Publishable Summary for 20IND03 FutureCom
RF Measurements for future communications applications

Overview

European manufacturers of telecommunications equipment, telecom operators, and regulators face ever-increasing customer demands in terms of higher data rates and energy consumption. Higher data rates translate to energy consumption as well as higher frequencies for amplifiers, integrated circuits, and printed circuit boards (PCBs). The widespread implementation of future communications such as 5th generation (5G) and Connected Autonomous Vehicles (CAVs) presents challenges for the developed technology as electronic radio frequency (RF) components, circuits, subsystems, and systems must be characterised and demonstrate good performance in "real world" operating conditions. However, European NMIs/DIs currently lack the capacity to carry out such RF measurements necessary to support the communications sector. This project will address this issue by developing measurement capabilities that enable devices and systems to be electrically tested under realistic (i.e., end-user) operating conditions, including appropriate environmental conditions.

Need

Industry is one of the pillars of the European economy; the manufacturing sector in the EU accounts for 2 million enterprises, 33 million jobs, and 60% of productivity growth. Digitising European industry is one of the key strategies of the European Commission (EC), and communications technologies such as the Internet of Things (IoT) and 5th generation (5G) play a very important role in this. The rollout of the global 5G communications infrastructure is now well under way in several parts of the world and is set to continue during much of this decade as more countries have access to this new global network. 5G subscriptions are expected to grow from 190 million in 2020 to 2.8 billion by 2025, and 5G is expected to carry nearly half of the world's mobile data by 2025. Europe is currently lagging behind other world regions in the communications sector, as has been shown with the implementation of 5G, and this technology power shift has caused disharmony between nations. To regain Europe's place at the forefront of future communications, direct investment in this area is urgently needed.

European NMIs need to develop and provide capabilities and solutions to the challenges that European industry is currently facing. For example, the development of device characterisation under real-world environmental conditions is critical for active devices to be used successfully in future communications applications. In addition, the production of antennas integrated on-chip, and the development of new high-frequency probing techniques and measurements of devices subjected to modulated signals are also essential for next generation millimetre wave communications systems.

Further to this, problems in communications systems due to Passive Inter-Modulation (PIM) are growing in telecommunications base stations as more power and wider bandwidths are required to transmit higher data rates. Therefore, it is essential that reliable measurement capabilities are established within Europe to enable the evaluation and validation of devices in these real-world testing scenarios.

Objectives

The project concentrates on the issues currently faced by the industry for future communications applications and its overall goal is to evaluate active circuits, PCBs, signal- and power-integrity in FPGAs and PIM and to investigate the effects of different temperatures and humidities corresponding to real-world environmental operating conditions. The specific objectives of the project are as follows:

1. To characterise active devices (e.g. transistors realised in Gallium-Nitride (GaN), Silicon-Germanium (SiGe) and Complementary Metal-Oxide-Semiconductor (CMOS) technologies) and circuits, particularly high-power amplifiers (HPA), under realistic operating conditions (i.e. non-50 Ω) at frequencies that include the millimetre-wave bands (e.g. to at least 200 GHz). The characterisation includes the linearity response

of the devices and encompass multi-physics methods, mixed domain measurements (combining digital- and analogue-domains), new probing techniques and assessments of antennas integrated on-chip.

2. To evaluate the impact of signal-integrity (SI) and power-integrity (PI) on Field-Programmable Gate Array (FPGA) chips, including the quantification of effects caused by electromagnetic interference (EMI) on high-speed digital circuits during operation. This should include i) the design of rules for the location of components (e.g. integrated circuits) on chip and on printed circuit boards (PCBs) based on in-situ assessments of performance; and ii) the development of methods to validate test data and assess parasitic effects due to components operating simultaneously in close proximity on chip.
3. To assess the system operation performance in real world and harsh environments (e.g. below- and above-ambient temperatures, different climate conditions and changing levels of relative humidity (RH). This includes the development of methods for assessing the performance of the electronic components and circuits in diverse operating applications (e.g. Connected and Autonomous Vehicles (CAVs) and New Space).
4. To develop and validate novel measurement methods to evaluate the PIM of RF electrical signals used in communications systems. These methods are suited for industry-grade connectors (e.g. Sub-Miniature version A (SMA), 7/16 and type-N connectors, and, newer variants including the 4.3/10 connector).
5. To facilitate the take up of the technology and measurement infrastructure developed in the project by the measurement supply chain (NMIs, calibration laboratories), standards developing organisations (IEEE) and end users (in the fields of telecommunications, automotive, defence, space and security).

Progress beyond the state of the art

Several previous EURAMET projects have addressed device evaluation for new communications technologies. The 16ENG06 ADVENT project demonstrated state of the art multi-physics device characterisation for energy-efficient communication systems, whilst the SIB62 HF-Circuits, 14IND10 MET5G, 14IND02 PlanarCal, and 18SIB09 TEMMT projects have made good progress on measurement techniques in transmission media (i.e., coaxial line, waveguide, and planar circuits) and for multi-port devices. Currently, the measurements of components and systems undertaken in laboratory conditions do not represent their performance operating in “real world” environmental conditions. These real-world situations are where the devices that need to be characterised are either operating in a harsh environment (e.g., at very high or very low temperatures or RH) or in a non-optimum configuration (e.g., under large-signal operating conditions or in electronic circuits where neighbouring components are causing substantial signal interference).

The present characterisation techniques for active devices lack a unified approach for calibration and uncertainty evaluation. These methods do not support non-50 Ohm (Ω) loading conditions or multi-layer substrates up to 220 GHz. This project goes beyond the state of the art by generating further knowledge and suitable measurement methods for active devices which are applicable to end-users of future communications systems.

Future communications applications will require high levels of Signal Integrity (SI) to ensure reliable high-speed data transfer, and high-speed electronic components such as Central Processing Unit (CPUs), FPGAs, Digital to Analogue Convertors (DACs) and Analogue to Digital Converters (ADCs), and being capable of handling hundreds of channels and thousands of input/output connections on a single chip. The traceable standards for balanced transmission lines for digital communications were designed in previous projects. This project has gone further by investigate together SI, PI, and EMI of high-speed digital circuits at both component and PCB levels: significant progress has been made by the development of on-wafer test structures and reference printed circuit boards, and the corresponding methodology, for accurate SI characterisation at both chip and board level. In addition, an FPGA-based VNA has shown the potential for portability and has contributed to PI analysis. The next step is to initiate EMI characterisation at chip and board level, comprehensively covering all aspects (SI, PI, EMI) at multiple levels (chip and board).

The operation of electronic devices and their integration into systems operating under realistic environmental conditions and the performance of such components during their life cycle are being investigated by this project. The project goes beyond the current state of the art by taking selected devices from those used in objectives 1 and 2 and testing them “in-operando” under diverse real-world operating conditions.

PIM measurements, in theory, are currently well understood; however, they are still quite difficult as multiple signals and very sensitive receivers are required. The very large dynamic ranges of PIM measurements present a real challenge to even state of the art instruments, but identifying PIM in any system is necessary to enable full use of limited bandwidth. To meet these challenges, many PIM measurement methods were investigated within this project, and new measurement capabilities were developed. At this stage, a capability for measurement of high-power RF signals and the S-Parameter of industrial RF connector systems (4.3-10 and 7/16) are already established. Additionally, a capability for measurement of PIM signals were also developed at the involved participant laboratories. The impact of the measurement conditions on the measured PIM was under investigation and it is currently being analysed.

Results

Objective 1: Traceable Measurements of Active Devices

EM simulations on ISS mono-layer (fused silica) and multi-layer substrates structures have been completed. The power calibration of the VNA measurement receivers for frequencies up to 50 GHz using both direct comparison and the feed-through power transfer techniques was investigated, and the corresponding uncertainty framework has been developed. The power sensor calibrations were then performed from 120 GHz to 170 GHz using direct comparison methods. The draft Good Practice Guide (GPG) for characterising active devices and circuits operating under non-50 Ω loading conditions and for large-signal measurement systems up to 220 GHz has been prepared. The transfer standards for power calibration are identified, with diodes as suitable devices for RF power calibration, as demonstrated in the WR5 band. Working with the project's Technical Advisory Group (TAG) members, the partners have investigated European commercial semiconductor foundries; a list of European GaN semiconductor manufacturers has been produced; and the project has characterised the chosen active GaN devices.

Test structures and calibration standards have been designed and fabricated, and the devices have been characterized under linear and non-linear operations with 50 ohm and non-50 ohm load terminations. Thermal device characterization using a thermo-reflectance system and Raman measurement methods have been completed. The measurements of passive structures were performed to determine the limitation of the electro-optical (EO) near-field probing system. The measurement resolution of less than 20 um at 4 GHz has been determined, and differences observed in the modulated signal will significantly impact active device performance.

Furthermore, a study is conducted into the uncertainty sources of active impedance tuners. A behavioural model was developed for vector modulators used in active impedance tuners, allowing accurate uncertainty propagation for uncertainty estimation in load-pull measurements. An investigative study has been conducted into the sensitivity of the transfer function between IQ mixers' RF-to-LO ports for the DC IQ driving signals. The measurement software has been developed for automated load-pull measurements at VSL.

A 50-um pitch GSG probe for on-wafer measurements has been manufactured using novel technique developed under this project and initial measurements were completed. The spatial dimensions of the probe were measured using electron microscopy. The probe design was further modified by optimizing the Cr/W layer to improve GSG pin resistance and new probe has been fabricated for further evaluation.

The evaluations of their large-signal measurement systems for the characterization of the CMOS, HBT, and GaN HEMT active devices under non-50 Ω loading conditions up to 220 GHz (including the in-band linearity performance, i.e., EVM) are ongoing. Preliminary small signal power-controlled measurements on the CMOS devices have been carried out. The measurements of PAs under realistic loading conditions using modulated signals while simultaneously observing temperature and electric fields using thermo-reflectance and electro-optical near-field probing are ongoing.

The thermal and EO measurements on passive and active devices have been completed. Electrical measurements on power amplifiers have been completed in CW mode, and the two-tone measurements are being conducted. The PA under realistic loading conditions using modulated signals is planned to be measured.

The updated version of the draft GPG will be restructured to produce a final 'Good Practice Guide' for the characterization of active devices and circuits operating under non-50 Ω loading conditions and for large-signal measurement systems up to 220 GHz.

Objective 2: Signal Integrity (SI) and Power Integrity (PI) of FPGA Chips and PCBs

Our ongoing research has made significant progress through the design and evaluation of on-wafer structures, reference PCBs, and measurement methodologies. These achievements help enhancing the reliability and accuracy of RF circuits at both chip and board levels for future communications applications.

On-wafer thin film microstrip line (TFMSL) reference structures were designed, fabricated, and distributed to the three involved partners for testing and comparisons. The impact on SI and PI was evaluated, through multimode S-parameter measurements on various chips, seeking validation against our established guidelines derived from 3D electromagnetic (EM) simulations. Test structures with variations in width, bends, and diverse neighbouring structures were utilised, aiming to enhance our understanding of component performance.

Furthermore, reference PCBs were designed and produced to assess the traceability of de-embedding procedures. Time-domain analysis, focusing on the impact of receiver characteristics on data rate, provided insights through electromagnetic simulation. Design guidelines were established to achieve the desired eye-opening and jitter-to-bit period ratio versus data rate. The comparison between an FPGA-based vector network analyser (VNA) and an actual VNA indicated a reasonable level of agreement, contributing to PI analysis.

For the next stage, wafers for electromagnetic interference (EMI) characterisation, similar to those for SI and PI analysis, have been manufactured and the board used for the FPGA- based VNA was selected. The measurement system, including the electromagnetic field probes, has been set up by two partners, using an electric field probe and a magnetic field probe, respectively, with a view to completing the work for a full analysis of circuit performance at chip and board level.

Objective 3: Environmental Testing of Electronic Circuits

Suitable standards documents have been considered to inform the definition of the test procedures for PCB and on-wafer environmental age testing. A second (improved) version of the test printed circuit board (PCB) has been designed and fabricated. It consists of an FR4 type substrate with four metal layers and is designed to be fitted with end-launch connectors for electrical testing at frequencies up to about 10 GHz. Environmental chambers have been adapted for use with RF test equipment for PCB environmental in-operando testing. Some PCB environmental age testing (thermal cycling, temperature humidity bias testing and isothermal ageing) has been completed whilst other testing and the analysis of the results is ongoing. Similarly, some PCB environmental in-operando testing (at various levels of controlled condensation) has been completed whilst other testing (at above and below ambient temperature and at low and high levels of relative humidity) and the analysis of the results is ongoing.

Some commercial on-wafer planar circuits have been procured for testing. Work has been done on establishing the on-wafer environmental test procedures. Some on-wafer environmental age testing (thermal cycling, temperature humidity bias testing and isothermal ageing) has been completed whilst other testing (including cryogenic testing) and the analysis of the results is ongoing. Similarly, some on-wafer environmental in-operando testing (at above ambient temperatures) has been completed whilst other testing (including at cryogenic temperatures) and the analysis of the results is ongoing.

Objective 4: Measurements Method for PIM in Communication Systems

For a precise and traceable PIM measurements, the adapters used during the measurement process and the power of RF signals need to be accurately measured. In this project, different measurement capabilities for precise and traceable RF power and S-Parameter in industrial RF connector systems (4.3-10 and 7/16 connector types at frequency ranges of 1.8 GHz to 2.1 GHz) were successfully established. Using these new capabilities, the measurements of high-power signals have been performed and the corrected RF power measurements including the uncertainty budget were obtained by PTB, CMI and INTA. The result analysis and the measurement comparison were completed and CMC entries for high-power measurements up to 55 dBm (~300 W) were obtained by CMI.

For PIM signals measurement, a new PIM measurement capability has been established at the WP4 partner laboratories. PTB has been working on a newly developed vectorial PIM measurement system whereas CMI has developed a one-amplifier scalar PIM measurement system. Two different sets of PIM travelling-standards were used for PIM measurement at the involved partner laboratories. The PIM measurement results, including the uncertainty budget, are being analyzed by the pilot laboratory.

For a precise measurement of PIM, it is important to investigate the other factors that may contribute to the measured PIM such as the ambient temperature and the relative humidity. For this purpose, PIM testing under different measurement conditions were considered by PTB and INTA. PIM testing at different; power levels, frequency, torque, relative humidity and ambient temperatures were carried out and the measurement results are currently being analyzed.

Impact

So far, the research undertaken under this project has led to eleven accepted peer-reviewed papers. One of them has been published in the IEEE Instrumentation and Measurement Magazine and its title is "Uncertainties in Small-Signal and Large-Signal Measurements of RF Amplifiers Using a VNA". Three papers have been published in international scientific journals. The remaining ten papers that have been published in the proceedings, which includes the following conferences: 2022 IEEE International Symposium on Measurements & Networking (M&N), Conference on Precision Electromagnetic Measurements 2022 (CPEM), Mulcopim 2022, 2023 IEEE 27th Workshop on Signal and Power Integrity (SPI), and Microwave Measurement Conference (ARFTG). This project has also provided inputs to 11 Technical Committees and/or Working Groups for fifteen international standards developed or under development by the IEEE, ETSI and IEC, including IEEE 287 part 1, 2, and 3, IEEE P2822 part 2, and IEC 62037.

The project has also been advertised to stakeholders via its website, a Twitter page (https://twitter.com/FutureComEMPIR), and a FutureCom LinkedIn discussion group (https://www.linkedin.com/groups/14027647/).

Impact on industrial and other user communities

The project directly involves industrial end users in its Technical Advisory Group (TAG). The project updated progress to the TAG members at Month 9, 18 and 27 meetings. All partners are in regular touch with the TAG member in their respective project activities.

The project has delivered a successful one-day workshop entitled "Measurement methods for passive intermodulation and environmental testing of electronic circuits" was held on Monday 18th September 2023 at the Berlin Messe in Germany. It was jointly organized by NPL and PTB under the umbrella of the European Microwave Week 2023. The workshop was attended by several participants from both industry and academia. There were two panel sessions, where in-depth discussions were held on the results and very constructive feedback was received from the participants and stakeholders.

A second workshop will be held in Rome in the month of July 2024 as a side event of the IEEE International Symposium on Measurement and Networking. The workshop agenda will contain topics and achievements regarding the measurement and characterization of active devices and circuits and the signal integrity and power integrity of FPGA chips and PCBs.

Impact on the metrology and scientific communities

The project has already participated in a Research Mobility Grant (RMG), and a researcher successfully completed a 3-month visit to NPL for joint research and the transfer of knowledge from an established NMI to a developing NMI. This has enabled a new project partner to play an active role in delivering some very important activities in the project. As well as the usual knowledge transfer mechanisms for this area of technology (e.g., by linking with IEEE-sponsored activities), the partners are engaging with the European Microwave Association (EuMA) as the preferred route for knowledge transfer within the European region. This is being achieved through active participation in the annual EuMW events and the EuMCE.

The project's results were disseminated through two short training courses; the first training course organised by Surrey and VSL on "non-50 Ohm and Multiphysics measurement", and the second organised by NPL on "Harsh Environmental Testing of RF and Microwave Circuits for Future Communications Technologies". The audience was composed of more than 35 attendees for both courses. In addition, the project is working to produce two Good Practice Guides; one for characterisation of active devices and circuits under large-signal measurement, and another for reliable PIM measurement of RF electrical signals used in communications systems.

Impact on relevant standards

The project has participated in 23 technical committee meetings and made contributions to several standards, including: IEEE P2822 Recommended Practice for Microwave, Millimeter-wave and THz On-Wafer Calibrations, De- Embedding and Measurements, DIN EN 62037, and several IEC 62037, 60153, 6116, and 63138 standards. The project partners, who are members of these technical committees, regularly inform the committees about the results of this project and will endeavour to ensure they are incorporated in any updates to standards.

Longer-term economic, social and environmental impacts

Guidelines for designing circuits with optimal SI and PI have the potential to bring economic benefits through cost efficiency, productivity gains and market competitiveness. They can also contribute to positive social impacts ensuring reliability, safety, and improved user experiences but also enhances connectivity, making advanced technology more accessible to a wider range of users. From an environmental perspective, these guidelines support energy efficiency and contribute to the reduction of electronic waste, aligning with broader sustainability goals.
A new measurement system was developed for PIM measurement using a single amplifier instead of two amplifiers which reduces the power consumption and thus reducing the carbon footprint of the measurement system.

List of Publications

1) Ahmed Sayegh, Frauke Gellersen, Friederike Stein, and Karsten Kuhlmann, "Evaluation and Comparison of PIM Measurement Uncertainty using Different Methods," *Mulcopim 2022*, pp. 1-9, Valencia, Oct. 2022. https://doi.org/10.7795/810.20221118
2) D. Allal et al., "RF Measurements for Future Communication Applications: an Overview," *2022 IEEE International Symposium on Measurements & Networking (M&N)*, Padua, Italy, 2022, pp. 1-6. https://doi.org/10.5281/zenodo.7899777
3) Phung, G. N. and Arz, U., "Modeling and Analytical Description of Parasitic Probe Effects in Measurements of Conductor-Backed Coplanar Waveguides," *Advances in Radio Science*, ARS-20, 119–129. https://doi.org/10.5194/ars-20-119-2023.
4) M. García-Patrón, M. Rodríguez, J. A. Ruiz-Cruz and I. Montero, "Uncertainty Budget in Microwave High-Power Testing," *IEEE Transactions on Instrumentation and Measurement*, Vol. 72, pp. 1-12, 2023, Art no. 1009512. https://doi.org/10.1109/TIM.2023.3317909
5) G. N. Phung et al., "Recommendations for the Design of Differential Thin-Film Microstrip Lines," 2023 IEEE 27th Workshop on Signal and Power Integrity (SPI), Aveiro, Portugal, 2023, pp. 1-4. https://doi.org/10.1109/SPI57109.2023.10145555
6) K. Lahbacha et al., "Signal Integrity Analysis of Coupled Thin-Film Microstrip Lines (TFMSLs)," 2023 IEEE 27th Workshop on Signal and Power Integrity (SPI), Aveiro, Portugal, 2023, pp. 1-4. https://doi.org/10.1109/SPI57109.2023.10145525

This list is also available here: https://www.euramet.org/repository/research-publications-repository-link/

Project start date and duration:		1 September 2021, 36 months
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Internal Funded Partners: 1. NPL, United Kingdom 2. CMI, Czech Republic 3. IMBiH, Bosnia and Herzegovina 4. INTA, Spain 5. LNE, France 6. PTB, Germany 7. TUBITAK, Turkey 8. VSL, Netherlands	External Funded Partners: 9. FH Aachen, Germany 10. SURREY, United Kingdom 11. TU Delft, Netherlands 12. UNICAS, Italy	Unfunded Partners: 13. Anritsu, United Kingdom 14. INEX, United Kingdom 15. Keysight BE, Belgium 16. METAS, Switzerland 17. NIBNV, Belgium 18. Nokia, Germany 19. Rosenberger, Germany 20. Thales, France
RMG1: IMBiH, Bosnia & Herzegovina (Employing organisation), NPL, United Kingdom (Guest-working organisation)		