FINAL PUBLISHABLE REPORT

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Internal Funded Partners: 1 TUBITAK, Turkey 2 CMI, Czech Republic 3 GUM, Poland 4 INTA, Spain 5 RISE Sweden 6 SIQ, Slovenia	External Funded Partners: 7 NIS, Egypt 8 NQIS, Greece 9 UPC, Spain	Unfunded Partners: 10 METAS, Switzerland

TABLE OF CONTENTS

1 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 aimed to develop research and measurement capacities as well as expertise for emerging EURAMET countries in RF&MW. It was achieved 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 have been 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).

2 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 has brought 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 are 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 in this project previously ignored the effect of higher harmonics in low-power measurements and they were not able to characterise power sensors for low-power. There was also a problem with RF&MW high-power measurements ($P \geq 1$ W) used in long-distance communication, broadcasting radar applications and other applications.

The characterisation of high-power measurement equipment such as wattmeters was 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 were needed to increase the quality of EMC test/calibration and measurements, in particular, advanced verification methods using vector network analysers (VNAs). Prior to the start of this project, knowledge transfer between EMC and RF&MW laboratories was 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 was growing constantly and prior to this project this situation was 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 needed to be transferred to those NMIs with less experience.

3 Objectives

The overall objective of this project was to improve the European measurement and research capability for RF&MW metrology and to establish a basis for future cooperation between European NMIs. This enabled 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 were 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 were 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 with 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 were improved for traceability of loop antennas and pulse generators and existing verification methods also were improved for EMC immunity/emissions by using advanced RF&MW metrology methods and VNAs. Therefore, an efficient knowledge link was 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 also developed a strategy to offer calibration services in their own country and in neighbouring countries. The individual strategies were 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 was 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 was conducted for these purposes. The results of this survey were 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 were prepared.

4 Results

4.1 Objective 1: S-parameter measurements with lower uncertainty and to develop/enhance impedance and S-parameters traceability across Europe

Many modern technologies depend on the reliable transmission of fast electromagnetic signals. The design of such systems depends, among other things, on the accurate knowledge of reflectivity and transmissivity of radio frequency and microwave (RF&MW) components. The necessary information can be obtained through measurements of scattering parameters, commonly referred to as S-parameters. S-Parameters are fundamental measurement quantities in RF&MW metrology. Establishing traceability for these quantities and evaluating uncertainties reliably are closely related and both are demanding tasks for various reasons. For the successful implementation of a particular toolset, training and competences are needed. Therefore the work, which was done in this part of the project, was all about enabling the receiving partners in that respect.

A four-day training workshop, which was given by METAS to the receiving partners (CMI, GUM, INTA, NIS, NQIS, SIQ, RISE, TUBITAK), provided details about the different steps to set up traceability in coaxial S-parameters and to correctly evaluate uncertainties in these measurements. A crucial step in this process was the metrology software VNA Tools (www.metas.ch/vnatools), which was developed by METAS in 2008. VNA

Tools is powerful but sophisticated software. In order to unleash its full potential, it is necessary to understand its fundamental principles and building blocks. Other parts of the training workshop covered theoretical and metrological concepts and best measurement practice.

The remaining part of the project was dedicated to applying the gained knowledge in practice. The activities were divided into two strands; (1) establishing S-parameter traceability by performing a so-called "primary experiment" on a set of coaxial reference standards and (2) evaluating S-parameter uncertainties with VNA Tools in a measurement comparison on another set of measurement standards.

For the primary experiment, a set of reference standards was selected, in this case, air-dielectric lines of different lengths in the 3.5 mm coaxial system to be used up to 33 GHz, see Fig. 1, and a set of flush shorts. The reference standards were made available by TUBITAK. Both, air-dielectric lines and flush shorts, are of pure metallic structure and thus suitable to be calculable standards. In the first step, a mechanical model of the standards was developed by SIQ and METAS. For this, the standards were subdivided into different sections as shown in Fig. 2 for the air-dielectric line. A similar type of model was established for the flush shorts. Parameterisation of the different sections was done in preparation for the dimensional measurements. Fig. 3 shows an example for the female connector interface. CMI, METAS and TUBITAK carried out mechanical measurements using their in-house length laboratories and own measurement setups.

Based on the dimensional measurements a combination of analytical calculations and numerical field simulations were carried out by TUBITAK, NIS and METAS to determine the model S-parameters of the air-dielectric lines and the flush shorts. Results of the mechanical characterisations and subsequent modelling were compared and discussed. The results were not always in agreement, but in the further course of the project, in particular during the one-day workshop described below, the differences were able to be sorted out.

In the next step, TUBITAK, CMI and METAS performed electrical measurements of the standards with a VNA. It was important to apply stabilising measures during these measurements, as e.g. employing dielectric spacers in the measurements of the air-dielectric lines, see Fig. 1. It is also important to apply an optimised measurement sequence and appropriate handling of the devices to avoid unnecessary measurement errors.

Fig. 1. Air-dielectric lines used as reference standards for S-parameter traceability.

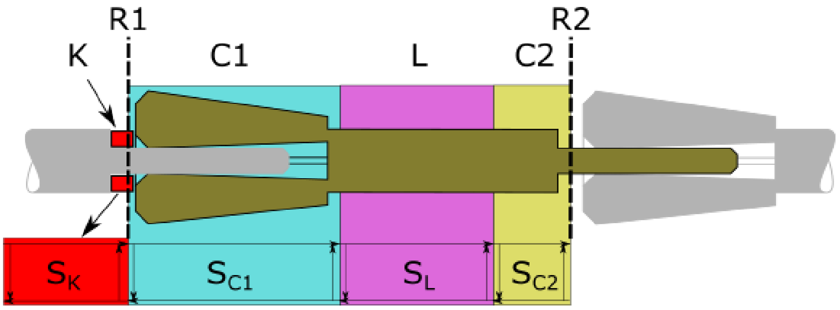


Fig. 2. Mechanical model of air-dielectric coaxial line. Shown is only the inner conductor. The device is separated in four parts, dielectric spacer to fix the longitudinal position (K), connector on the left (C1), line section (L) and connector on the right (C2). Each part is parametrised and characterised separately with appropriate dimensional measurement tools. The S-parameters of each part, indicated by S_K, S_{C1}, S_L and S_{C2}, are calculated. The S-parameter of the entire air-dielectric line is calculated by cascading the S-parameters of the individual parts. Dimensions are not to scale for illustration purposes.

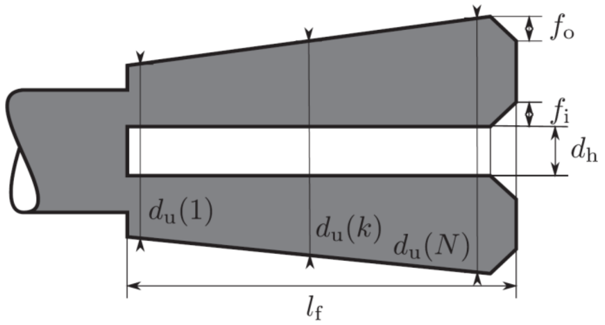


Fig. 3. Model of female socket. This corresponds to section C1 in Figure 2. The indicated dimensions were measured dimensionally.

In a final step, the modelled and the measured S-parameter data was combined in a large optimisation procedure.

METAS organised another one-day training workshop to discuss the outcomes/results of the work so far performed and to initiate the final phase of the primary experiment. The optimisation procedure is an overdetermined non-linear regression in which a set of free parameters were determined. The free parameters are the unknown error coefficients of the VNA as well as properties of the air-dielectric lines dependent on material parameters and surface roughness, as e.g. the propagation constant in the line section of the air-dielectric lines. At microwave frequencies, these effects are difficult to model. Some of the free parameters were part of a cross-frequency parameterisation, which made it necessary to solve the optimisation over all frequencies at once. However, this results in a numerically demanding optimisation problem with several thousand free parameters. Here again, the VNA Tools software was put to good use, because it has built-in performance optimisation and is suitable to tackle such a large optimisation problem. TUBITAK, CMI, SIQ and NQIS performed the optimisation and came up with S-parameters for the reference standards. The optimisation procedure is not just a push of a button operation. Instead, it is possible to fine-tune various settings and it is crucial to read and understand the outcomes to spot potential problems. For example problems can originate in models, which are not appropriate, bad measurements or in simple typographic errors. The partners were confronted with these types of problems and were given the opportunity to learn about debugging strategies and deepen their understanding of the whole procedure.

The entire characterisation procedure including the outcome (i.e. estimates of the S-parameters of the primary standards with associated uncertainties) was documented by SIQ in a report, which was reviewed by the partners involved.

The second strand of this part of the project was the evaluation of the uncertainties associated with S-parameters with the help of VNA Tools. The receiving partners (CMI, GUM, INTA, NIS, NQIS, SIQ, RISE and TUBITAK) were asked to characterise their VNA measurement systems in order to populate the database of VNA Tools. This is a vital step in the entire process of evaluating measurement uncertainties. The database contains the basic uncertainty contributions related to VNA measurements. Any negligence or error in these measurements will potentially result in wrong uncertainties for the S-parameters. The partners were able to apply the knowledge gained in the initial workshop at METAS for this step.

In order to test the reliability of the uncertainties obtained with VNA Tools at the different partner institutes, a measurement comparison was set up. All partners (CMI, GUM, INTA, NIS, NQIS, SIQ, RISE, TUBITAK and METAS) participated in this comparison. The comparison was also registered as EURAMET Technical Committee for Electricity and Magnetism (TC-EM) project 1426. This guarantees publication of the final report on the EURAMET website. A technical protocol was written by SIQ and reviewed by the partners to determine the details of the comparison, such as parameters to be measured. In the first step, a set of stable calibration artefacts in the coaxial Type-N system up to 18 GHz was chosen. The artefacts were provided by INTA, SIQ, METAS and consisted of male and female one-port components (open, short, load), an adapter, a 6 dB attenuator and a power splitter. METAS acted as the pilot laboratory of the comparison and organised the shipping of the standards. The partners performed the measurements according to a comparison schedule. METAS collected the data from partners and performed an analysis of the data. Outcomes of the analysis were a comparison reference value (CRV) for each standard, for each S-parameter and for each frequency point and degrees of equivalence (DoE) with respect to the CRVs for each laboratory. This resulted in a large number of results, which were further reduced by calculating the percentage ratio of compliance with the CRV at the 95% level over the entire frequency range. This is illustrated in Fig. 4. With the compliance ratios, it was possible to make compact summary statements related to the performance of the partners for each S-parameter. This was supplemented with a further summary graph, which showed the average expanded uncertainty over the entire frequency range per S-parameter and for each participant.

Finally, METAS wrote a comparison report containing the summary statements for each S-parameter. In addition, the entire electronic data set was made available to the partners for further detailed investigations using the VNA Tools Data Viewer. The report was reviewed by the partners and then submitted to EURAMET TC-EM. The results of the comparison were generally in good agreement with a few exceptions, subject to instabilities in the measurement setup, underestimated uncertainty contributions or configuration errors. The comparison raised the awareness for these type of problems amongst the partners.

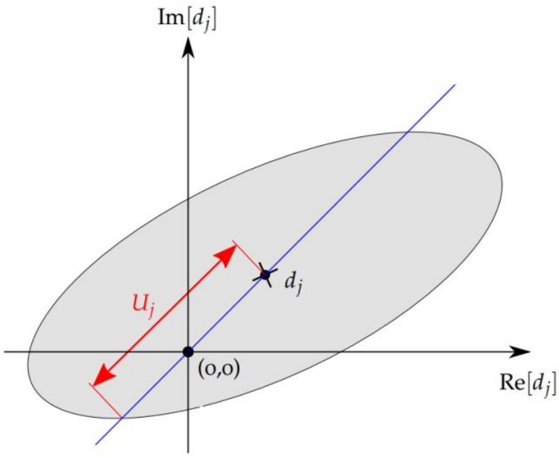


Fig. 4. Graphical interpretation of the compliance criterion applied in the measurement comparison. The degree of equivalence (DoE) is the difference between participant data and comparison reference value. For S-parameters, this is a complex value with real and imaginary components. The elliptically bounded gray area corresponds to the 95% uncertainty region associated with the estimate of the DoE d_j at an arbitrary frequency point. U_j is the distance (in red) between d_j and the intersection with the elliptical boundary, given by the straight blue line through d_j and (0,0). The compliance rate corresponds to the fraction of data points over frequency for which the point (0,0) is covered by the elliptical uncertainty region.

Summary

Key outputs related to this objective were the two reports produced, one related to the primary experiment/traceability and the other one summarising the results of the measurement comparison. IN addition, training activity and two workshops 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 to characterise primary standards. The partners have gained the ability to model calibration standards for S-parameters and to perform rigorous uncertainty evaluationbased on a full measurement model. To demonstrate the new abilities of the partners, an inter-laboratory comparisons on S-parameter measurements of one-port, two-port and three-port standards was completed. The comparison was also registered as a EURAMET TC-EM 1426 comparison project.

More important though was the competence gain of the partners in employing state of the art strategies and tools to improve their metrological capabilities in the field of S-parameter measurements. With the gained knowledge, CMI and TUBITAK are now able to perform the primary characterisation of their own calculable impedance standards using VNA Tools II. This has allowed CMI and TUBITAK to achieve a set of traceable standards with lower measurement uncertainty. In addition, SIQ has extended the frequency range for S - parameters measurement from 3 GHz up to 26.5 GHz.

4.2 *Objective 2: Improve the reliability and precision of RF power measurements under low and high-power conditions*

Most high-frequency electronic devices include long- and short-distance communication units which generate low- and high-power. In order to obtain traceable and accurate measurements at low- and high-power in RF&MW metrology, power sensors, power meters and high power attenuators which are used for the power measurements must be characterised accurately. To improve partners’ power measurement accuracy and capability this project has addressed the effects of higher harmonics on low power measurements, characterisation of power sensors for low power measurement, voltage reflection coefficient (VRC) of signal generator measurement; and characterisation of high power attenuators for high power measurements, through training events, workshops and inter-laboratory comparisons.

4.2.1. Calibration of power sensors for low-power measurement

A one-day training course for the calibration of diode power sensors using the direct comparison technique (making use of a two- or a three-sensor configuration, one of them being the unit under test) was organised by TUBITAK and CMI. The training course was held at METAS in November 2016. METAS also presented their measurement setup for this kind of calibrations and shared their knowledge with the other partners (INTA, SIQ, GUM, NQIS and NIS). The partners established their own measurement setups and performed preliminary measurements regarding the characterisation of diode sensors normally used for low power measurements.

INTA prepared a technical protocol of an inter-laboratory comparison exercise regarding the characterisation of a diode sensor. A type-N diode standard was used (up to 18 GHz) and circulated together with the associated power meter, interconnection cable and reference attenuator. This reduced the influence of miscellaneous equipment needed for the calibration. The attenuator for reduction of power at all frequencies (if needed) was provided by each comparison participant. The comparison was started in April 2018 and completed in May 2019. The analysis report for the comparison was circulated among the partners and based on this. INTA, SIQ, GUM, NQIS, NIS, CMI and TUBITAK have been produced best practice guide on the calibration of power sensors for low-power measurement.

Additionally, partners (INTA, SIQ, GUM, NQIS, NIS, CMI and TUBITAK) gained knowledge on the characterisation of power sensor for low-power measurement and implemented it to measure reliable and precise power measurement under low power. INTA, as an example, has been successfully applying this approach in the calibration of diode power sensors sent by its customers, as well as in the calibration of thermocouple sensors (fitted with Type-N, PC 3.5 mm and PC 2.4 mm connectors) with the three-sensors (direct comparison) technique. The results, as compared with the previously characterised performance of the units under test made by the manufacturer, have been proven satisfactory.

4.2.2. Investigation of the effect of high-power on the attenuator and power sensor combination

Microwave high-power traceability is established at mW levels using microcalorimeters as reference devices. They are used mainly by NMIs to calibrate thermistors or thermal power sensors which are then used by calibration laboratories for traceable measurements and calibrations of RF&MW power. They operate by converting RF&MW power into DC signal which is then measured by an appropriate power meter. The power meters then display the measured values in power units. However, these sensors are upward limited to power levels which can be directly measured, which is typically about up to 100mW or 1W (+20 dBm to +30dBm). Therefore to be able to measure higher powers up to kW range in a traceable manner, additional reference attenuators and/or couplers have to be used to lower the level suitably for measurements using traceable mW range power sensors. These reference attenuators and couplers have to be traceably calibrated and their influence considered when measuring power and calculating measurement uncertainty.

Different methods were investigated for the characterisation of high power devices. To get lower uncertainty for high power measurements ($P \geq 1$ W) attenuator/power sensor combination has been used given in Fig. 5.(a) where calibration plane is connected directly to the output connector of the source. Even if the cable has to be used, the uncertainty is smaller than in the case of using the coupler.

For the calibration of insertion (thru) power meters in terms of high power at the output connector using attenuator/power sensor combination, this is better because the calibration plane is at the output connector of the device under test (DUT). Moving the calibration plane to the input connector is possible but additional uncertainty is introduced. So, in this case, it is better to use a coupler/power sensor method which provides the smallest uncertainty for calibration plane at the INPUT connector of the DUT. Calibration of terminating power meters is only possible using coupler/power sensor combination as shown in given in Fig. 5.(b).

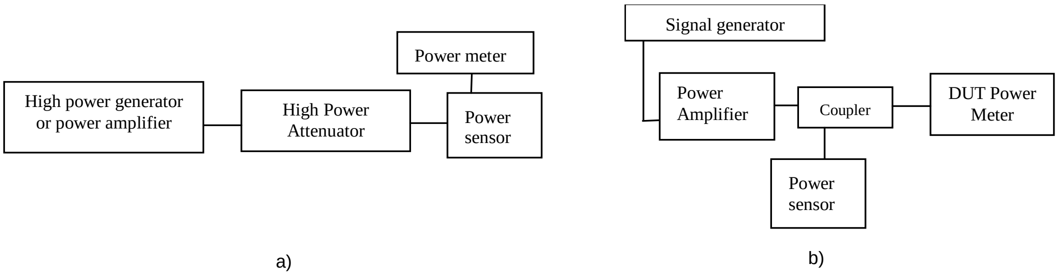


Fig. 5. Calibration setup for high-power source measurement using a) attenuator/power sensor combination and b) coupler/power sensor combination.

With all high-power measurements, one of the biggest sources of uncertainty is due to the output reflection coefficient of the sources and amplifiers. Such reflection coefficients can be quite big and when measured are available for calculations. But in many cases, reflection coefficients are only given or measured as scalar quantities and can therefore not be used for corrections. Instead the reflection coefficients' magnitudes can only be used to estimate the uncertainty due to source mismatch. Adding additional padding attenuators to the output of high-power equipment should also not be used as it lowers the power available to the measuring system. Further to this, a significant source of uncertainty for high power measurements is the characterisation of reference attenuators, couplers and cables. Transmission magnitude uncertainty of these devices directly affects the uncertainty of power measurements.

In many cases, such sources are so significant that making accurate vector corrections is not really practical. The only exception is in the case of coupler measurements where source reflection coefficient is not being used for corrections, but in this case calibration of other coupler parameters has to be very accurate for this to have any influence on overall uncertainty. This means that calculations of effective calibration factors can be done using only magnitudes of attenuation values or coupling factors and directivities. Hence any mismatches can then be estimated from magnitudes of reflection coefficients.

However, in practice it is not advisable to use more than three cascaded cables/attenuators as the uncertainty of the measurement is affected by the uncertainty of the calibration factor of the complete set and this is increased by each attenuator/cable added to the chain. Attenuation uncertainty of each device in the chain is directly added to the uncertainty of effective calibration factor. During high-power measurements equipment is also heated by the dissipated power which gives rise to additional errors in measurements due to changes in attenuation or drift of power sensor reading under elevated temperatures. Therefore, these effects have to be investigated for different measurement and calibration setups and any deviations should be added to the overall uncertainty.

The partners (SIQ, CMI, and INTA) have produced and exchanged information about their proposed measurement setups and measurement techniques for characterisation of high-power attenuators in small- as well as under large-signal conditions. Preliminary measurements were performed at these institutes using their own artefacts under test. A calibration setup which was established at INTA is given in Fig. 6 as an example. In order to demonstrate the partners knowledge gained an inter-laboratory comparison was organised. The comparison results were evaluated and based on this the partners have been produced best practice guide on the measurement of high-power.

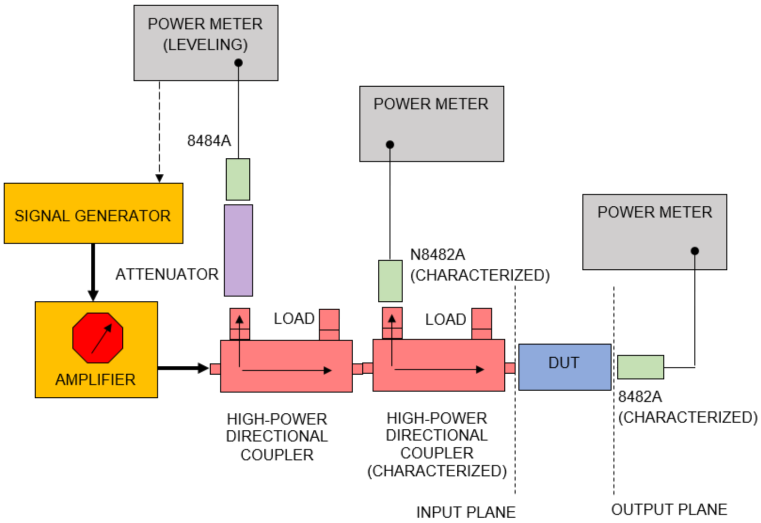


Fig. 6. INTA setup for characterisation of wattmeters (application to the measurement of high-power attenuators)

4.2.3. Characterisation of output VRC of microwave signal generators

The output VRC is one of the main performance parameters of microwave signal generators. However, it is difficult to measure and therefore is usually substituted by the specified maximum (or typical) VRC which can be found in the manufacturer's specifications or datasheets. Partners shared their knowledge to overcome these difficulties with an inter-laboratory comparison where they used different techniques.
Three different methods for measurement of output VRC of microwave signal generators were compared and analysed by partners (INTA, SIQ, GUM, NQIS, TUBITAK, NIS and METAS.
These methods are;

(i) Ripple technique; a scalar method which relies on the interaction between two signals, the main signal reflected by high reflection (a short) and the signal reflected at the generator's output connector. The two signals are separated by means of a directional device (a coupler) and their path difference increased by means of an airline. The interaction between the two signals, as a consequence of the path difference introduced by the airline, gives rise to a ripple signal whose peak-to-peak value (divided by two) indicates the magnitude of the output VRC of the generator under test.

(ii) Injection technique; a scalar method in which an auxiliary generator is used in combination with the DUT, connected via a directional bridge or a directional coupler (Fig. 7). The auxiliary generator injects a signal which has a small fixed frequency offset (for example 10 Hz) from the DUT's output frequency. The difference in frequency should be within the control bandwidth of the level control. The original and reflected signals will add and subtract at a rate of 10 Hz. The resultant signal is detected with a spectrum analyser in 'zero span' mode, connected to the third port of the bridge / coupler. The variation in amplitude with time is observed using the cursors to measure the maximum and minimum. With the DUT replaced by an open and a short, a reference level can also be measured.

(iii) Passive reflectometer method; the different states of the switchable reflect standard are characterised using a calibrated VNA. The method is used for the measurement of the complex source match of RF generators with a nominal impedance of 50Ω (Fig. 8).

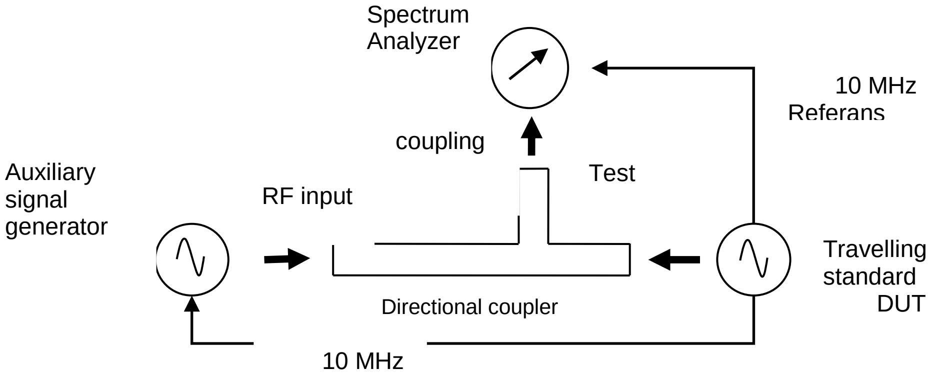


Fig. 7. Injection technique setup for characterisation of output VRC of microwave signal generators.

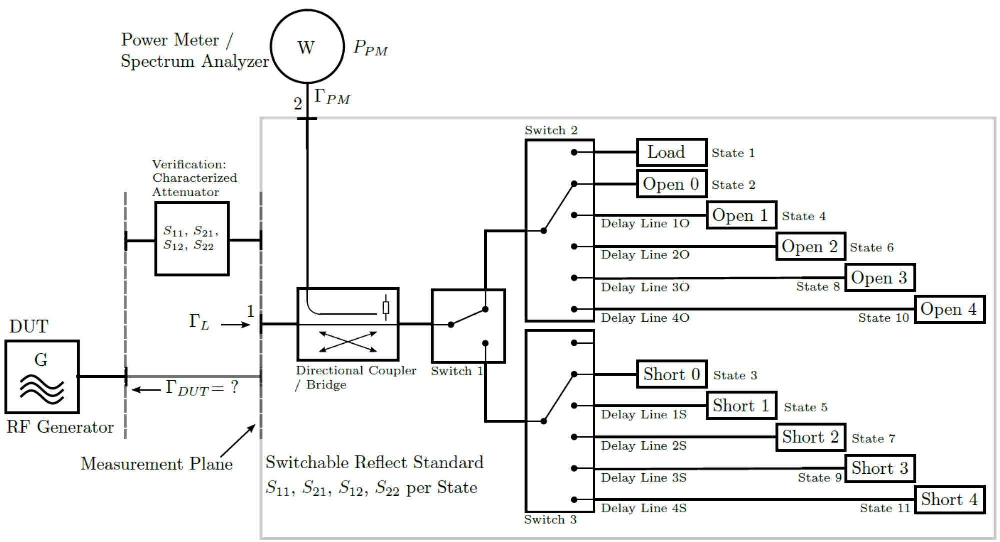


Fig. 8. Passive reflectometer setup for characterisation of output VRC of microwave signal generators (METAS).

Following the completion of the intercomparsions an he analysis report of the results was produced which showed that the measurement results of the different methods are satisfactory.

The comparison has also been registered and successfully completed as a project with EURAMET TC-EM project 1461 and the comparison final report can be found at: https://www.euramet.org/

4.2.4. Investigation of the effect of harmonics on low-power measurements

The traceability of microwave low-power to SI units is provided through a primary level measurement system typically around 0 dBm nominal power with thermistor sensors used as transfer standards. Thermistor sensors are suitable for the most accurate power measurements in metrological laboratories but they are not very suitable for most practical applications. One of the main limitations of thermistors includes their low dynamic range (max. 30 dB). For most applications, diode-type power sensors (DTPS) with significantly higher dynamic range (50 dB to 90 dB) are widely used allowing power levels in the range -70 dBm to +20 dBm to be measured. There are currently various types of DTPSs with different internal architecture which are optimised for different applications. DTPSs can operate either in quadratic, linear or transition regimes and some power sensors contain two or more diode detectors, each of which works in the quadratic regime for a particular power range. However, when a signal is generated by a microwave signal generator, it also contains harmonics. These harmonics causes errors during the measurement of the DTPSs which works in the quadratic regime. In this part of the project, different DTPS i.e. R&S NRV-Z1, R&S NRV-Z4, HP8484A, HP ECP-E26A, Agilent E4413A were modelled and measured to evaluate the measurement errors caused by the presence of higher-order harmonics.

The measurement method was based on the fact that the indication of the power meter with DTPSs operating above the square-law region is dependent on the phase shift between the fundamental and higher harmonic components. The measurement setup consists of two microwave generators (the fundamental and higher harmonic components) and a coupling device/two-resistor power splitter that creates a composite signal (see Fig. 9). Sufficient isolation of both generators is provided by the setup and a set of filters can optionally be used to suppress the unwanted higher-order harmonics of the fundamental frequency. The use of phase-locked synthesisers is necessary as the phase shift between the fundamental and higher harmonic components must be adjusted to obtain a maximum/minimum reading of the power meter. The phase shift can be changed between 0° and 360° either directly in the generator or by slightly detuning the frequency of the second generator. The detuning creates a slowly varying change of the power meter reading so that the user can easily monitor the minimum/maximum power reading.

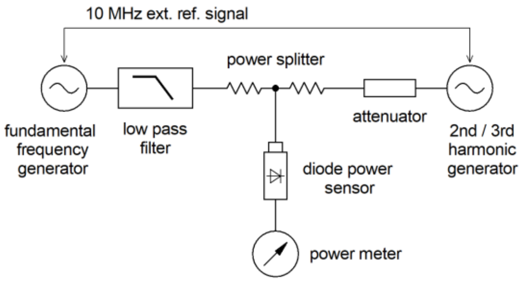


Fig. 9. Setup for characterisation of DTPS with a power splitter and sources of signal with known second and third harmonics.

The project's aim was to find a general approximating formula which can help the users to predict the behaviour of sensors with respect to harmonics on the basis of only several measurements. Regarding the characterisation of the curves, the following equation was proposed

$$\delta\ (\%) = kr^{er}\left[\left(\frac{P_m}{P}\right)^{ep_1 ep_2} + 1\right]^{-\frac{1}{ep_2}}, \tag{1}$$

where δ is the maximum measurement error in (%), P is the power level in mW, r is the higher harmonic suppression, P_m and k are constants optimised for the best fit to the measured or modelled values, ep_2 does influence the bending of the curves and is usually optimised only for the best fit to the modelled values and er, ep_1 are fixed constants chosen depending on the harmonic order and detector type. When the sensor is to be characterised on the basis of measurement, P_m and k are optimised separately for the second and third harmonic.

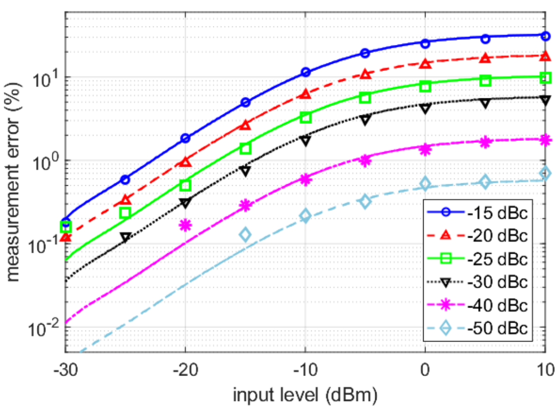


Fig. 10. Modelled and measured worst-case errors due to 2. harm. (R&S NRV-Z1 sensor), lines = fit by Eq. (1), symbols = measured (f = 2.5 GHz).

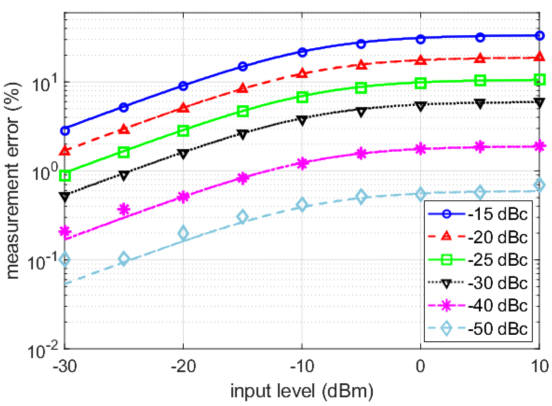


Fig. 11. Modelled and measured worst-case errors due to 3. harm.(R&S NRV-Z1 sensor), lines = fit by Eq. (1), symbols = measured (f = 2.5 GHz).

As an example, the worst-case results obtained by measurement and Eq. (1) for R&S NRV-Z1 are compared in graphs presented in Fig. 10 and Fig. 11. Here it can be seen that the approximating formula provides acceptable results for the sensor which shows the peak detecting behaviour.

Summary

In summary this objective was achieved. A workshop on the Monte Carlo (MC) method and training on characterising of diode-type power sensor was held, during which the 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 3 inter-laboratory comparisons were developed between partners on; (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 have been completed and the results showed good agreement. A comparison on the measurement of output VRC of a microwave generator was also registered as a EURAMET TC-EM 1461 comparison project.

The partners INTA, NQIS, GUM and NIS now have the capability to accurately calibrate diode-type power sensor including vector correction as well as the capability to measure of output VRC of a microwave generator. SIQ, INTA and CMI have also gained experience of characterising a high-power attenuator in its operating conditions (elevated temperature) and its effect on the measurement uncertainty of calibration of high-power attenuators and sensors.

A report about harmonics effects on power measurements using diode type power sensors was produced by the project 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 the help of CMI. Moreover, CMI, TUBITAK and NIS have gained knowledge to evaluate the measurement error caused by the presence of higher harmonics when using diode type power sensors. This knowledge has helped the partners to perform more reliable and accurate power measurement.The knowledge gained by this work has also been transferred to end users via the project's best practice guides on low-power measurement using diode power sensors in the presence of higher harmonics.

4.3 Objective 3: Improved calibration and testing procedures for EMC using RF&MW metrology

EMC is used to describe how well electrical and electronic equipment is able to function in an electromagnetic environment without introducing electromagnetic disturbances that interfere with the operation of other electrical products in the environment. Manufacturers must test their products that are electromagnetically compatible with relevant regulations in order to avoid EMC related issues. However, new verification methods are needed to increase the quality of EMC test/calibration and measurements, in particular, advanced verification methods using VNAs.

4.3.1. Traceability for pulsed measurement

In order to provide the traceability for pulsed measurements, a variety of methods for the calibration of pulse generators were investigated. Pulse generators are used for the calibration of EMI receivers and spectrum analyzers with quasi-peak (QP) detector. Thus to compare different methods for pulse generator calibration, the measurement of the quantity spectrum amplitude $S(f)$ in units [dBμV/MHz] was chosen.

According to the EN 55016-1-1 standard, a pulse generator is an instrument capable of generating time-domain rectangular pulses, or a pulse-modulated RF signal. Rectangular pulses are typically used for lower frequencies (bands A/B), and pulse-modulated RF signals for higher frequencies (bands C/D) because of the risk of receiver damage due to high peak voltages. In order to limit intermodulation effects in measuring receivers, the spectrum above the upper limit of the frequency band needs to be limited. The base-band pulse generators are usually comprised of an energy-storage device (electrostatic, magnetic field) and a switch which discharges a fraction or all of the energy into a load. The pulse-modulated RF generator uses a harmonic signal with a pulse envelope. This spectrum is uniform in a given bandwidth, which implies that pulses with longer duration can be used with lower amplitudes compared to base-band pulse generators (lower risk of measuring receiver damage).

A variety of 4 different methods for a pulse generator calibration were demonstrated on the calibration of the CISPR pulse generator Schwarzbeck IGUU2916 (base-band pulse generator, characterised within the project interlaboratory comparison). The generator is shown in Fig. 12.

Fig. 12. CISPR pulse generator Schwarzbeck IGUU 2916.

The 4-different methods for pulse generator calibration were:

a. Fourier transform of time-domain pulse waveform:

The spectrum amplitude is determined by direct acquisition of the pulse generator output voltage using an oscilloscope and conversion to the frequency domain. For this purpose, a digital real-time oscilloscope (DRTO) or an equivalent-time sampling oscilloscope (DSO) can be used. The method is useful for base-band pulse generators, it is simple and time-efficient. Corrections for the cable (attenuator) properties and oscilloscope transfer function must be performed.

b. Intermediate-frequency measurement method:

This method uses an EMI measuring receiver and its intermediate frequency output. The method uses a pulse signal and a reference CW signal (with known level) connected to a narrow-band filter, whereas the output of the filter (intermediate frequency) is acquired using an oscilloscope. The spectrum amplitude is then calculated from the response to both input signals at the frequency of the tuned filter (receiver). The accuracy of the method is dependent on the accurate characterisation of the receiver impulse bandwidth (IBW).

c. Measurement of pulse amplitude and duration:

This method uses an oscilloscope, whereas the pulse is sampled with high time resolution. The method is most suitable for pulse-modulated RF generators. The spectrum amplitude is calculated from the area of the pulse [V·s]. The pulse repetition rate should be stable and the correction factor should not change with CW frequency. The method is also applicable for base-band pulse generators. The pulse shape must be very close to rectangular.

d. Measurement of one spectrum line amplitude:

The principle of this method is a comparison of one spectrum line of the pulse signal with a known CW signal spectrum (equal frequency). This method assumes that the generator pulse repetition frequency is high enough so that only one spectral line falls within the EMI receiver filter bandwidth. The nominal filter bandwidths for the 6 dB amplitude drop are 200 Hz (band A), 9 kHz (band B) and 120 kHz (band C/D), respectively. The maximum pulse repetition rate of the IGUU2916 main generator is 200 Hz, thus only the band A is able to be verified. In other bands, the Aux generator must be used (max. amplitude 40 dBµV and max. repetition rate 20 kHz).

Comparison of the 4 pulse generator calibration methods:

The results of the comparsion of the pulse generator calibration methods showed that method a (Fourier transform of time-domain pulse waveform) can achieve the lowest measurement uncertainty and is simple to perform. It requires fast digital real-time or sampling oscilloscope and the spectrum of the measured waveform must be corrected for known attenuation of the signal path.

Method b) uses an EMI receiver which is more common in calibration laboratories. The measurement uncertainty is also comparable to method a). However, one has to be careful and not to overload the receiver input, as time-domain pulse generators use high peak amplitudes which may destroy the input mixer.

Method c) is more suitable for pulse-modulated RF generators and the results for a base-band pulse generator IGUU 2916 band C/D are not reliable due to the distorted pulse shape. The measurement uncertainty is slightly higher than that of methods a) and b).

Method d) is applicable only for pulse generators with very high pulse repetition rates (at least 500 Hz for band A, 10 kHz for band B and 120 kHz for band C/D). The results achieved for band A and B of the IGUU 2916 Aux generator are comparable to method a) for the same generator, however, the measurement uncertainty is rather high due to noise and low repeatability of the pulses. The goal uncertainty of maximum ±0.5 dB given in standards could not be achieved using method d).

The measured results with the 4-different methods and the measurement uncertainties except for method d) are summarised in Table. 1.

		Method a		Method b		Method c	
Band	Frequency (MHz)	*S*(*f*)	Unc.	*S*(*f*)	Unc.	*S*(*f*)	Unc.
A	0.009	139.90	0.13	139.84	0.21	139.81	0.22
	0.01	139.83	0.13	139.87	0.21	139.81	0.22
	0.05	139.77	0.12	139.83	0.21	139.68	0.22
	0.1	139.79	0.11	139.84	0.21	139.24	0.22
	0.15	139.79	0.11	140.25	0.21	138.49	0.22
B	0.15	107.11	0.21	107.40	0.12	106.86	0.22
	0.6	106.90	0.23	107.20	0.12	106.86	0.22
	1	106.93	0.20	107.06	0.12	106.85	0.22
	10	106.94	0.22	107.05	0.12	105.95	0.22
	30	106.75	0.22	106.54	0.12	96.40	0.23
C/D	50	90.08	0.16	89.62	0.14	90.94	0.25
	120	90.04	0.17	89.20	0.14	85.85	0.25
	300	90.14	0.16	88.96	0.14	78.35	0.25
	500	90.12	0.18	88.57	0.14	73.91	0.25
	1000	89.57	0.20	88.61	0.15	45.79	0.26

Table. 1. Summary of measured results using different methods. IGUU 2916 Main generator, amplitude setting 60 dBμV. The spectrum amplitude S(f) is given in dBμV/MHz and the associated measurement uncertainty in dB (k=2).

Method a = Fourier transform of the time-domain pulse waveform
Method b = Intermediate-frequency measurement method
Method c = Measurement of pulse amplitude and duration

4.3.2. Investigation of support effects on test results in both emission and immunity tests using VNAs

The effects of insulation supports commonly used in both emission and immunity tests on test results were studied using VNAs. The investigation consisted of two parts; (i) the conducted tests and (ii) the radiated tests.

The conducted immunity test is one of the major EMC immunity tests and widely performed in laboratories in the frequency range 150 kHz - 80 MHz using CDNs in accordance with IEC61000-4-6 and sometimes extended to 230 MHz. The principle of the test is to induce electric and magnetic disturbance inside the Equipment Under Test (EUT) by applying a conducted disturbance signal in Common Mode (CM) on the EUT input and output cables. The disturbance is applied via a defined source impedance of 150 Ω.

In the scope of the project, the effect of different supports on conducted immunity test results was investigated; e.g. styrofoam, molding polyamide, and wood (all are used to isolate EUTs from the ground plane as stipulated by the standard in conducted immunity tests). In addition, the conducted immunity test was performed on the actual EUT (the electronic thermometer) by using these supports and its effect on the test results was investigated. To able to measure the CM loop impedance of the test setup, two current probes were used along with one precisely known resistor and a VNA.

Firstly, the CM impedance was measured for each support. Then, the actual EUT (thermo-hygrometer) which is connected to the CDN was placed on each support in turn in order to measure the loop impedance (see Fig. 13) and subsequently, the CM impedance, injected current, temperature and humidity parameters were measured. The results related to this setup are presented in Fig. 14. It should be noted that the conclusions are also applicable to conducted emission tests.

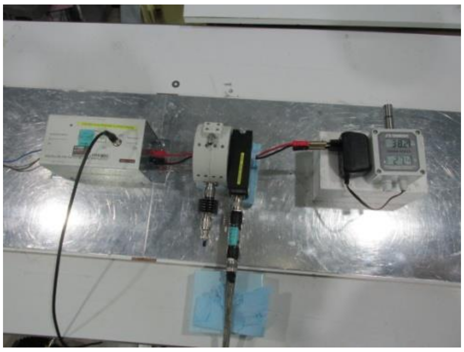
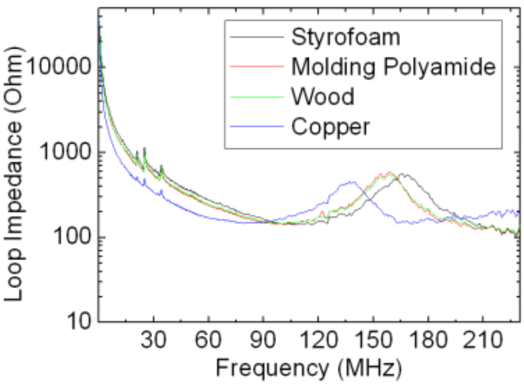
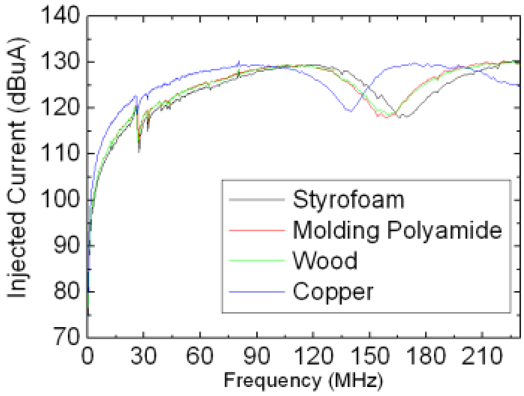


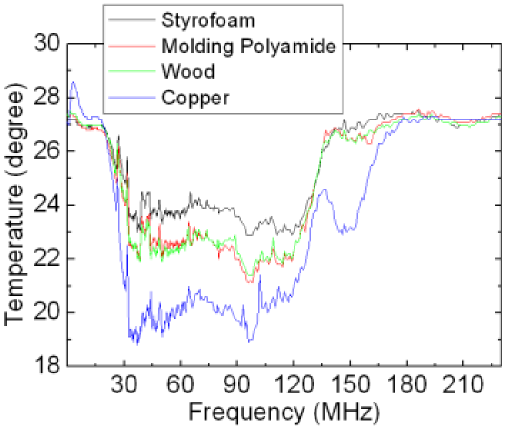
Fig. 13. Conducted immunity test setups of the electronic thermometer with CDN.



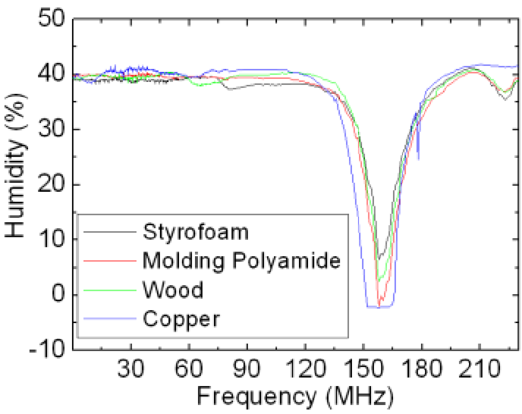
(a)



(b)



(c)



(d)

Fig. 14. Results of thermo-hygrometer and supports with CDN (a) loop impedance values, (b) injected current, (c) temperature susceptibility level, (d) humidity susceptibility level.

In the first part of this work, the influence of supports commonly used on conducted immunity and conducted emission EMC tests was measured along with loop impedance values and induced currents. Although many types of dielectric materials are used in conducted immunity and conducted emission measurements on account of the fact that they are just non-metallic, some of them give unacceptable uncertainty contributions to measurement results. The measurement results also revealled that the use of the styrofoam type supports in conducted immunity and conducted emission tests leads to the minimum measurement errors and consequently minimum uncertainty level.

In the second part of this work, the effects of supports on radiated emission testing were focused on. The radiated immunity and emissions measurement set-up considered in this study was according to the CISPR25 standard. The reason for this was that it was more suitable to produce higher differences due to the reduced distance between the reference on-table ground plane and the cables of the EUT. Moreover, it was a similar situation compared with the conducted immunity, as the cables were 5 cm above the ground plane, using a support material between the cables and the ground plane.

Measurements was performed to obtain the transfer function between the Bilog antenna and the Line Impedance Stabilisation Network (LISN) output (via the current coupled on the wires above the isolation material). Moreover, a biconic antenna was used to measure the transfer function with the Bilog antenna in order to measure the electric field that occurs when an EUT is placed over the isolation material. A diagram of the measurement set-up is in Fig. 15.

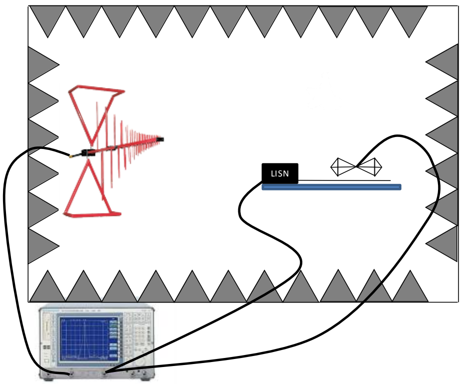


Fig. 15. Measurement set-up to study the effect of the support materials according to CISPR25 for emissions and immunity tests.

The transfer function with the “air” (reference value) measurement was compared to the three measurements with the Styrofoam and the measurement results for both the LISN and biconic antenna are presented in Fig. 16.a – Fig. 16.b. Additionally, in order to complete the study, another measurement was conducted with plastic material (Fig. 16.c).

A significant frequency shift due to the support material was not observed in Fig. 16.a - Fig. 16.b and the amplitude differences could be attributable to the test repeatability i.e. mounting and dismounting the test set-up in order to exchange the isolation material. These slight differences are close to 2-3 dB. However, a remarkable frequency deviation was observed due to the plastic material in Fig. 16.c. Therefore, from the emissions point of view, this could be critical for narrow band interferences as differences up to 6 dB can occur. Therefore the project concluded that the Styrofoam is the best material and introduces the lowest uncertainty to the radiated emissions and immunity tests.

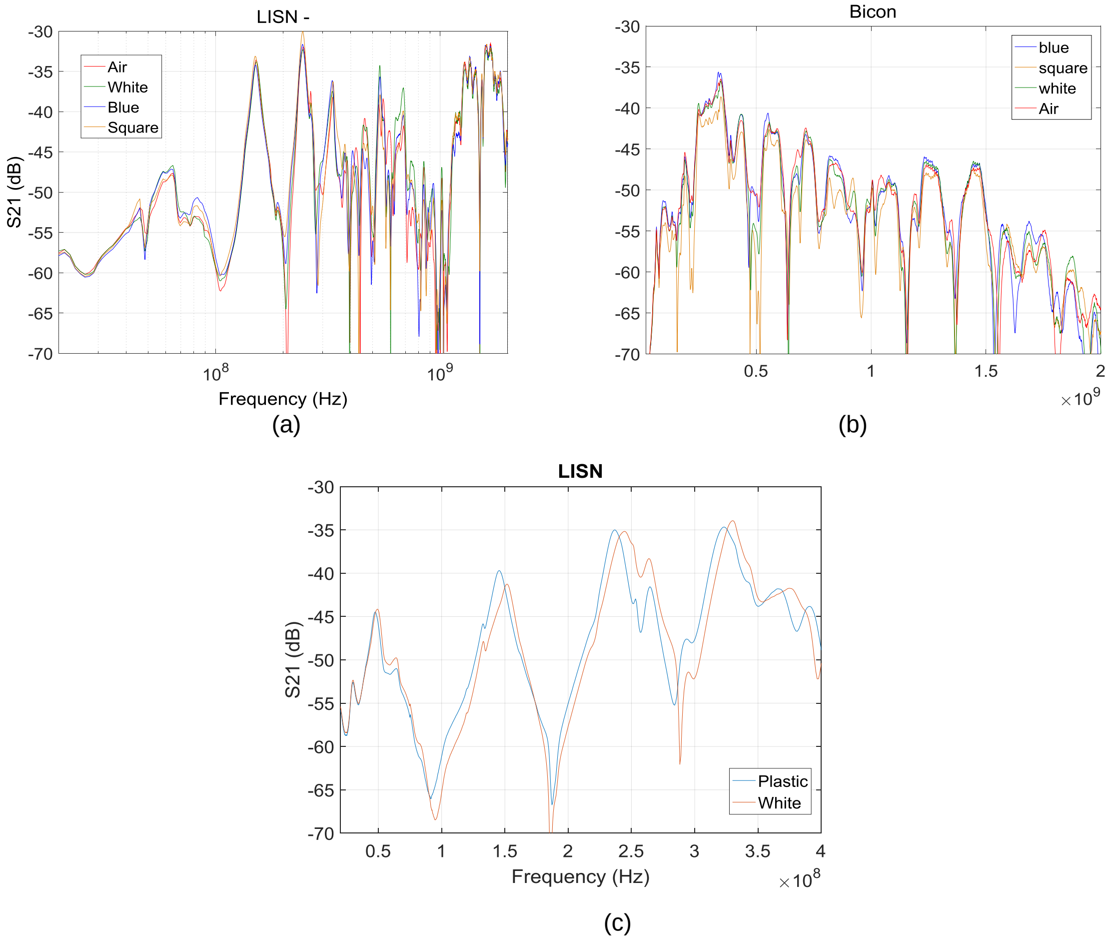


Fig. 16. Transfer function between a) the Bilog antenna and the LISN when the different Styrofoam materials are employed, b) the Bilog antenna and the biconic antenna comparison when the different Styrofoam materials are employed, c) the Bilog antenna and the LISN when the unknown plastic material is employed.

4.3.3. 'Just-before-test' VNA verification methods for EMC emission/immunity conducted tests

Conducted emission and conducted immunity tests are performed by using LISNs and CDNs respectively in test laboratories in accordance with emission standards such as CISPR22 for conducted emission tests and immunity standards such as IEC61000-4-6 for conducted immunity tests. As per the accreditation rules stipulated by IEC17025, every laboratory must perform verifications to ensure the quality and precision of test results using just-before-test verifications. This is because just-before-test verifications can detect errors beforehand in the test setup and prevent testing errors. Two different just-before-test verification methods (i) VNA and (ii) time-domain methodology were developed by the project for conducted immunity and emission tests.

A just-before-test verification method was developed using a VNA for a quick measurement of CM and DM impedance values of the LISN system for conducted emission tests, and CM impedance of CDNs for conducted immunity tests. The VNA just-before-test verification method can be used to demonstrate possible impedance-related issues including the most insidious ones such as breakdowns inside LISNs or CDNs, problematic 50 Ω terminators or cables, and weak grounding of LISNs & CDNs. Such insidious issues may not be easily detected by standard verification methods such as applying a known signal at the LISN EUT input. The impedance measurement setup with VNA and two current probes is presented in Fig. 17.

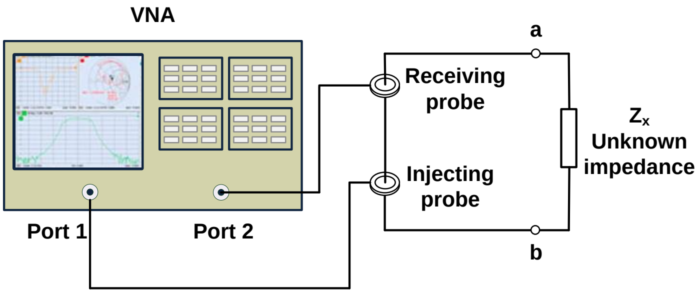
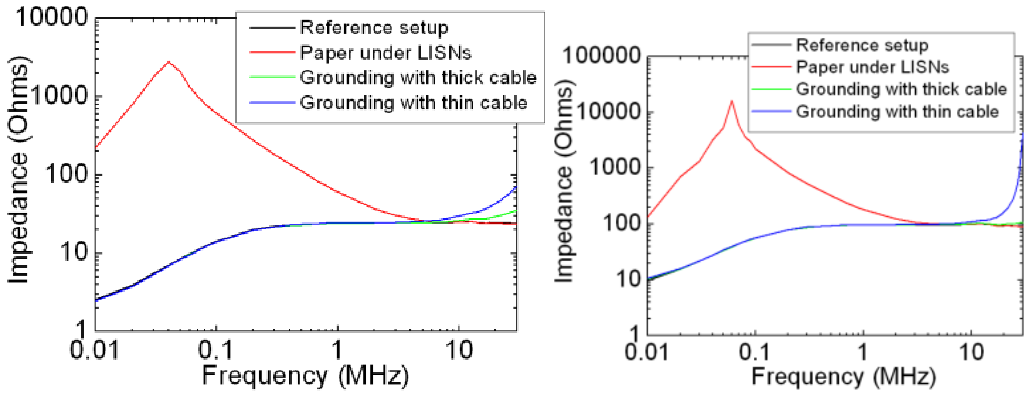


Fig. 17. Impedance measurement setup by using VNA and two current probes.

The effectiveness of the proposed just-before-test verification method was tested in failure scenarios such as poor LISN grounding and defective 50 ohm terminators. The just-before-test verification for conducted emission testing was based on both the CM and DM loop impedance measurements of the LISN system.

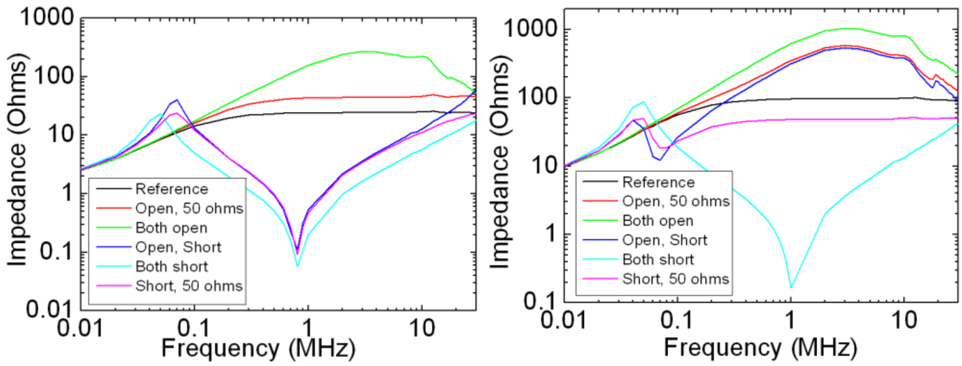
The just-before-test verification for conducted immunity testing was based only on the CM loop impedance measurement of each CDN. Through this verification setup, similar to the conducted emission verification, CDN-related or grounding issues can be easily detected. While the ideal setup was a well-grounded CDN with a proper 50 Ω terminator, the insidious issue scenarios used were termination and grounding scenarios.

The measurement results related to grounding and termination issues of the LISN and CDN are shown in Fig. 18 - Fig. 20.



(a) (b)

Fig. 18. Results of LISN grounding-related issues (a) CM, (b) DM



(a) (b)

Fig. 19. Results of termination-related issues (a) CM, (b) DM

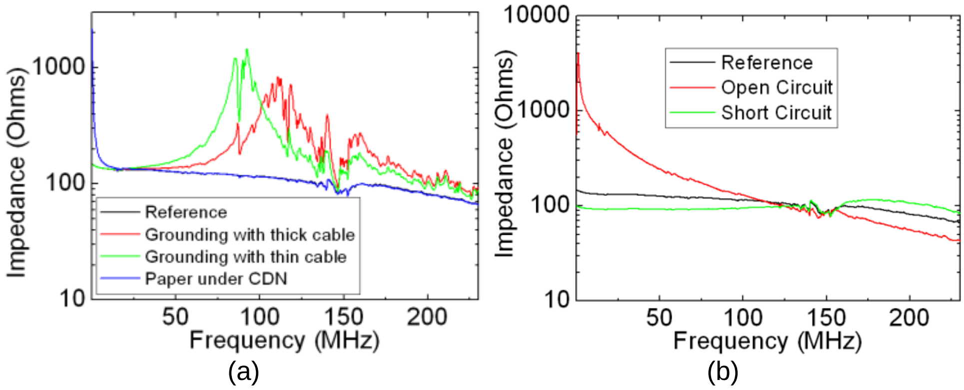
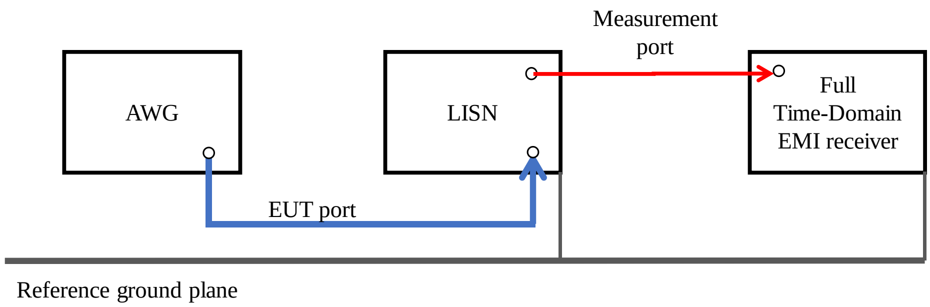


Fig. 20. Results of CDN-related issues in (a) CM impedance, (b) termination

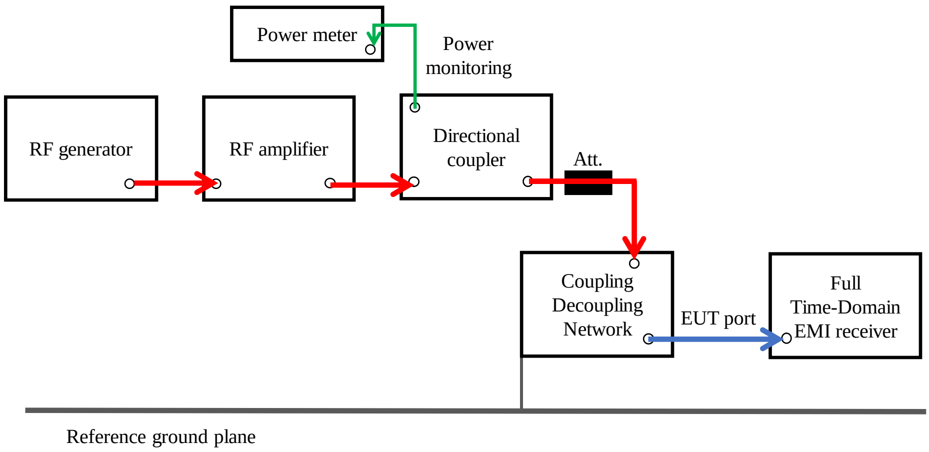
In addition to the VNA just-before-test verification method, a novel approach based on time-domain measurements and use of arbitrary waveform generator (AWG) was proposed by the project to perform quick and efficient just-before-test verifications.

The just-before-test verification methodology for the conducted emission testing was based on the use of AWG configuring a multi-tone or a representative EUT interference waveform used as the reference source in combination with the time-domain receiver. Although other types of instrumentation like frequency sweeps can be used to perform the just-before-test verification, using time-domain instrumentation like oscilloscopes should improve the speed and capabilities of the method. Hence, the AWG replaces the EUT and is connected to the LISN, while the RF output of the LISN are connected to the time-domain EMI receiver. In contrast, the just-before-test verification method for the conducted immunity verification is based on placing the time-domain EMI measuring system instead of the EUT. A time-domain EMI measurement system software is run via a laptop and used to continuously capture the signal with a max-hold option. In this way, the measurement system can obtain the frequency range between 150 kHz and 80 MHz and computes the spectrum. The schematic diagram of the conducted emission and immunity measurement setups and measurement results of example failure scenarios are shown in Fig. 22 - Fig. 24.



(a)

Fig. 21(a). Schematic of the just-before-test verification method conducted emission.



(b)

Fig. 22(b). Schematic of the just-before-test verification method conducted immunity.

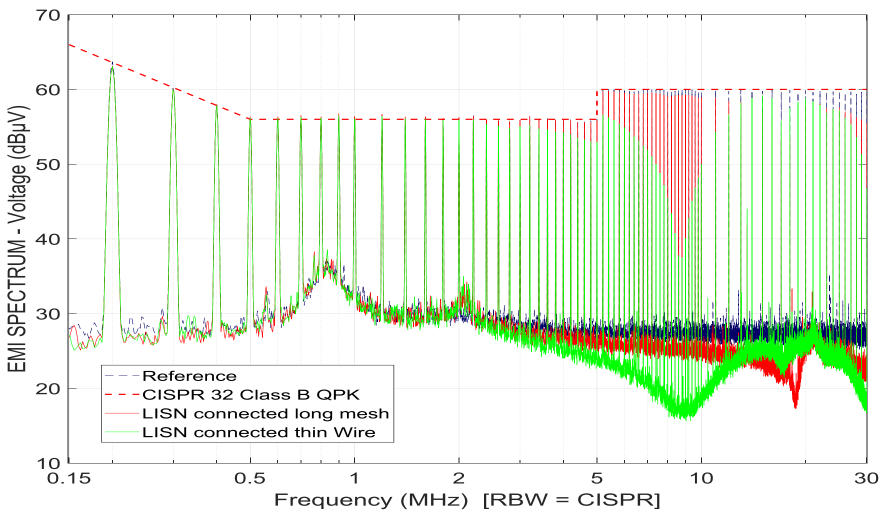
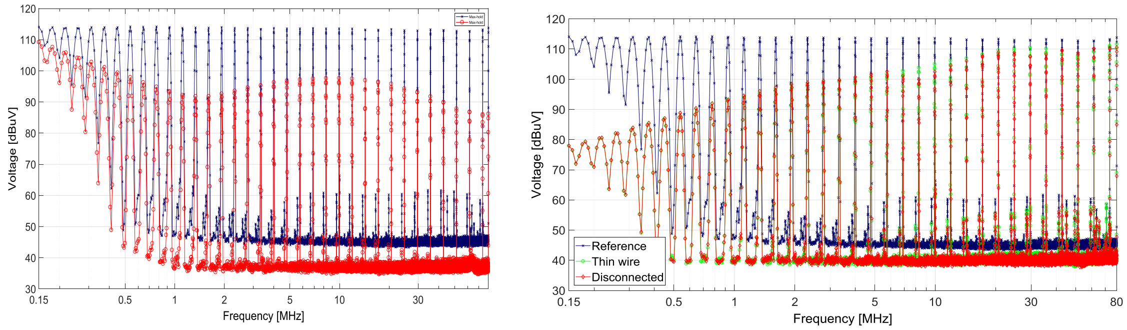


Fig. 23. Results of the just-before-test conducted emission verification method for the different LISN grounding conditions. In blue the reference measurement, in red when the connection is done through a thin wire and in green when it is done by means of a mesh.



(a) (b)

Fig. 24. Results of the conducted immunity just-before-test verification method when (a) the CDN is placed in reverse position (red colour) compared with the reference in blue, (b) . the CDN is connected to the ground plane in a poor manner

4.3.4. Traceable calibration of loop antennas using VNA

Loop antennas are widely used in a variety of test applications in order to measure the magnetic fields, especially below 30 MHz. They are commonly calibrated as per the standards IEEE 291 and SAE-ARP 958.

In this part of the project, the three antenna loop calibration method using a VNA was investigated. To do this, several loop antennas were calibrated with different standard loop antenna calibration methods i.e. (i) Helmholtz coil (H.C.), (ii) reference transmitting loop antenna (Ref. ant.), and (iii) Transverse ElectroMagnetic cell (TEM) methods. Following this, the results of the standard loop antenna calibration methods were compared with the three loop antenna calibration method results. Moreover, the advantages and disadvantages of the three antenna method with the use of a VNA were demonstrated with respect to the other standard methods such as the standard field method of IEEE 291. The measurement setups related to the three antenna loop calibration method and the measurement results are given in Fig. 25 and Fig. 26 respectively.

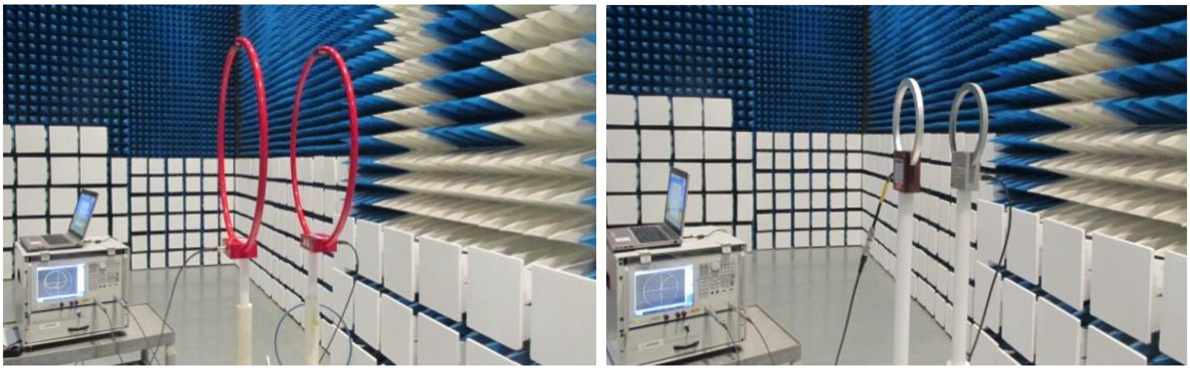
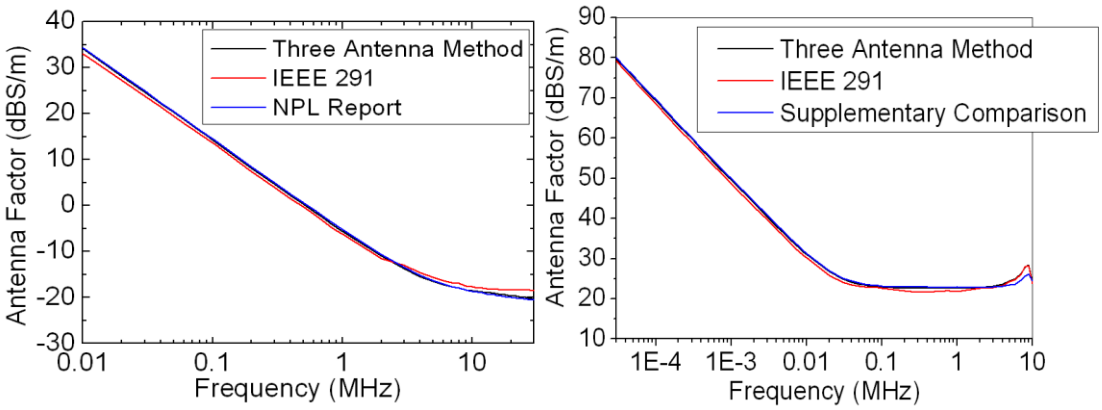


Fig. 25. Three-antenna loop calibration setup of (a) large commercial antenna (ETS Model: 6512), b) RE101 antenna (R&S Model: HZ-10).



(a) (b)

Fig. 26. Antenna factor results (a) large commercial antenna (ETS Model:6512) at 25 cm, (b) RE101 antenna (R&S Model: HZ-10) at 12 cm.

From the results it could be concluded that, the three-antenna loop calibration method was significantly more promising in terms of low uncertainty and ease of use in comparison to the other standard loop antenna calibration methods which were time-consuming and exhaustive. The three antenna method also prevented the burden of measuring the current on the transmitting antenna and the bother of the inclusion of cable losses. Moreover, the measurement uncertainty of the three antenna method was calculated as less than 1 dB.

Summary

In summary this objective was achieved. This project has successfully integrated the strength of RF&MW metrology, specifically the use of VNAs, into EMC tests and calibrations. It has established a link between the areas of RF&MW and EMC, which has not only embraced the integration of RF&MW metrology into the

EMC field but has also promoted 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 have also contributed to the improvement of the EMC test and measurement capability of the project partners.

The influences of a variety of support materials; (e.g. styrofoam, moulding polyamide, wood) in actual EMC tests were investigated using loop impedance measurements with a VNA. The results showed the effects of the support materials on the test results together with a significant link to the injected current, the loop impedance and the susceptibility of the equipment under test (EUT). In addition to this, S-parameters of the same support material samples at a high frequency, 2 GHz, were measured by using a WR 430 waveguide.

New and effective just-before-test verification methods that use a VNA were developed in order to be able to detect issues, particularly the most insidious ones, with conducted emission and immunity test setups just before tests. This just-before-test verification research has been expanded to low-frequency immunity tests to verify an entire low-frequency immunity test system. In this context, the project has integrated an 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. This has been done by using 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.

The project consortium also successfully evaluated the new CISPR25 chamber validation method and demonstrated effective applicability of the method along with the active role of network analysers in chamber validation measurements. Finally, the three antenna calibration method for loop antennas was successfully compared with the standard methods as per IEEE291, SAE-ARP958. Based on the results of the comparison measurements, the advantages of the three antenna method have been demonstrated in terms of lower uncertainty (< 1 dB) and ease of use in comparison to standard methods.

4.4 Objective 4 - 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 has been produced. Partners also produced their own short and long term strategic reports to offer calibration services in their own country and in neighbouring countries. The prepared individual strategies have been discussed during the EURAMET TC-EM SC-RF&MW experts meeting (including EMC) in April 2019. The participants from other EURAMET countries at the meeting appreciated the improved measurement capabilities of the project partners. They indicated that the long-term strategies of some of the partners could be a good starting point for future cooperation in more demanding mutual research projects, especially in the area of power and S-parameters measurements.

4.5 Objective 5 - Identify key industrial and scientific needs for stakeholders in RF&MW metrology

A questionnaire to identify the RF&MW and EMC capabilities and needs of emerging metrology institutes who were not part of this consortium, partners and stakeholders' was undertaken. The results showed that training on power, S-parameters and EMC measurements was required. Therefore, a training course and two workshops on power, S-parameters and EMC measurements were held for such NMIs, stakeholders and customers. In total 73 participants attended the training courses and workshops and these events were hosted at TUBITAK. Examples of those who attended are Trescal - Denmark, SMD - Belgium, MBM - Montenegro, Metronet - Romania, GEOSTM - Georgia, Vestel –Turkey, Esim – Turkey, Arçelik – Turkey.

5 training sessions and 4 workshops were also organised by the consortium for NMI partners to improve their knowledge on RFMW and EMC topics such as (i) MC methods, (ii) S-parameters traceability, (iii) traceable characterisation of pulse generators, (iv) characterisation of calculable primary standard, (v) advanced modelling and rigorous uncertainty calculation using specialised software, (vi) the calibration of diode type power sensors respectively, (vii) RF&MW calibrations of EMC devices, (viii) use of EMC components in EMC testing and (ix) probability pass or fail test.

5 Impact

The results of this project have been disseminated to the end-users in industry, calibration laboratories, academia and metrology community via training course, workshops, and publications at trade journals, well-known peer-reviewed journals and conferences. These are given below.

- 14 international/national scientific conference papers in proceedings of EMC Europe 2017 and 2018 conference, APEMC 2017 and 2018, I2MTC 2017, CPEM 2017, IEEE EMC SIPI Symposium, 6th Congreso Español de Metrología and ESA Workshop on Aerospace EMC.
- A total of 12 open access publications of which, 3 scientific journal papers were in IEEE Transactions on Instrumentation and Measurement and IEEE Transactions on Electromagnetic Compatibility.
- 3 trade journal papers in Signal Integrity Journal, CalLab Magazine and the IEEE Electromagnetic Compatibility Magazine.
- Totally 13 training courses and workshops including practical laboratory application on S-parameters, power and EMC measurements were organised for the project partners, non-consortium NMIs and stakeholders.

The outputs of the project have been also shared using the project website (http://rfmw.cmi.cz), ResearchGate, LinkedIn and Twitter.

Impact on industrial and other user communities

At the end of this project, participating NMIs have gained 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 was tailored to their stakeholders' 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 was produced.

Project partners have gained knowledge on the characterisation of calculable impedance standards including connector effects. For example TUBITAK has measured calculable impedance standards for the first time using dimensional and electrical parameters, which it can now provide to its customers. SIQ has also extended their frequency range for S -parameters measurements from 3 GHz up to 26.5 GHz and can offer this service to stakeholders.

In addition, the new just-before-test low-frequency immunity verification & testing methods, developed by the project, have been put into service at TUBITAK and are currently being used in EMC tests. The three loop-antenna calibration method (successfully investigated in the project) is also being used in loop antenna calibrations for customers at TUBITAK.

Impact on the metrology and scientific communities

The project identified the RF&MW and EMC capability needs of partners and emerging metrology institutes who were not part of consortium through a questionnaire. Based on the results two workshops and a training course for project partners, stakeholders and emerging NMIs (outside of the consortium) were held at TUBITAK.

The project successfully completed 6 comparisons to disseminate knowledge and to establish and enhance the metrological performance of project partners. The comparisons were on (i) calculable primary calibration standards (TUBITAK, CMI and METAS), (ii) S-parameter measurements (SIQ, INTA, CMI, NQIS, NIS, RISE, GUM, TUBITAK and METAS), (iii) power sensor measurement for low-power (INTA, SIQ, NQIS, CMI, NIS, TUBITAK and GUM), (iv) measurement of output VRC of a microwave generator (INTA, SIQ, GUM, NQIS, TUBITAK, NIS and METAS), (v) characterisation of a high power attenuator (SIQ, INTA and CMI) and (vi) traceable characterisation of pulse generator (SIQ, RISE, NQIS, TUBITAK, UPC and CMI).

The project also produced four best practice guides for stakeholders and end users, which are available on the project website. Three of the best practice guides 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 is on the traceability of pulse measurement in EMC.

Impact on relevant standards

At the EURAMET TC-EM RFMW meeting in April 2017 and 2019, TUBITAK and UPC presented the project outline and the calibrations and comparisons requested by EMC laboratories were discussed during the. At the EURAMET TC-EM RFMW meeting in April 2019 project partners presented the project's long-term strategy reports and the results of the project's registered EURAMET comparisons s EM-1426 and EM-1461.

Moreover, the project's outputs have been shared with the European metrology community via national standards organisations such as the TSE (Turkish Standards Institution) working group MTC 036 EMC, the UNMZ (Czech office for standards) committee TNK 47 Electromagnetic compatibility, AEN/CTN 208-Aenor Spanish Committee on Electromagnetic Compatibility, the Slovenian SIST/ Technical Committee for Electromagnetic compatibility, the SEK (Swedish; Svensk Elstandard) group TK EMC and the Polish Committee for Standardisation (Polski Komitet Normalizacyjny – PKN) group KT 104 Electromagnetic compatibility.

Longer-term economic, social and environmental impacts

The project's results 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 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.

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 support the prevention of incorrect testing of devices, thereby making a positive financial impact on the European economy.

6 List of publications

[1]. 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. DOI: 10.1109/EMCEurope.2017.8094786

[2]. 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. DOI: 10.1109/EMCEurope.2017.8094729

[3]. 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. DOI: 10.1109/TIM.2018.2794941

[4]. 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. DOI: 10.1109/EMCEurope.2017.8094694

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[6]. 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 (I^2MTC 2017)*, Torino, Italy, 22-25 May 2017, pp. 785-790. DOI: 10.1109/I2MTC.2017.7969789

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[8]. K. Dražil, J. Grajciar, T. Pavlíček, M. Celep and M. Hudlička, "Harmonics Effects on Microwave Power Measurement Using Diode Sensors," in *IEEE Transactions on Instrumentation and Measurement*, vol. 68, no. 6, pp. 1852-1859, June 2019. DOI: 10.1109/TIM.2019.2905885

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[10]. Soydan Cakir, Osman Sen, Mesut Ozturk, "Investigation of Ripple Voltage Across Capacitor in Military CS101 Test by Using FFT-Based Time Domain Solution," in *Proc. of the IEEE EMC SIPI Symposium*, Long Beach, CA, USA, pp. 1-6, August 2018. DOI: 10.1109/EMCSI.2018.8495307

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7 Contact details

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