Final Publishable JRP Summary for JRP SIB62 HFCircuits
Metrology for new electrical measurement quantities in high-frequency circuits

Overview

Industrial electronics that operate in the high-frequency range (radio frequency, microwave and millimetre-wave) require traceable measurements to support their development. The lack of measurement techniques and intsrumentation can prevent their use in a wide variety of applications such as next-generation communications, health-care monitoring, security and climate change monitoring. This project developed an extensive range of measuring services that have enabled electronics manufacturers and instrument manufacturers to demonstrate traceability to the SI for their measurements, and enabled them to justify and defend performance indicators such as product specifications. These outcomes have benefitted all sectors of the high-frequency electrical and electronics industries, and major contributions have also been made to a European guidance documents (e.g. EURAMET Calibration Guide cg-12, 2007) and international standards such as IEEE Std 287-2007, IEEE Std 1785.2-2016 and IEEE Std 1785.3-2016.

Need for the project

In recent years, high-frequency instrumentation has expanded in medical and security scanners, and transceivers (i.e. transmitters and/or receivers) for consumer electronics and environmental monitoring. It includes millimetre and submillimetre wave electronic components, high-speed digital printed circuit boards (PCBs), and waveguides and coaxial cables (used for connecting electronic components).

The requirements of these cutting-edge, high-frequency industrial electronics applications have driven test equipment manufacturers to develop new types of instrumentation. However, these new classes of instruments for measuring new properties or different aspects of existing properties, fell outside the traceability previously supported by European and other National Metrology Institutes (NMIs). As a result, end-user requirements for calibration and traceability to SI units are not being met. This has a detrimental effect on trading and the supply chain as they need to confirm the performance of the product against a specifiation anad give confidnece that it is performing as expected. To address this, new measurement methods with well characterised uncertainties are needed.

In addition, specialist calibration techniques are needed to achieve the necessary level of testing accuracy for component test set-ups including multiple simultaneous connections to electronic components (i.e. multi-port network analysers). There is also a lack of specialist measurement set-ups for the accurate characterisation of high power/large-signal devices, such as transistors used in communications transceivers (i.e. base stations), and new nano-electronic devices (based on carbon-nano-tubes).

Finally, the EURAMET Guide that impacts this sector of industry needed comprehensively revising in order to bring it up-to-date with current end-user requirements. This was driven by the need to improve uncertainties and to bring measurements in line with the “Guide to the Expression of Uncertainty in Measurement“ (GUM). Revised or new Institute of Electrical and Electronics Engineers (IEEE) standards for high-frequency (i.e. millimetre and submillimetre wavelength) waveguides and precision coaxial connectors were also needed.

Scientific and technical objectives

The project addressed the following scientific and technical objectives:

1. Traceability and verification for millimetre-wave and submillimetre-wave electronics and electromagnetics in coaxial line (to 110 GHz) and waveguide (to 1.1 THz);

2. Traceability and verification techniques for multi-port device configurations including the use of electronic calibration units (ECUs) for vector network analysers (VNAs);
3. Traceability and verification techniques for high-speed digital PCBs for Signal Integrity applications, including differential transmission lines;
4. Traceability and verification techniques for large-signal/non-linear device characterisation (e.g. high-power transistors and power amplifiers) and nano-scale devices (e.g. carbon-nano-tubes, graphene-related electronics and organic macromolecules);
5. Input to a revised version of the EURAMET Guide; the development of IEEE standard P1785; and the revision of IEEE standard P287. Input will also be made to a third IEEE standard-making activity (via a Special Interest Group), in the area of defining nonlinear measurement quantities.

Objectives 1 and 3 concentrated on the general requirements for high-frequencey electronics. Objective 2 was specifc to multiple simultaneous connections. Objective 4 concentrated on high power/large signal devices and nano devices. The final objective looked at the practicalities of how to carry out tests and ensure they are standardised. This included developing a revision of the EURAMET Guide cg-12 to bring these measurements in line with the GUM.

Results

Traceability and verification for millimetre-wave and submillimetre-wave electronics and electromagnetics in coaxial line (to 110 GHz) and waveguide (to 1.1 THz)

Significant extensions to high-frequency measurement traceability capabilities have been achieved:

- coaxial line traceability in the 1.85 mm connector type (that operates at frequencies up to at least 65 GHz)
- traceability in the 1 mm connector type (that operates at frequencies up to at least 110 GHz)
- traceable measurements on rectangular waveguides, in the 110 GHz to 170 GHz band
- traceable measurements in both the millimetre- and submillimetre-wave bands (140 GHz to 220 GHz, 220 GHz to 325 GHz, 750 GHz to 1.1 THz)

In both coaxial lines and waveguides, the measurements have been for one- and two-port devices, providing reflection and transmission coefficients. These are state-of-the-art capabilities that put Europe at the forefront of millimetre- and submillimetre-wave metrology and will ensure traceability for the new technologies being developed by instrument manufacturers, such as developments in 5G mobile communications. This is important because it will ensure reliable measurements are now available to underpin test specifications of products and services in this area of technology. These measurements were not previously available because the required test equipment and reference standards were not available. New products operating at these very high-frequencies can now be tested using traceable measurement systems. This will ensure that tests made by different companies can be demonstrated as equivalent. This ensures the integrity of product specifications in the supplier-customer chain.

Traceability and verification techniques for multi-port device configurations including the use of ECUs for VNAs

VNAs are widely used in industry for characterising the electrical performance of circuits and electronic components, and ECUs enable rapid, automatic and accurate calibration of these analysers. ECUs are used extensively by European calibration and test facilities for routine calibration of VNAs.

Multi-port devices include integrated circuits and microprocessors as used in the computer industry. These devices need to be accurately characterised prior to use in electronic circuits and therefore reliable multi-port VNA calibrations are vital for their accurate characterisation.

A series of comparisons were undertaken for multi-port network analyser calibration techniques between: (i) 4-port calibrations and multiple 2-port calibrations (i.e quick calibrations); and (ii) full 4-port calibrations. The so-called ‘quick’ calibrations are often used in industry to save time but they can potentially result in a loss of accuracy. The results showed that all types of calibration gave acceptable results for most end-user applications, however, for high accuracy work, the full 4-port calibration technique was the preferred and most accurate option. The choice of calibration routine is critical in achieving traceability for multi-port devices and so the project's comparisons have verified this traceability route.

Methods for monitoring the operational status of ECUs were developed and, using these, data was gathered for verifying the operational stability of ECUs over short time periods (minutes and hours), and, over long time periods (months and years). This data has been used to improve overall knowledge of the operational performance of ECUs for VNAs. This new knowledge will make a significant impact on the end-user community by informing them how often their ECUs need to be re-calibrated.

Traceability and verification techniques for high-speed digital PCBs for signal integrity applications, including differential transmission lines

Designs for a range of different types of calibration standards for high-speed digital PCBs were developed and the effects of different signal path lengths on electrical signals travelling simultaneously along PCB dual conductor lines were investigated. Asymmetries in signal path lengths can cause distortions in the transmitted signals.

A new reference standard PCB including striplines was designed and fabricated to provide a way for end-users to verify signal integrity applications, including the use of differential transmission lines. The reference PCBs have also enabled bespoke calibration techniques to be developed so that end-users can directly characterise components mounted on the surface of PCBs.

Traceability and verification techniques for large-signal / non-linear device characterisation (e.g. high-power transistors and power amplifiers) and nano-scale devices (e.g. carbon-nano-tubes, graphene-related electronics and organic macromolecules)

Large Signal Network Analysers (LSNA) and Nonlinear Vector Network Analysers (NVNA) are used for characterising transistors found in mobile phones and base stations. Two reference devices were developed, fabricated and tested for use by industry and academia for verifying their performance.The new large-signal reference device outperformed previous designs. Long term tests have also demonstrated good stability for the device over significant time periods of up to several weeks. This means that a characterisation of the large-signal reference device remains useable over these longer periods of time and therefore end-users do not need to spend time re-characterising the reference device, which is a time consuming process

Existing commercially available impedance standards are often not suitable for making measurements at the nano scale because the values of the impedances that need to be measured are often very different from the values of existing impedance standards. A range of extreme impedance standards suitable for both calibration and verification of nano-scale devices were designed, fabricated and characterised. These standards can be used to calibrate a measurement system (such as a network analyser) so that it is optimised for measurements of devices with intrinsic impedance values much greater than the usual reference impedance of 50 ohms. This is particularly relevant to carbon-based devices (e.g. devices containing carbon nano-tubes and/or graphene) that can be used in high-frequency electronics applications such as resistors, capacitors and transistors. The extreme impedance standards were subsequently tested using a conventional network analyser, which demonstrated the versatility of these extreme impedance standards over a wide range of operating conditions.

Input to European and International industry-level documentation

A report was submitted to the IEEE 287 standard Working Group, which summarised the investigations undertaken and findings of this project into performance characteristics of precision coaxial connectors. The report will be incorporated into the on-going revision that is taking place of the IEEE 287 standard, the global 'industry' reference for connectors of this type.

A document providing performance indications for waveguide devices operating to 1100 GHz was submitted to the IEEE P1785 standard Working Group. This has contributed to two of the three new IEEE standards that this Working Group has developed and published, i.e. IEEE Std 1785.2-2016 “Waveguide Interfaces” and IEEE Std 1785.3-2016 “Uncertainty Specifications”.

The “EURAMET Guidelines on the Evaluation of VNA” document Guide cg-12 has been fully revised by the project and submitted to EURAMET.

Actual and potential impact

The project successfully developed and introduced new, applied measurement traceability and assurance techniques to enable the exploitation of new instrumentation capabilities that have been developed by manufacturers of test equipment. This will support the new product development of European electronics companies by ensuring test equipment has been proven independently via the technical outcomes from this project.

The project had a number of uptakes:

- New measurement services which extend the upper frequency range of NMI traceability in coaxial lines to 110 GHz and waveguides to 1.1 THz. These will ensure traceability for new technologies being developed by instrument manufacturers such as developments in communications e.g. 5G.
- Several NMIs have extended their calibration capabilities to include multi-port measurements and methods for using ECUs with VNAs.
- NPL is now evaluating whether a customer calibration service for users of ECUs should be introduced based on the work achieved in this project. At the present time, there are no other NMIs offering such a service.
- The project developed a reference PCB to act as a verification device for the end-user community and to enable bespoke calibration techniques so that users can directly characterise components mounted on the surface of the PCBs.
- LA Techniques Ltd, a UK SME, has been an early user of the project’s work on PCBs, using it to verify their technique for establishing calibrations directly at the connection points for devices mounted on PCBs.
- A large-signal reference device has been developed for the verification of measurement systems, such as NVNAs and LSNAs, which are used for characterising transistors found in mobile phones and base stations. The project established measurement capability for nonlinear measurements and measurements that exceed the conventional reference impedance of 50 ohms – i.e. extreme impedance measurements.
- It is planned to use the large-signal reference device developed in the project in the follow-on EMPIR project 14IND10, MET5G and by measurement companies such as project partner Keysight BE). The device will be used as a travelling standard during a round robin measurement comparison exercise.
- Keysight BE and R&S had components and test equipment included in the investigations in the project. This has effectively benchmarked the performance of their systems, in particular their VNAs. This provides useful, independent, evaluation of these components and equipment within the context of this project.

Dissemination

In addition, dissemination activities by the project have ensured that links to the end-user community have been strengthened by providing:

- Three training courses, for end users, on: (i) “Good Practice with VNAs”, at VSL, The Netherlands, in June 2014; (ii) “Multiport VNA Measurements”, at METAS, Switzerland, in June 2015; (iii) “Revision of EURAMET VNA Guide cg-12', at NPL, UK, in June 2016. All three courses involved project’s partners as instructors and each course was attended by approximately 40 participants.
- Three workshops, for end users, on: (i) “Electronic Calibration Units”, (ii) “Plans and Considerations for the Upcoming Revision of the EURAMET VNA Calibration Guide” and (iii) “Uncertainties for VNA Measurements”.

- Six European ANAMET technical seminars featuring presentations describing the technical outputs from the project were held concurrently with the training courses and workshops.
- 91 presentations at international scientific conferences and the publishing of 52 scientific papers, including contributing to a chapter in a new book on the subject of terahertz metrology.
- Regular six-monthly teleconferences with the project's Stakeholder Advisory Group (SAG); a group of 6 international experts in the project's scientific areas.
- A project web-site (www.hfcircuits.org) for end-users, and a LinkedIn Discussion Group.

Standards

Developing guides and standards has benefited electronics manufacturers and instrument makers by standardising equipment and methods used by the end-users. Two new international standards (IEEE Std 1785.2-2016 and IEEE Std 1785.3-2016) have been published which contain significant input from the project. These standards were developed in a timely manner and contain information which is useful to industry and the end-user community.

A Calibration Guide (EURAMET cg-12) has been submitted to EURAMET. The Euramet Guidelines are important because they provide a common method for evaluating the performance of VNAs that can be used by both end-users and international accreditation bodies.

Potential impact

The new measurement traceability and verification techniques that have been developed by the project will enable test equipment manufacturers and electronic component manufacturers to establish new products with much greater confidence. This includes verifying the credibility of new products and establishing protocols and procedures that can be universally understood and adopted.

List of publications

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SIB62 HFCircuits

JRP start date and duration:	01 June 2013; 3 years
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The EMRP is jointly funded by the EMRP participating countries within EURAMET and the European Union