# RF Measurements for Future Communication Applications: an Overview

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***Abstract*—In this paper research activities developed within the FutureCom project are presented. The project, funded by the European Metrology Programme for Innovation and Research (EMPIR), aims at evaluating and characterizing: (i) active devices, (ii) signal- and power integrity of field programmable gate array (FPGA) circuits, (iii) operational performance of electronic circuits in real–world and harsh environments (e.g. below and above ambient temperatures and at different levels of humidity), (iv) passive inter-modulation (PIM) in communication systems considering different values of temperature and humidity corresponding to the typical operating conditions that we can experience in real-world scenarios. An overview of the FutureCom project is provided here, then the research activities are described.**

***Index Terms*—FPGA, signal integrity, power integrity, passive inter-modulation, metrological characterization**

## I. Introduction

During the last decades till nowadays, communication customers demand reliable connections, preferably wireless, characterized by very high data rates.

To satisfy this request, during the last years, many wireless communication standards have been issued [1]–[3], and other standards are being developed [4]. Focusing the attention on this last standard, it is the more recent release of the 5$^{th}$ generation of mobile communication systems (5G).

Currently, we are assisting to the commercial rollout of the global 5G communications infrastructure in several parts of the world. This process, that is recently started, is expected to continue during much of this decade allowing more countries to have access to this new network. In fact, a recent study [5] has highlighted that during the 3$^{rd}$ quarter of 2021 the 5G subscriptions were 660 million, globally and it forecasts they are expected to grow to 4.4 billion by the end of 2027, representing the 49% of all mobile subscriptions.

Analyzing the distribution of the 5G subscriptions all over the world, it is possible to note that in the Northeast Asia region they represent 24% of mobile communication subscription, thanks to the positive impact on Chinese and South Korean markets. This percentage is around 20% in North America and only 6% in Western Europe [5].

The reason, behind this slow development of this technology, is due to the difficulties in transferring the achievements obtained by the research to their implementation in real devices available to the end-users, after a suitable production and testing phase carried out by the manufacturing industry.

This testing phase is fundamental to have devices that will be able to operate in actual operating conditions. For example, for developing self–drive capabilities, enabled by the 5G infrastructure, in a car, it should be equipped with electronic devices that must operate over a wide range of temperatures, as those could be experienced at different latitudes and longitudes around the world.

In this paper the preliminary results of the research activities



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developed within the FutureCom project – "RF measurements for future communication applications" are presented [6].

Stemming from the past experience of the project partners in (a) RF components characterization at different climatic conditions [7], [8], (b) S–parameters measurement [9], and (c) RF and power measurement [10], the project aims at providing effective technological solutions to the main issues currently faced by the industries for future communications. In particular, its main objectives regard:

(i) The characterization of active devices and circuits under realistic operating conditions and frequency ranges including millimeter-wave bands.
(ii) The evaluation of the signal integrity and power integrity on Field Programmable Gate Array (FPGA) circuits.
(iii) The performance assessment of communication system devices under different climate conditions.
(iv) The development of a novel measurement method for evaluating the passive inter–modulation (PIM) of RF signals.

A good practice guide describing the methodologies developed for the above-mentioned goals will be provided at the end of the project.

To reach these goals, the project involves: 8 European National Metrology Institutes (NMIs), one Designated Institutes (DI), 4 academic research institutes, and 7 industrial partners (telecommunication companies, RF, semiconductor, and measurement instrument manufacturers).

The paper is organized as follows: Section II provides an overview of the project, and preliminary results are reported in Section III. Finally, conclusions are given in Section IV.

## II. An Overview of the FutureCom Project

To effectively achieve the above-mentioned technical objectives, the project has been structured into four work packages (WPs), one per objective.

### A. Measurement of active devices and circuits (WP1)

For achieving the promised high data rates, modern communication systems must use wide frequency bands. To this aim, they are designed to deploy high-frequency bands.

Therefore, active devices and circuits, adopted in the development of these systems must operate in conditions far away from the classical impedance-matched linear measurement systems. Hence, successful commercial uptake of these systems needs measurement instruments able to characterize nonlinear active devices which operate in a non-50 Ω loading environment. Furthermore, this measurement capability must be validated until the sub–THz frequency range.

The goal of this work package will be the development of the measurement methods for the characterization of active devices and circuits, operating under realistic conditions (non-50 Ω impedance loading) at frequencies that include the millimeter-wave bands.

To this aim, the linearity response of the devices will be analyzed and new probing techniques will be developed.

### B. Signal integrity (SI) and power integrity (PI) of FPGA chips and PCBs (WP2)

Signal integrity and power integrity is fundamental. Especially when high-speed digital circuits, like FPGAs and CPUs, operate at a very high frequency. At the moment, many testing setups and instruments are available for this purpose. Even though they are, in general, traceable, no link is made, in terms of location and measured parameters, to the device under test (DUT).

The goal of this work package is aimed at completing the traceability chain to the DUT. Furthermore, PI aspects and traceable characterization of electromagnetic interference on FPGA will be also investigated.

### C. Environmental testing of electronic circuits (WP3)

The assessment of the system component performance in real and harsh environments is fundamental to warrant the expected performance. This means that they must be tested at the appropriate temperature and humidity levels.

Furthermore, the performance of electronic components changes during their lifetime. To better understanding this aspect, and also how the environmental conditions can affect the performance, accelerated aging tests should be carried out simulating the real operating and environmental conditions.

Consequently, the goal of this work package will be the development of methods for the assessment of components' performance in real and harsh environments and different operating conditions.

Two different types of electronic circuits will be considered for the environmental test: PCBs; and planar circuits on wafer substrates.

As the environmental test regards, two different types of tests will be taken into account: (i) age testing, where the electronic components are electrically tested before and after being subjected to a range of environmental tests; and (ii) in–operando testing, where the electronic components are tested whilst operating under realistic conditions.

### D. Measurement methods for passive inter-modulation in communication systems (WP4)

Passive inter-modulation in communication systems can produce undesired signals that can fall into other channels, causing a negative impact on many network key performance indicators (KPI), such as call drops, etc.

Modern communication systems need very high signal bandwidths to provide a service with very high data rates. In these systems, if PIM exceeds a specified threshold value, the required high signal bandwidth cannot be achieved. To avoid this issue, all RF components of the system must be tested.

To this aim, recently many manufacturers have developed PIM analyzers, but unfortunately, at the moment, traceable PIM measurement cannot be carried out, because there is no NMI in the world able to provide a traceable characterization of PIM signals.

The objective of this work package is the development and the validation of novel measurement methods for evaluating

Fig. 1. Vector PIM measurement system in use at PTB.

the PIM of RF electrical signals used in communications systems. Thanks to these methods, a setup for characterizing PIM references and/or calibrating PIM analyzers will be developed.

Based on an earlier work demonstrating and verifying a measurement system for narrowband measurements of complex non-linear frequency transfer functions [11], FH Aachen in cooperation with Heuermann HF-Technik GmbH has extended the scalar PIM analyzer (PIA) by Rosenberger with a phase-repeatable vector network analyzer developed in-house [12], providing PTB with a vector measurement system (Fig. 1). This system can provide calibrated mixed–frequency measurements based on the without-thru calibration method [13], which requires an additional power detector and phase reference. Research is currently underway at PTB to make this method traceable in the future. Alongside their partners, the Spanish National Institute of Aerospace Technique (INTA) will support these activities by providing its tests capabilities to perform PIM testing under different environmental and power conditions, namely thermal cycles between ±150 °C and RF power up to 500 W per carrier.

Additionally, a novel PIM standard is being developed at FH Aachen. This standard will enable the repeatable generation of IM signals at adjustable levels that are largely independent of environmental influences. This standard will then be characterized by the participating project partners within the scope of their respective capabilities. Based on the measured data, this standard can then be used for verification and possibly for calibration of non-linear large signal measurement systems.

## III. Preliminary Results

In this section, preliminary results regarding the ongoing research activity, carried out in each WP, are given.

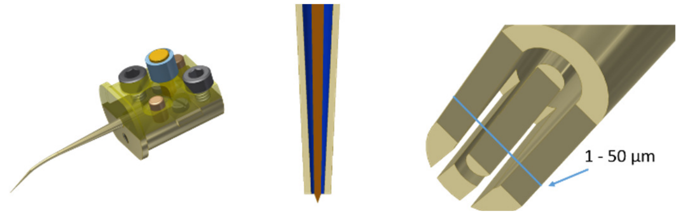



Fig. 2. Left: design of probe with holder. Center: probe construction, brown: PtIr inner conductor, blue: quarz glass dielectric, green beige: deposited Pt as outer conductor. Right: Ground-Signal-Ground structure at the probe's tip.

### *A. Measurement of active devices and circuits (WP1)*

As previously described in Section II, for developing new methods for the characterization of active devices and circuits, the designing of new probing techniques plays a very important role.

Considering the increasing frequencies adopted by modern and future communication networks, in this framework, the problems with parasitic effects in on-wafer measurements become more pronounced.

With the aim of solving this problem, within the project a novel type of small pitch sized and shielded on-wafer probe will be developed and tested. The current approach is based on a pulled platinum coated glass capillary with a platinum iridium wire inside. Platinum is used because it is acceptable in most semiconductor environments and it is a non-oxidizing noble metal. The platinum iridium wire is chosen because of its with quartz glass compatible melting temperature. Fig. 2 reports the main characteristics of the probe under development.

Furthermore, with mobile communication systems requiring increased data capacity, the current progression towards higher frequencies and new standards (i.e. 5G and beyond) is needed. Active load-pull measurements using modulated signals can provide accurate measurement of devices in non-50 Ω conditions. This is necessary to support a successful uptake of these higher frequency signals and new communication standards.

We show a partial demonstration of active load-pull in

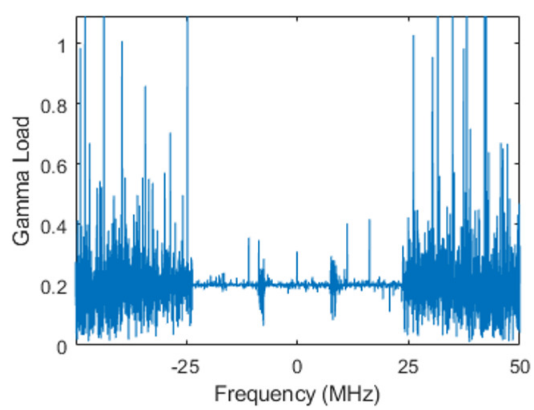



Fig. 3. Load reflection coefficient vs frequency after the emulation load pull algorithm has converged.

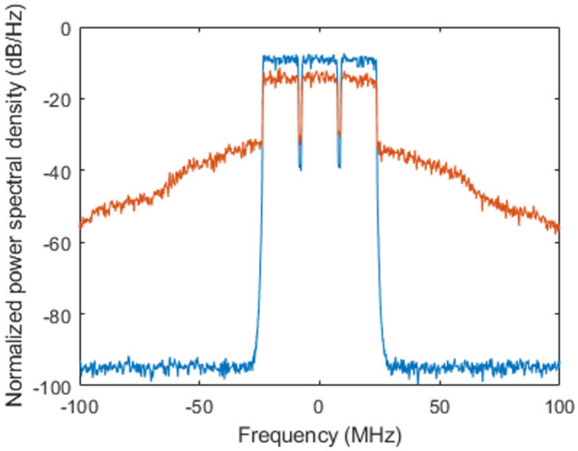



Fig. 4. Frequency spectrum of input signal (blue) and resulting output signal (red) under the load condition of Fig. 3.

an emulation context [14], [15]. These techniques allow for realistic non-50 Ω testing, reproducing the actual environment under which RF devices and components will be used. Which thus can predict device performance without need to realize a complete circuit or system. Some multi carrier OFDM signals using active load-pull on a GAN power amplifier have been tested, with the results below showing the realized reflection coefficient over frequency (Fig. 3) and the spectrum of the signal used (Fig. 4). These reflection coefficients will determine the performance of the DUT, including linearity, distortion, and efficiency and are thus essential information to an RF designer.

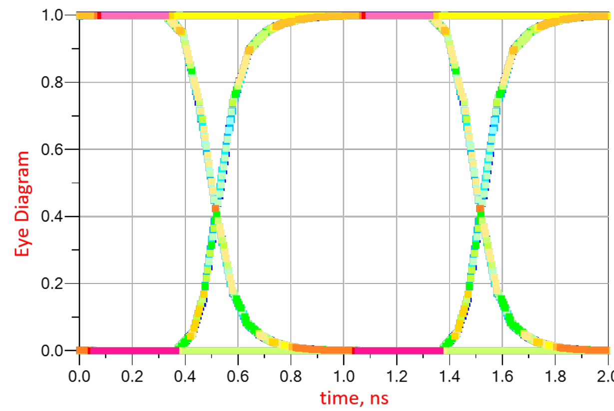
### *B. Signal integrity (SI) and power integrity (PI) of FPGA chips and PCBs (WP2)*

Assessing the signal and power integrity is a major challenge when designing high-speed digital circuits working at frequencies above 1 GHz, therefore specific tasks of this Project will be devoted to such a topic.

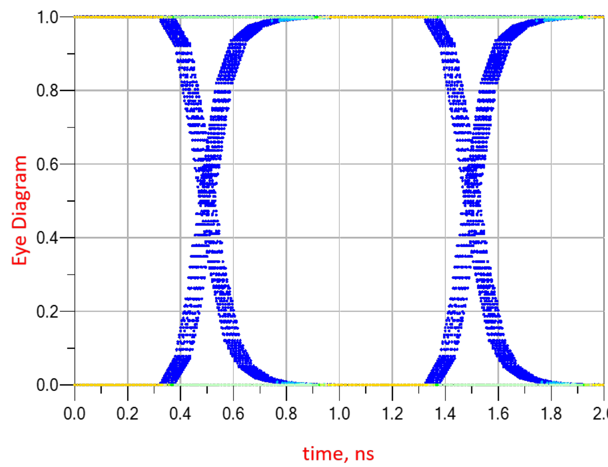
Preliminary analysis has been devoted to assessing the effect of terminal and line mismatch on the signal integrity, by comparing two technological solutions for realizing the substrate of the wafer structure: Case 1 refers to the use of SiOx:H films, whereas Case 2 refers to Su8. A microstrip line has been designed with the nominal parameters given in table I, that ensure for both cases a nominal characteristic impedance $Z_0$ = 50 Ω.

TABLE I
NOMINAL VALUES OF THE PARAMETERS FOR THE CONSIDERED CASE STUDIES.

| Parameters | Case 1 SiOx:H | Case 2 Su8 |
|---|---|---|
| Dielectric relative permittivity | 4 | 2.85 |
| Dielectric loss tangent (@10 GHz) | 0.01 | 0.01 |
| Dielectric thickness (μm) | 10 | 20 |
| Metal conductivity (MS/m) | 59 | 59 |
| Trace width (μm) | 20 | 52 |
| Trace thickness (μm) | 0.5 | 0.5 |




(a) Case 1

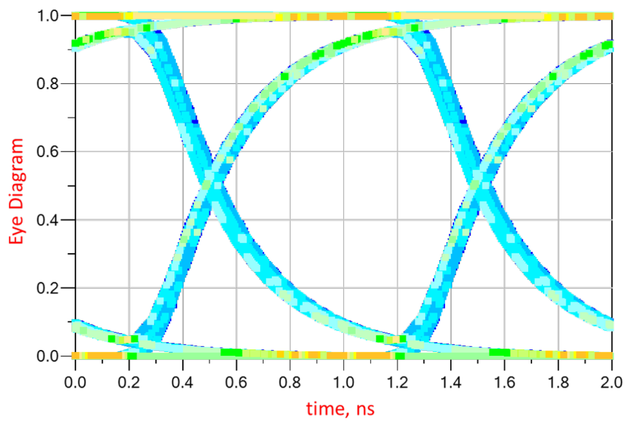



(b) Case 2

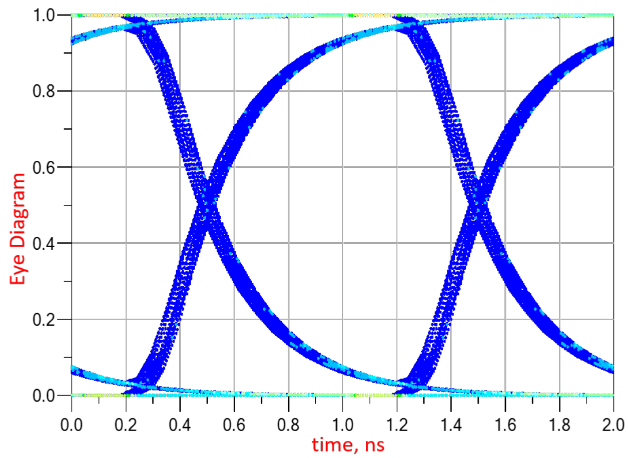
Fig. 5. Eye diagrams obtained for the considered digital signaling system working at 1 Gbps, in the matched case.

The microstrip line has been tested as a digital channel working at a very high bit rate: to this end, the line was driven by a voltage square pulse train with $V_{low}$ = 0 V, $V_{high}$ = 1 V, rise and fall times equal to $t_r$ = $t_f$ = 1 ps, bit rate of 1 Gbps. The source was terminated with a 50 Ω matching resistance of to avoid any reflection from the driver section. The digital channel was terminated on a capacitor of 1 pF, emulating the receiver (buffer). The interconnect length is assumed to be 15 mm. The eye-diagram plots obtained for the two cases are reported in Fig. 5, for the nominal case (matched line). They show comparable performance both in terms of eye opening and time jitter, with a slightly better behavior for Case 1.

Next, the two solutions have been compared also in a more critical condition, considering a larger capacitance for the buffer (5 pF) and assuming a line made by three tracts of 5 mm length. The external tracts have been again matched to $Z_0$, whereas the inner one was mismatched, by assuming a line width $W$ equal to 10 μm (case 1) and to 40 μm (case 2). The new results are plotted in Fig. 6. By comparing the two cases, once again the results are comparable, even if now a slightly better performance is observed for Case 2. As a




(a) Case 1




(b) Case 2

Fig. 6. Eye diagrams obtained for the considered digital signaling system working at 1 Gbps, in the mismatched case.

conclusion, both the technological solutions can be taken into consideration to realize the testing prototypes for this Project.

### *C. Environmental testing of electronic circuits (WP3)*

Currently most accelerated environmental testing is undertaken using DC bias voltages representative of DC applications. However, the impact of this environmental testing for high-frequency applications is not widely understood and needs further investigation. For DC measurements of insulation resistance, there is a range of standard test methods designed to give insight and understanding of appropriate clearance and creepage distances for electronic assemblies. Such, state of the art measurement consists of insulation resistance measurements of up to $10^{14}$ $\Omega$ over several hundred channels. The large number of channels is necessary to be able to gain statistically relevant data within a single test run and it should be noted that throughout testing, large bias voltages are held across the samples. Furthermore, the high temperature, humidity and bias voltage are all driving factors in electrochemical degradation processes which can cause the failure of electronic assemblies in the field.

In this framework, the activity of WP3 has been focused on the analysis of most relevant technical standards defined for environmental testing of electronic circuits. The analysis has been carried out by considering several kinds of fields of application like automotive one and industrial ones to cite a few. A deep analysis of the literature has been made for identifying the most suitable standard to be applied in the project, for performing the following type of testing:

- test#1: Electrically test PCBs before and after they have been subjected to various environmental conditions;
- test#2: Electrically test PCBs operating under a range of environmental conditions;
- test#3: Electrically test on-wafer circuits before and after they have been subjected to various environmental conditions;
- test#4: Electrically test on-wafer circuits operating under a range of environmental conditions.

### *D. Measurement methods for passive inter-modulation in communication systems (WP4)*

In the context of the FutureCom WP4 activities a first step towards a traceable uncertainty budget is made. Therefore, different approaches are analyzed and compared initially on the basis of a scalar PIM Analyzer. Generally, the IEC 62037-1 [16] presents the course of action for measurements of passive intermodulation. This standard also includes the calculation of a measurement uncertainty budget. We are working on a more detailed uncertainty budget and the specifics are submitted to be published in [17].

We evaluate amongst others the connector repeatability and drift contributions. Especially, the power level uncertainty of the two carriers is considered individually. For this purpose, two different methods are used to analyze the carrier power uncertainty. The first method determines the carrier power level uncertainty using a fitted analytical model for a two-tone power sweep [18], [19] while the second method calculates the carrier power uncertainty based on measurements of one-tone power sweeps. The two obtained budgets are then compared with the budget yielded by the IEC 62037-1 approach. The detailed procedures for the PIM measurement uncertainty calculations for every contributor can be found in [17].

Measurements are done using a scalar PIM Site Analyzer (PIA) from Rosenberger with 7/16 connector type, Low PIM load and a DUT. The latter is a PIM standard from Spinner GmbH (-80 dB at 2.05 GHz, 2 x 43 dBm) which is connected via a 4.3-10 to 7/16 adapter to the analyzer while the other end is connected to the Low PIM load.

The results of the PIM measurement uncertainty budget are shown in Fig. 7, where the PIM3 uncertainty versus two-tone power in dBm is plotted. It reveals a passable agreement between the model-based and the measurement-based method. We could figure out that the connector repeatability has only a minor impact whereas the drift is found to be an important contributor to the overall uncertainty budget. The newly added contributors expand the proposed uncertainty budget from IEC 62037-1 significantly. Future works at higher power levels

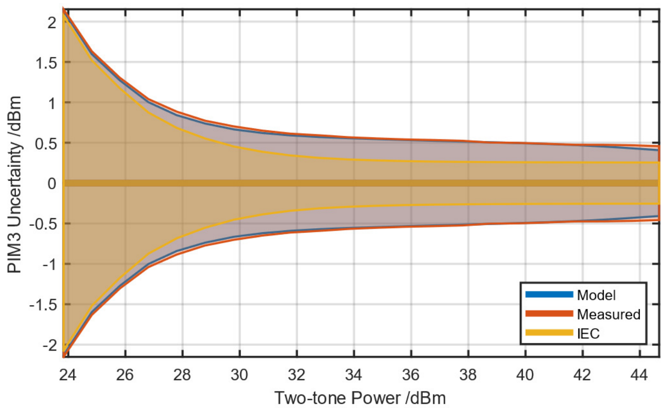



Fig. 7. PIM3 uncertainty calculated using the proposed methods and the IEC 62037-1 method.

and wider temperature span will be arranged with INTA's collaboration.

Furthermore, PTB is very involved in the IEC TC 46 working group 6 (Passive Intermodulation Measurement). In the last 9 months, the parts 1, 2, 3, 5, and 6 of the IEC standard 62037 were updated, and the new parts 7 and 8 have been written and will probably be published in summer 2022.

## Conclusions

Future communication networks will be developed to meet the increasing demand of fast and reliable connection of modern users. To effectively realize them in real-world scenarios, measurement and testing for the characterization of devices and components, under different environmental conditions, play a very important role.

In this framework, the FutureCom project is aimed at providing effective technological measurement solutions to the several issues which make difficult the above-mentioned characterization. The preliminary results obtained by the FutureCom project have been presented in this paper.

Regarding WP1 activities, the development of an innovative probe for the characterization of active devices and circuit which operate at very high frequencies has been presented.

The assessment of the effect of terminal and line mismatch on the signal integrity, by comparing two technological solutions for realizing the substrate of the wafer structure has been carried out in WP2. In WP3, several technical standards for environmental and age and in–operando testing have been studied and analyzed to develop the first test setups.

The first investigation of PIM measurement uncertainty budget within the framework of WP4 activities suggests a reasonable expansion of relevant uncertainty contributors to the measurement uncertainty budget proposed in the IEC 62037-1. The impact of power level uncertainties, considered individually, and the drift contributions are significant, whereas connector repeatability has a minor influence on the overall budget. Two methods are demonstrated to calculate the power level uncertainty of each carrier. As they only show slight deviations, the model-based method could be an alternative if an approximation of uncertainty is tolerable. Furthermore, a new method will be developed for evaluating the PIM uncertainty budget using a traceable vectorial PIM measurement system.

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