Final Publishable JRP Summary for IND16 Ultrafast
Metrology for ultrafast electronics and high-speed communications

Overview

The steady increase of the operating frequency and bandwidth of new communication systems and remote sensing applications continuously improves the quality of life of many people worldwide. As proposed in the International Technology Roadmap for Semiconductors, this development is expected to continue undamped over the next decade. However, this activity faces unsolved metrology challenges, which this project aimed to solve.

Need for the project

The use of higher frequency bands for mobile data transmission as well as higher electronic processing speeds requires that suitable high-frequency measurements can be made in the design, production and implementation of ultrafast systems. One of the main challenges was the exact measurement of continuous wave (cw) and pulsed high-frequency signals. This would support the traceable calibration of ultrafast sampling oscilloscopes and pulse generators and consequently be important for manufacturers of high-speed and high frequency measurement instrumentation. Using such instrumentation for measurements over long time windows often yields time traces with more than 10,000 data points. The uncertainty evaluation and propagation for such signals was still not satisfactorily solved. Thus, the development of a corresponding software tool for use by calibration labs, NMIs and industry was necessary. As new communication systems evolve, channels and antennas for such systems need to be reliably characterised. This especially holds for systems operating at frequencies beyond those used today, since the underlying technology changes to a large extent. Finally, the exact measurement of digital signals was a requirement that needed to be addressed to support present and future developments in ultrafast communications. This especially holds for vector signals analysers and generators whose present calibration schemes are not traceable. Addressing this issue would primarily support manufacturers and users of vector signal analysers and generators and the equipment suppliers that they support. In general, this research project aimed to support European industry to play a global lead role in ultrafast electronics and high-speed communications for both present, as well as next-generation, technology.

Scientific and technical objectives

In order to address the metrological challenges described above the following four scientific and technological objectives were set:

1) The development of laser-based techniques for the measurement of pulsed and cw high-frequency signals, which was the prerequisite for traceable characterisation of high-speed and high-frequency measurement instrumentation such as ultrafast sampling oscilloscopes and pulse generators.
2) The provision of a software tool for uncertainty propagation that could be applied to large data sets and available free of charge. This was the prerequisite for characterising state-of-the-art measurement equipment, which can record 10,000 data points and more.
3) Investigation of antenna and channel properties in the mm- and sub-mm wave range, which was the prerequisite for the establishment of novel communication links at frequencies as yet unallocated for mobile communications; and

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4) To establish methods for traceable calibration of vector signal generators and analysers and to develop tools for a better understanding of the measurement uncertainty of digital signals. This was a prerequisite for breaking a circular calibration chain, which is sometimes used for digital-signal equipment.

Results

Development of laser-based techniques for the measurement of pulsed and cw high-frequency signals

The project has shown that laser-based measurement techniques could be used to separate forward and backward propagating voltage pulses on planar waveguides. This even held for temporally overlapping pulses. Such a method is a prerequisite for the development of a laser-based vector network analyser.

A broadband voltage pulse standard with 500 MHz frequency spacing and frequency components exceeding 500 GHz was realised. The time-domain shape, and thus frequency-domain spectrum, of the voltage pulses were exactly known; and this pulse standard was based on time-domain electro-optic measurements only.

An asynchronous electro-optic sampling technique to measure of electrical pulse generators was developed. This technique allowed for the construction of covariance matrices with full rank and was important for uncertainty propagation.

Laser-based measurement techniques have been employed for spatially resolved phase and amplitude measurements of free-space GHz and THz signals with low invasiveness of the detection system.

Provision of a software tool for uncertainty propagation that can be applied to long data sets and is available free of charge

A covariance matrix is required to propagate waveform uncertainties between the time-domain and frequency-domain but the storage requirement grows as the square of the trace-length making this approach impractical for large data sets. The project partners have developed an algorithm where the result grows proportional to the trace length (n) only. It uses a combination of principal component analysis and key elements of the original data to approximate the covariance matrix. It has been found that this algorithm works satisfactorily with matrices that are rank-deficient, reducing the measurement burden. Once the results are in compressed format there is no need to recreate the full covariance matrix. Arithmetic operations (+, -, x, ÷) can be performed on the compressed format results so that the elements of an uncertainty budget can be combined and corrections, such as impedance match, can be applied. The performance of the algorithm has been independently verified by Monte-Carlo simulation.

The compression algorithm has been implemented in Matlab, a widely used programming language, and as a stand-alone version (Python) that offers a significant speed advantage. Both software implementations and supporting user guides are available free from the project website.

Investigation of antenna and channel properties in the mm- and sub-mm wave range

Antenna scanners operating in the far-field have been designed and built. They have been used to measure planar antennas, horn antennas, and open-ended waveguides. As suitable devices under test, array antennas have been designed, built and characterized. Measurements were compared to results from a near-field scanner.

Propagation measurements from 50 GHz to 325 GHz were performed in various scenarios relevant for future THz communication systems. Magnitude and phase measurements give information about the path, direction, interference and the attenuation of the signals. Scattering (different surfaces with different roughness and scattering of hydrometeors) and diffraction effects (e.g. caused by humans blocking the beam) on the propagation conditions have been examined.

Transmission measurements of digital signals at 300 GHz with different digital modulation schemes were performed to investigate the feasibility of implementing such frequencies in future communication systems.

Establish methods for traceable calibration of vector signal generators and analysers and develop tools for a better understanding of the measurement uncertainty of digital signals

A universal method for calibration of vector signal analyzers and vector signal generators has been developed. This work resulted in two calibration guides which will be disseminated to the industry. The technique uses digital oscilloscopes traceable to the electro-optic sampling system and proper broadband input signals. Moreover, various hardware impairments, dominant in vector signal analyzers and generators contributing to the quality of the modulated signal have been studied.

A simple software tool for the demodulation of basic digitally modulated signals was created using an object-oriented language. It allows one to calculate the error vector magnitude, EVM, of a signal acquired with a sampling device (i.e., oscilloscope or vector signal analyzer). The software is also able to calculate the EVM uncertainty. The developed compression algorithm mentioned above has been proven to be suitable for complex communications signals. The software is available free of charge.

The accuracy of one commercial software package for the analysis of digital signals was studied using artificial signals with calculable EVM. This general method provides users of different commercial vector signal analysis software with the measurement uncertainty information.

Actual and potential impact

Dissemination activities

The project outputs have been disseminated widely to the academic and industrial communities:

- Project members gave 53 presentations at national and international conferences, 9 peers-reviewed journal papers and two trade journal papers were submitted and 16 training activities were undertaken.
- Project members gave plenary talks at the International Conference on Infrared, Millimeter and Terahertz Waves 2013 (Thomas Kleine-Ostmann, "THz metrology") and Conference on Precision Electromagnetic Measurements 2014 (Mark Bieler, "The femtosecond laser as a microwave instrument").
- Project members received the CPEM 2012 Early Career Programme Award (Martin Hudlicka, CMI) and the 3rd place of the Student award at the IRMMW-THz Conference 2012 (Heiko Füser, PTB).
- A workshop at European Microwave Conference 2013 (Do You Have Confidence in Your RF Waveforms? Developments in Waveform Metrology and Uncertainty Propagation for RF and Digital Signals) has been organized. Additionally a workshop on Digital Signals has been organized.
- Links to two international (IEC TC 85, IEEE 802.15) and three national (DKE/UK 767.4, DKE/K964, VDI/VDE-GMA FA 8.17) standards committees have been established. Members of the project contributed to a new standard on the calculation of waveform parameter uncertainties (IEC TC 85, WG22).This new standard is expected to be made public in 2015 and is applicable to all industries that generate, transmit, detect, receive, measure and/or analyse step- and impulse-like waveforms.
- Seven user guides have been written, which will be disseminated to users at industry, calibration laboratories and National Metrology Institutes.

Uptake

So far, there have been five uptakes of the software packages developed in this project, including global NMIs and businesses in the US, Argentina and New Zealand, as well as companies in Europe. Maintenance of the software has continued since the end of the project and is publically available. The software and algorithms developed have also been used in another EMRP project, EMRP JRP IND51 "Metrology for optical and RF communication systems".

New and enhanced calibration services are likely to be established at the NMI level and will include ultrafast waveform measurements and measurements of digital signals.

Commercial calibration laboratories are also expected to uptake some of the results and offer new services, such as the traceable calibration of vector signal generators and analysers for wireless communications. Some of the project results have already been shared with two commercial calibration laboratories. Project partner Agilent UK (now Keysight Technologies, with headquarters located in Santa Clara, USA) are one of the leading-edge manufacturers of Signal Analysers, Signal Generators and Conformance Test Solutions for the wireless communication industry. Both the commercial calibration laboratories and Keysight Technologies have already expressed the project results as very helpful for their future work, but further uptake is expected to require additional cooperation between NMIs and industrial partners.

So far, NMIs have been the main users of the user guides developed in the project. However, depending on possible industry uptake, commercial calibration laboratories are also expected to employ these guides.

The application of the uncertainty propagation software for different projects suggests that impact can also be achieved in other fields such as spectroscopy at terahertz (THz) frequencies. The application of covariance compression and data alignment to THz time-domain spectroscopy (THz-TDS) has the objective of improving calibration dissemination. The improvement of the measurement uncertainties of the THz-TDS from 11% to 0.15% overcomes a long-standing problem and suggests that the algorithms developed in this project may have wider application.

Intermediate impacts and contribution to wider and longer-term socio-economic and policy impacts

While prediction of future trends with confidence is difficult, new communications systems will use higher-frequency spectrum and will benefit from the project work. The development of advanced optical communication modulation formats and the increasing use of non-linear RF measurements to improve electrical efficiency are all dependent on high-speed electrical waveform metrology that is underpinned by the work presented here. Results of the research project will impact on various different areas of modern life; and while the major impact will be economic, there will also be environmental and social impacts.

The improved methods for characterisation of high-frequency measurement instrumentation directly increase the level of confidence in their design and fabrication processes because various quantities can be measured with smaller uncertainties. Engineers can then design more advanced and competitive products in the area of ultrafast communications. This includes, but is not limited to, ultrafast sampling oscilloscopes and vector signal analysers and generators.

The project results may also reduce costs of last mile deployment using wireless communication links. Such communication links at frequencies beyond those in use for communication applications today will have to rely on very different techniques; and some of the problems encountered with new communication links have been highlighted through this work.

In the environmental and health sector, the project will help to decrease transmitted power: In order to reduce energy consumption, microwave and integrated circuits are nowadays driven beyond their linear mode of operation. This requires the exact characterisation of the time or frequency behaviour of these circuits and corresponding measurement techniques have been developed in this project.

Society may also benefit from the project as the project outputs will help to ensure availability of information at any place and at any time. Wireless communication systems use a variety of advanced modulation and coding techniques in order to increase the data rates and to make links more reliable and robust. The traceable characterisation of corresponding measurement devices has been studied in this project.

List of publications

Martin Hudlička, “Metrology of digitally modulated signals”, Metrologie, Vol.21, 2012, pp. 11-15.

D. Humphreys, M. Akmal, “Channel timebase errors for Digital Sampling Oscilloscopes”, Digest on Conference on Precision Electrical Measurements 2012, DOI: 10.1109/CPEM.2012.6251032 pp. 520 – 521.

P.D. Hale, D.F. Williams, A. Dienstfrey, J. Wang, J. Jargon, D.A. Humphreys, M. Harper, H. Füser, M. Bieler, “Traceability of high-speed electrical waveforms at NIST, NPL, and PTB”, Digest of Conference on Precision Electrical Measurements 2012, DOI: 10.1109/CPEM.2012.6251033 pp. 522 – 523.

D. Humphreys, J. Miall, “Traceable measurement of source and receiver EVM using a Real-Time Oscilloscope”, Digest of Conference on Precision Electrical Measurements 2012 DOI: 10.1109/CPEM. 2012.6250685, pp. 110 – 111.

M. Hudlicka, C. Jastrow, T. Schrader, T. Kleine-Ostmann, " Waveform metrology for error vector magnitude measurements in a 300 GHz transmission system", Digest of Conference on Precision Electrical Measurements 2012, DOI: 10.1109/CPEM.2012.6251035, pp. 526 – 527.

Wei Tian, D. Allal, G. Boudebs, M. Charles, O. Ndiaye, P. Vincent, "Development of an electro-optic sampling system at LNE", Digest of Conference on Precision Electrical Measurements 2012, DOI: 10.1109/CPEM.2012.6251099, pp. 654 – 655.

David Humphreys and James Miall, "Traceable Measurement of Source and Receiver EVM using a Real-Time Oscilloscope", IEEE Trans Instrumentation and Measurement, No. 62, Vol. 6, 2013 pp. 1413-1416.

D.A. Humphreys, P.M. Harris, J.M. Miall, "Instrument related structure in covariance matrices used for uncertainty propagation", Proceedings of the 42nd European Microwave Conference, Nov. 2012, pp. 1304 – 1307.

Martin Hudlicka, Mohammed Salhi, D.A. Humphreys, "Towards Metrological Characterization of Vector Signal Analyzers", Proceedings of the 42nd European Microwave Conference, Nov. 2012, pp. 558 – 561.

M. Bieler and H. Füser, "Realization of an ultra-broadband voltage pulse standard utilizing time-domain optoelectronic techniques," in *Proc. SPIE 8624, Terahertz, RF, Millimeter, and Submillimeter-Wave Technology and Applications VI*, 2013, pp. 862417.

H. Füser and M. Bieler, "Frequency, amplitude, and phase measurements of GHz and THz sources using unstabilized THz frequency combs," in *Proc. SPIE 8624, Terahertz, RF, Millimeter, and Submillimeter-Wave Technology and Applications VI*, 2013, pp. 86240T.

Thomas Kleine-Ostmann, "THz metrology", Digest of 38th International Conference on Infrared, Millimeter, and Terahertz Waves (IRMMW-THz), Sep. 1-6, 2013, DOI 10.1109/IRMMW-THz.2013.6665913.

M. Salhi, T. Kleine-Ostmann, and T. Schrader, "Design and characterization of 4×4-phased-array patch antennas at 77 GHz and 94 GHz", Digest of 38th International Conference on Infrared, Millimeter, and Terahertz Waves (IRMMW-THz), Sep. 1-6, 2013, DOI 10.1109/IRMMW-THz.2013.6665641.

T. Kleine-Ostmann, M. Salhi, M. Kannicht, S. Priebe, T. Kürner, and T. Schrader, "Broadband Channel Measurements between 50 GHz and 325 GHz: Comparison of Different Propagation Scenarios", Digest of 38th International Conference on Infrared, Millimeter, and Terahertz Waves (IRMMW-THz), 2013 DOI 10.1109/IRMMW-THz.2013.6665493.

Mohammed Salhi, Carolin Peiss, Michael Botschka, Thomas Kleine-Ostmann, and Thorsten Schrader, "Characterization of 4x4 Planar Antenna Arrays for the Frequencies 77 GHz and 94 GHz Using an Antenna Scanning System", Asia-Pacific Microwave Conference Proceedings (APMC), 5-8 Nov. 2013, pp.1106 – 1108, DOI 10.1109/APMC.2013.6695036.

M. Salhi; T. Kleine-Ostmann, M. Kannicht, S. Priebe, T. Kürner; T. Schrader, "Broadband channel propagation measurements on millimeter and sub-millimeter waves in a desktop download scenario", Asia Pacific Microwave Conference Proceedings (APMC), 5-8 Nov. 2013, pp. 1109 – 1111, DOI: 10.1109/APMC.2013.6695037.

Heiko Füser and Mark Bieler, "THz frequency combs", Journal of Infrared, Millimeter, and Terahertz Waves, vol. 35, pp. 585–609, 2014, DOI: 10.1007/s10762-013-0038-8.

David Humphreys, Peter Harris, Faisal Mubarak, Dongsheng Zhao, Manuel Rodríguez-Higuero and Kari Ojasalo, "Principal Component Analysis Compression Method for Covariance Matrices used for Uncertainty Propagation", IEEE Trans Instrumentation and Measurement, submitted Jan 2014, available (early access) at http://ieeexplore.ieee.org/Xplore/home.jsp.

M. Hudlicka, D. A. Humphreys, F. Mubarak, M. Salhi, "How to characterize vector response of future broadband instrumentation, Microwave Engineering Europe, February 2014, online issue, available at http://www.tm-eetimes.com/en/how-to-characterize-vector-response-of-future-broadband-instrumentation.html?cmp_id=71&news_id=222918833.

Martin Hudlička, David A. Humphreys, Mohammed Salhi and Faisal A. Mubarak, "Characterise vector response of broadband instruments", EE Times-Asia, Download available at http://www.eetasia.com/STATIC/PDF/201403/EEOL_2014MAR18_TEST_NET_TA_01.pdf?SOURCES=DOWNLOAD.

M. Hudlicka, M. A. Salhi, T. Kleine-Ostmann, T. Schrader, “Characterization of a 300 GHz Transmission System for Digital Communications”, IEEE Trans. on Terahertz Science and Technology, submitted in April 2014.

Kari Ojasalo, Martin Hudlicka and David A. Humphreys, “Uncertainty of communication signals measurement”, Digest of Conference on Precision Electrical Measurements 2014, 24th August 2014, pp. 338 – 339.

David A. Humphreys, Martin Hudlicka, and Irshaad Fatadin, “Calibration of Wideband Digital Real-time Oscilloscopes”, Digest of Conference on Precision Electrical Measurements 2014, 24th August 2014, pp. 698 – 699.

David A Humphreys and Mira Naftaly, “Dynamic range improvement of THz spectroscopy”, Digest of Conference on Precision Electrical Measurements 2014, 24th August 2014, pp. 704 – 705.

David Humphreys, Mira Naftaly, John Molloy, “Effect of Time-Delay Errors on THz Spectroscopy Dynamic Range” Digest of 39th Int. Conf. on Infrared, Millimeter, and THz Waves , September 2014, digest details not yet available.

David A. Humphreys, Martin Hudlicka, and Irshaad Fatadin, “Calibration of Wideband Digital Real-time Oscilloscopes”, IEEE transactions on Instrumentation and Measurement, submitted in Aug. 2014.

Y. Deng, H. Füser, and M. Bieler, “Absolute intensity measurements of cw GHz and THz radiation using electro-optic sampling”, IEEE transactions on instrumentation and measurement, submitted in Aug. 2014.

M. Salhi, T. Kleine-Ostmann, G. Gentille, M. Spirito, and T. Schrader, “Planar Millimeter Wave Patch Antenna Arrays at 77 GHz and 94 GHz for Metrological Investigations”, IEEE Transactions on Antennas and Propagation, submitted Sept. 2014.

H. Füser, M. Bieler, S. Ahmed, and F. Verbeyst, "Asynchronous electro-optic sampling of all-electronically generated ultrashort voltage pulses", Measurement, Science and Technology , submitted Sept. 2014.

M. Salhi, T. Kleine-Ostmann, and T. Schrader, “Antenna Characterization and Channel Measurements in the mm and Sub-mm Wave Region”, Microwave Journal, submitted Oct. 2014.

David Humphreys, Mira Naftaly, John Molloy, “Dynamic range improvement of THz spectroscopy by digital signal processing and covariance analysis”, to be submitted to IEEE Trans. Terahertz Science and Technology.

David Humphreys, Peter Harris, Faisal Mubarak, Dongsheng Zhao, Manuel Rodríguez-Higuero and Kari Ojasalo, “Do you have confidence in your RF waveforms?", to be submitted to Microwave Journal.

D. Allal, Y. Le Sage, A. Litwin, J.M. Lerat, “Cable effect correction for millimeter wave far-field radiation pattern measurements”, to be submitted to Progress In Electromagnetics Research Letters.

M. Salhi, T. Kleine-Ostmann, and T. Schrader, “Broadband millimeter wave propagation measurements in indoor scenarios for future THz communication systems“, to be submitted to IEEE Transactions on Antennas and Propagation.

M. Salhi, T. Granz, S. Rey, T. Kürner, T. Kleine-Ostmann, and T. Schrader, “Investigations on error vector magnitude for different modulation schemes in a 300 GHz transmission link”, to be submitted to IEEE Transactions on Instrumentation and Measurement.

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JRP-Coordinator: Mark Bieler, Dr, PTB Tel: +49-531-592-2540 E-mail: mark.bieler@ptb.de JRP website address: http://www.ptb.de/emrp/ultrafast.html	
JRP-Partners: JRP-Partner 1 PTB, Germany JRP-Partner 2 CMI, Czech Republic JRP-Partner 3 INTA, Spain JRP-Partner 4 LNE, France	JRP-Partner 5 MIKES, Finland JRP-Partner 6 NPL, United Kingdom JRP-Partner 7 VSL, Netherlands JRP-Partner 8 Agilent UK, United Kingdom
REG1-Researcher (associated Home Organisation)	Sajjad Ahmed, NIBNV, Belgium
REG2-Researcher (associated Home Organisation)	Gennaro Gentile, TU Delft, Netherlands

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