relatively large number of samples to train.
Therefore, we propose to replace the LSTM model in RUDDER with an associative memory network, such as modern Hopfield networks [3] as these require substantially fewer samples. We introduce Hopfield-RUDDER [4] and evaluate it on a number of controlled environments with episodic reward. In order to use the associative memory from modern Hopfield networks in partially observable settings we introduce the *Reset-Max* history, a lightweight history compression method that works well in this setting and is easy to train with a small number of samples. By associating state-action pairs with the expected quality of already evaluated designs the episodic reward can be decomposed and assigned to important events, therefore speeding up learning.

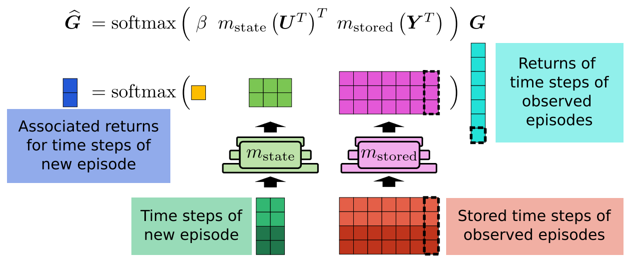

Figure 2: Illustration of modern Hopfield networks for return decomposition in Hopfield-RUDDER.

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Object Classification using Radar

Christian Huber, Silicon Austria Labs GmbH
SAL supervisor: Pedro Julian, Silicon Austria Labs GmbH
University supervisor: Reinhard Feger, Johannes Kepler University, Linz

1 Abstract

Radar sensors are widely used in many application, like object detection, blind spot monitoring, cross traffic alerts or parking assistants in cars. In this project we want to focus on classification of objects perceived by radar sensors. For this purpose, we plan to create a dedicated dataset. Using this dataset, we want to investigate accuracy in behaviour of classification algorithms in specified environments. As part of this the impact of radar system limitations on the classification performance will be investigated.

2 Introduction

Radar sensors have interesting properties for sensing the environment. They are cheap, work at high frequencies and they are hardly affected by weather or lightning condition.
Although, there are multiple approaches for combining data from radar with other sensors, like cameras, there is not much work on object classification using radar data only. Some papers perform this tasks on simulated data [1, 2] or with very specific settings, like classifying aircraft and ships [1, 3]. In either case, there is very limited background information contained in the data. Our preliminary results have shown that additional background information from an indoor environment significantly deteriorates the classification performance of simple machine learning algorithms.
To be able to perform fast experiments and develop smaller and faster networks we create a MNIST like toy dataset [5]. Based on that dataset, we will performing multiple experiments aimed on getting a better understanding for the radar data and classification algorithms.

3 Measurement setting

For our measurements we use a 77 Ghz Frequency Modulated Continuous Wave (FMCW) radar with 12 transceiver and 16 receiver antennas. Our prediction targets are aluminium foil balloons in shapes of digits from zero to nine. We distinguish two main setting. First, using a stationary fixed radar, we move the targets across the receptive field of the radar antennas (see Fig. 1). Second, using a statically placed target, we move the radar in order to perceive the object from different perspectives. The later setting we consider to be more difficult, because background information cannot be removed by decluttering.

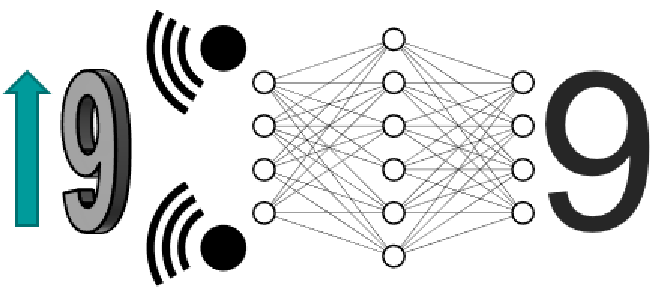

Figure 1: Classification of metal digits.

4 Experiments

We perform multiple experiments to understand the possibilities and limitations of the information coming from a radar sensor. The experiments will be evaluated on there performance in terms of classification accuracy as well as overall system complexity (time for data preprocessing and classification).
We want to determine which data preprocessing method are beneficial for the classification task. While LSTM (Long-Short Term Memory) [6] architectures might be suitable for raw input response data, CNNs (Convolutional Neural Network) [7] may work better with Range-Doppler maps and Transformer [8] based networks may dominate voxel shaped representations.
Another aspect of this work is the impact of system limitations on classification accuracy. Therefore, we simulate Radio Frequency devices with lower bandwidth and reduced snapshot rate. To reduce the snapshot rate, we equidistantly subsample the recorded snapshots. To lower the bandwidth, we compute an ideal band-limited version of our recorded data.

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OFDM Time Domain Equalization with Transformers

Simon Schmid
SAL supervisor: Pedro Julian, Silicon Austria Labs GmbH
University supervisor: Sepp Hochreiter, Johannes Kepler University Linz

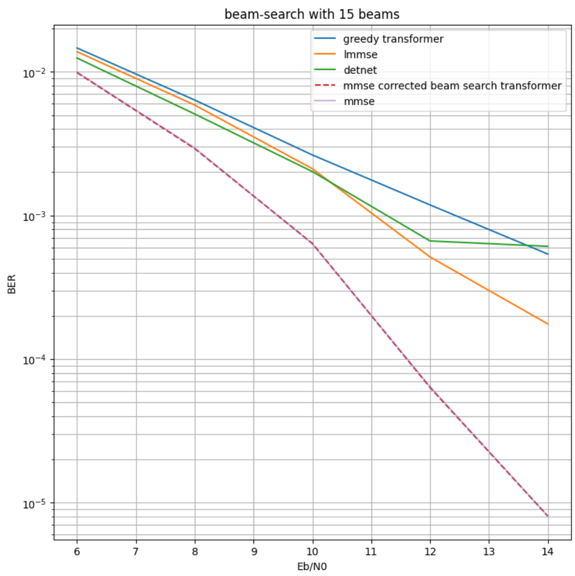
Wireless Communication always needs some way of dealing the with noise and interference that are introduced by transmission channels. Traditionally, this is done with model-based approaches. The model deals with describing the channel, which allows a receiver to estimate the introduced errors and remove it, a process that is called Equalization. These methods are already really successful and widely used.
OFDM works in the frequency domain modelled by a linear multipath channel model with AWGN (Additive White Gaussian Noise). All traditional and machine learning models so far use this model and also work in the frequency domain.

$$\mathbf{y} = \mathbf{H}\mathbf{x} + \mathbf{n} \tag{15.1}$$

Here, $\mathbf{H}$ is the frequency response of the system and $\mathbf{n}$ a white gaussian noise vector with known standard deviation. The data $\mathbf{x}$ sent over the channel is a quadrature amplitude modulated baseband signal.
In this work, the equalization problem is treated as a sequence to sequence translation problem, which means working with the model in time-domain, not frequency-domain. This means, the received signal $\mathbf{y}$ is not used but the time-domain equivalent of $\mathbf{y}$. Together with other relevant data it is fed to an encoder module which generates a high-dimensional encoding of the signal.
This encoded signal is then used with a decoder module which decodes the signal symbol by symbol in an auto-regressive fashion. The big advantage coming from this auto-regressive decoding is the possibility to use the beam-search strategy to generate multiple distinct solutions for the decoded signal.
A beam-search with N beams generates a set S of what the model sees as the N most likely candidate solutions for the target-signal $\mathbf{x}$. Since the model could still have made an error in the prediction, the best way to select the correct candidate is computing the mean squared error to the received signal $\mathbf{y}$ and selecting the candidate which produces the minimal error:

$$\hat{\mathbf{x}} = \min_{\mathbf{x} \in S} (\mathbf{y} - \mathbf{H}\mathbf{x})^2 \tag{15.2}$$

This is the same way as the maximum likelihood equalizer would select its predicted solution but with only N candidates, this is computationally feasible.
Another problem that has to be solved emerged with the training of machine learning models for equalization. All of the models seem to behave much worse for high signal to noise ratios compared to the classical non-machine learning models. This seems to happen for all machine-learning based models which hints to a more fundamental problem.
It could be that the comparably low error rate at high SNR makes it more and more difficult to get rid of the errors that are still be made. This is made even more difficult as current training-approaches use the correct signal $\mathbf{x}$ as the target to train, which could be problematic. The reason for this is the fact that the maximum likelihood estimator as the optimal estimator also makes errors, but these errors are not correctable, since they come from the noise $\mathbf{n}$. If a model trains on such errors, the resulting loss is not beneficial to the model since the resulting adaption tries to correct an error that cannot be corrected. During training, the percentage of this type of error grows since the model eliminates more and more of the errors that can in fact be corrected. Therefore it could be that at some point a large portion of the loss tries to correct errors that cannot be corrected and overloads the loss that comes from errors that can. These problems are why this work also tries to find better training-strategies that go beyond the straightforward training on just the target $\mathbf{x}$.



Comparison of a trained transformer with beamsearch postprocessing to the LMMSE, detnet and MMSE. The transformer with beamsearch is extremely close to the optimal BER.

Low Power Integrated Circuits for Deep Neural Network Architectures

Nicolas Rodriguez, Silicon Austria Labs GmbH
SAL supervisor: Pedro Julian, Silicon Austria Labs GmbH
University supervisor: Pedro Julian, UNS Argentinia

1 Introduction

In the past decades, along with the exponential growth of computing systems, Machine Learning and Deep Neural Network algorithms became popular in solving complex tasks such as image processing recognition, classification, segmentation, etc. From just a couple of fully-connected hidden layers to Convolutional Neural Networks (CNNs) with a huge number of parameters, these networks and their training methods began to evolve, developing different techniques that increase their performance while reducing the number of required parameters.

In recent years, some articles introduced morphological computations for image processing (filters that are based on the geometrical properties of the objects in the image) at the first layers of Deep Neural Networks, while keeping the last fully connected layers, improving the network performance as this morphological filters extract more complex features than regular convolutions. This Morphological Neural Networks (MNN) train a structuring element for the filter and the morphological operation is in most cases fixed. Some MNNs use approximations to be able to train and let the network learn the operation itself, but only the two basic ones: erosion and dilation.

At the same time, several hardware architectures were proposed to implement Neural Network accelerators optimizing different aspects such as speed, power-consumption, number of neurons, etc. Most of them performing only one layer at a time , either convolutional or linear, and too large to be used in embedded devices. The purpose of this PhD Thesis is to investigate and develop different computational units, also non-linear operations and time-based computations, to achieve low-power Integrated Circuit (IC) implementations that can allow more complex Neural Network computations in Internet of Things devices.

2 Methods

One proposed algorithm that already has an efficient time-based hardware implementation is the so called Simplicial Piece-Wise Linear (SPWL), which approximates an objective function by dividing its input range into smaller regions (called Simplices) where the result is computed as a linear interpolation of the values of the objective function at the corners of each sub-region (Simplex). With this Simplicial partition it is possible to represent many complex functions but comes at a cost of a large memory to store all the coefficients required for the computations, which scales exponentially with the number of inputs of the target function, as every Simplex has its own set of parameters. This limits its use to the smallest (but mostly used) kernels of CNNs. The current SPWL time-based hardware implementation encodes the inputs x_i into time domain by comparing it with a reference signal r, see Fig. 1, and accumulates the selected coefficients based on the time-encoded signals so no multiplier is used. This makes the SPWL more efficient than standard linear or convolutional implementations and promising to design accelerators for edge computing. As an alternative, we can use Simplices that have the same coefficients (Symmetric SPWL), reducing significantly the required memory but being able to represent only symmetric functions.

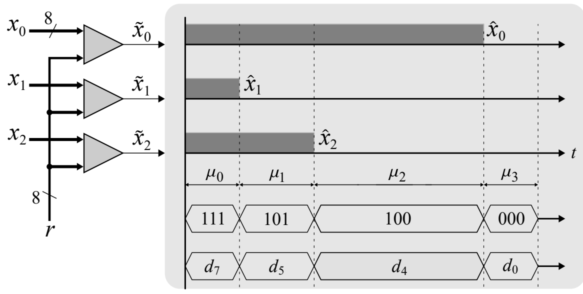


Figure 1: *Time Based decomposition example for Simplicial Piece-Wise Linear (SPWL) architecture. Time encoded signal used as addresses (d_i) to select coefficients for SPWL function.*

3 Results and Discussion

Since morphological functions are essentially symmetric with respect to its inputs, they can be represented by a symmetric function (or a sequence of symmetric functions). Therefore, it is possible to learn much more complex MNN architectures using the aforementioned Symmetric SPWL algorithm. In this regard, we developed a backpropagation algorithm for the SPWL (also symmetric ones) and integrated into Pytorch framework, achieving better performance in classifying UCMerced dataset (aerial images) than most of the state-of-the-art CNNs.

In terms of hardware design we optimized the comparators used by the SPWL implementation to time encode the inputs and extended their functionality. The use of Dynamic CMOS logic instead of the usual Complementary CMOS was analyzed and tested to produce IC implementations with even less power consumption.

As future work we plan to extend the analysis of Neural Networks using Symmetric SPWL for other image processing tasks, as well as explore alternatives of non-linear computational units with time-based implementation for low-power IC designs.

Formal Analysis, Verification, and Automated Modeling of Artificial Intelligence Components

Edi Muškardin, Silicon Austria Labs GmbH
SAL supervisor: Ingo Pill, Silicon Austria Labs GmbH
University supervisor: Bernhard Aichernig, TU Graz

Artificial Intelligence (AI) has been the driving force behind many advances in various fields in the last decade, especially in the computer science domain. While AI, or more specifically deep neural networks often offer novel solutions to a diverse set of real-world problems, their internal reasoning and decision making remains puzzling to researchers. The purpose of this Ph.D. thesis will be put concisely as both Formal Methods for AI (FM4AI) and AI for Formal Methods (AI4FM). In the former we explore the applicability of formal methods, more concretely, automata learning, in the context of verification and automated modeling of AI components, while in the latter we investigate the use of AI methods to solve challenges found in the formal methods domain.

1 Formal Methods for AI

The impressive performance of artificial neural networks (ANNs) has made them an effective asset in our computing toolbox, and has been an enabler for innovative intelligent systems like autonomous vehicles. Prompted by their popularity, we have also seen significant advancements in their verification, which needs new concepts since ANNs differ significantly from traditional software (or hardware). In the scope of FM4AI, we analyze recurrent neural networks (RNNs) due to their ability to model sequential data which makes them well-suited for applications with stateful reactive behavior. We study the automatic modeling of RNNs input-output behavior (Fig. 1). Extracted models can be used for explainability, model checking, as well as basis for active RNN training. Furthermore, we will study the internal behavior of RNNs to better understand how RNNs make stateful decisions.

2 AI for Formal Methods

Black-box systems are inherently hard to verify. Many verification techniques, like model checking, require formal models as a basis. However, such models often do not exist, or they might be outdated. Active automata learning helps to address this issue by offering to automatically infer formal models from system interactions. Most research, however, has been focusing on deterministic systems. We are interested in the development of an efficient approach to learn models of stochastic reactive systems, and in our future work will continue to extend state-of-the-art in the automata learning field. Aside from algorithmic advances in the formal methods domain, we explore the use of AI techniques to deal with the most challenging aspects of automata learning, such as abstraction and hypothesis falsification.

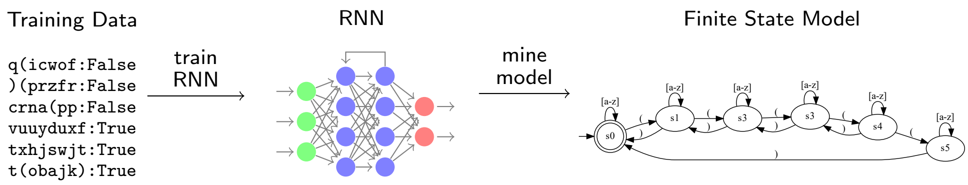


Figure 1: Extraction of Finite-State Models from RNN.

Neural Network based Predistortion for Power Amplifiers

Ignacio Cousseau, Johannes Kepler Universität Linz
SAL supervisor: Pedro Julian, Silicon Austria Labs GmbH
University supervisor: Pedro Julian, UNS Argentina

1 Introduction

The radio frequency power amplifier (PA) is a key component in the transmitter of a digital communications system. PA operation implies a trade-off between efficiency and linearity. Preferably, PAs are operated as close as possible to the saturation point, to achieve high efficiency. On the other hand, modern standard communication signals have high spectral efficiency and usually large peak-to-average power ratios (PAPR). Mildly nonlinear amplifier topologies, like class AB, could be backed-off to avoid operation in saturation, but this results in poor efficiency.
A widely spreaded solution is the use of digital predistortion (DPD). A predistorter block is placed before the PA, such that the amplified output signal is linearized or, in other words, the PA nonlinear behavior is compensated. For ease of implementation and robustness, predistortion is usually performed in the digital baseband domain. Moreover, the nonlinear PA behavior exhibits memory effects and also generates intermodulation products outside the frequency band of the modulated input signal. This is the so-called spectral regrowth or leakage, for which the usual metric is the adjacent channel leakage ratio (ACLR).
Since the objective of the predistorter is to invert the PA nonlinearity, PA behavioral modeling and DPD design are closely related. A classic approach for nonlinear modeling is the use of Volterra series and its many simplifications (memory polynomials, general memory polynomials, Wiener and Hammerstein models). For this approach, the obtention of the DPD coefficients is often reduced to solving a linear-in-parameters equation using least-squares, which in this case is often a poorly-conditioned problem.

2 Current work

Lately, neural networks (NNs) have been used for modeling and predistortion, since their capability to approximate nonlinear functions is well known. To obtain measurements from an actual PA, RF WebLab was used [1]. This is a remote measurement system located at Chalmers University. The PA operates at a center frequency of 2.4GHz and an OFDM-like signal with 20MHz bandwidth was used as input. The input power level was set at the maximum allowed value.
The power spectral density of the PA output signal with and without DPD are shown in Figure 1. Two NN-based predistortion approaches were considered. For the first approach [2], a NN with time-delayed inputs is used to approximate the output-input PA function (post-distorter), which is then used as predistorter. For the second approach [3], two steps are done: first, a NN is trained to model the PA memoryless behavior and then a DPD NN is trained through backpropagation.

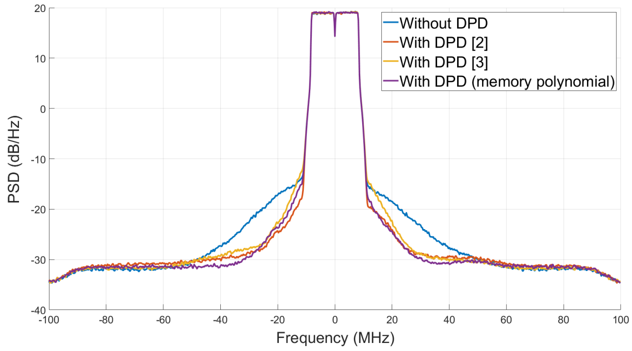


Figure 1: PA output PSD with and without predistortion for an OFDM signal.

3 Research Outlook

In recent literature, different NN architectures have been proposed for PA modeling and predistortion, including RNNs and CNNs. In these works, NN based-predistortion is aimed towards higher frequencies (tens of GHz) and bandwidth (hundreds of MHz), where the PA exhibits strong nonlinear behavior. DPD analysis has also been extended to MIMO arrays, with focus on reducing implementation complexity.
The proposed predistortion approaches are usually implemented in FPGA/ASIC designs, for which complexity has to be evaluated. Further analysis is needed in this regard.

4 Bibliography

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Part III

Communication and Networking

Trustworthy Industrial Wireless Sensor Networks

Julian Karoliny, Silicon Austria Labs GmbH
SAL supervisor: Hans-Peter Bernhard, Silicon Austria Labs GmbH
University supervisor: Andreas Springer, Johannes Kepler University Linz

1 Introduction

The main topic of my research is to find methods for improving the performance, security, and trustworthiness of wireless sensor networks (WSNs). Especially in industrial use-cases, WSNs have to fulfil stringent requirements such as high synchronization, low power consumption, and deterministic latency. To meet these conditions also in wirelessly challenging locations, one key element is to continuously observe the RF surrounding and quickly adapt to changes. Especially in the unlicensed 2.4 GHz frequency band, many technologies like Bluetooth® Low Energy (BLE), Wireless Local Area Network (WLAN), Thread, etc. share the same channels, and collisions are unavoidable. A typical approach to minimize the number of collisions is to measure the traffic or error rates and avoid highly occupied channels or exclude these channels from hop lists. Though random access to the channel is a usual approach in a wireless network protocol, some parts will have deterministic, somehow periodic access to the channel, especially true for connected devices and sensor networks. This work presents a method to measure the interference in WSNs, which will allow us to identify and track the source of the disturbance. In this context, interference is referred to as access to the channel by an external device, may it be cross-technology or inter-technology interference.

2 Interference Measurement and Tracking

The interference measurement itself is performed with low-cost sensor nodes, which continuously measure the signal level of the channel and report the measured Received Signal Strength Indicator (RSSI) data to a central unit. To reduce the amount of data, only the average and maximum signal level in 1 ms timeslot resolution is measured. Since this approach does not rely on decoding received messages, the channel access and interference of multiple communication protocols and devices can be observed. For example, if a BLE channel is measured, the interference of other communication standards like WLAN and Thread can be observed since their channels overlap with the measured one. The goal now is to find patterns and access behaviour in this channel measurement and include this information in the own wireless network.

For processing and visualisation purposes, we further group the data in superframes combining multiple of these 1 ms timeslots. Fig. 1 depicts the result of one such interference measurement with 100 timeslots per 100 ms superframe. If in a timeslot the measured signal level is above a -90 dBm threshold, it is marked black, otherwise, it is left empty. The measurement itself is still an array of RSSI values, however, depicted as 2D image to visualize the pattern of specific interferences. Low-power

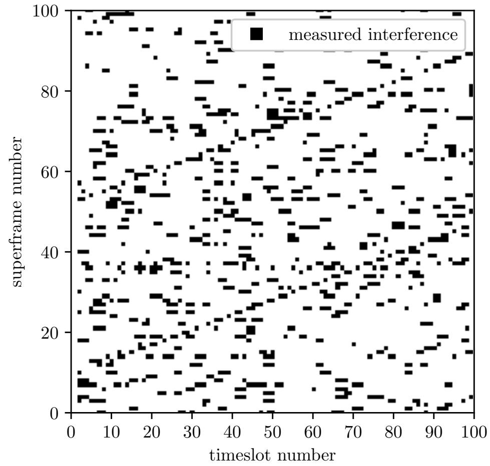

Figure 1: Example interference measurement.

networks and protocols rely on deterministic transmission which often results in periodic channel access with a distinct pattern in the channel measurement. For example, if we assume a superframe period of 100 ms, the interference of an IEEE 802.11 WLAN beacon with a period of 102.4 ms will appear in each subsequent superframe a certain amount of timeslots later. This is also the case for the measurement in Fig. 1, where two periodic interferers are in close proximity to the interference measurement node. One of these interferers imitates the access behaviour of the WLAN beacon which can be seen as the two lines moving to the right. The other one uses a period of 94.2 ms and is harder to distinguish from the noise.

3 Contribution and Research Outlook

The focus of my current research is to use interference measurements like in Fig. 1 to gain more information about the disturbance. The main challenge here is to assign the different measured signals to the different interferer sources and track them over time. This will allow to

- identify the source of interference, e.g, what communication standard or device it is.
- localize the source based on RSSI measurements from multiple distributed sniffer nodes.
- find interference patterns to predict and avoid future channel collisions with the own WSN.

This enables the possibility to apply countermeasures that will improve the performance, functionality, and security in WSN and may especially benefit the use of wireless technologies in critical industrial applications.

Wireless Communications for Resilient Automation

Armin Hadžiaganović, Silicon Austria Labs GmbH
SAL supervisor: Hans-Peter Bernhard, Silicon Austria Labs GmbH
University supervisor: Andreas Springer, Johannes Kepler University Linz

1 Summary

Industrial automation is an evolving trend that brings us new production capabilities but also new risks and requirements. Today we are often speaking about autonomous production systems known as Cyber-Physical Systems (CPS). CPS relies on a strong bond between software and hardware, and especially on the data exchange between components of CPS. Therefore, CPS requires reliable and real-time communication between industrial devices. Communication is in most cases maintained over wired medium using different proprietary physical layer communication protocols. Wired communication links are seen as reliable and secure, but their installation and maintenance drastically increase the production operating costs. Therefore, with the latest advancements in wireless communication technologies and the increasing need for flexibility in emerging industrial applications, wireless communications are becoming a desirable choice for industrial communication systems. Additional benefits of wireless communications in industrial environments allow reduced configuration and maintenance costs, modular industrial processes, and inherent mobility support. However, wireless communication channels are characterized as unreliable, insecure, and much more error-prone than the wire-line channel.

Broadly speaking, the purpose of my PhD topic is to increase the resilience of wireless communication to meet the high requirements of industry and CPS. In general, the most strict communication requirements are conditioned by safety-related systems. Safety-related systems are defined by functional safety standards and they are an important part of every automated process. A safety-related system aims to mitigate, control, or prevent a hazardous failure and take the system to a safe state when predefined conditions are violated.

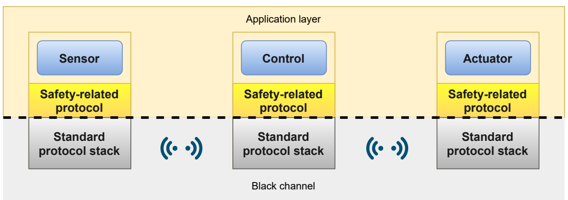

Figure 1: Safety-related communication over black channel

A safety-related system consists of several safety-related parts of control systems (SRP/CSs) such as sensors, actuators, logic, and the connection in between. To gain the resilience of a system, all parts have to be resilient, including the communication links. State-of-the-art solutions utilize cyclic communication and specialized safety-related communication protocols to continuously monitor the state of communication links. This approach still has to be proven in wireless communications. Through my PhD research, I will tackle different safety-related communication protocols and different wireless communication standards to propose a new optimal way to monitor the communication links and ensure industrial safety.

In addition, while safety provides communication availability, security relates to preventing an intentional attack on CPS. The most common security threats in wireless communicatons are denial of service caused by message flooding, spoofing and session hijacking by the user with invalid credentials, and eavesdropping where data is being intercepted by the unauthorized party. Security is an additional essential needed for replacing wired communications in the industry with wireless communication.

My latest research was focused on evaluating the requirements of safety-critical communications in different use cases and experimentally measuring the boundary conditions we can achieve using the IEEE 802.11 wireless communication. I have experimentally tested the usability of fail-safe protocol openSAFETY in standardized IEEE 802.11 network and proven that with default configuration IEEE 802.11n and 802.11ac standards can not comply with industrial requirements, mainly due to the poor system availability. To further investigate the reasons and causes of systematic failures in communications, I have implemented a simulation environment based on OMNET++ network simulator and openSAFETY. The integration of openSAFETY in OMNET++ will enable easier testing of new concept implementations. The simulation-based findings would then be tested experimentally using laboratory setups or available 5G test beds. Additionally, I am working on ideas of extending 5G/6G networks with dedicated features for safety-critical communications, such as sensing the environment and enabling situational awareness. Communication technology (5G/6G) would use sensing to predict the degradation of the quality of service and preemptively apply protective measures.

Developing 5G-based testbed for Analyzing Time Sensitive Networks

Arash Sahbafard, Silicon Austria Labs GmbH
SAL supervisor: Hans-Peter Bernhard, Silicon Austria Labs GmbH
University supervisor: Andreas Springer, Johannes Kepler University Linz

1 Summary

The 5G communication system is expected to support a wide range of emerging applications. To support diverse application requirements, the international telecommunication union (ITU) categorised 5G services as enhanced mobile broadband (eMBB), massive machine type communication (mMTC), and ultra-reliable low latency communication (URLLC). The URLLC service supports scenarios that require high service availability with low-latency bounds. URLLC targets applications such as remote health care, vehicle-to-vehicle (V2V) communication, and industrial automation. However, depending on the application communication constraints, reliability and latency requirements may vary. URLLC, in general, is a challenging service that entails employing advanced techniques to support high demanding applications. Some related challenges in achieving URLLC may include quality of service (QoS) support, error handling, handover, and scheduling. The URLLC feature enables support for application that require high service availability and time critical communication. Examples may include industrial use cases such as control-control communication or human-robot interaction. To analyze 5G communication system for industrial applications, 5G URLLC features are to be developed and evaluated. Furthermore, features to support time sensitive networks (TSN) are to be incorporated. To TSN with 5G, time synchronization between the network components is imperative. TSN requires a common clock distribution in the network. Today, the radio hardware used based on 5G system (the most used one is the USRP) provides the time reference, but that time reference is not shared with other components in the network. To support TSN either the radio resource unit (RRU) needs to act as a precision time protocol (PTP) grandmaster in the system or if an external PTP grandmaster is used, the radios would need to be synchronized to the external PTP grandmaster. Since the plan is to continue working on URRLC features, implementation of uplink configured-grant transmission will be carried out. This will be followed with integration of TSN features such as time synchronization and scheduling as shown in Fig.1.

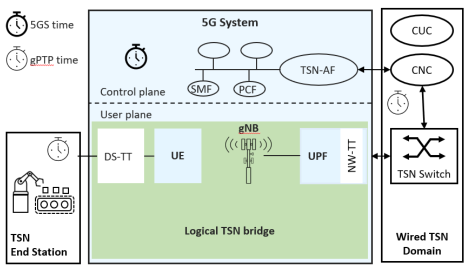

Figure 1: integration of TSN with 5G

3GPP third generation partnership project

5GS 5G system

5G 5^{th} generation

BS base station

CG configured grant

DL downlink

eMBB enhanced mobile broadband

gNB gNodeB

GF grant free

HARQ hybrid automatic repeat request

ITU international telecommunication union

mMTC massive machine type communication

NR new radio

OFDM orthogonal frequency division multiplexing

PI preemption indication

QoS quality of service

RAN radio access network

SCS sub-carrier spacing

TTI transmission time interval

URLLC ultra-reliable low latency communication

UL uplink

UE user equipment

V2V vehicle-to-vehicle

SR Scheduling Request

Real-Time Adaptive Impedance Matching for Wireless Power Transfer Systems

Jose Romero Lopera, Silicon Austria Labs GmbH
SAL supervisor: Bernhard Auinger, Silicon Austria Labs GmbH
University supervisor: Jasmin Grosinger, TU Graz

1 Introduction

Wireless power transfer (WPT) is a method for transferring energy between a transmitter (TX) and a receiver (RX) without a physical connection. Typical applications of such systems are wireless charging of mobile phones, electric vehicles, or medical implants. Inductive coupling and magnetic resonant coupling (MRC) are non-radiative WPT principles which operate under the basis of evanescent magnetic field coupling between the TX and the RX, using electrically short coil antennas. WPT systems based on magnetic resonant coupling operate optimally for a particuar static TX and RX coil arrangement. The system will not operate in its optimal condition if one coil antenna changes its position relative to the other coil antenna.

2 System Overview

In this project, we intend to build a WPT system based on MRC with real-time adaptive control to optimize efficiency of the WPT system for varying coil arrangements. Variations in the mutual coupling between the coil antennas due to a changing in TX and RX arrangement will change the impedances at the TX coil antenna input, as indicated by Z_{in} at the proposed system structure shown in Fig. 1

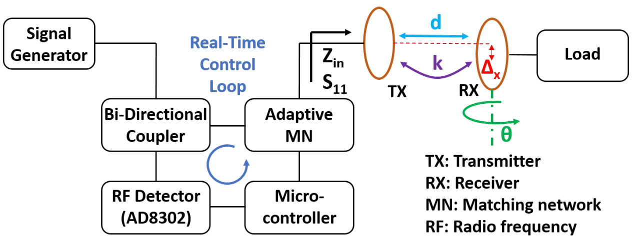

Figure 1: Real-time adaptive WPT system structure.

This impedance change can be re-adjusted to its optimum by an adaptive matching network connected at the input of the TX coil antenna to optimize the power transfer efficiency (PTE). The matching network (MN) includes varactors to adjust the input impedance of the system. The adaptive matching network is controlled by a microcontroller that transforms the TX-RX system's input impedance Z_{in} to the source impedance of the signal generator when variations in Z_{in} occur. The microcontroller is driven using an optimization algorithm based on deep learning trained with data for different coil antenna arrangements. Thus, the algorithm adjusts the matching network varactor values to optimize PTE for the present coil arrangement.

3 Training Data

The tranining data was gathered by TX-RX channel measurements, which also allows us to define the impedance range of the adaptive matching network. A pair of printed spiral coils (PSCs) based on the ISO/IEC 14443-1 class 1 were designed and simulated in CST Studio and then sent to production as printed circuit boards (PCBs). The PSCs were compensated using a series-series (SS) topology to resonate at the design frequency of 13.56 MHz. The scattering parameters (S-parameters) of the channel between the two PSCs have been measured in the lab using an R&S vector network analyzer under variation of horizontal and vertical misalignment Δ_x,Δ_y, azimuthal tilt Θ and inter-coil distance d, as shown in Figure 2.

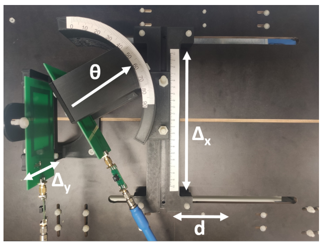

Figure 2: Testbench for channel measurements.

The S-parameters of the system with 50 Ω source and load terminations will show optimum WPT at perfect matching conditions for a specific combination of Δ_x,Δ_y,Θ, and d. This optimum occurs when the TX reflection coefficient S_{11} crosses the center of the Smith chart, and the TX-RX transmission coefficient S_{21} shows a maximum at 13.56 MHz. This situation is shown in Figure 3 at d $=$ 40 mm for the ideal case of perfect coil alignment over the distance, where each trace corresponds to an inter-coil distance from 14 to 70 mm in steps of 1 mm. This result is consistent with what the CST simulations predicted. Future work will make use of this data as the training dataset for a deep learning algorithm to find the optimum values required by the adaptive matching network to optimize PTE.

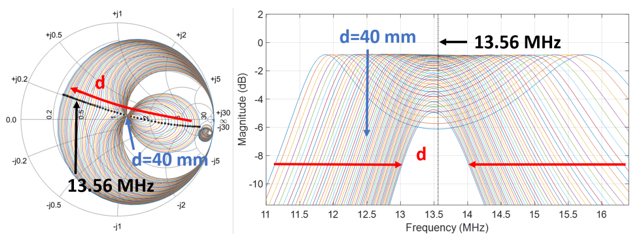

Figure 3: S-parameters of the TX-RX channel for Δ_x,Δ_y,$\Theta = 0$ and d=14-70 mm. Left-S_{11}, right-S_{21}.

Interoperability with WPT Systems

Richard Fischbacher, Institute of Microwave and Photonic Engineering, Graz University of Technology, Graz, Austria
SAL supervisor: Bernhard Auinger, Silicon Austria Labs GmbH
University supervisor: Wolfgang Bösch, and Jasmin Grosinger Graz University of Technology, Graz, Austria

The dissertation investigates reliable wireless power transfer (WPT) systems and their interoperability and coexistence with other systems. We specifically focus on Qi WPT systems, which are defined by the Qi standard and operate via inductive coupling. A specific use case for Qi WPT systems is mobile charging, e.g., charging smartphones and smartwatches. In this case, the WPT system uses a charger (transmitter, TX) to charge handheld devices (receiver, RX) wirelessly. In this work, the operation frequency of the Qi WPT system is 106 kHz. The Qi standard states that it is essential to establish a communication link between the TX and RX. The communication includes transmitting crucial data to support foreign object detection (FOD), preventing the destruction of low-power near-field communication (NFC) devices, monitoring the charging process, and monitoring safety-relevant data, e.g., battery temperature.

The NFC technology is an excellent candidate to provide a communication link between WPT TX and RX via an NFC reader and an NFC transponder (tag). The NFC technology operates at a frequency of 13.56 MHz relying on inductive coupling. Both systems' simultaneous reliable operation needs to be guaranteed. Thus, interoperability and coexistence analyses need to be conducted to ensure the optimal functionality of both systems.

Following a methodological approach, we have investigated WPT and NFC system interoperability issues via circuit-level simulations in Cadence AWR. Such circuit-level simulations allow faster system analyses than finite element simulations (FEM). A first interoperability analysis using a narrowband equivalent circuit (EC) model concluded that the NFC tag to reader communication quality is severely impaired by strong capacitive coupling between the WPT and NFC coil antennas [R. Fischbacher et al., "EC Model for WPT and NFC systems interoperability analysis", Radio Wireless Week 2021].

In the following, we developed a broadband EC model of a Qi WPT and NFC system to conduct broadband interoperability and coexistence analyses, which allow investigations of higher-order harmonics (e.g., WPT and NFC systems' interoperability) [R. Fischbacher et al., "Broadband EC Models of Coil Antennas for Inductively Coupled Systems", Wireless Power Week 2022]. In our work, we developed a novel methodology to create broadband coil antenna EC models of inductively coupled systems. The broadband EC models are based on vector network analyzer measurements of the WPT and NFC systems' prototype shown in Fig. 1. The setup consists of modular printed circuit boards (PCBs). It was designed to model the above-mentioned application, i.e., charging of a handheld device. The bottom part models the charger (WPT TX and NFC reader) and the top part models the handheld device (WPT RX and NFC tag).

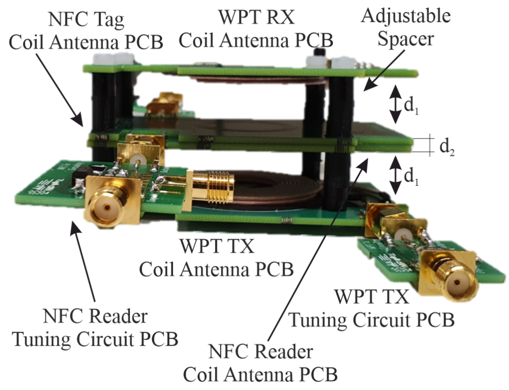

Figure 1: WPT and NFC systems' prototype setup with $d_1 = 12$ mm and $d_2 = 3$ mm.

The broadband EC model was further verified by comparing measurement and circuit-level simulations of the interoperating WPT and NFC systems. In particular, we assumed an NFC system using 100 % amplitude shift keying in the uplink (reader-to-tag link) and amplitude modulation via load modulation in the downlink (tag-to-reader link) with a bit-rate of 106 kbit/s following the ISO/IEC 14443A standard. The Qi WPT system was supplied according to the power class 0 specification of the Qi standard. Figure 2 shows in-phase and quaraduture-phase components of the logical states '0' and '1' of the NFC tag to reader communication signal via a signal constellation diagram. The figure shows good agreement between measurement and circuit-level simulation. In the future, we will work on developing broadband EC models for miniaturized WPT systems to conduct broadband interoperability and coexistence analysis, applying and verifying the developed methodology further.

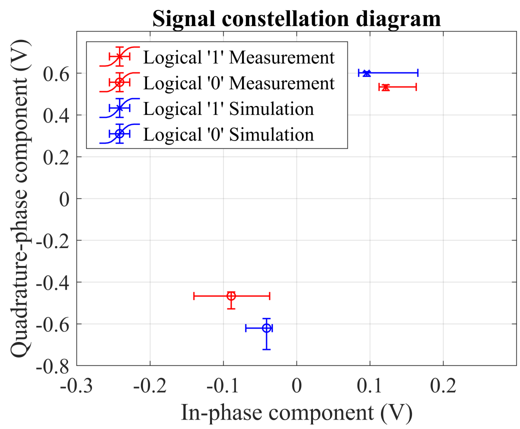

Figure 2: Signal constellation diagram of NFC tag to reader communication signal.

Sub-6GHz GaN Doherty Power Amplifier

Abdolhamid Noori, Silicon Austria Labs GmbH
SAL supervisor: Gernot Hueber, Silicon Austria Labs GmbH
University supervisor:

1 Introduction

The semiconductor material used for transistors has traditionally been Si, but there are more options available to engineers. These include SiC, GaAs, and GaN. Of these choices, GaN is rapidly becoming the preferred semiconductor material for many transistor applications. Gallium nitride (GaN) is a wide bandgap semiconductor material in the same category as SiC. GaN has a higher power density, high electron mobility, supporting more gain at higher frequencies, and does so with better efficiency compared to the equivalent LDMOS technology. GaN also has a high activation energy, which results in excellent thermal properties and a significantly higher breakdown voltage. These benefits can lead to better efficiency (even at higher frequencies), a smaller form factor, lower overall system class, increased reliability, and best-in-class performance. The use of GaN transistors supports key RF demands such as high gain, low power consumption, high throughput, and extremely fast switching speeds.
Wireless communications signals often have high peak-to-average power ratio (PAPR), as shown in Figure 1. If an amplifier is designed to operate efficiently at the peaks (and with good linearity), it will be much less efficient at average power levels. As shown in the figure, we can consider the signal operating in two regions, low power and high power.

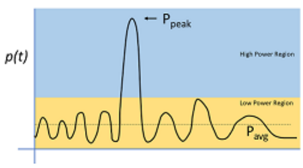

Figure 1: Wireless signals often have a high PAPR

The Doherty amplifier uses two amplifiers to optimize the overall PA performance. The carrier amplifier (or main amplifier) handles the low-power region while the peaking amplifier (or auxiliary amplifier) handles the high-power region. This sounds simple, but the practical implementation can be challenging. Figure 2 shows a classic Doherty amplifier with two amplifier paths, both fed from a hybrid coupler. The carrier amplifier is always on while the peaking amp remains idle unless the signal moves into the high-power region. In the high-power region, the peaking amp turns on and provides additional amplification to support the higher output power. In other words, an auxiliary transistor provides gain only when the main transistor begins to compress, then the overall gain can remain relatively constant for higher input and output levels, Figure 3. Two important design challenges are 1) splitting and recombining the signal while maintaining time alignment 2) turning on the peaking amplifier under the proper conditions while maintaining linearity.

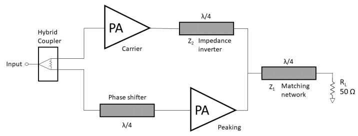

Figure 2: The classic Doherty amplifier uses two amplifier paths to optimize power efficiency

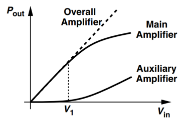

Figure 3: Carrier and Peaking amplifier power contributions

2 Project Overview

The project is defined as a sub-6 GHz, 3.4GHz-3.8GHz, 48 dBm GaN doherty power amplifier. The circuit is designed in Infineon 80um GaN technology with 28V supply in the typical corner. The project is planed into two parts as follows: 1. Building Block 1 (BB1): which is the main path, consists of two class-AB PAs as driver and carrier PA and their interstage matching. 2. Building Block 2 (BB2): which is auxiliary path and includeds a class-AB PA as driver and a class-C PA as peaking PA and their interstage matching. The load of each path must set for max PAE and max output power at 2 dB gain compression. These blocks will be fully integrated in one MMIC and all will have GSG pad at input and output. Due to the heating issue, the other required blocks to implement DPA will design off-chip.

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Part IV

Power Electronics and Modeling

Optimized Control for a Bi-Directional On-Board Charger

Thomas Langbauer, Silicon Austria Labs GmbH
SAL supervisor: Rudolf Krall, Silicon Austria Labs GmbH
University supervisor: Anette Mütze, TU Graz

1 Abstract

The aim of the PhD thesis is to study the influence of the control scheme with respect to improving the key performance parameters, like efficiency, power density and reliability of a bi-directional on-board charger for automotive applications. Common on-board chargers use two transformers in the design to ensure galvanic isolation for the high and low voltage battery, our "Tiny Power Box" (TPB) design uses a multiport approach, which includes just one transformer. This approach enables higher power density, but makes the control more complex.

2 Research questions

Within the "Tiny Power Box" project the following research questions were defined for my PhD work:

- How does control effect the three parameters efficiency, power density and lifetime?
- How can the controller of a three-port series resonant converter ensure to work at best efficiency over a wide range of input voltages?
- How can control enable or support power dense power electronic desings and be used to develop new conventional optimization schemes e.g. to avoid enormous overdesign?
- How is control best realized and implemented e.g. can losses be shifted in between components in a converter system for potential lifetime enhancement?

3 Delivered results

In power dense designs there is not only the temperature dependency of the losses in devices also the electrical behaviour is influenced by the temperature. To get ac-

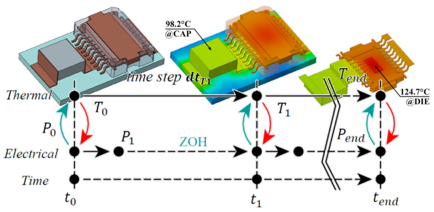

Figure 1: The coupled electro-thermal co-simulation

curate simulations results, a coupled electro-thermal co-simulation, like indicated in Fig. 1, was developed and publicated in two papers. When the first lab demonstrators arrived, the control design work started, where I implemented a control algorithm to meet the power factor, efficiency and conducted emission requirements. In Fig. 2 the current and voltage measurements and the

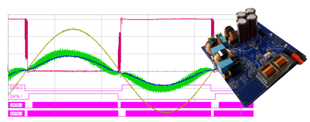

Figure 2: Lab demonstrator and measurements of the power factor correction (PFC) stage

lab demonstrator are shown. We could show, that the conventional pre-charging relay for a DC-link can be neglected for our design approach and so additional power density is gained. A new control algorithm for the used multiport series-resonant converter approach was developed, which ensures best efficiency, especially for different port voltage ratings at partial load. The demonstrator and circuit are shown in Fig. 3. The power flow control is shown in a further publication, where the operation at best efficiency is highlighted. Therefore the frequency and phase angles of the port voltages are adopted based on loss/efficiency tracking. During my six months research

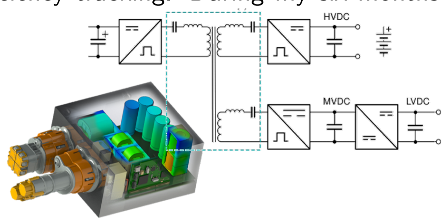

Figure 3: Multiport circuit and the current demonstrator

abroad period at the Power Electronic Systems Laboratory (PES) at ETH Zurich, within a team we verified a control methodology to either shrink the losses or the DC-link capacitor volume for a three phase PFC, which will be used as input stage for the industrial three phase TPB demonstrator. Also a comparative evaluation between a ARCP and 3L-TCM topology was performed and presented at a conference.

4 Ongoing work

Next steps will be to estimate lifetime of the used PFC stage, within simulations. The used thermal models are verified by thermal measurements of the lab demonstrator. Well established reliability algorithms from literature will be used to show how a change in the control behaviour influences the lifetime. To avoid overtemperature, the control should reduce the transferred power in the on-board charger based on virtual sensor measurements. Temperature sensors are placed close to devices and physical models are used in an observer to estimate junction temperatures from the semiconductors. Also overall control scheme of the demonstrators will be tested.

Topology Comparison for a a High Efficiency Compact Onboard Charger

Franz Vollmaier, Silicon Austria Labs GmbH
SAL supervisor: Bernhard Auinger, Silicon Austria Labs GmbH
University supervisor: Anette Mütze, TU-Graz

1 Abstract

The number of electric vehicles is continuously rising over the last years, therefore the number of onboard chargers increases simultaneously. With respect to environmental care, the efficiency of this chargers will get more and more important, resulting in a need for highly efficient chargers. This thesis will therefore investigate into several circuit topologies for bidirectional power conversion used in onboard chargers. It will focus on transient circuit simulation including individual component losses with respect to power density. To do so, different state of the art power devices like SiC and GaN as well as passive components will be comprehensively characterized and modelled in simulation. In addition, a new series-resonant multiport topology will be introduced, modelled and its performance shown by measurements on a prototype.

2 Introduction

Onboard chargers with power ratings in the kilowatt range and the capabilities to be powered from either a single phase or three phase grids are key components for electric vehicles and industrial carriers such as electric forklifts and warehouse robots. For those applications power converters need to be designed not just for fulfilling high efficiency targets only, also power density as well as cost aspects are important. In addition modern onboard chargers are not just used for charging the galvanically isolated main battery, having a voltage range of 400 V, they will be used also to provide the isolated 12 V auxiliary power domain. To do so a new series-resonant multiport topology will be shown. It will provide, in addition to the inherent galvanic isolation, also a possibility to transfer power fully bidirectional on all ports supporting vehicle to grid capabilities too.

3 Research Questions

Considering the constrains of modern onboard chargers, first a comprehensive study of possible topologies will be done, followed by precise component loss modelling. This will be used for a sophisticated system simulation that provides the basis to answer the following research questions:

- How can modern power devices like SiC and GaN be characterized with respect of switching losses for different switch configurations?
- How can a system level simulation be combined with accurate simulation of component losses including parasitic effects?
- How can restrictions be overcome so that high power density and efficiency can be achieved at the same time for different topologies?
- What are the limits of multiport series resonant converters?
- Can current state of the art foil capacitors be exchanged by low ESR ceramic capacitors for resonant topologies?

4 Expected Results

To evaluate the performance of the proposed novel onboard charger the following results have been analyzed and discussed in three conference papers and will be comprehensively analyzed within the **final thesis**.

- Detailed comparison of candidate topologies used for high voltage automotive charging applications.
- Precise modelling of active and passive components to achieve accurate results within circuit simulation.
- Improvements of existing topologies in order to satisfy given system-level requirements and achieving state-of-the-art power density and efficiency.
- Introducing a novel approach for switching loss integration into system level simulation
- Comparison of simulated switching loss results with measurements using custom made testbench
- Full hardware design of the chosen topology for a compact demonstrator.
- Comparison of measured and simulated results with respect to key performance parameters, e.g. efficiency and total harmonic distortion.

5 Conclusion and Outlook

This thesis description gives insights into a novel topology for an automotive as well as an industrial onboard charger and raised important questions which will be answered using extensive simulation combined with precise component modelling in several publications. The **final thesis** will include measurements based on a hardware prototype to validate the simulation methodology as well as the performance of the new proposed series-resonant multiport topology.

Iterative Solvers and Hybrid Discontinuous Galerkin Methods for Wave Equations

Michael Leumüller, Technische Universität Wien
SAL supervisor: Bernhard Auinger, Silicon Austria Labs GmbH
University supervisor: Joachim Schöberl, Technische Universität Wien

1 Introduction

For electromagnetic compatibility or high frequency communication tools to simulate the electromagnetic fields are necessary. Maxwell's equations describe these fields. In the time harmonic setting with a magnetic vector potential $\mathbf{A}$ on the domain Ω they take the shape of

$$\mathrm{curl}\mu^{-1}\mathrm{curl}\mathbf{A} - \kappa^2\mathbf{A} = \mathbf{0} \text{ in } \Omega, \tag{27.1}$$

with $\kappa := j\omega\sigma + \omega^2\varepsilon$. Where μ, ε, σ are given physical parameters, $\omega = 2\pi f$ is the angular frequency. For large frequencies (27.1) is highly indefinite leading to oscillatory solutions. This makes solving the problem complicated. One method that accomplishes this is the finite element method (FEM), which is accurate, but has large computational costs, due to the needed small mesh size.
Usually, preconditioned iterative solvers are applied to reduce the computational costs in FEM, but many of these methods are only proven to be working in the elliptic case. The goal is to develop an iterative solver for the indefinite problem. Therefore, the hybrid discontinuous Galerkin (HDG) method for wave equations, introduced in [1], is applied.

1.1 Hybrid Discontinuous Galerkin Method for Wave Equations

In the FEM the partial differential equation is discretised by finite elements (FEs). They need to satisfy a strong continuity. In case of (27.1) this means continuity of the tangential field

$$\mathbf{A}_l \times \mathbf{n}_l = \mathbf{A}_r \times \mathbf{n}_r$$

on interfaces Γ, where $\mathbf{A}_l$ denotes the filed on one side of Γ and $\mathbf{A}_r$ on the opposite side. To increase the flexibility of FEM discontinuous Galerkin (DG) methods have been developed. In these methods the strong continuity of the FEs over interfaces is broken on purpose and enforced in a weak sense. This doubles the degrees of freedoms (DoFs) on interfaces. The methods have advantageous properties for simulations in the time domain. For simulations in the frequency domain they have the flaw that they increase the size of the FEM system matrix and also the coupling between elements as can be seen in Figure 1 on the left. The HDG method solves this issue by introducing additional FEs $\widehat{\mathbf{A}}$ which represent the solution on Γ

$$\widehat{\mathbf{A}} := \mathbf{A}_l \times \mathbf{n}_l = \mathbf{A}_r \times \mathbf{n}_r.$$

Now, FEs on each side of Γ only couple with $\widehat{\mathbf{A}}$, see Figure 1 in the middle. The direct coupling between neighbouring elements has been eliminated, but the DoFs on interfaces has been tripled, further increasing the size of the system matrix.

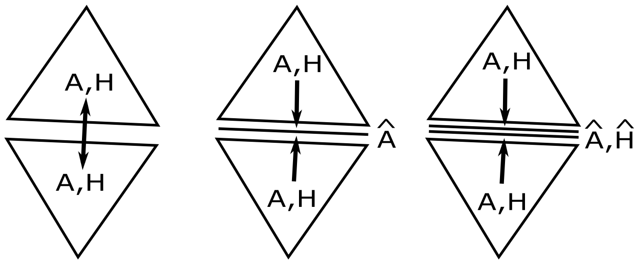

Figure 1: Coupling of finite elements for DG on the left, standard HDG in the middle and for HDG in wave equations on the right.

For the elliptic case the DoFs on elements can be eliminated by Schur complements resulting in a linear equation for DoFs on the interfaces called the skeleton variables. The Schur complements represent small problems defined on each element, which are always solvable in the elliptic case. For the indefinite wave equation this does not hold. In [1] the introduction of an additional surface space representing the flux of the solution between elements

$$\widehat{\mathbf{H}} := \mu^{-1}\mathrm{curl}\mathbf{A}_l \times \mathbf{n}_l = \mu^{-1}\mathrm{curl}\mathbf{A}_r \times \mathbf{n}_r$$

has been suggested, see Figure 1 on the right, to achieve solvability.

2 Goals

The empirical studies suggest that the resulting problem is well posed, stable and that the Schur complement approach is viable independent of the frequency. A goal is to proof that the discrete problem is well-prosed, which shall be accomplished by verifying a $\inf - \sup$ condition, following the ideas in [2]. Additionally, fast and efficient iterative solvers for the resulting system of linear equations on the skeleton variables $\widehat{\mathbf{A}}, \widehat{\mathbf{H}}$ will be explored. They will be based on the conjugate gradient method in combination with preconditioning.

3 Bibliography

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Broadband Characterization of Ferromagnetic Materials used in Passive Components

Christian Riener
SAL supervisor: Bernhard Auinger, Silicon Austria Labs GmbH
University supervisor: Thomas Bauernfeind, TU-Graz

1 Introduction

Electromagnetic interference (EMI) became a very important issue over the last decades and filter structures are required to ensure a reliable operation of electronic based systems (EBS). Passive components including multi layer ceramic capacitors (MLCC) and inductors are used in such filter structures to suppress EMI. However, several effects influence the behavior of these MLCCs and inductors. The compound materials used in these components suffer from dispersion effects, hence the permittivity and the permeability alter as the frequency moves towards higher frequency values [1]. Furthermore, MLCCs and inductors suffer from ferroelectric- and ferromagnetic effects, respectively. Therefore, applying a DC bias to an MLCC or inductor might lead to a significantly different value in capacitance and inductance [1].

Characterizing the frequency dependent material properties is a very complicated issue since they change with the lattice structure, temperature and DC biasing. Furthermore, manufacturers usually do not provide samples of the compound bulk material. Even if they would provide such samples there would be still a significant influence on the material properties due to the integration of conducting structures within these bulk materials. Therefore, a reliable material characterization cannot be derived directly from measurements.

To approach the issue of material characterization one may measure the impedance characteristic of the passive components of interest. Presuming, one knows the internal structures of the investigated component an accurate numerical model can be deployed to fit material properties to the model. Different optimization strategies may be utilized within the numerical simulation framework to acquire an accurate approximation of the material behavior.

In the following, a method is presented for determining the material behavior using numerical simulations over a wide frequency range. This method exploits the Kramers-Kronig (KK) relation to determine the complex permeability $\mu_{r_{(\omega)}} = \mu'_{r_{(\omega)}} - j\mu'_{r_{(\omega)}}$ of a surface-mounted (SMT) inductor comprising an Mn-Zn ferrite. The parameter $\mu''_{r_{(\omega)}}$ accounts for the losses within the ferrite.

2 Kramers-Kronig Relation

As discussed in [2] the KK ralation is defined as

$$\mu'_{r_{(\omega)}} = 1 + \frac{2}{\pi}\int_0^\infty \frac{\psi\mu''_{r_{(\psi)}} - \omega\mu''_{r_{(\omega)}}}{\psi^2 - \omega^2} d\psi \qquad (28.1)$$

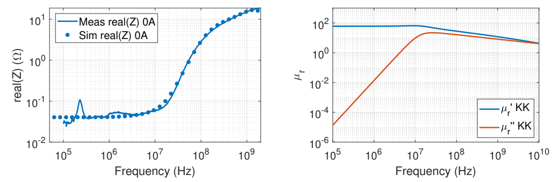
$$\mu''_{r_{(\omega)}} = \frac{-2\omega}{\pi}\int_0^\infty \frac{\mu'_{r_{(\psi)}} - \mu'_{r_{(\omega)}}}{\psi^2 - \omega^2} d\psi \qquad (28.2)$$

where ω represents the angular frequency. Equations (28.1) and (28.2) can be used to calculate $\mu'_{r_{(\omega)}}$ from $\mu''_{r_{(\omega)}}$ and vice versa, respectively.

In [1] the author showed that the ferrite losses exhibit a bell shape, hence one may use the fractional polynomial

$$\mu''_{r_{(\omega)}} = \frac{B(\frac{\omega}{\omega_1})^m}{1 + (\frac{\omega}{\omega_1})^{1-n+m}} \qquad (28.3)$$

to prescribe the material losses $\mu''_{r_{(\omega)}}$ of the ferrite. The corresponding $\mu'_{r_{(\omega)}}$ can be calculated by substituting (28.3) into (28.1). The parameters B, ω_1, m and n are unknown and they must the approximated with an optimization algorithm, e.g. Nelder-Mead [3]. Fig. 1 (a) depicts the simulated and measured losses of a SMT inductor with the material characteristic shown in (b). The losses within the component are approximated very accurately over a wide frequency range.



(a) (b)

Figure 1: (a) Measured and simulated losses of a SMT inductor with material properties depicted in (b). (b) Fitted material characteristic of the ferrite material.

The presented method facilitates an efficient method to determine the material properties of passive components. The presented workflow is also applicable for MLCCs to determine the material properties of dielectric materials. Furthermore, this method can be utilized to consider ferroelectric- and ferromagnetic effects due to DC biasing.

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Part V

Sensing and Integration

Characterization of Ion Contamination during Anodic Bonding

Yucheng ZHANG, Silicon Austria Labs GmbH
SAL supervisor: Dr. Norbert Cselyuszka, Silicon Austria Labs GmbH
University supervisor: Prof. Klaus-Dieter Lang, Prof. Martin Schneider-Ramelow, TU Berlin

1 Introduction

Anodic bonding is now widely adapted in the semiconductor industry as a wafer-level packaging method. The name *anodic* refers to the result that anode material is oxidized to form a permanent bond to cathode material with assistance of an external electric field, thus this technique was also named *field-assisted bonding* by its founder Pomerantz in the 70s. Though many wafer-level bonding techniques have been developed in recent years, anodic bonding's high tolerance for surface roughness, low environmental requirement and strong robustness allow it to remain a preferred choice for many packaging applications.

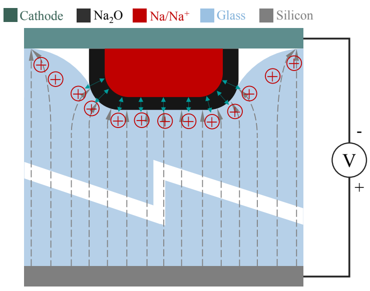


Figure 1: Na Accumulation at Cathode

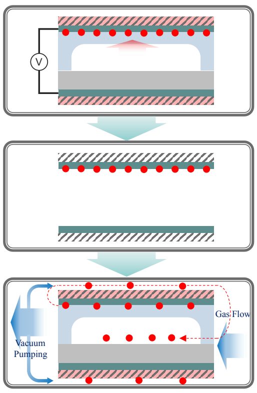


Figure 2: Na Migration inside Chamber during Anodic Bonding

Not every material can be anodically bonded. The fundamental requirement for anode material is to not give out movable ions during bonding, while the requirement for cathode material is to contain movable ions and to form solid electrolyte at elevated temperature ($\approx 400\ ^\circ C$). After years of development, numerous materials were found to be suitable for anodic bonding, among which the mostly used is silicon as anode material and borosilicate-glass containing alkali ions as cathode material. During bonding process, due to the oxidation of anode material as mentioned before, alkali ions receive electrons at cathode and moves out of the system to maintain an electrical equilibrium of the system, which often leads to an accumulation of alkali metal on the external electrodes after bonding, also shown in Figure 1.

$$\text{On the cathode side:} \quad O^{2-} + Si \xrightarrow[\text{external power supply}]{\text{high temperature}} SiO_2 + e^-$$

$$\text{On the anode side:} \quad M^+ + e^- \xrightarrow[\text{external power supply}]{\text{high temperature}} M$$

The alkali metal residual combined with the fact, that the most common used alkali elements, sodium (Na) and potassium (Ka), both of which have melting points lower than 100 °C, could allow alkali metal to reenter the bonding system through gas flow at bonding temperature, therefore cause electric failure to the system, as shown in Figure 2.

2 Methodology and Plan

This thesis is aimed to characterize this phenomenon:

- A series of experiments has been used to categorize failure mechanisms, which revealed the dependency of electric failure on contaminant and gas pressure.
- Several contaminant sensitive structures are proposed based on piezoresistive material and technology platform provided by industrial partners, and are bonded with design of experiments to provide information for selection and improvement in terms of sensitivity, range and stability.
- The final design will be utilized both at SAL and industrial partners, as part of long-term monitoring system.
- Chip design and process flow optimization are planed to eliminate any potential electric failure that are related to anodic bonding.

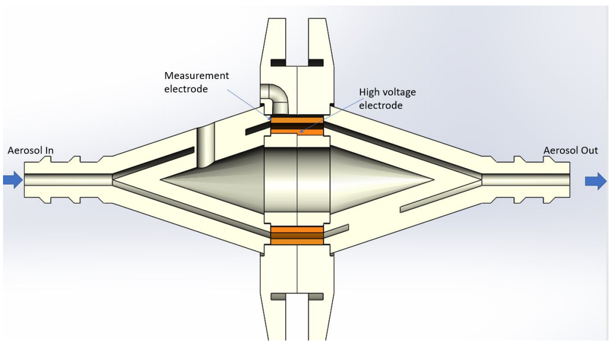
By achieving this goal, anodic bonding can be employed to more applications that are traditionally considered to be contaminant sensitive and thus can only be fabricated with other techniques.

Miniaturized Portable Emission Measurement System (PEMS)

Tanja Wallner, Silicon Austria Labs GmbH
SAL supervisor: Andreu Llobera, Silicon Austria Labs GmbH
University supervisor: Alexander Bergmann, TU Graz

The rising political interest to tackle adverse health effects of particle emissions leads to the implementation of increasingly stricter emission legislation standards. To guarantee compliance with these emission standards, advanced technologies for particle measurement, especially for small particles and very low concentrations, have to be designed. Existing Portable Emission Measurement Systems (PEMS) are heavy, bulky, energy-consuming, and very expensive. Therefore, a high demand on reliable low-cost sensors for fleet emission monitoring arises. Further uses of the sensor could be the detection of particle filter failure and defeat devices as well as the use of the sensor as an engine development measurement tool. The focus of the dissertation lies on the identification of a new sensor principle for particle number determination and an in-depth evaluation of the selected principle regarding its characteristics as well as its applicability in a miniaturized PEMS.

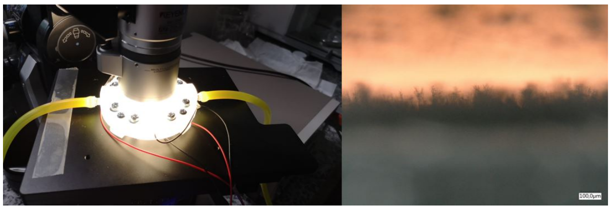
Electrostatic particle measurement offers great potential for the detection of charged particles in harsh environments. An aerosol is conveyed into a high voltage region between two electrodes and the resulting sensor signal is proportional to the aerosol particle concentration.



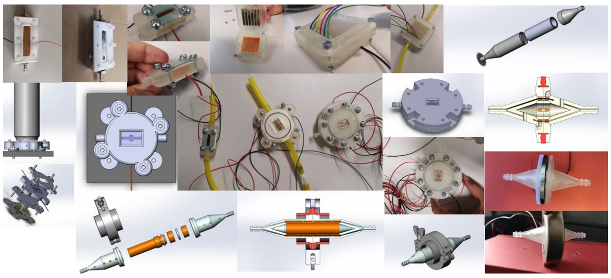
Despite the simple sensor principle, the underlying effect up to now remains poorly understood. According to the latest literature, the measured current is either generated by the dendritic formation and a resulting equilibrium state of incoming and breaking particles or charging of particles due to the high voltage applied, generating a measurable leakage current.

We are working on a novel implementation of the electrostatic particle sensor incorporating an optically accessible measurement region to assess the existing ambiguity in the literature about the underlying physical effects that cause the measurement signal.

Progress has been made in the construction of several prototypes. First prototypes are designed to investigate the underlying physical effect using an optical accessible sensor, revealing dendritic formation as the main sensor effect.



In addition to that several other prototypes were designed so overcome sensor drift, air tighten the sensor and investigate the influence of the velocity and electrostatic field on the sensor signal.



Furthermore, we investigate the results of a characterization of the designed sensor and the commercially available EmiSense PM-Trac in a novel arrangement, including the effects of different particle species, particle sizes and charge distributions (bipolar charged, unipolar charged, and neutral aerosol) as well as different ratios of organic to elemental carbon. The sensor response is referenced with state-of-the-art laboratory-grade particle number and particle mass instruments. The obtained experimental results reveal a time-resolved sensor response over a wide concentration range and are further compared with an extended analytical model based on the work of Bibly et al. Outputs of the model as well as experimental results will be used for further design iterations of a new prototype.

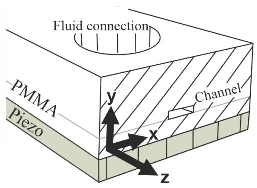
Acoustic Particle Manipulation Along Three Orthogonal Directions in Laser Engraved Microfluidic Channels

Andreas Fuchsluger, Johannes Kepler University, Linz
SAL supervisor: Annalisa Depastina, Norbert Cselyuszka Silicon Austria Labs GmbH
University supervisor: Bernhard Jakoby, Johannes Kepler University Linz

1 Abstract

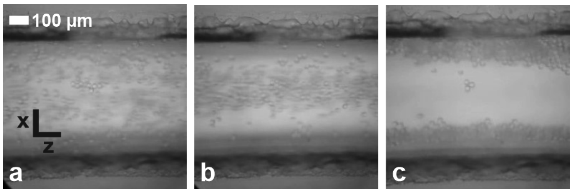
Acoustofluidic particle manipulation in three orthogonal directions was performed in simple and low-budget microfluidic chips that were laser-engraved and laser-cut out of PMMA sheets. Besides the focusing and separation of particles orthogonal to the channel axis, which can be used in so-called flow through separators, we were also able to accumulate the particles at acoustic vibration nodes along the channel axis and to lift them up in vertical direction in the same experimental configuration.

2 Setup



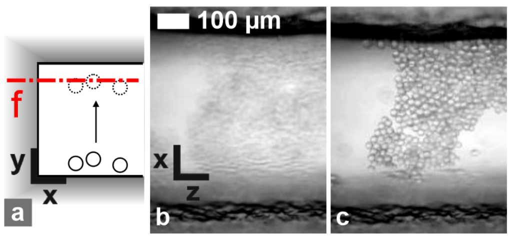
A PZT plate transducer attached to the bottom of the microfluidic chip is used for acoustic actuation and a thin layer of glycerol between PZT and chip serves as acoustic coupling medium.

3 Manipulation in x-Direction:



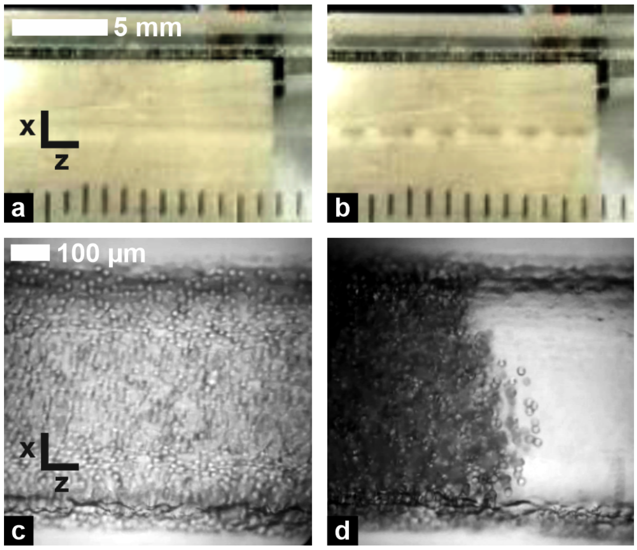
Focusing and separation in streaming fluid: Particles are equally distributed as long as the transducer is off (a). Acoustic actuation with a frequency of 828 kHz focuses the particles in the center of the channel (b). Actuation with 1908 kHz leads to separation into two lines (c).

4 Manipulation in y-Direction:



Uplifting effect: Sketch of the cross-section of the channel (a). The particles are settled on the floor of the channel as long the transducer is off (b). When actuated with a frequency of 1809 kHz, the particles are lifted upwards and appear sharp as they are moving into the focal plane f of the microscope (c).

5 Manipulation in z-Direction:



By actuating the system with a frequency of 173 kHz the particles accumulate at nodes that are allocated along the channel axis. The particles are uniformly distributed over the channel area in the quiescent fluid (a,c). Transducer on (b,d): Observation through the microscope shows that the primarily uniform distribution of particles changes into a (binary) Bernoulli distribution with a sharp separation between crowded areas and nearly completely particle-free spaces.

6 Conclusion and Discussion

In the conducted experiments, we observed particle manipulation in three orthogonal directions using the same experimental configuration. It yet has to be determined—likewise with numerical simulations—what particular oscillation modes of the entire system lead to the acoustic pressure gradients in the microfluidic channel. But all its components, i.e., the piezo-ceramic transducer, the PMMA block, and the channel itself supposedly contribute with varying amounts at different actuation frequencies.

7 Acknowledgements

This project was performed within the COMET Centre ASSIC Austrian Smart Systems Integration Research Center, which is funded by BMVIT, BMDW, and the Austrian provinces of Carinthia and Styria, within the framework of COMET—Competence Centers for Excellent Technologies. The COMET program is run by FFG.

Design and Evaluation of energy-autonomous ultra-thin Wireless Sensor Nodes for Rotor Blade Monitoring of Wind Turbines

Thomas Schaechtle, University of Freiburg
SAL supervisor: Alfred Binder, Silicon Austria Labs GmbH
University supervisor: Stefan J. Rupitsch,University of Freiburg

1 Abstract

Wind turbines are exposed to harsh environmental conditions, which have a particularly strong impact on their rotor blades. In order to be able to determine the present state and predict aging effects, it is of great interest to acquire local measurement data on the rotor blade itself. For this purpose an energy-autonomous, ultra-thin wireless sensor node is required.
This work addresses the functional components of such a wireless sensor node. This includes suitable energy harvesting sources and their power densities, the conversion and storage of the energy as well as the design and evaluation of suitable sensors and energy-aware signal processing. The sensor node is designed and fabricated and its function is demonstrated on a small-scale wind turbine with a nominal output power of less than 1 kW.

2 Introduction and Motivation

Safe operation of wind turbines after its intended life span and reduction of safety downtimes is desired. For this

- the monitoring of ice layer thickness
- and the detection of mechanical peak loads due to impacts of birds, bats, ice shedding or wind gusts

is required.

3 Measurement Concept

The main elements of the wireless sensor node consist of a radio transceiver, an energy harvester, an energy storage and the sensors. These are briefly explained in the following subsections.

3.1 Radio transceiver

A radio transceiver establishes a wireless communication and transmits acquired information to a base station located in the nacelle of the wind turbine. In addition, the radio transceiver contains a microcontroller on which all key functions of the sensor node are implemented.

3.2 Energy Harvester

An energy harvester converts ambient energy into electrical energy. It enables the maintenance-free operation of the sensor node. In outdoor areas, solar radiation has the highest energy density. The operation has to be designed for the worst conditions occuring in the winter months when the sky is cloudy or the harvester is covered with ice. Therefore, a solar cell is chosen as the primary energy source with increased efficiency at low light intensities.

3.3 Energy Storage

A novel solid state lithium ion technology was selected after extensive comparison of secondary cell technologies. It has benefical charge and discharge characteristics and an extended temperature range, especially suitable for low temperatures down to -40 C.

3.4 Ice Layer Thickness Monitoring

To measure the layer thickness of ice, the difference in relative permittivity of ice and water to air is exploited. The change in capacitance over the layer thickness is simulated with a coplanar sensor setup and compared to measurements under laboratory conditions. Preliminary results of a FE-simulation are shown in Fig. 1.

3.5 Peak Load Detection

For quasi-continuous detection of mechanical peak loads, an acceleration sensor in ultra low power mode with a threshold wake-up is used at low sampling rate of 20 Hz. In this way, an impact can be detected and further analyses can be carried out. Additional spectral analysis can be acquired at scheduled intervals to detect long-term changes for a predictive maintenance database. The measurement setup and a modal analysis after excitation with an impulse hammer is shown in Fig. 2.

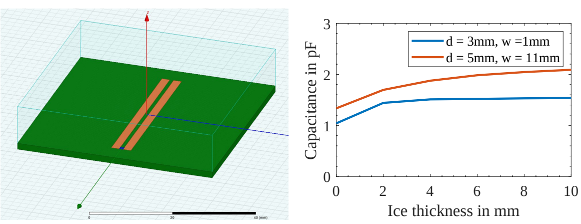


Figure 1: Simulation of capacitive ice layer detection – (left) Geometry of the simulation model with width w and distance d of the capacitor plates and (right) the simulated capacitances for two selected geometries over varying ice thickness.

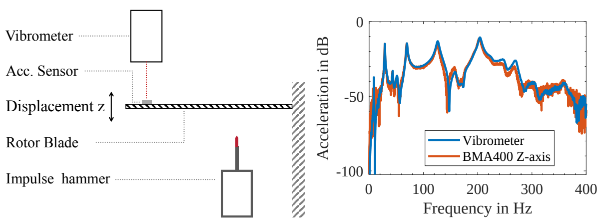


Figure 2: Modal Analysis of a smallscale Rotor Blade – (left) Measurement setup and (right) measured accelerations of a MEMS acceleration sensor compared to a Laser-Doppler-Vibrometer.

High-bandwidth thermal characterization and control

Thomas Kimmer, Silicon Austria Labs GmbH
SAL supervisor: Timothy A. Polom, Silicon Austria Labs GmbH
University supervisor: Tobias Reimann, Ilmenau University of Technology

1 Abstract

The main topic of my research is to find methods and techniques for characterization of the thermal behavior of wide band-gap power semiconductors in power electronic systems. The aim is to improve the accuracy of the thermal monitoring while avoiding time consuming off-line calibrations. Thermal impedance spectroscopy over multiple frequency decades without interrupting the normal converter operation. The extracted magnitude and phase of the signal allow an effective state-of-health diagnostic as they reflect structural changes in the device e.g. delamination. Evaluated in simulations and experiments for state-of-the-art SiC-MOSFETs and GaN HEMTs.

2 Introduction

A transient thermal measurement method to characterize packaged power devices will be developed. The method will be used to identify distinct thermal response properties of different prototype packages, allowing for their performance to be bench-marked. The plan is to apply the method at discrete points during lifetime tests providing key data in the interest of power electronics reliability. Analytical and, if needed, computational modeling studies will be completed to complement test results. The method will ultimately be utilized to profile for a demonstrator hardware.

3 Thermal characterization

A typical representation of the thermal behavior of a power semiconductors is the description with FOSTER or CAUER-chains that represent the thermal impedance Z_{th} of the device. These are RC-networks that can be extracted by exciting the thermal response with a given power signal. The RC values can be generated either by FEM or by experimental measurement. The new method that is used in this work extracts the Z_{th} by an injection of sinusoidal currents I_D (drain-current) or I_C (collector-current) in the power semiconductor and uses thermal sensitive electrical parameters to estimate the device virtual junction-temperature T_{vj}. This can be realized by various parameters e.g. the MOSFET static parameters like the on-state-resistance R_{DSon} or the gate-source threshold voltage $V_{GS(th)}$.
It has been observed that during a sinusoidal injection of the current imposes harmonics on the measured R_{DSon} signal.

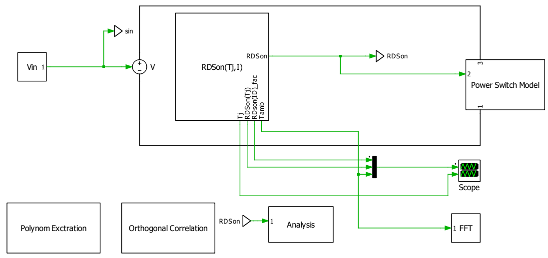


Figure 1: PLECS simulation of thermal sensitive electrical parameter R_{DSon}

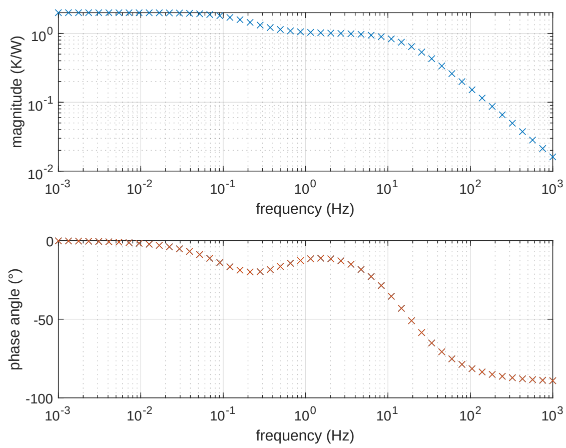


Figure 2: Bode diagram showing the thermal-impedance as a function of frequency

These harmonics can be used to estimate the thermal model of the device. I developed PLECS [1] and MATLAB-Models [2] to describe this behavior. In the future I want to apply this method *in-situ* in a converter for the project ECSEL HiEFFICIENT in an interleaved bi-directional buck-boost automotive HV battery charging system.

4 Outlook

For thermal management predictive maintenance efforts aim to ensure more safe and reliable operation of future converter systems. Known methods will be evaluated for the use in the target power semiconductor technology and it's packaging variants and further developed to achieve this target.

Hybrid integration of ultra-thin chips (UTC) on flexible, printed electronics

Muhammad Hassan Malik, Silicon Austria Labs GmbH
SAL supervisor: Ali Roshanghias, Silicon Austria Labs GmbH
University supervisor: Hubert Zangl, University Klagenfurt

1 Introduction

The introduction of flexible electronics has been a game-changer in the world of technology. It opens the doors to a vast spectrum of applications from consumer electronics to biomedical applications. Apart from being lightweight these flexible electronic packages provide other advantages such as low power consumption and smaller form factors. The flexibility of these packages is mostly limited by the rigid components integrated into them. Since the advent of ultra-thin chips and sensors, there has been a keen interest in developing complete or hybrid flexible printed electronic packages. Although there has been development in the integration of ultra-thin chips (UTC) on a conventional rigid substrate, integration on a flexible substrate has its challenges. These challenges range from the type of substrate, limitations in process temperatures and pressure, circuitry printing on substrates, and integration of UTC on the substrates. This also allows the use of biodegradable substrates such as paper and PET which further adds the advantage of being environmentally friendly. Furthermore, the reliability of these packages is also of interest. However, very limited information is available on the integration of UTC on printed flexible substrates.
This thesis deals with the development of hybrid/ flexible electronic packages with the focus on integration techniques for ultra-thin chips and devices on flexible substrates coupled with developing printing techniques for printed circuits on a flexible substrate of the art to the community.

2 Research questions

- Which techniques can be used for integrating ultra-thin chips to flex or hybrid substrates?
- Which substrates can be utilized in realizing a hybrid flex package?
- Handling of ultra-thin chip/die? Handling UTC without damage?
- Which printing techniques can be used for printing on biodegradable substrates such as Paper (inkjet, EHD, and Screen printing)?
- Can embedding ultra-thin chips be done cost-effectively?
- How can the reliability of these systems be increased?

3 Methods

- Literature review on current limitations and techniques being implemented in ultra-thin chip integration, available printing technologies, and their application prospects.
- Printing of test structures with screen printing.
- Printing of test structures with inkjet printing.
- Developing printing parameters on EHD.
- Developing techniques for encapsulating/ embedding UTC.
- Using different bonding techniques for integrating UTC on Flexible and hybrid substrates.
- Electrical characterization of a complete package.
- Mechanical characterization of packages including reliability and failure analysis.

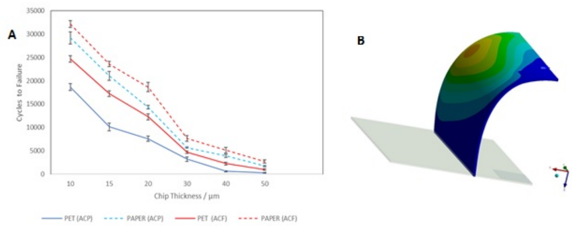


Figure 1: The results of the cyclic bending test; the effects of die thickness, adhesives (anisotropic conductive paste/ACP, anisotropic conductive film/ACF), and substrates on the failure cycle, (B) Simulated deformation in the y-direction of the bent die and substrate. In grey, the undeformed configuration. The red arrow indicates the imposed displacement at the substrate boundary [1]

4 Results

From the recent work carried out, we investigated the possibility of flip-chip bonding ultra-thin chips to flexible substrates such as paper and PET, followed by evaluating the effect of chip thickness on the bendability of the whole package. The results can be viewed in Figure 1(A) complimented by the deformation in the bent package, shown in Figure 1(B).

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Colorimetric gas-sensing

Mario Poschner, Silicon Austria Labs GmbH
SAL supervisor: Rudolf Heer, Silicon Austria Labs GmbH
University supervisor: Hubert Zangl, Alpen-Adria-Universität Klagenfurt, Klagenfurt, Austria

1 Introduction

Gas-sensing is still a challenging area in the field of technical sciences. An implementation which is reusable, power-efficient and sensible to a variety of gases is the ultimate goal. Colorimetric gas-sensing is a new approach which could target all this issues. Different chemical dyes are used to induce a reversible color-change when a specific gas is detected. The vision of the work is the realization of this novel chemical sensing.

Technologies to be investigated and optimized:

- Gas sensing matrix containing more than 1.000 sensors made of customized colorimetric polymers deposited on top of CMOS camera pixels.
- Multi-wavelength structures illumination using microLED platforms.
- Pattern recognition on data to identify different types of "smells".
- Autonomous machine learning model providing a framework for auto-calibration to detect pre-defined reference states.

2 Implementation

A vast number of colorimetric polymers (more than 1.000) are inkjet-printed on a CMOS-chip. This is combined with artificial neural network-based data analysis in the sensor. A multitude of such self-contained units will be distributed to form a sensing network. For the sensor chip realization, a multiwavelength LED matrix is developed to illuminate the colorimetric polymer spots with carefully adjusted wavelengths to detect the change of absorption due to gas exposure of the sensor chip. The very high number of pixels / wavelength combinations will not only result in highest sensitivity and selectivity of chemical sensors but will enable the opportunity to provide measurements for a range of applications from air quality to product qualities to food ripeness e.g. An illustration of the system can be seen in Fig. 1.

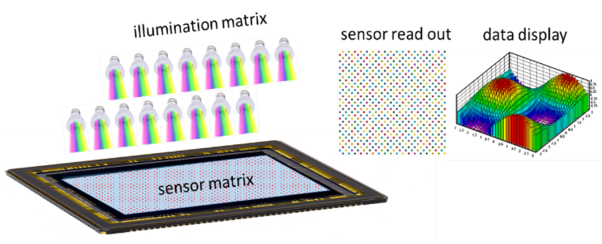

Figure 1: A high number of dyes are printed on a CMOS-chip, a LED-matrix gives the lighting for the absorption which is then analysed by AI-methods

Major building blocks to be realized

- Functional Polymers
  - Development of target specific dyes and polymers to achieve a maximal number of pixels which build the foundation of the measurement setup.
  - Formulation of functional inks ready for application by inkjet printing.
- Electronic System
  - Creating a microcontroller based compact camera module including data transfer to a host laptop.
  - Creating the illumination matrix with single pixel control.
  - Realization of the mechanical fixation of all components.
- Data analysis and software
  - Research for AI / ML based signal analysis using image processing techniques to provide insights on the status and the development of gas concentrations.

3 Results

Collection of dyes and proof of their functionality:
A collection of eight different metalloporphyrines and 3 PH-indicators give response to 45 different gases. Their functionality were prooved by UV/Vis adsorption experiments and by simple color-change experiments with micropipette deposition.

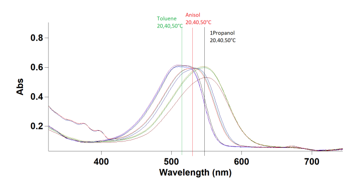

Figure 2: UV/Vis record of a colorchange by analyte exposure

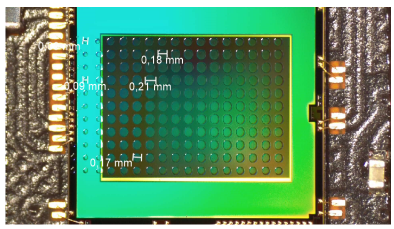

Figure 3: Inkjet printing of dyes on CMOS-chip. The dyes are successfully printed as tiny spots of the size of 100 micrometer on a CMOS-chip.

Semiconductor Device Package Multiphysics Modelling And Characterization

Abinash Pradhan, Silicon Austria Labs GmbH
SAL supervisor: Alfred Binder & Thomas Moldaschl, Silicon Austria Labs GmbH
University supervisor: Rik W. De Doncker, RWTH Aachen University

Power electronics (PE) is contributing to a sustainable and decarbonized transportation system by the use of Wide Band gap (WBG) technologies. WBG switches based on Gallium Nitride (GaN) exhibit benefits like low loss high switching speeds, higher blocking voltages, can be operated at high switching frequencies and can withstand high operating temperatures. These benefits help in meeting the transportation system demands like high efficiency, high power density and lifetime improvement.
However, the use of traditional PE packages limits the potential of WBG switches. For e.g., high switching speeds in conjunction with layout parasitic inductance can cause voltage overshoots. This voltage stress affects the lifetime of the WBG switches. Secondly, highly integrated and power dense PE systems need to dissipate high heat flux densities from a smaller volume. This is important because ineffective cooling can lead to high switch junction temperature and eventually damage it. Also, the system efficiency decreases at elevated temperatures.
The implementation of advanced packages for e.g., System in Package (SiP), System on Chip (SoC), and Embedded packages (see Figure 1 and 2) for WBG switch based PE systems is essential to exploit the switches' potential to the fullest. This in turn helps in fulfilling the PE system objectives - integration of PE parts (at component level, sub-system and system level) and volume reduction, and lifetime improvement. This design and analyses of the above mentioned packages are the main objectives of this PhD.
The first task focuses on sub-system level simulation starting with establishment of CAD models for PCB based embedded packages - one with a single GaN SoC (half bridge with integrated gate drivers), Figure 1 and 2, and another with multiple GaN SoCs, followed by their comprehensive multi-physics simulation (electrical, coupled electro-thermal, and coupled thermo-mechanical simulations) in ANSYS platform. The embedded package will be optimized electrically (reduction of parasitics), electrothermally (reduction of hotspots, maintaining GaN HEMT junction temperature below rated value), and thermomechanically (reduction of thermo-mechanical stress to avoid strain, cracks, warpage etc.)
The second task focuses on system level analysis of an electric powertrain inverter and an OBC (on-board charger) that employs the above mentioned embedded packages in Surface-mount technology (SMT). For the system level simulation, reduced order models (ROMs) will be used because they use fewer development cycles and minimal computational resources. In other words, ROMs are simplifications of high-fidelity complex models but maintain a system's dominant effects. For this task specific elec-

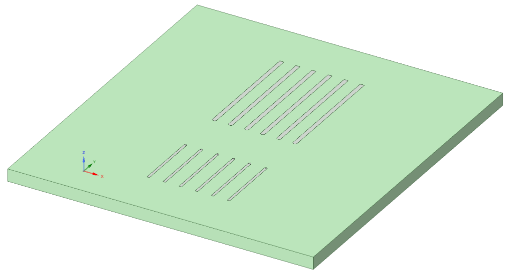

Figure 1: PCB based embedded package with a single GaN SoC.

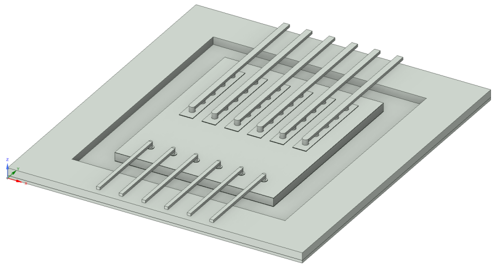

Figure 2: PCB based embedded package with a single GaN SoC - Internal View.

trical, thermal, and mechanical ROMs (for e.g., ROMs based on package parasitics, chip's temperature gradient, strain etc.) will be built using ANSYS ROM methods and used during system level simulation for analysis of coupling effects.
Additionally the importance of macroscopic thermal metamaterials for heat transfer in power electronic systems is being researched. Basically, macroscopic thermal metamaterials are materials composed of engineered, microscopic structures that exhibit unique thermal performance characteristics based primarily on their physical structures and patterning, rather than just their chemical composition or bulk material properties. So, the usage of thermal metamaterials to manipulate heat flow while avoiding thermal crosstalk and local hot spots is being investigated for embedded packages and high power power electronic systems.
The final task focuses on the development of an in-house prototype of a power electronic system containing SMT embedded package, carrying out its experimental analysis for validation of the simulation results, and its performance comparison with the state of the art, see E. M. Dede, et al., "Design of Anisotropic Thermal Conductivity in Multilayer Printed Circuit Boards," IEEE Transactions on Components, Packaging and Manufacturing Technology, vol. 5, no. 12, pp. 1763–1774, Dec. 2015, doi: 10.1109/TCPMT.2015.2473103.

A Fully Printed Biodegradable Sensor System

Lukas Rauter, Silicon Austria Labs GmbH, Lisa Maria Faller, Carinthian University of Applied Science
SAL supervisor: Jürgen Kosel, Silicon Austria Labs GmbH
University supervisor: Hubert Zangl, University Klagenfurt

1 Introduction

Additive manufacturing (AM) is the digital controlled sequential layering of material and therefore fundamentally differs from conventional manufacturing methods in electronics industry. AM has a high potential to increase the sustainability of part production in general, since it is a low-waste processing technology and needs less energy compared to others. In this respect, AM can be a measure towards the green deal as issued by the European Commission in 2019[1]. According to this green deal, Europe should be the first CO_2 neutral continent by 2025.
One major subgoal for achieving the green deal is 'mobilizing industry for a clean and circular economy'. Lightweight engineering through AM provides measures towards this subgoal, as several benefits can be obtained simultaneously: a) lightweight engineering saves CO_2 in transport industry , b) using AM complex lightweight components can be realized economically and in a resource-saving manner[2], and c) AM is considered a disruptive technology that has the potential to radically change the way we currently manufacture, offering the potential to develop local material recycling and manufacturing loops . The use of renewable materials in smart lightweight constructions offers many advantages with respect to the reduction of CO2 emissions and sustainability, as the used materials are biodegradable after expiration of their lifetime. However, monitoring of parameters such as moisture or strain are of high importance with respect to safety and reliability of such systems. A sensor system consisting of humidity, temperature and strain sensors would therefore be desirable, which could serve for process control during manufacturing as well as for in-situ monitoring while deployed in an application. In order to maintain the advantageous properties of these materials it is necessary that sensors embedded for condition monitoring are also sustainable and lightweight.

2 Methods

This thesis deals with the development of a fully printed biodegradable sensor system for integration into lightweight construction parts (Figure 1).
In order to cope with the variability of size and shape of the construction elements, additive manufacturing methods are preferred and inkjet printing technology will be primarily investigated as fabrication method. The focus of the work is on the evaluation of substrate and ink materials as well as an experimental investigation of their compatibility and the applicability of inkjet technology. Sensor prototypes as well as the final system will be fabricated following simulations and analytical analysis and will be further subjected to physical and electrical test measurements to determine the sensor sensitivity, robustness and biodegradability. Wire connections as well as chemical substances needed for batteries should be avoided. Therefore, the integrated system should ultimately be read out passively and wireless, which, together with the requirement to keep the dimensions of the overall system compact, creates unique design challenges.

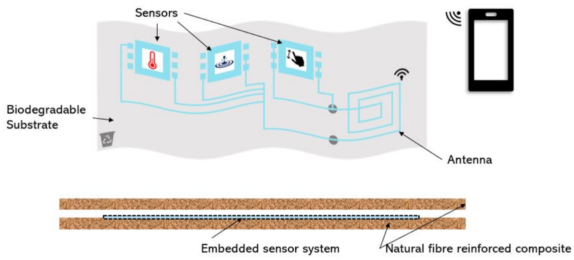

Figure 1: Schematic illustration of the final sensor system composed of three sensing elements which could be read out passively.

3 Results and Discussion

The main part of this PhD thesis was carried out within the scope of the EFRE funded project "Smarter Leichtbau 4.1". It is based on the results of the project "Smarter Leichtbau 4.0", where wire bonded sensors for monitoring humidity, temperature and strain were developed and manufactured by means of inkjet printing on uncoated paper substrate. In the follow-up project 4.1, we managed to replace disturbing wire connections by integrating an commercial NFC Si chip. The chip, connected to all three sensing elements, can be read out fast and easily via a smartphone app using an attached inkjet printed antenna.
Due to the three-dimensional expansion and rigidness of the NFC chip, it could be a mechanical weak point in the thin lightweight laminates and should therefore be removed from the system. By means of inductive coupling with a PCB reader antenna, the system, composed of capacitive (humidity and strain) and resistive (temperature) sensors and a printed antenna, can be read by monitoring of its resonance frequency and the quality factor. Embedding the sensors in the natural fiber composites and subsequent test measurements show excellent results for temperature measurements with minimal hysteresis and very good repeatability.

[1]Online: The European Green Deal
[2]Online: OECD, The Next Production Revolution

Power-aware signal processing for wireless smart sensors based on compressive sensing

Dailys Arronde Pérez, University of Klagenfurt
SAL supervisor: Jürgen Kosel, Silicon Austria Labs GmbH
University supervisor: Hubert Zangl, University of klagenfurt

1 Introduction

The limited energy resources of wireless smart sensors have been one of the main restrictions for their extensive deployment in monitoring and control applications. Introducing a Compressive Sensing (CS) scheme can substantially reduce the high impact of sampling rate on the overall power consumption of the sensor node. In this work, a power-aware signal processing framework for smart sensors is proposed, which is based on CS including uncertainty analysis. To cope with the resource constraints of wireless sensors, this framework aims to combine an optimal sampling strategy with a low complexity reconstruction algorithm. In addition, the integration of uncertainty analysis within the entire signal chain provides a useful tool for optimization on the system level. The performance of the proposed framework will be evaluated in a wireless sensor node, combining simulation and experimental results.

2 Compressive Sensing Framework

In many applications, the signal has a sparse representation in the frequency-domain and the energy efficiency of wireless sensors acquiring such signals can be significantly improved by using a non-uniform sampler (NUS) [1]. Instead of acquiring N samples of the signal s, in a CS framework a set of $M \ll N$ measurements is generated by a linear dimensionality reduction of the form

$$\mathbf{y} = \mathbf{\Phi}\mathbf{s} + \mathbf{n}, \tag{38.1}$$

where $\mathbf{\Phi}$ is a $[M \times N]$ measurement matrix that should satisfy certain conditions [2] and $\mathbf{n}$ accounts for additive white noise in the measurement process. The sparse representation can be in terms of a frame or dictionary, meaning that the signal can be represented in terms of its largest κ coefficients without significant loss. Stable recovery of sparse signals can be guaranteed under certain conditions from just $M = \mathcal{O}(\kappa \log(N/\kappa))$ measurements via convex optimization or iterative greedy algorithms. Figure 1 shows a block diagram of the proposed framework.

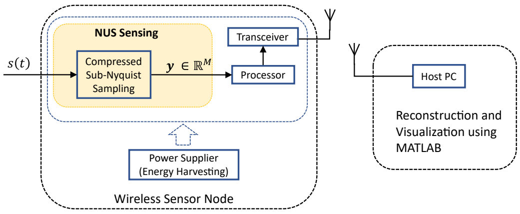

Figure 1: Setup for power-aware signal processing framework with NUS sensing principle.

3 Opti2: A reconstruction approach for periodic signals

Periodic signals are common in many applications and they have, in general, a sparse representation in the frequency domain. To account for a high accuracy estimation of such signals, a two-stage optimization approach, called Opti2, is proposed in [3] for the reconstruction of periodic signals that can be expressed in terms of fundamental frequency and harmonics. In the first stage, one of the existing reconstruction techniques for compressible signals is employed and used as input to the second stage, where an iterative non-linear optimization is solved to improve the estimation of the signal's parameters. Experimental results show that Opti2 outperforms previously proposed algorithms for recovering spectrally sparse signals with a relatively low computational effort.

4 Uncertainty Analysis

Another important parameter with respect to sensors is the achievable uncertainty limit at a certain measurement rate. To provide a more complete software solution for the evaluation of uncertainty in measurements, a toolbox for automatic uncertainty propagation has been developed, which comprises different methods for uncertainty determination: Taylor series approximation, Monte Carlo and Unscented Transform. The latter helps to overcome some of the limitations of the other two approaches, specially when dealing with non-linear systems. The toolbox in available in [4].

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[4] https://www.aau.at/en/smart-systems-technologies/sensors-and-actuators/downloads/

All Al(Sc)N platform for functional integrated photonics

Spettel Jasmin, Silicon Austria Labs GmbH
SAL supervisor: Thang Duy Dao, Silicon Austria Labs GmbH
University supervisor: Guillermo Villanueva, EPFL Lausanne

Integrated photonics have attracted more and more interest in recent years. They enable compact solutions for a variety of applications, such as bio-chemical sensing, communication, computing, and quantum information processing. In this regard, the silicon platform has been extensively studied, since this material has many advantages, as for example usage of mature and highly scalable complementary metal-oxide semiconductor (CMOS) fabrication processes, high-index contrast with its oxide allowing compact components, and low absorption at telecom wavelengths. However, there are also some drawbacks. The bandgap of silicon is indirect and rather small, limiting the transparency window to wavelengths above 1.1 µm. Moreover, since silicon does not show second order non-linearities no advantage of Pockels effect or second order generation can be taken.

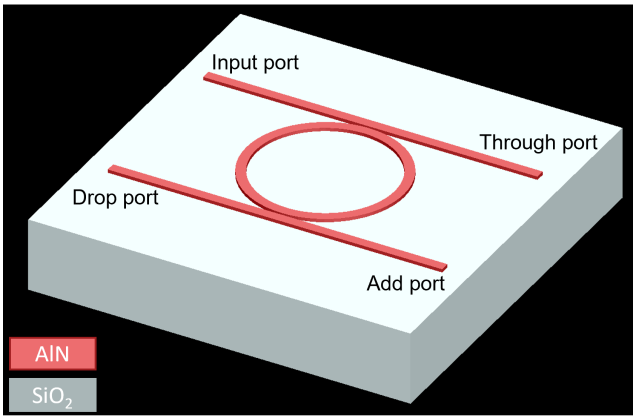

Figure 1: Schematic representation of a micro ring resonator as example of a photonic component

To overcome this limitations, aluminium nitride (AlN) is proposed as an alternative material. It is a wide-bandgap semiconductor with a moderate refractive index and low-optical-loss achievable, allowing its applications in a wide range of wavelengths from ultraviolet to mid-infrared. Due to its non-centrosymmetric crystal structure, it shows not only third order non-linearities (Kerr effect) but also second order non-linearities (Pockels effect). Since it has a rather high thermal conductivity and low thermo-optic coefficient, it is less sensitive to temperature fluctuations than silicon platforms and can handle high optical power, which is particularly important for devices relaying on non-linearities, e.g. for second and third harmonic generation or Pockels modualtor. In this regard the absence of two-photon absorption is also advantageous. Moreover, it is compatible with CMOS fabrication processes and the index contrast with SiO_2 is reasonably high, allowing compact devices due to high light-confinement in the waveguides. Furthermore, AlN is a piezoelectric material. This may allow the integration of micro-electromechanical systems (MEMS) and photonics on the same platform. Provided that AlN can be grown to satisfy both piezo and optical requirements, this would lead to possible applications with electro-mechanical and opto-mechanical devices. AlN might not only enable the integration of photonics with MEMS, but also with acoustic devices due to its high bulk acoustic and surface acoustic wave velocity.

The development of such an all Al(Sc)N platform for functional integrated photonics is the aim of this thesis. In other words, the goal is to have photonic and e.g. MEMS devices integrated on one single Al(Sc)N platform. To accomplish this goal, first the focus will be on process development for the deposition of the Al(Sc)N layer on silicon oxide or quartz. Low optical losses, smooth surfaces, and a high piezoelectric coefficient are targeted. For this purpose, also doping with scandium (Sc) to enhance the piezoelectric and non-linear response will be investigated. In addition to the deposition process also other microfabrication processes, such as lithography and etching will be optimized and extensive characterization of the material is planed (SEM, EDX, spectroscopic ellipsometry, Raman spectroscopy, stress measurements, surface roughness characterization, XRD, . . .). The second part of the thesis focuses on simulations to develop a passive demonstrator, such as a micro ring resonator (see e.g. Fig. 1) for sensing applications. Hence, commercial simulation software such as Lumerical, COMSOL, and/or RSoft will be used. After the design of the device a layout will be drawn and the fabrication of the demonstrator will be tackled. This passive demonstrator will additionally be used for optical characterization purpose to investigate the capabilities of Al(Sc)N photonics using the developed fabrication processes. Therefore, additional test structures might be developed and included in the layout. With the learnings of the first two parts of the thesis a second demonstrator is planned. This one is intended to be an active device, which can be archived by adding functionalities to a micro ring resonator. There are several possibilities to do so, as for example taking advantage of the high electro-optic effect of Al(Sc)N to tune the resonance frequency of the micro ring resonator or using additional piezoelectric actuation.

A sustainable and self-sufficient flexible sensor platform for chemical gas detection

Johanna Zikulnig, Silicon Austria Labs GmbH
SAL supervisor: Jürgen Kosel, Silicon Austria Labs GmbH
University supervisor: Sandro Carrara, École Polytechnique Fédérale de Lausanne (EPFL)

1 Introduction

Nowadays, the measurement of blood sugar concentration in diabetes patients is still highly invasive by picking a finger and subsequent blood analysis. Considering that 1 in 11 eleven adults suffer from diabetes, the monitoring of blood sugar concentration is everyday-life for around 425 Million adults worldwide. In addition, the estimated number of unrecorded cases is around 400 Million cases and the number of people affected by diabetes is expected to rise significantly [1]. As part of the strategic project FLEXS, the development of a minimally invasive, highly integrated system for continuously determining the blood sugar concentration by analyzing the concentration levels of biomarker (Acetone) gases in exhaled breath is targeted. Present state-of-the-art metal oxide sensors cannot be operated at room temperature [1]. Furthermore, the clinically relevant concentration of Acetone in exhaled breath is below the level of detection of commercial sensors. Aside from technologically limiting factors, those sensors are generally not sustainable, due to the materials and fabrication technologies involved. Consequently, an innovative sensor concept based on organic materials will be developed. The proposed sensor system is self-sufficient using hybrid integration of a commercial passive wireless sensor chip, sustainable materials and additive manufacturing technologies (Inkjet- and Aerosoljet printing) to minimize resource consumption.

2 Methods

In a first approach, Chitosan-based sensors on glass and biocompatible TPU substrate have been fabricated (see Fig. 1). The Chitosan was formulated as hydrogel according to [2] and then drop-casted onto the substrate. After drying, the Ag-electrodes were inkjet-printed onto the chitosan polymer layer and cured by means of intense pulsed flashlight irradiation (PulseForge 1200).
To characterize the Chitosan based sensors, their sensitivity towards environmental influences, such as changes in temperature and humidity levels are observed.

3 Results and Discussion

Fig. 2 shows the logarithmic humidity response of the Chitosan-based sensors at room temperature (T = 20^oC const.).
Humidity in exhaled breath is dependent on the individual as well as geographical locations [3] which must be considered to increase the reproducibility and reliability in breath analysis. However, accordig to [4], a humid environment enhaces the sensitivity of Chitosan for the sensing of Acetone, which is beneficial for the proposed use case.

[1]Online: Diabetes Online

Figure 1: Chitosan based VOC gas sensor on TPU substrate.

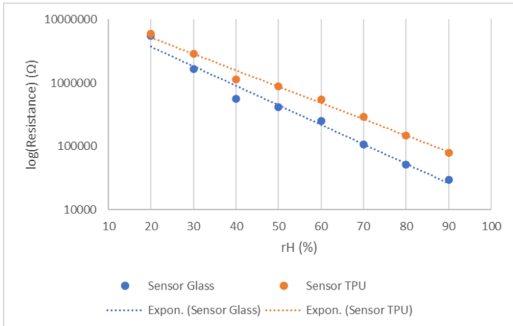

Figure 2: Logarithmic humidity response of Chitosan-based sensors (T = 20^oC const.)

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Polarity Control of AlScN Thin Films for Piezoelectric Multilayers

Jannick Fammels, Silicon Austria Labs GmbH
SAL supervisor: Dmytro Solonenko, Silicon Austria Labs GmbH
University supervisor: Andrew C. Kummel, University of California, San Diego

1 Introduction

The market for piezoelectric thin film based devices, worth over five billion dollars, is projected to grow by more than 15% annually, with the two dominant materials being AlN and PZT. While AlN shows high figures of merit for receiver applications, the significantly higher piezoelectric coefficient in PZT makes it a better material for transmitters and actuators. However, AlN also exhibits many additional advantageous properties compared to PZT, such as high breakdown fields, higher fatigue resistance, bipolar actuation, and CMOS compatibility. The disadvantage of AlN can be somewhat ameliorated by the incorporation of scandium into the AlN lattice, facilitating an increase of up to 400% of the piezoelectric coefficient d_{33}. While this increase is significant, the piezoelectric coefficient of PZT is still at least four times larger. Next to the material engineering of AlN-ScN solid solutions, a challenging but promising option is improving the piezoelectric response with a structural approach. While this does not increase the response of individual films, depositing a multilayer stack of several piezoelectric films with top-, bottom-, and interstitial electrodes results in improved piezoelectric properties of the entire structure compared to a single piezoelectric film of equivalent thickness.

Figure 1: Simplified multilayer structure of AlScN films with alternating polarity and Mo electrodes on Si substrate. At least four AlScN layers are required to achieve the same performance as a PZT film of equivalent thickness.

Since the mechanical displacement of a piezoelectric layer does not depend on the layer thickness, but only on the applied voltage, a multilayer structure with *n* piezoelectric films can theoretically show a displacement of *n*-times the displacement of a single film. To reduce capacitive coupling, multilayer stiffness, and complexity, the AlScN layers must be deposited with alternating polarity, so that each interstitial electrode can serve two piezoelectric layers (Fig.1). Since the direction of the electric field is inverted for each subsequent layer, the inversion of film polarity is necessary to actuate the layers in the same direction. This is because piezoelectric layers with the same polarity but inversely applied electric field would be actuated in opposite directions, resulting in a net actuation of zero.

2 Methods

The most thoroughly investigated and cost-effective deposition technique for AlScN films is magnetron sputtering, which is possible at SAL with the Evatec Clusterline in Villach. Magnetron sputter epitaxy of AlScN utilizes ion bombardment of metallic Al- and Sc-targets to remove atoms and atom clusters that subsequently settle on a substrate. The ion source is comprised of a nitrogen plasma, which reacts with the particles settling on the substrate to AlScN. This process, using separate Al and Sc targets, as well as a reactive nitrogen plasma, is called reactive co-sputtering.

3 Challenges

Depositing piezoelectric multilayer structures provides several challenges. Firstly, AlScN film polarity and its dependence on deposition parameters has to be well understood and controlled to deposit different films with alternating polarity. Secondly, sputtered AlScN films exhibit increasing surface roughness with increasing film thickness, which decreases crystal orientation and piezoelectric performance of the following layers. So called abnormally oriented grains pose a particular obstacle in this regard. Thirdly, the stress of the multilayer has a significant impact on the piezoelectric performance. An additional predicament results from the fact that most deposition parameters affect all three of these aspects simultaneously, rendering iterative property optimization more challenging. One way around this issue is the compartmentalization of the deposition process of a single layer into different steps that aid in the optimization of individual properties at a time. For example, the stress can be optimized in the first part of the deposition process, whereas the orientation can be optimized during the second part, resulting in highly oriented films with low stress. A similar additional step is feasible for inducing the intended film polarity at the beginning of the deposition using an AlN seed layer that has been optimized for this purpose.