A Mixed Signal ASIC for Detection of Acoustic Emergency Signals in Road Traffic

Matthias Mielke, André Schäfer, and Rainer Brück

Abstract — **In larger cities, emergency vehicles of fire services, emergency services, and police are often impeded by other road users. Although the emergency vehicles use visual and acoustic warning signals to become noticeable, they are not always perceived soon by other road users. This can lead to dangerous traffic situations, unacceptable delay for the emergency vehicle, and even accidents with other road users. To address this issue, and raise the awareness, and lower the reaction time of the driver, a driver assistance system was developed which monitors the ambient noise behind the car and informs the driver when an acoustic emergency signal is detected. Special attention was paid to simplicity of the algorithm for easy implementation in an integrated circuit. The circuit is not only applicable in road traffic. It can also form a basis for environmental sound interpretation for the use in assistive listening devices.**

Index Terms — **automatic siren detection, digital signal processing, driver assistance system, mixed signal integrated circuit**

I. Introduction

TODAY, modern cars are equipped with a variety of systems assisting the driver. Most of these systems increase the driving comfort, like navigation systems, and the security by assisting the driver in tasks like parking or by stabilizing the car in critical situations (e.g. Electronic Stability Control). All of these systems have in common, that they monitor the car's environment. Depending on the application area of the system, it uses different types of sensor; e.g. cameras for parking assistance, acceleration-, and gyro sensors for electronic stability control, and wheel speed sensors for anti-lock braking systems. The presented system monitors the acoustic surroundings of the car and extracts emergency signals of fire services, emergency services, and police from the ambient noise. If a warning signal of an emergency vehicle is detected, it is signaled to the driver, to make him aware of the emergency vehicle earlier. Especially hearing-impaired people can benefit from such a system, since hearing-impaired using assistive listening devices often have difficulties in noisy environments [1].

Matthias Mielke is with the Institute of Microsystems Technology, University of Siegen, Siegen, 57068, Germany, phone: +49 271-740-2391; fax: +49 271-740-2473; e-mail: matthias.mielke@uni-siegen.de.

André Schäfer is with the Institute of Microsystems Technology, University of Siegen, Siegen, 57068, Germany, e-mail: andre.schaefer@uni-siegen.de.

Rainer Brück is with the Institute of Microsystems Technology, University of Siegen, Siegen, 57068, Germany, e-mail: rainer.brueck@uni-siegen.de.

The system was developed and implemented in a microchip by a group of students in the context of their studies. The system called Automatic Siren Detection (ASD) is able to filter acoustic emergency signals from German ambulance, police, and fire department cars. The ASD-chip can be used as a driver assistance system to generate a warning signal for the driver or reduce car radio volume. The following chapter presents shortly the research in the area of recognition of acoustic emergency signals done in the past. The third chapter gives a brief introduction to the development activities. In the beginning of the fourth chapter, the German norm DIN 14610 [2] is introduced, which defines the composition of acoustic signals of emergency vehicles in Germany. On top of this norm, the concept of signal processing for the detection of an emergency signal and the realization in a mixed signal ASIC will be presented. In chapter five, the design-flow, the verification and the testing of the chip are presented. Test results are summarized in chapter six. Closing, the conclusion is drawn and the plans for future developments are presented in chapter seven.

II. Research

The detection of acoustic emergency signals is not often focus of research in the area of signal processing. Past research was motivated by the need for assistive devices for hearing-impaired and deaf people.

In this context, the authors of [3] conducted experiments with the Mahalanobis distance [4] as a classifier for domestic alerting signals. The inputs for the classifier are the power spectra of recorded sounds of two different ring tones from a cell phone. The experiments show that the Mahalanobis distance seems to be a robust and practical tool for classification of alerting sounds, which are in general brief, distinctive and approximately periodic.

Beside the more basic study of Dubin presented above, some attempts were made to create complete systems for detection of alerting signals. A device for application in the household is presented in [5]. The application demanded a system which is capable of detecting and differentiating four different types of sound – a door bell, two telephones, and a smoke alarm. Audio analysis is conducted by a bank of active analog filters, to watch the necessary frequencies. The Sound classification, based on the output of the filter bank, is realized in a Programmable Logic Device (PLD) for adaptability to different environments.

Whereas the described approach is specifically designed for the application in the household, the device described in [6] is dedicated for the use as mobile device. It consists of a microphone and circuitry for recording the ambient noise, digital signal processor for data processing and an electro tactile interface for signaling to the user. After recording of a dataset, this dataset is processed with a Fast Fourier Transform (FFT) to obtain the frequency spectrum of the audio signal. A time of 250 ms is processed by the FFT in ten windows a 25 ms. Different temporal and spectral features, in sum 16, are extracted from those results and the classification is done with different statistical methods. Four different classes of alerting signals are defined, plus one class which can be trained by the user. Even the system is intended for mobile use, its weight of 1.5 kg and its operating time of maximal three hours made it impractical.

Opposing to the approach in [3], the authors of [7] developed a complex, neuronal system for detection of acoustic warning signals from emergency vehicles of fire and police departments. Input data, in form of wave-files, is processed with a FFT with a window size of 10 ms. From the resulting spectra, Mel Frequency Cepstral Coefficients are extracted as features for the classification process. An artificial neural network [8] consisting of three layers is used as classifier, which enables the system to learn different emergency signals and to detect these signals with great confidence. With the approach of using artificial neural networks for classification, the system is not only restricted to the recognition of some specific emergency signals. But the system's software runs a standard PC and is, due to its need of processing power and complexity of the system, only limited suitable for direct implementation in an integrated circuit. The approach presented in this work, was to create a system detecting emergency signals with adequate accuracy, which can be implemented in an integrated circuit to easy integrate it in a car.

III. Chip Development in Education

The concept and the chip were developed by a project group of students at the department of electrical engineering and computer science at the University of Siegen. A project group is a major activity in the course of studies for students of electrical- and computer-engineering. Dependant on the field of study of the individual student, the intended effort is between 300 and 900 hours. A project group consists of six to twelve students, dealing with a developmental and scientific task applying technical and scientific methods. Besides the training of the technical and professional skills, the training of the so called "soft skills" like teamwork, self organization, independent work and presentation skills is also a mayor goal.

To create an industry-oriented, realistic scenario, the project group was treated as an independent design team. The Institute of Microsystems Technology acts as the customer of the developed microchip. At the beginning of the project, project group and customer developed an idea for the concrete microchip. Based on that idea, the project group developed concepts for realization, the specification and the design. The project group was responsible for scheduling, cost- and personal planning, and management of the development process. The project group, represented by a student group leader, had to account their decisions in monthly management reports and discussions with the customer.

Two research assistants of the Institute of Microsystems Technology were available as contact persons for questions concerning the concept and realization of the chip, and the management of the project work.

IV. The Chip

Following, the norm DIN 14610 that defines the acoustic signals of emergency vehicles in Germany is presented. On top of this norm, a concept for extracting and identifying signals is shown in section B. The implementation of the shown concept in a mixed signals ASIC is presented in section C.

A. *Acoustic Emergency Signals according to DIN 14610*

The German norm DIN 14610 defines the composition of acoustic warning signals of emergency vehicles in Germany and provides the basis for the concept of the microchip. The warning signal can be categorized as a "hi-lo" sequence. It consists of a sequence of a tone with a low frequency followed by a tone with high frequency. Both tones lie in the frequency band between 360 Hz and 630 Hz. The ratio between low and high tone's frequency shall be 1 to 1.333, with variations allowed between 1 to 1.293 and 1 to 1.426. It is allowed to complement the two basic tones with more tones whose frequency may vary by a maximum of 5% from the basic tones.

A complete cycle of an emergency signal consists of two repetitions of the change in tone pitch and must run automatically. A cycle must have duration of 3 seconds with an allowed deviation of ± 0.5 seconds. In figure 1, a complete cycle of the emergency signal is shown.

Additionally to the regulations codifying the tone sequence, the norm gives specific constraints concerning the sound level of the signal. It constitutes that the basic tones must reach a sound level of at least 110 dB and some of the overtones in the range between 1000 Hz and 4000 Hz at least 104 dB in a distance of 3.5 meters. For the presented implementation of the microchip, only the regulations concerning the structure of the emergency signal were consulted.

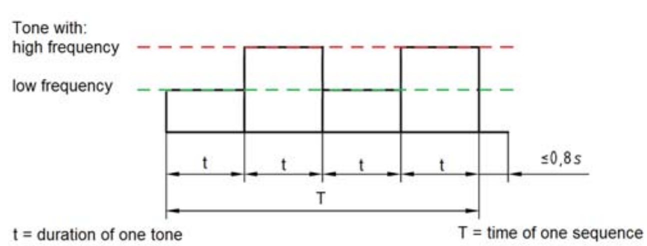

Figure 1. Complete cycle of emergency signal

B. *Detection of Emergency Signals*

In pattern recognition some form of standard approach is applied to different problems [9], in which the necessary tasks are executed sequentially. The results from the earlier stage are the input of the next stage. In figure 2 (a) the basic flow with the main tasks/components is illustrated. The observed Environment is shown at the left side of the image. A sensor is used to observe the properties of interest. In the area of acoustic pattern recognition, this is usually a microphone. The signals from the sensor are recorded and the recorded signal is a pattern which, in the next step, is preprocessed to simplify the following pattern matching process and to enhance the recognition rate. From the results, features are extracted to reduce the amount of data as input for the classification. The extracted features are then analyzed by a classifier which returns the class of a pattern. The characteristics of the classes are trained by a learning algorithm with the help of a database of patterns from a specific class.

The above described DIN norm defines a narrow band for the base tones of warning signals for emergency vehicles in Germany, which allow the automatic recognition by an integrated system. Adopting the above described approach, four steps for the classification of an acoustic emergency signal have to be conducted:

1. Recording of the ambient sound,
2. decomposition of the ambient noise into a spectrum of single tones (preprocessing),
3. extraction of a set of features for the classification, and
4. the actual classification. The classifier checks whether the extracted features form a sequence according the DIN standard with the results from former cycles.

It is important to ensure that the typical ambient noise and sound effects are taken into account and have little or no influence on the outcome of the detection. Most important for the application in a car, is the Doppler Effect [10], since the difference in speed between two cars can result in significant frequency shifts of an acoustic signal.

In operation, the ambient noise is recorded with a microphone and filtered by an analog circuitry. The analog signal is digitized and the resulting data are analyzed using an autocorrelation algorithm [11] to the existence of tones in the frequency range of interest. To simplify the autocorrelation algorithm it was assumed that the emergency vehicle is approaching from behind with a higher speed than the own vehicle. The basis for this restriction is the assumption that the driver notices the visual warning signals in front of his car early due to fact that he looks into the direction he is driving, whereas warning signals – either visual or acoustic – behind the car are noticed delayed by the driver. The autocorrelation algorithm was chosen because of its ability to reveal harmonic signals which are buried by random noise. For the system it was assumed that the ambient noise is random and overlay the acoustic signal of the emergency vehicle. Basis for the assumption were the movement of the car and the manifold sources of ambient noise (e.g. people, other vehicles, airflow). When an emergency vehicle with active acoustic warning signal approaches a car, the frequency of the warning signal is shifted because of the Doppler Effect. If the emergency vehicle approaches a car from behind with a higher speed, the pitch of the siren shifts to a higher frequency. This frequency shift must be taken into account when analyzing the acoustic environment. A frequency shift up to +45 Hertz shall be taken into account, which is sufficient for a speed difference of 80 km/h between the emergency vehicle and the car. Considering

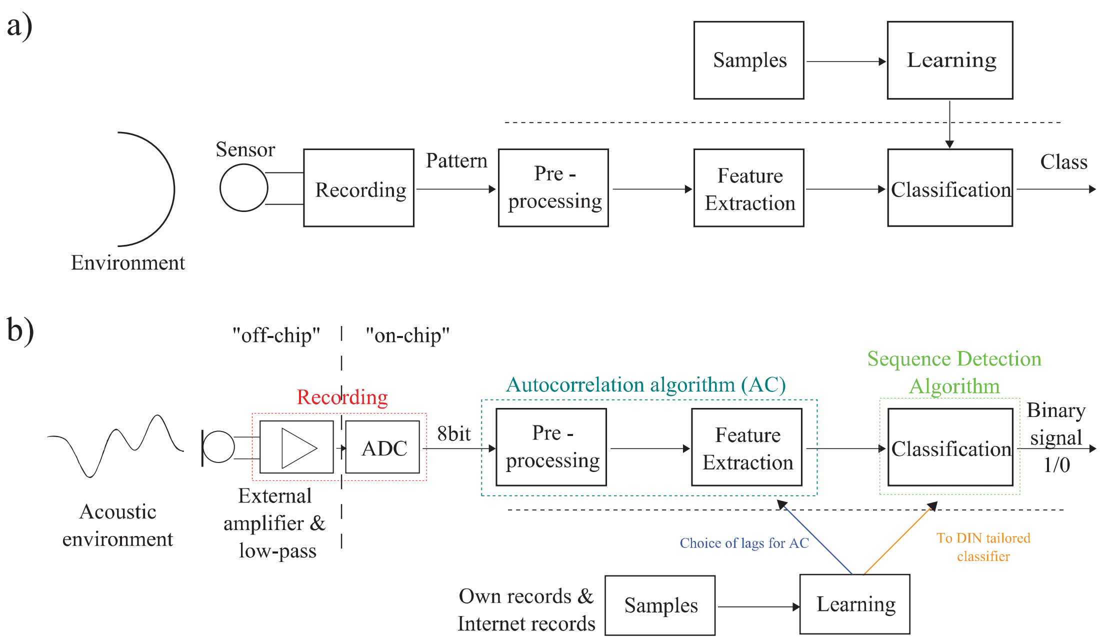

Figure 2. (a) Pattern recognition flow according to [9], (b) components of presented system in flow.

a frequency shift of +45 Hertz, the system must monitor the frequency range between 360 Hertz and 675 Hertz.

With these restrictions and a defined sampling frequency $f_{sample} = 22.222\ kHz$ the overall autocorrelation algorithm for discrete –time signals can be simplified to

$$\Phi_{xx}(\tau) = \sum x(t) * x(t+\tau), \text{ with } \tau \in \{31, \cdots, 63\}. \quad (1)$$

With

$$f(\tau) = \frac{f_{sample}}{\tau} \quad (2)$$

and $f_{sample} = 22.222\ kHz$ can be calculated, which frequency corresponds to a shift by τ. For the shifts *τ=31* and *τ=63* we obtain

$$f(31) = \frac{22.222\ kHz}{31} \approx 0.718 kHz$$

as upper limit frequency and

$$f(63) = \frac{22.222\ kHz}{63} \approx 0.353 kHz$$

as lower limit frequency. So, the autocorrelation algorithm examines the frequency range between 353 Hertz to 718 Hertz.

After the data from the microphone has been processed with the autocorrelation algorithm, the frequency spectrum is examined whether a significant high or a low tone, as described in DIN 14610, is present in the sampled data. At first, it is checked if a significant tone is present, that is the case when the maximum value in the results of the autocorrelation is much higher than the minimum value. This is checked by determining the *minimum* and *maximum* values in the results of the autocorrelation and calculating *maximum – minimum*. Is the result bigger than 100000 the tone at the position of the *maximum* is assumed to be significant. The value of 100000 was identified by experiments. After a significant tone is identified, its tone pitch is determined. The pitch is indicated by the position in the results of the autocorrelation (see (2)). If the position of the *maximum* is below 45, the identified tone is marked as a tone with a low pitch, otherwise as a tone with high pitch.

When the classifier finds at least ten tones with low frequency and ten tones with high frequency in 60 following processing cycles, an emergency signal is detected and displayed.

In figure 2 (b) the above introduced approach of the microchip is integrated in the approach illustrated in figure 2 (a). The four steps for the recognition are not transferred one to one in the chip. The preprocessing- and the feature extraction- steps are both performed with the autocorrelation algorithm. Feature extraction is done implicitly by the choice of the range for the lags $\tau \in \{31, \cdots, 63\}$. The classification algorithm was developed by analysis of sound records recorded in road traffic and records from the internet.

C. Detection of Emergency Signals

The presented approach is implemented in hardware as a proof of concept. In operation, the ambient noise is recorded with a standard electrets condenser microphone. The weak signal of the microphone is amplified by a non-inverting operational amplifier with adjustable gain from 160 to 1800. After amplification of the signal, it is filtered by a passive, analog low-pass to cut off frequencies above 10 kHz. All the circuitry for the recording of the audio signals was build with off-chip components. The analog audio signal is digitalized by an on chip 8-Bit Analogue to Digital Converter (ADC). The used ADC works according to the principle of successive approximation [12] and is clocked at a frequency of 1 MHz. The digitized values are then processed on the chip, which consists of three major blocks (red in Fig. 3): the implementation of the autocorrelation algorithm (AC) for extracting harmonic signals from ambient noise, a module for detection of a tone sequence as described above (SDA) and a superior module controlling the work and the test modes of the chip (control). Besides the three main blocks, the chip consists of the above described analog to digital converter and three memory modules for storing samples and calculation results. These modules are provided by austriamicrosystems.

The recording of the ambient sound is controlled by the control module. A conversion of the input signal by the 8-Bit analog to digital converter is started every 45 clocks. With the clock frequency of 1 MHz of the ADC and a sampling every 45 clock cycles, an effective sampling rate of circa $f_{sample} = \frac{1MHz}{45} \approx 22.222 kHz$ is achieved. At the beginning of a new conversion, the ADC saves the current analog voltage in a sample & hold circuit and converts it to a digital value in the following nine clock cycles.

At the beginning of a new processing cycle, samples are taken by the ADC and stored in the 192x8-Bit memory *mem_samples*. As soon as 192 samples are stored in the

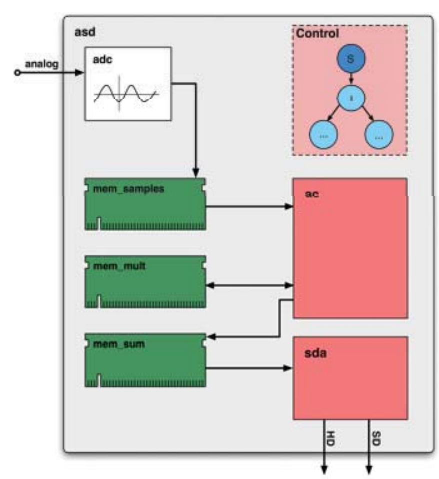

Figure 3. Block diagram of the chip.

memory, the autocorrelation algorithm is started by the control unit. The autocorrelation function is calculated for every τ in {31 … 63}. The calculation for a specific τ is done in two steps: First, the samples t at the positions {0 … 127} are multiplied with the value at t + τ and the results are saved in the 128x8-Bit memory *mem_mult* at position t. Second, when all 128 multiplications are performed, the values in *mem_mult* are accumulated and the result is saved in the 33x24-Bit memory *mem_sum* at position τ (see Fig. 4). When the autocorrelation algorithm finished the calculation for τ=63, it is switched off and the control starts the sequence detection algorithm.

The sequence detection algorithm analyses the output of the autocorrelation algorithm in *mem_sum.* The goal is to decide whether a significant tone, that is a tone with high amplitude, is present in the ambient noise. For detection, the algorithm searches the results of the AC in mem_sum for the minimal value *min* and maximal value *max*. Additionally, the SDA saves the position in which the maximal value was found (*maxPos*). To determine if a significant tone is present in the results of the AC, *min* is subtracted from *max*. If the result is bigger than a threshold, a significant tone with amplitude *max* is found and the tone classified on the basis of its position in *mem_sum*, because the position indicates the frequency (see section B). If *max* is saved in a position smaller than 45, it is a tone with low pitch and the counter *count_low* is increased, otherwise a tone with high pitch is detected and the counter *count_high* is increased. Control turns off the SDA and begins a new processing cycle. If SDA detects in 60 processing cycles at least ten low and ten high tones, it is assumed that an acoustic emergency signal is found and the chip's output *Horn Detected* is set.

V. Design-Flow and Verification

A. Overview of the Design-Flow

At the beginning of the project the algorithms were programmed and tested in Dephi. After this proof of concept the behavioral descriptions of the algorithms were implemented in VHDL and simulated. For the simulation Mentor's Modelsim was used. When the system showed the desired behavior, Cadence's Encounter RTL Compiler was used for synthesis of the VHDL code. On this occasion, the standard-cell libraries of the technology of austriamicrosystems were integrated. The result was exported to First Encounter, where Place and Route was executed. The placed and routed design was imported into the Design Framework II (DFII). In DFII, the final assembly of digital core, memory cells, ADC and pad-ring was carried out. Finally, the Design Rule Check (DRC) and the Layout Versus Schematic (LVS) were carried out in DFII. Simulations at the electrical level were only performed for certain aspects of the design. The chip was manufactured into 0.35µm mixed signal technology by austriamicrosystems. After manufacturing the ASD chip was tested on a developed board.

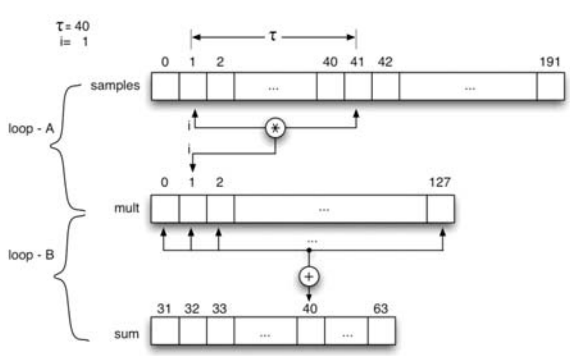

Figure 4. Two step calculation of the autocorrelation algorithm.

B. Verification

The chip was verified extensively on his function during the development. A reference implementation was already developed in the concept phase in Delphi. This program reads in audio files and carries out an autocorrelation about the data and a subsequent recognition (as on top described). If a warning signal was recognized, this is signaled at the GUI. This program became tested first with recordings of driving noises without acoustic warning signals, followed by pure warning signals without driving noises and in the end with recording of warning signals with driving noises.

During the implementing of the ASD algorithms in VHDL a test bench was provided which compares the intermediate steps of the calculation and the results. Beside the tests with audio files, as on top described, the VHDL implementation was tested with extreme values and random numbers.

Beside the simulations on behavioral level the equivalence of the net lists was checked during the transformation of the design from the behavioral view in the structural view and during the transformation of the structural view in the geometrical view by the Cadence Conformal Logic Equivalence Checker. The resulting gds2-file of the digital core area was imported into DFII. In the framework, the digital core area was complemented with the memory modules, the ADC and the pad-ring. The completed design was tested for design rule violations by Assura DRC. When the DRC showed no violations, layout and schematic were compared by Assura LVS. After finishing the design, crucial parts were simulated in an electrical simulation. Different transient and DC analysis were performed with the Cadence simulator Spectre. After manufacturing by austriamicrosystems the functionality of the chips was tested under laboratory conditions.

C. Testing

The chip is equipped with a debug-interface for functional testing. The interface consists of an 8-Bit width, parallel bus and a signal valid *data*, indicating that valid data is available at the eight data pins. The data rate of the bus is 100 kHz. The timing diagram of the debug interface is shown in Fig. 5.

The mode of the chip is controlled by a 3-Bit width input mode select. When the value "000" is applied at mode select, the chip works in normal operation mode and no data is output at the debug interface. When a value other than "000" is

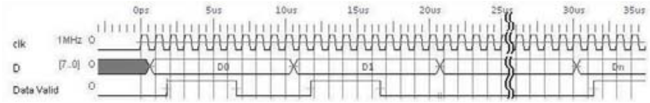

Figure 5. Timing diagram of the debug interface.

applied the chip is set into the test mode determined by the value of mode select. In test mode, the chip finishes the processing cycle and begins to output data at the debug interface. The test mode, selected by the value applied at mode select, determines what data will be output. So it is possible to read the sampled values from the chip and feed them to a reference implementation (e.g. a microcontroller- or PC-program) and compare the values from the chip. With the test modes a step by step execution is possible, to monitor the internal activities of the chip from one processing cycle to the next.

D. *Test setup*

The test of the ready microchip carried out on a test board. This test system is equipped with the external, analogue components, a 1 MHz oscillator, voltage regulators and protective circuit against variations of the voltage source and an AVR-microcontroller to control the test modes and to communicate with a computer. The data from the the test bus are read in by the microcontroller and send to a PC via the RS232 interface. The test system consists of two boards, one with the developed microchip and the necessary external components and the second with the microcontroller and the RS-232 interface. The board with the microchip can work independently from the microcontroller-board (Fig. 6). On the connected pc, the values from the microchip could be compared to the results of the reverence implementing. Mistakes appeared during the processing, could be recognized thus and be analyzed further. As test stimuli different recordings of acoustic warning signals were used again.

VI. Results

The chips were tested under laboratory conditions. First, the chips' current consumption of the twenty packaged chips was checked. The tested chips have a current consumption of circa 260 µA, giving an idle power consumption of about 860 µW. After this basic test, functional tests were done with the twenty packaged chips. The first stimuli for the tests were generated by an arbitrary waveform generator of type Agilent 33220A. The generator was programmed to generate waveforms according to the DIN 14610. When the chip is working and an input signal is applied the current raises up to circa 480 µA, giving a power consumption of circa 1.6 mW. In later tests, the system was connected to a laptop's headphone connector. The stimuli were the sounds of videos showing emergency vehicles in road traffic. The functional tests revealed that the results from the AC-algorithm do not match the results from the reference implementation. The reasons for the wrong results of the calculation are intermittent errors in the highest bit (changes from '0' to '1') of one factor for calculating the

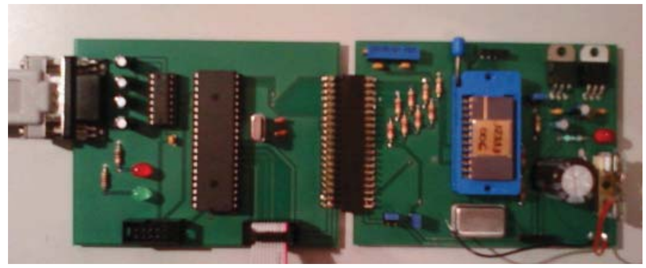

Figure 6. Test board (left), ASD board (right).

multiplication in the AC. Noticeable, it seems that the bit changes occur in the later calculation steps when the values from the higher addresses of *mem_samples* are read. With the implemented test modes, it can be shown that the bit change occurs not in the memory or when it is read out. As a consequence, the change must occur in the autocorrelation unit. Since this behavior was not found in the simulations of the placed and routed chip, it is assumed that the bit changes are the results of crosstalk.

Further tests showed that to counters, *count_low* and *count_high*, in the SDA do not work properly. When *count_low*/*count_high* has the value 0 two events are necessary to increase the value to 1. One event is not counted and gets lost.

Even if the tests showed flaws in the execution of the algorithms, the complete system is capable of recognizing acoustic emergency signals. The errors influence the rate of wrong recognitions; more precisely the rate of false-positives, that is the rate of non-warning signals categorized as warning signals. Because the chip was not working flawlessly, no tests for signal noise ratio were made.

VII. Conclusion and Future Work

The authors presented a procedure for extracting and detecting acoustic signals from emergency vehicles in road traffic. This method was developed and implemented in a microchip by a group of students at the University of Siegen [13]. The chip was realized in a 0.35µm technology with four metal layers from austriamicrosystems. A photograph of the die is shown in Fig. 7.

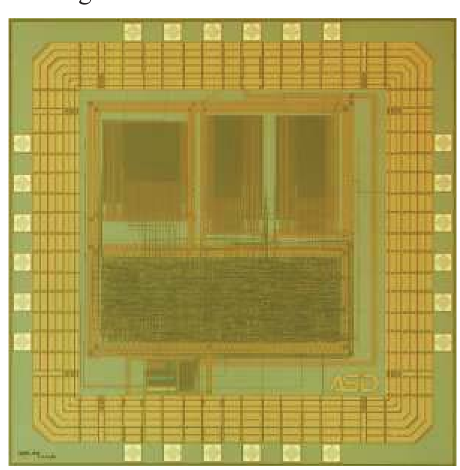

Figure 7. Microphotograph of the microchip

First tests revealed some flaws in the fabricated devices that influence the recognition negatively. However, functional tests showed that the chip is able to detect emergency signals in ambient noise. In the test setup the chip signals a warning signal by an LED. Temporary a CAN-bus interface for the chip is in development.

The presented chip is tailored to the German norm DIN 14610. As a consequence it is not capable of recognizing acoustic signals of emergency vehicles with alarm units not designed to the norm. For a broad usability the system must be modified to recognize other warning signals too. In the future a more versatile system, which is not limited to the DIN 14610, will be developed. Algorithms for a versatile system will be evaluated in the future. For feature extraction and the classification algorithms from speech recognition will be evaluated for their applicability to the problem.

Despite the presented application scenario in the car, the chip can bring benefit to deaf people in road traffic and the household. A versatile, programmable, small and energy efficient system can detect different dangerous scenarios in road traffic (e.g. approaching emergency vehicles) and signals in the household like the door bell.

Acknowledgment

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Matthias Mielke was born in Siegen, Germany in 1981. From 2002 to 2008 he studied applied computer science with application in electrical engineering at University of Siegen, Germany. He received his Diploma in computer science from the department of computer science and electrical engineering of the University of Siegen in 2008.

He worked as a Digital Designer at Guntermann & Drunck GmbH, Germany for two years. Since the beginning of 2009, he works as a Research Assistant at the Institute of Microsystems Technology at the University of Siegen. His current research interests are focused on the design and implementation of integrated circuits and microsystems.

Mr. Mielke is member of the IEEE.

André Schäfer was born in Siegen, Germany in 1976. From 1998 to 2005 he studied Computer Engineering at University of Siegen, Germany.

He worked as a Research Assistant from 2005 to now at the Institute of Microsystems Technology at the University of Siegen.

His research was in the field of lab on microchip and constraint verification at design of microelectronic systems. Since 2009 his new research focus is in computer engineering in education. His current focus is on experiments and lab tasks which promote the competence and skill development for embedded micro and nano systems**.**

Rainer Brück was born in Borken, Germany in 1958. From 1977 to 1983 he studied computer science at Dortmund University, Germany. He received a doctoral degree (Dr. rer. nat.) in computer science from Dortmund University in 1989. In 1996 he received the venia legendi in computer science.

He worked as a research assistant from 1983 to 1989 and as an assistant professor from 1989 – 1996, both at the computer science department of Dortmund university. His research was in the field of electronic design automation. From 1986 to 1996 he headed the physical research group, where the first commercially successful analog layout compaction system CAMBIO-XT was realized. Since 1993 the focus of his research shifted to the field of MEMS design and design tools. From 1996 to 1998 he worked as an associate professor at the mathematics and computer science department at Friedrich-Schiller-Universität Jena, Germany. Since 1998 he is working as a Full Professor at the electrical engineering and computer science department of University of Siegen, Germany. His current research focus is in computer aided product engineering for MEMS and IC systems.

Prof. Brück is a member of GI, VDE and VDI.