Publishable Summary for 15RPT01 RFMicrowave
Development of RF and microwave metrology capability

Overview

The radio frequency and microwave (RF&MW) field has undergone revolutionary changes in the last 40 years and today, RF&MW technology is more pervasive than ever. This is especially true for commercial markets, where modern applications include cellular and smart phones, wireless networking, direct broadcast satellite, television, global positioning systems, wideband radio and radar systems, and microwave remote sensing systems for environment, biomedical and healthcare applications (to name but a few). This project aims to develop research and measurement capacities as well as expertise for emerging EURAMET countries in RF&MW. It will do this by transferring theoretical and practical know-how between the project partners and by combining their skills to focus on microwave and electromagnetic compatibility (EMC) measurements. The outcomes of this project will be vital for reducing the gap between the European countries in terms of metrological capabilities in radio frequency (100 kHz – 300 MHz) and microwave frequency (300 MHz – 300 GHz).

Need

New technologies in the health, energy, security, environmental, industrial and communication sectors require novel RF&MW devices and measurement methods which currently are under research and development (R&D). However, this R&D brings new challenges to the underpinning metrology for RF&MW as it requires advanced technologies.

Scattering parameter (S-parameter) measurements, RF power measurements, EMC tests and calibrations are important areas in RF&MW metrology. These are used to ensure and increase product quality and end user confidence. The reliability of S-parameter measurements depends on how well the characterisation and modelling of RF&MW components is performed, therefore, the devices used for this need to be calibrated accurately and their measurement uncertainty must be calculated precisely. However recent R&D has shown that the simplified characterisation and modelling approach that is currently used for RF&MW components is inadequate.

Most high frequency electronic devices include short distance communication units which generate low-power ($P \leq 0.01$ mW). In order to obtain traceable and accurate measurements at low-power in RF&MW metrology, power sensors which are used for low-power measurements must be characterised accurately. Due to the difficulty of characterising harmonic effects, some less developed NMIs ignore the effect of higher harmonics in low-power measurements and they are not able to characterise power sensors for low-power. There is also a problem with RF&MW high-power measurements ($P \geq 1$ W) used in long distance communication, broadcasting radar applications and other applications. Characterisation of high-power measurement equipment such as wattmeters is generally performed using an 'attenuator and power sensor' combination in which both are calibrated at mid-power level (0.01 mW $< P < 1$ W). The characterisation parameters of the attenuator and power sensor should be at the same power levels, however, this assumption does not describe the actual situation.

EMC is the interaction of electrical and electronic equipment with the electromagnetic environment, and other equipment. In order to avoid EMC related issues electronic goods manufacturers must test their products that are electromagnetically compatible with relevant regulations. However, new verification methods are needed to increase the quality of EMC test/calibration and measurements, in particular advanced verification methods using vector network analysers (VNAs). Knowledge transfer between EMC and RF&MW laboratories is very weak, which reduces awareness in measurements/calibrations and, therefore the overall quality of both EMC and RF&MW measurements.

The gap between developed and currently developing countries is growing constantly and this situation is even more pronounced for RF&MW metrology. In order to prevent further widening of this gap in RF&MW

metrology, the knowledge and expertise of the more developed NMIs needs to be transferred to those NMIs with less experience.

Objectives

The overall objective of this project is to improve the European measurement and research capability for RF&MW metrology and to establish a basis for future cooperation between European NMIs. This will enable less developed European NMIs to build necessary research capacity, as well as improving their calibration and measurement capabilities (CMCs) and reducing the increasing technological gap between NMIs. The specific objectives of the project are to:

1. **Improve S-parameter measurements with lower uncertainty and to develop/enhance impedance and S-parameters traceability across Europe** by improving the measurement and research capacities of NMI partners and bringing them to level to be able to adequately support the needs of their stakeholders. The primary traceability and uncertainty budget for the S-parameter measurements will be established through calculable calibration standards with the use of specialised software tools.
2. **Improve the reliability and precision of RF power measurements under low and high-power conditions**, power sensor measurements for low-power as well as to investigate the effects of higher harmonics in the response of power sensors to cover the stakeholder needs. Also to provide the NMI partners the ability to measure and determine output reflection coefficients of signal generators via knowledge transfer.
3. **Investigate advanced calibration methods and established test procedures for EMC** with use of RF&MW metrology. EMC calibration methods will be improved for traceability of loop antennas and pulse generators and existing verification methods will also be improved for EMC immunity/emissions by using advanced RF&MW metrology methods and VNAs. Therefore, an efficient knowledge link will be established between EMC and RF&MW experts across Europe.
4. **Develop an individual strategy for each partner for long-term operation of capacity development**, including regulatory support, research collaborations, quality schemes and accreditation. Each partner will also develop a strategy to offer calibration services in their own country and in neighbouring countries. The individual strategies will be discussed within the consortium and with other EURAMET NMIs/DIs to ensure that a coordinated and optimised approach to the development of traceability in RF&MW metrology is developed for Europe as a whole.
5. **Identify key industrial and scientific needs for stakeholders in RF&MW metrology**. At the beginning of this project, a survey on stakeholders' needs will be conducted for these purposes. The results of this survey will be instrumental to maximise the impact of this project within the European community of NMIs and industrial end-users via knowledge transfer, training and dissemination for this purpose, meetings, hands-on training sessions, technical papers and best practice guides will be prepared.

Progress beyond the state of the art

This project will support modelling of calibration standards for S-parameters and rigorous uncertainty propagation through a measurement model that represents the entire measurement process from the calibration of the VNA to the result of the Device under Test (DUT). Advances in modelling and new software capabilities (VNA Tools II developed by METAS) have prepared the path to this more consistent approach that the project will use, and should provide better agreement with internationally accepted guidelines. METAS has transferred their knowledge and experience to the partners TUBITAK, CMI, SIQ, INTA, RISE, NIS and NQIS, as part of a training course and workshops on characterisation calculable primary calibration standards and specialised software tools (VNA Tools II). The partners now have improved their characterisation of calculable calibration standards and their S-parameter measurement abilities using this knowledge transfer. TUBITAK, CMI, SIQ, INTA, RISE, NIS and NQIS are currently in the process of comparisons on calculable primary calibration standards and S-parameter measurements for one-, two- and three- port devices with the help of VNA Tools II.

The project will also address the traceability with respect to the calibration of power sensors for low-power at partners GUM, SIQ, NQIS, NIS and INTA. The traceability approach will be based on the experience of

TUBITAK and CMI and will use characterised adapters and attenuators. So far, TUBITAK and CMI have established their own measurement setups and performed preliminary measurements regarding characterisation of diode sensors used for low power measurements. In addition to this, SIQ, INTA and CMI have produced and exchanged information about their proposed measurement setups and measurement techniques for the characterisation of 'attenuator and power sensor' combination in small- as well as under large-signal conditions. Moreover, SIQ, INTA, NIS, TUBITAK and CMI produced and distributed information about harmonics effects on power measurements using low-power diode sensors and equivalent circuits. NQIS, INTA and TUBITAK have also established their own setups for the measurement of the output voltage reflection coefficient (VRC) of a microwave generator. Three comparisons on (1) the calibration of diode type power sensors, (2) the output VRC of a microwave generator and (3) the characterisation of a high power attenuator have been organised for the implementation and enhancement of the gained information.

The strength of RF&MW and VNA metrology will be used by this project to increase the quality of EMC test/calibration and measurements, e.g., 'just-before-test' verification methods using VNAs have been already developed in the project. Such 'just-before-test' verification methods will be able to efficiently detect insidious issues just before conducting emission and immunity tests and thereby significantly increase the quality of EMC measurements. These new and effective just-before-test verification methods developed in the project have also been expanded to low frequency immunity testing by means of the Fast Fourier Transform (FFT)-based time domain methodology, which has been never done before. Furthermore, the extensive investigation of the three loop-antenna calibration method has been experimentally finalised by performing standard SAE-ARP950&IEEE calibration methods and comparing their results with the three antenna method. The project will also transfer knowledge and awareness from the EMC field to the RF&MW field and vice-versa. Consequently, this knowledge link between the two fields will support an increase in the quality of metrology and help to fill existing knowledge gaps with the joint research effort of TUBITAK, RISE, UPC and SIQ.

Results

Improve S-parameter measurements with lower uncertainty and to develop/enhance impedance and S-parameters traceability across Europe

In order to increase S parameter measurement accuracy among the project partners, primary traceability and uncertainty budget for the S-parameter measurements will be established through calculable calibration standards with use of specialised software tools. The project will also establish new measurement software for the project partners CMI, GUM, INTA, SIQ, RISE, NIS, NQIS and TUBITAK who regularly perform S-parameters measurements.

A training and two workshops activities were organised, in which, the partners CMI, INTA, SIQ, RISE, NIS, NQIS, GUM and TUBITAK learned from METAS how to use specialised software tools (VNA Tools II) to evaluate reliable VNA measurement uncertainties and applied their S-parameter measurement system. Partners have gained the ability for modelling of calibration standards for S-parameters and calculating rigorous uncertainty propagation through a measurement model and new software capabilities. To prove the acquired ability of the partners, two interlaboratory comparisons on S-parameter measurements of one-port, two-port and three-port standards and calculable primary calibration standards have been organised and completed and the results are currently being evaluated.

Improve the reliability and precision of RF power measurements under low and high-power conditions

To improve project partners' power measurement accuracy and capability on the characterisation of power sensors for low power measurement; this project will address the effects of higher harmonics on low power measurements; the measured VRC value of signal generators for power measurement; and the characterisation of high power attenuators for high power measurements, through training events, workshops and intercomparisons.

A workshop on the Monte Carlo (MC) method and training on characterising of diode-type power sensor has been organised. During the training, partners INTA, NQIS, GUM and NIS gained experience in characterising of diode-type power sensor using direct comparison technique and established own measurement setup. Technical protocols for three inter-laboratory comparisons have been circulated between partners and approved; (i) power sensor measurements for low-power (diode type power sensor), (ii) measurement of output VRC of a microwave generator and (iii) characterisation of a high power attenuator. These comparisons are currently ongoing.

A report about harmonics effects on power measurements using diode type power sensors has also been produced and equivalent circuits for diode-type power sensors were identified based on the findings from this report. NIS and TUBITAK have established known harmonics generating system and characterised their diode type power sensors with help of CMI.

Investigate advanced calibration methods and established test procedures for EMC

This project will attempt to integrate the strength of RF&MW metrology, specifically the use of VNAs, into EMC tests and calibrations. It will establish a link between the areas of RF&MW and EMC that does not only embrace the integration of RF&MW metrology into the EMC field but also promotes an efficient knowledge transfer/exchange between the two fields. Improved EMC test system verification using VNAs and just-before-tests, the effect of non-metallic objects on EMC test standards, and the traceable calibration of loop antenna using a VNA and pulse generator will also contribute to improving the EMC test and measurement capability of project partners.

The influences of a variety of support materials; styrofoam, moulding polyamide, wood in actual EMC tests were investigated and successfully finalised by means of loop impedance measurements with a VNA. Consequently, the effects of the used support materials on the test results along with a good link to the injected current, the loop impedance and the susceptibility of the equipment under test (EUT) were demonstrated. In addition to the investigation of the support material samples in actual EMC tests, S-parameters of the same samples at a high frequency, 2 GHz, were measured by using a WR 430 waveguide. Further to this, new and effective just-before-test verification methods that use a VNA were developed in order to be able to detect all issues, including the most insidious ones, with conducted emission and immunity test setups just before tests. This just-before-test verification research has been also expanded to low-frequency immunity tests to verify an entire low-frequency immunity test system. In this context, the project consortium have jointly integrated a FFT-based time domain solution into just-before-test verification methods in order to easily separate low-frequency voltage ripples from the AC power frequency of the EUT by means of a simple oscilloscope and a piece of FFT-based software, which has significantly simplified low-frequency testing and just-before-test verifications and made them more accurate under the adverse AC power supply frequency in comparison with the hardware filtering solutions. Finally, the three antenna calibration method for loop antennas was successfully implemented and effectively compared with the standard methods performed as per international standards such as IEEE291, SAE-ARP958. After the comparison measurements, the advantages of the three antenna method have been clearly set out and demonstrated in terms of lower uncertainty less than 1 dB and ease of use in comparison to standard methods.

Develop an individual strategy for each partner for long-term operation of capacity development

An individual strategy for each partner for long-term operation of capacity development, including regulatory support, research collaborations, quality schemes and accreditation will be produced. Partners are starting to produce their short and long term strategic reports.

Identify key industrial and scientific needs for stakeholders in RF&MW metrology

Stakeholders' needs will be identified by this project and so far a questionnaire to identify the RF&MW and EMC capabilities of emerging metrology institutes who are not part of this consortium and partners was prepared and distributed. The collected questionnaires have been analysed and the training needs of such NMIs for topics on RFMW and EMC have been determined. It is planned to organise the training for these topics in March 2019.

Impact

Impact on industrial and other user communities

At the end of this project, participating NMIs will gain the necessary knowledge and skills to provide 'new' or enhanced RF&MW measurements and services for their stakeholders. To ensure this, the participation of each partner in the project has been designed according to their and their stakeholders' particular needs. In addition, an individual strategy for each partner for long-term operation of capacity development, including regulatory support, research collaborations, quality schemes and accreditation will also be produced. To achieve the desired goal, 4 workshops and 5 training sessions have been completed on Monte Carlo methods, S-parameters traceability, traceable characterisation of pulse generators, characterisation of calculable primary standard, advanced modelling and rigorous uncertainty calculation using specialised

software, the calibration of diode type power sensors respectively, RF&MW calibrations of EMC devices, use of EMC components in EMC testing and probability pass or fail test. The new just-before-test low-frequency immunity verification & testing methods, which were developed in the project, have been put into service at TUBITAK and are currently being used in actual EMC tests. Also, the three loop-antenna calibration method thoroughly investigated in the project has started to be used in loop antenna calibrations at TUBITAK.

Impact on the metrology and scientific communities

In order to identify the needs of partners and emerging metrology institutes who are not part of this consortium on RF&MW and EMC capabilities, a questionnaire has been distributed and analysed. Further to these activities, there will be another 2 workshops and a training course for project partners, collaborators and emerging NMIs (outside of the consortium) as the project progresses.

The project partners have produced 1 peer-reviewed paper and 11 conference papers presented in the prestigious metrology and EMC conferences such as 6th Congreso Español de Metrología, EMC Europe 2017/2018, APEMC 2017/2018, IEEE EMC SIPI 2018 and CPEM 2018.

The project will also include 6 comparisons to disseminate knowledge and to establish and enhance the metrological performance of project partners. Six comparisons have already been started amongst partners on calculable primary calibration standards (TUBITAK, CMI and METAS), S-parameter measurements (SIQ, INTA, CMI, NQIS, NIS, RISE, GUM, TUBITAK and METAS), power sensor measurement for low-power (INTA, SIQ, NQIS, CMI, NIS, TUBITAK and GUM), measurement of output VRC of a microwave generator (INTA, SIQ, GUM, NQIS, TUBITAK, NIS and METAS), characterisation of a high power attenuator (SIQ, INTA and CMI) and traceable characterisation of pulse generator (SIQ, RISE, NQIS, TUBITAK, UPC and CMI).

Finally, the project will produce four best practice guides for stakeholders and end users, which will be available through project website. Three of the best practice guides will be related to power measurements on the calibration of power sensor for low-power measurements, high-power measurements and the harmonic effect on low-power measurements, and the fourth guide will be on the traceability of pulse measurement in EMC.

Impact on relevant standards

TUBITAK presented the project outline and “calibration needs of EMC laboratories and expectations from RF&Microwave laboratories” at the EURAMET TC-EM RFMW meeting in April 2017. The calibrations and comparisons requested by EMC laboratories were discussed during the meeting. Additionally, UPC presented work on novel time-domain EMI receivers.

Longer-term economic, social and environmental impacts

The project’s results will have an indirect social impact through the improved quality and safety of electronic devices. Everyday sources of RF electromagnetic fields are telecommunication devices, broadcasting antennas, microwave ovens and other white goods. High frequency electromagnetic waves affect the human body in different ways, therefore this project will enhance consumer protection with more reliably calibrated devices. The electromagnetic spectrum is also a limited natural resource which has been progressively occupied by rapidly developing wireless applications. The spectrum is currently too crowded to allow new uses of this resource and for this reason, electromagnetic interference is a serious issue in terms of economic and social aspects. Further to this, electromagnetic interference (EMI) radiated from incompatible devices can be considered as environmental pollution and can have environmental consequences. Non-ionising radiation, also known as “electro-smog” is also a sensitive topic and by enhancing the quality of EMC measurements the project will contribute to such health & safety issues in society.

Finally, by enabling European Laboratories to perform regular checks and to control the EMC performance of products more precisely and reliably (with the power of RF&MW and VNAs), the outputs of this project will prevent incorrect testing of devices, thereby making a positive financial impact on the European economy.

List of publications

[1]. O. Sen, S. Cakir, S. Acak, "More insight into conducted immunity tests and investigation of support influences", in *Proc. of the Asia-Pacific International Electromagnetic Compatibility (APEMC) Symposium*, Seoul, Korea, June 2017, pp. 124-126.

[2]. O. Sen, S. Cakir, "Loop antenna calibrations with Inclusion of vector network analyser and comparison between calibration methods", *2017 International Symposium on Electromagnetic Compatibility - EMC EUROPE*, Angers, France, 2017, pp. 1-6.

[3]. M. Azpurua, J. Oliva, M. Pous, F. Silva, "Fast and automated verification of multi-channel full time-domain EMI measurement systems", in *Proc. of the 2017 IEEE International Instrumentation and Measurement Technology Conference (I²MTC 2017)*, Torino, Italy, 22-25 May 2017, pp. 785-790.

[4]. M. A. Azpúrua, M. Pous, J. A. Oliva, B. Pinter, M. Hudlička and F. Silva, "Waveform Approach for Assessing Conformity of CISPR 16-1-1 Measuring Receivers," in *IEEE Transactions on Instrumentation and Measurement*, vol. 67, no. 5, May 2018, pp. 1187-1198.

[5]. M. Pous, M. A. Azpúrua and F. Silva, "APD oudoors time-domain measurements for impulsive noise characterization", *2017 International Symposium on Electromagnetic Compatibility - EMC EUROPE*, Angers, France, 2017, pp. 1-6.

[6]. M. A. Azpúrua, J. A. Oliva, M. Pous and F. Silva, "Robust extreme value estimation for full time-domain EMI measurements", *2017 International Symposium on Electromagnetic Compatibility - EMC EUROPE*, Angers, France, 2017, pp. 1-6.

[7]. S. Cakir, M. Oztürk, B. Tektas, O. Şen, S. Acak, M. Pous, "FFT-Based Time Domain Solution to Power Frequency Issue of CS101 Testing for Military and Aerospace Equipment," in *Proc. of the 2018 IEEE International Symposium on Electromagnetic Compatibility and 2018 IEEE Asia-Pacific Symposium on Electromagnetic Compatibility (EMC/APEMC)*, May 2018, Singapore, pp. 177-182.

Project start date and duration:	01 June 2016, 36 months	
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