F2: *Pushing the Frontiers in Accuracy for Data Converters and Analog Circuits*

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The advances in high-precision analog front-end and data conversion circuits have opened up new opportunities in diverse application spaces. To keep fueling the evolution of emerging applications, such as health monitoring, industry 4.0, and internet of things, advanced sensing technology is required to further improve resolution, speed, as well as power and area efficiency of the system. This forum highlights the fundamental challenges with an emphasis on techniques to achieve the ultimate accuracy in analog circuits and data converters. Following an overview of analog-circuit challenges, a series of discussions start with essential high-accuracy voltage and frequency references along with the compensation techniques for their long-term drift, and then move on to the system-level functions of high-precision amplifiers, digital-to-analog converters, as well as overasampling and Nyquist-rate analog-to-digital converters, which are required to construct the overall signal chain.

Fundamental Challenges in Analog Circuit Design

Bernhard Boser, *University of California, Berkeley, Berkeley, CA*

High performance circuits must cope with a wide range of errors: component variations, drift, sensitivity to environmental factors, and noise. This presentation gives an overview of the extensive array of techniques developed to address such errors and discusses some representative examples. Inherently robust circuit topologies and self-calibration decouple performance from component non-idealities. Continuous calibration rejects time-varying errors such as drift and flicker noise. Sensitivity to undesired inputs, e.g. supply noise, temperature or packaging stress, requires specific techniques such as differential design or temperature compensation. In sensor systems, system-level techniques are often used, especially when truly random errors such as thermal and shot noise must be addressed.

Bernhard Boser received the Ph.D. from Stanford University in 1988. He was a Member of Technical Staff Bell Laboratories. In 1992 he joined the faculty of the EECS Department of UC Berkeley. His research is in the area of analog and mixed-signal circuits, with special emphasis on ADCs and micromechanical sensors and actuators. He served as the Editor-in-Chief of the IEEE Journal of Solid-State Circuits, as a President of the Solid-State Circuits Society and on the program committees of ISSCC, the VLSI Symposium, and Transducers. He is a Fellow of the IEEE and a co-founder of SiTime and Chirp Microsystems.

Designing High-Accuracy Bandgap Voltage References

Vadim Ivanov, *Texas Instruments, Tucson, AZ*

In this talk, various techniques for improving the accuracy of bandgap voltage references are presented. These include circuit techniques such as the use of low-noise topologies, low-offset chopped-feedback amplifiers, and fast-settling output buffers with low output impedance. Packaging techniques, multi-point temperature trimming and testing considerations are also presented.

Vadim Ivanov received MSEE (1980) and Ph.D. degrees (1987) in the USSR. From 1980 to 1991, he designed electronic systems and ASICs for naval navigation equipment in St. Petersburg, Russia, and, from 1991 to 1995, mixed-signal ASICs for sensors, GPS/GLONASS receivers and motor control. He joined Burr Brown (now Texas Instruments, Tucson) in 1996, where he is currently the Operational Amplifier Technologist. There, he has designed operational, instrumentation and power amplifiers, as well as references, switching and linear voltage regulators. He holds 108 patents on analog circuit techniques and has authored 30+ technical papers and three books on amplifier and ASIC design. He has been an SSCS distinguished lecturer and a member of the ISSCC technical program committee. He is currently a member of the ESSCIRC technical program committee.

Precision MEMS-Based Frequency References

Kamran Souri, *SiTime, Delft, The Netherlands*

Recently, MEMS-based frequency references have revolutionized the timing market by outperforming quartz-crystal oscillators in many applications, where they can offer lower power, smaller size, better stability, programmability, and higher reliability. In this talk, an overview of temperature-compensated MEMS-based frequency references is presented. This is followed by a detailed discussion of the various mixed-signal techniques required to achieve state-of-the-art performance.

Kamran Souri received his M.Sc. (cum laude) and Ph.D. degrees from TU-Delft, in 2009 and 2016, respectively. In 2014 he joined SiTime Corp., CA, USA, where he worked on mixed-signal circuits for MEMS-based frequency references. In 2017, he joined SiTime's Design Center in Delft, The Netherlands, where he is currently a Director of Circuit Design Engineering. His research interests include the design of energy-efficient sensor interfaces, data converters, precision analog circuits, and frequency references. He has authored or co-authored over 20 peer-reviewed scientific papers, one book, and holds several U.S. patents. For his Ph.D. research, Dr. Souri was awarded a 2013 IEEE Solid-State Circuits Society Pre-doctoral Achievement Award.

Circuit Techniques for Mechanical Stress Compensation

Mario Motz, *Infineon Technologies AG, Villach, Austria*

The stability of CMOS sensors, bandgap references and RC oscillators is limited by the mechanical stress caused by packaging soldering, moisture absorption or the mechanical creep of plastic encapsulation. Variations in mechanical stress give rise to long-term drift of sensors, the base-emitter voltages of transistors, and the mobility of charge carriers. In this talk, techniques to sense and compensate for the effects of mechanical stress in sensors, bandgap references and on-chip oscillators are presented, which improved the lifetime stability significantly, by 3 to 10 times.

Mario Motz (M'96) received the Diploma degree in technical cybernetics and automation techniques from TH Magdeburg, Germany, in 1983. Until 1990, he worked as a Design Engineer for A/D- and D/A-converters in HFO Frankfurt/Oder, Germany. In 1990, he joined Gaertner Elektronik, and in 1991, he joined ITT Intermetal (now TDK Micronas AG), Freiburg, Germany, where he designed Hall sensor ICs in CMOS technology. Since 1999, he has been with Siemens AG (now Infineon Technologies AG), Villach, Austria, where he is currently a Senior Principal Engineer. His main focus is on the design of sensor ICs, compensation techniques, ADCs, EMC-robust circuits and ultra-low-power circuits. He holds more than 100 patents in these areas.

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Precision Amplifiers: The Past and the Future

Qinwen Fan, *Delft University of Technology, Delft, The Netherlands*

Today, precision amplifiers achieve microvolt levels of offset, low flicker noise, high CMRR, and PSRR, specifications that faciltate the realization of high-accuracy, high-resolution measurement and instrumentation systems. Precision amplifiers are also widely used to interface a variety of sensors, e.g., thermistors, Hall sensors, biomedical sensors, current-sensing resistors etc. In this talk, the main milestones in the development of precision amplifiers are reviewed. This is followed by a discussion of their fundamental limitations, some new challenges and possible future directions.

Qinwen Fan received a B.Sc. in Electronic Science and Technology from Nankai University in China in 2006, and an M.Sc. (cum laude) in microelectronics from Delft University of Technology, The Netherlands in 2008. She continued her studies at Delft, where she received a Ph.D. degree in 2013, for a thesis on precision amplifiers. From 2012 to 2015, she worked at Maxim Integrated Products in Delft, and from 2015 to 2017, she worked at Mellanox, also in Delft. Since 2017, she has been an Assistant Professor at Delft University of Technology. Her current research interests include the design of precision analog circuits, Class-D audio amplifiers, and DC-DC converters for energy harvesters. She is a member of the technical program committee of ESSCIRC.

Digital-to-Analog Converters with High Linearity and Dynamic Range

Ayman Shabra, *MediaTek, Woburn, MA*

This presentation discusses the analog, mixed-signal, and algorithmic aspects of designing resistive RDACs with high dynamic range and linearity. It then describes various techniques to mitigate their main non-idealities: mismatch, intersymbol interference (ISI), reference modulation, summing junction modulation, voltage and temperature dependencies and parasitic coupling. The design of an RDAC that achieves 135dB dynamic range and -125dB THD is used as a case study.

Ayman Shabra received his B.S. degree from KFUPM, Saudi Arabia, and the M.S. and Ph.D. degrees in electrical engineering from MIT, Cambridge, MA. From 2001 to 2010, he was with Analog Devices and then MediaTek, where he was involved in the design of mixed-signal circuits for the wireless handset market. From 2010 to 2015, he was an Assistant Professor with Masdar Institute, UAE. Since 2015 he has been with MediaTek, where he designs mixed-signal circuits for emerging applications. He has served on the technical program committee of CICC.

Architectural and Design Challenges in High-Resolution Continuous-Time Delta-Sigma Data Converters

Shanthi Pavan, *IIT Madras, Chennai, India*

Energy-efficient, high-resolution continuous-time delta-sigma modulators need to overcome several issues that are typically neglected in the design of data converters that target more modest in-band noise spectral densities. Examples of such issues include flicker noise, interconnect resistance and DAC inter-symbol interference. This talk aims to provide some insight into these issues and describe techniques that can be used to address the formidable challenge of designing such converters. To place things in perspective, a practical design example is given.

Shanthi Pavan obtained the B.Tech degree in Electronics and Communication Engineering from IIT Madras and the M.S and Sc.D degrees from Columbia University, New York. Since 2002, he has been with IIT-Madras, where he is now an Institute Chair Professor of Electrical Engineering. He is a co-author of Understanding Delta-Sigma Data Converters (second edition), with Richard Schreier and Gabor Temes. Prof.Pavan has served as the Editor-in-Chief of the IEEE Transactions on Circuits and Systems, as a member of the TPC of ISSCC, and as Distinguished Lecturer of the Solid-State Circuits and Circuits-and-Systems Societies. He is a fellow of the Indian National Academy of Engineering, and an IEEE Fellow.

Intrinsically-Linear Data Converters

Jesper Steensgaard, *Analog Devices, Camas, WA*

Mismatch shaping (dynamic element matching) has enabled delta-sigma data converters to transition from single-bit to multi-bit topologies. This reduces the need for oversampling and suppresses artifacts such as idle tones. This transition has been taken to its natural conclusion in Nyquist-rate converters, with intrinsically-linear SAR ADCs providing exceptional precision (INL<1ppm), spectral purity (THD<-130dB), and state-of-the-art FoM. This transition and the principles upon which it is based are described, and then a comparison is made of the pros and cons of delta-sigma ADCs versus these highly-linear Nyquist-rate ADCs.

Jesper Steensgaard is a Fellow at Analog Devices with the Precision Converter Technology Group. Since 1994, he has been working on high-resolution mismatch-shaping data converters, initially focusing on oversampling (delta-sigma) ADCs and gradually shifting towards Nyquist-type ADCs. He received the M.Sc. and Ph.D. degrees in electronics from the Technical University of Denmark in 1994 and 1999, respectively. His interests include precision signal-chain system optimization and low-power circuit design.