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Authorship
Preparation of this Guide was led by Ahmed Sayegh of the Physikalisch-Technische Bundesanstalt (PTB), Braunschweig (Germany) with extensive input from all members of the EMPIR 20IND03 project ─ WP4 team. The discussion and input of all the partners in the project WP4 and their colleagues are greatly appreciated.

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Good Practice Guide for Reliable PIM Measurement of RF Electrical Signals used in Communications Systems

Contents

Preface

In the European FutureCom project [1], a major effort has been undertaken to establish new capabilities for Passive Intermodulation (PIM) measurement using industry-grade connectors like the 7/16 connector and the 4.3-10 connector, typically used for telecommunications installations such as 4G LTE and 5G base stations. The purpose of this Good Practice Guide (GPG) is to provide an overview of the main outcomes of this project together with useful information on recommended measurement practice, different sources of uncertainty and the determination of uncertainties. This Good Practice Guide is not intended to replace the existing PIM measurement guidelines available in the literature. Instead, it aims to present useful best practice recommendations gained from the work performed within the FutureCom project during the project's lifetime from 2021 until 2024.

The work in FutureCom (Work Package 4) has been focused on developing accurate measurement methods of PIM with considering the measurement uncertainties. To this end, different measurement capabilities for measurement of RF signals and PIM signals in industrial RF connector systems (4.3-10 and 7/16 at 1.8 GHz and 2.1 GHz frequency bands) were successfully established. In addition to that, new capabilities were developed for the measurement of scattering parameters (S-Parameter) of 4.3-10 and 7/16 connector-type adapters. Using these measurement capabilities, high-power RF signals and PIM signals were measured successfully, and the uncertainty budgets were determined. For a precise measurement of PIM, the impact of the environmental and measurement conditions (different RF power levels, torque, temperature & relative humidity) were also investigated. The investigation results confirmed that the measurement of PIM signals is strongly dependent on the temperature of the DUT at the measurement time and the RF power level at the DUT port while the relative humidity has a weak impact on the measured PIM. Only by taking all these factors into consideration, reliable uncertainties for PIM signals can be stated.

This Good Practice Guide is organized as follows. In the Introduction, an overview of the PIM measurement systems is given. Generally, PIM systems can be either scalar or vectorial systems. This section provides a brief description of both scalar and vectorial PIM systems, and some recommendations for the choice of the suitable equipment for a better PIM performance.

In Section 2, the calibration of PIM systems (both scalar and vectorial) is elaborated. In the beginning, a detailed description of the calibration standards is given, and then a guideline for performing the calibration process is provided. A short description of the 'Without Thru' calibration algorithm [2] is elaborated, which is used for calibrating the vectorial PIM system at the ETSI B1 frequency band (UMTS2100). This section also presents the methods that are used for establishing the traceability of the calibration standards, paving the way for traceable PIM measurements.

Section 3 addresses the verification process of the PIM measurement system after calibration. A guideline for performing the verification process is given in this section. A PIM standard with known PIM is required to verify the performance of the measurement system before the actual

PIM measurement. This section also contains a useful advice for identifying and resolving the errors related to PIM measurement method.

Section 4 provides a brief description of a typical PIM measurement process. It shows the importance of controlling the measurement setup from any mechanical stress or unstable measurement conditions. In this section, useful recommendations are also given for reducing the errors associated with the PIM measurement procedure.

In Section 5, the subject of uncertainties in PIM measurement is presented. The main uncertainty contributors are identified and evaluated. For vectorial PIM system, the uncertainty budget is calculated based on a modified measurement model, which is implemented through MATLAB software and VNATools [3] for uncertainty propagation. Examples of the uncertainty budget of PIM are also given in this section, illustrating the impact of each uncertainty contributor on the PIM measurements.

Section 6 presents the impact of the different measurement conditions (different RF power levels, torque, temperature & relative humidity) on the PIM measurements. The PIM measurement uncertainty cannot be expressed reliably without considering the impact of all these factors.

1 Introduction

Passive Intermodulation (PIM) is a form of intermodulation distortion that occurs when two or more RF signals pass through a nonlinear passive element such as corroded connectors or bad cables, which have been thought for long as linear elements [4]. In the past, PIM measurements were only required for a few systems, e.g. satellite communications or the newer generations of mobile communications. However today, PIM problems in cellular communications systems are growing as wider bandwidths are required to transmit higher data rates [5]. The higher signal bandwidths required cannot be achieved if the PIM level exceeds certain specification values. Today, the RF passive components installed in the RF signal path can generate intermodulation signals at - 100 dBm or higher, which can degrade the performance of the communication system. Therefore, it is essential to measure PIM accurately to avoid the PIM associated problems.

PIM measurement systems are generally described as a scalar or vectorial PIM systems. Scalar PIM systems can measure the PIM magnitude only, while the vectorial PIM systems are capable to measure both PIM magnitude and PIM phase. A general description of scalar PIM and vectorial PIM systems are given in Section 1.1 and Section 1.2, respectively.

1.1 Scalar PIM Measurement Systems

The typical setup of scalar PIM systems is composed of two RF signal generators, two RF power amplifiers, filter, combiner, duplexer and scalar receiver. The scalar PIM systems can be designed as portable PIM analyzers, which are mostly used for on-site PIM test, or as laboratory benchtop PIM systems. As an example, a block diagram of the scalar PIM system at INTA laboratory is shown in Figure 2 [6].

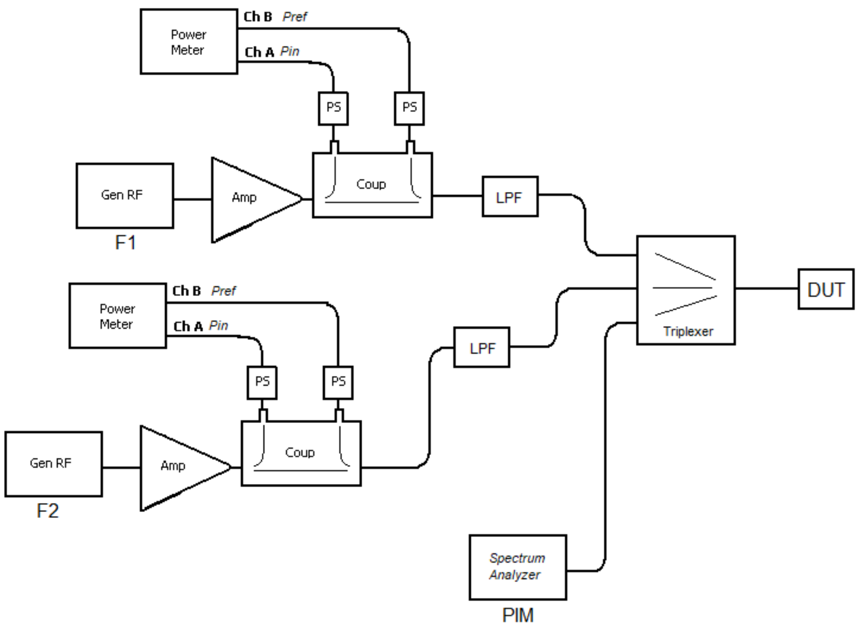

Figure 1. Block diagram of the scalar PIM system at INTA laboratory [6].

This scalar PIM system comprises of two high-power lines, each of which is made up of the following: RF generator, a high-power amplifier, a bidirectional coupler, two power sensors, a power meter, and a low pass filter. These two high-power lines end up in a triplexer (filter unit), which combines both high-power carriers, rejecting its 3rd-order PIM, and therefore feeding them into the device under test (DUT) clean of any spurious PIM. The PIM produced by the DUT travels backwards through triplexer to the spectrum analyzer, which is used as a receiver to measure the PIM level (magnitude only).

1.2 Vectorial PIM Measurement Systems

Vector-PIM systems are designed to measure the magnitude and phase of PIM signals. Within the framework of the Joint Research Project (JRP)−FutureCom project (WP4) [1], the participating partners (except PTB and FH Aachen) have used scalar PIM measurement systems. The PTB vectorial PIM system comprises of two VNA-based RF transmitter units, VNA-based receiver unit, two power amplifiers, two couplers, switch matrix and filter unit as shown in Figure 2. More details about this vectorial PIM system can be found in [7].

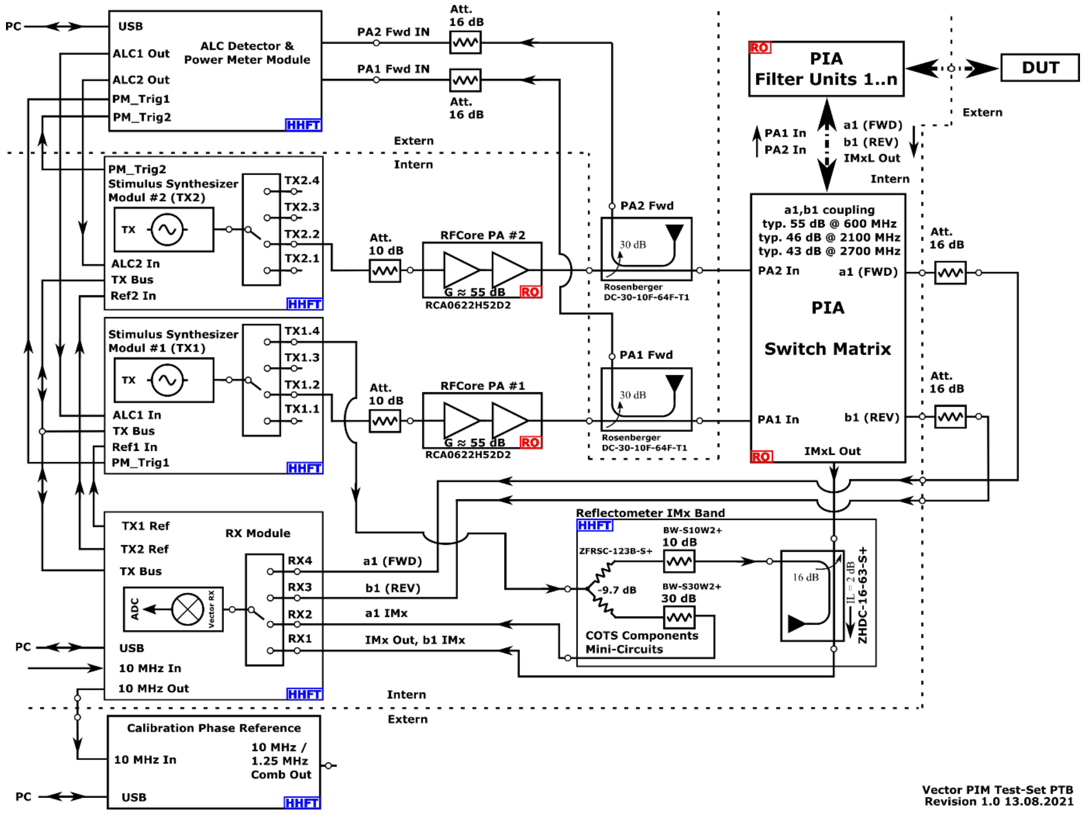

Figure 2. Block diagram of PTB vectorial PIM system.

It is observed that the RF power stability has a significant impact on the accuracy of the PIM measurements. Therefore, an automatic level control (ALC) is employed to monitor and control the RF output power delivered to the DUT. Two couplers are attached between the power amplifiers output and the ALC unit to minimize the drift of the RF output power.

1.3 Recommendations for Selection of PIM Measurement Equipment

This section provides recommendations for selecting suitable RF components (e.g. cables, adapters, PIM load, etc.) for PIM measurements, which are as follows.

- All the equipment utilized in the PIM measurement systems (both scalar and vectorial PIM systems) shall have low PIM levels. This might look obvious but unexpected PIM performance of system components can show up after the development of the measurement system. For instance, high-power amplifiers must have low harmonics and shall be properly filtered, to avoid the presence of harmonics.
- It is of utmost importance to ensure that the power amplifiers can provide accurate, stable, and consistent RF power over the time at the DUT input port. It is important to make sure that all the selected RF components, such as filter, combiner, duplexer, have low PIM levels.
- All the measurement equipment shall be included in calibration plans, principally the RF generators. Amongst the different parameters to calibrate, some of the most important are the frequency stability and the harmonics levels. Any derating on them may affect PIM performance, especially for very low-level PIM measurements.
- If the use of a cable between the DUT and the measurement system is unavoidable, the cable must be characterized and should produce a low PIM and also the cable uncertainty should be included in the uncertainty budget. It is also important to characterize the RF power at the cable end where the DUT is connected.
- The low-PIM load shall be capable of handling the maximum RF power of the two transmitters simultaneously; and at that high RF power it should produce a low PIM level.
- If applicable, the clocks of the utilized equipment shall be properly configured and synchronized, otherwise PIM will not be properly detected and measured.
- If any low-noise pre-amplifiers are to be used for PIM measurements, it is of the utmost importance to be sure that no saturation takes place, as it has a clearly nonlinear effect and in consequence the PIM level increases.
- Quality diplexers must be used to isolate the receiver from strong signals from the amplifier(s) to avoid creating parasitic intermodulation products inside the receiver.
- A spectrum analyzer could be used as an RF receiver in some measurement systems. The spectrum analyzer has been proven as one of the highest uncertainty contributors for PIM measurements. Therefore, among other characteristics, it is obvious that the precision of the spectrum analyzer affects the measurements.
- The stability of the RF output power of the amplifier can significantly affect the accuracy of the PIM measurement. Therefore, it is advised to use an automatic power level controller to ensure that the desired power is delivered consistently during the measurement time.

2 Calibration of PIM Measurement Systems

For accurate PIM measurements, the PIM system must be calibrated before performing the actual PIM measurement. The calibration involves characterization of the RF power delivered to the DUT reference plane, and calibration of the RF receiver at the expected PIM levels. Section 2.1 and Section 2.2 describe the calibration of the scalar and vectorial PIM measurement systems, respectively. Section 2.3 provides a good practice advice for PIM calibration.

2.1 Calibration of Scalar PIM measurement Systems

The calibration of scalar PIM systems is carried out in line with the guidance given in IEC62037-1 [8]. First, the two-tone RF power must be well characterized, using two calibration standards: a power meter and a calibrated RF attenuator. The power meter is connected in series with the RF attenuator to the output port of the PIM system (reference plane) where the DUT is connected. The power reading may be influenced by the presence of higher harmonic components in the signal, especially the reading of diode-type sensors is more sensitive to higher harmonic components compared to thermistor or thermoelectric sensors. The scattering parameters (S-Parameter) of the RF attenuator and the connecting adapters must be characterized beforehand. The power meter should be configured according to its manufacturer's recommendations.

In the JRP FutureCom Project, an RF power source (more than 30 dBm) was measured by different partners as a travelling RF power standard. As an example, the measurement setup at CMI laboratory is shown in Figure 3. The comparison results of RF power measurements show very good agreement among the results yielded by the participating laboratories. For example, Figure 4 shows the measured RF power by PTB, INTA and CMI at 36 dBm for frequencies 1805 MHz, 1820 MHz, 1830 MHz and 1840 MHz.

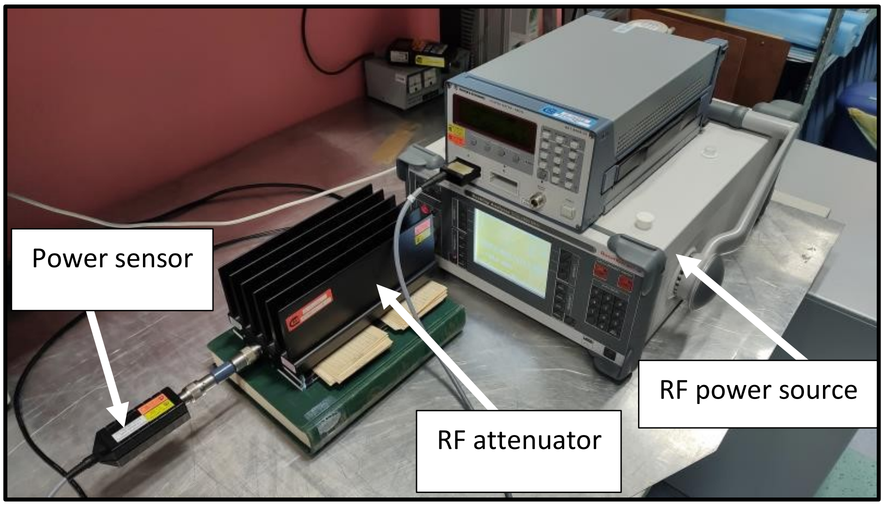

Figure 3. RF power characterization using a power meter and RF attenuator at CMI laboratory.

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It is observed that the RF power level stability is strongly dependent on the heating of the power amplifiers. While the power amplifier is active continuously to deliver a specific RF power, the measured power level deviates slightly over time. Figure 5 shows an example of the RF power deviation at 1805 MHz over 60 minutes. So, it is recommended to include the stability of the RF power (power deviation) in the uncertainty of the measured RF power.

Next, the RF receiver (e.g. spectrum analyzer) should be calibrated at the targeted frequency and power of the PIM signal. To this end, a reference RF source is required to calibrate the receiver. One option is to use a characterized PIM standard as a reference for calibrating the PIM receiver. However, this option requires characterization of the PIM standard itself beforehand. If a PIM reference is not available, a calibrated external RF signal source is the alternative to calibrate the PIM receiver, but care should be taken to consider the mismatch errors and the risk associated with the RF signal injected into the PIM analyzers (if applicable).

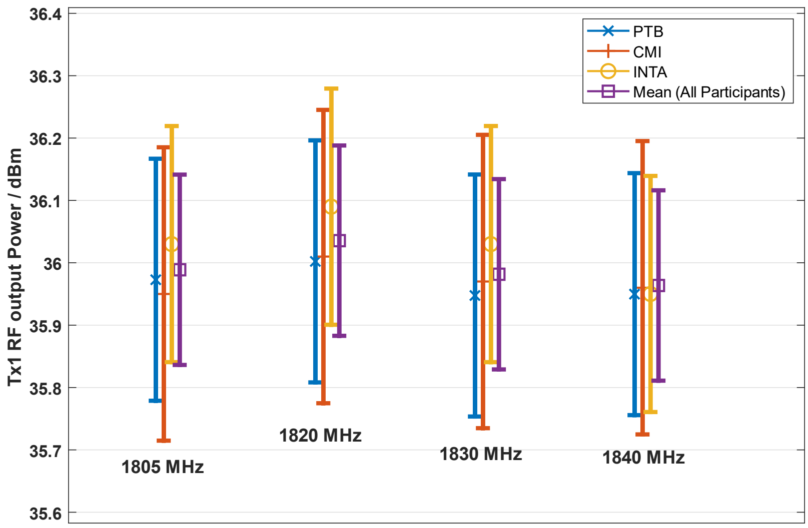

Figure 4. RF power measurement by PTB, CMI and INTA against the reference values at 36 dBm.

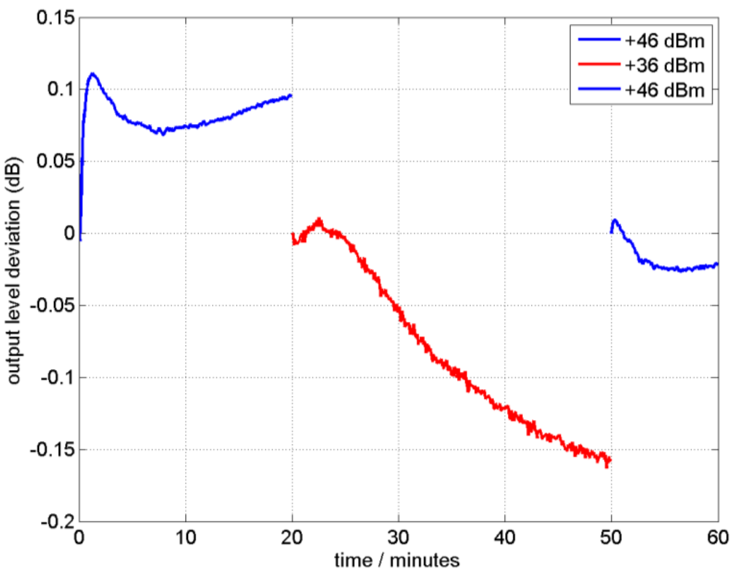

Figure 5. RF power measurement over 60 minutes at 1805 MHz.

2.2 Calibration of Vectorial PIM Measurement Systems

The vectorial PIM systems can be calibrated in the same way as the conventional VNA systems. However, the calibration algorithm must be capable to deal with the nonlinear measurements (such as PIM measurements). For the JRP FutureCom Project, PTB and FH Aachen partners have used vectorial PIM systems for their measurements. The PTB vectorial PIM system is calibrated using a 'WithoutThru' calibration algorithm. This calibration algorithm has the capability to deal with the nonlinear measurements. It requires five calibration standards: short, open, load, power meter and phase reference, as depicted in Figure 6. For PTB measurements, these calibration standards are of 4.3-10 connector type.

Figure 6. PTB calibration standards for 'Without Thru' calibration.

The traceability of these calibration standards was established as a part of the JRP FutureCom project. For the SOL calibration standards, the traceability was established by PTB and LNE with support from METAS. As an example, Figure 7 shows the reflection coefficient (S_{11}) of open standard of 4.3-10(f) connector type.

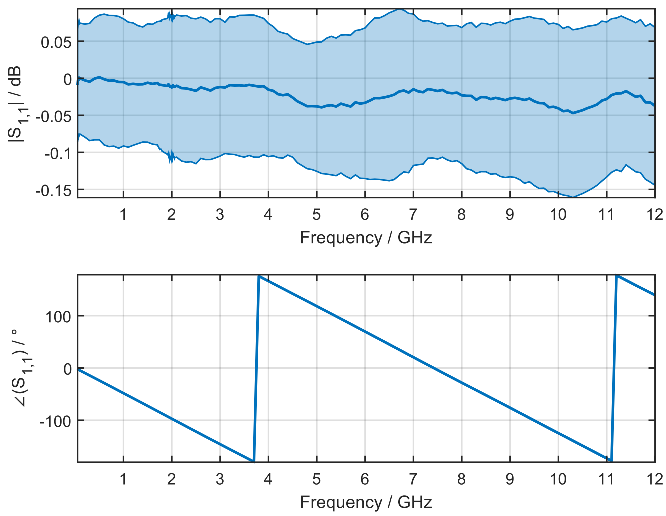

Figure 7. Reflection coefficient (S_{11}) of open calibration standard (4.3-10 type).

The third calibration standard is the power sensor. The reflection coefficient of the power sensor was characterized at PTB, and the power uncertainty was taken from the manufacturer datasheet. The fourth calibration standard is the phase reference (comb generator) from Heuermann HF-Technik GmbH as shown in Figure 6. The output signal of the comb generator (CG) was characterized using a calibrated oscilloscope and the phase of the measured output signal is depicted in Figure 8.

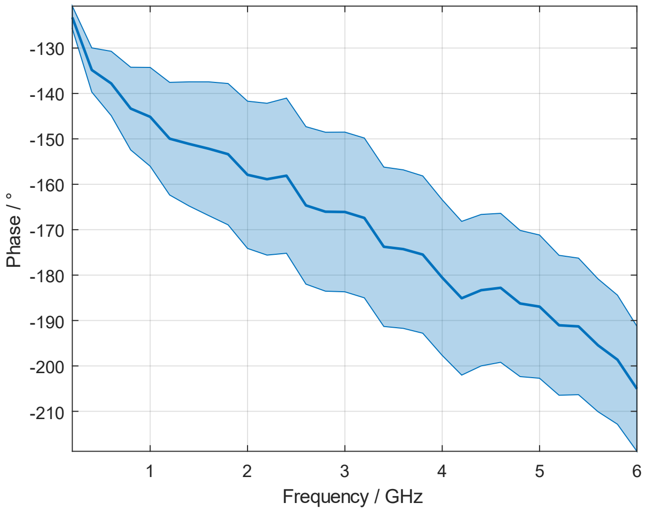

Figure 8. Phase of the CG output signal.

The PTB vectorial-PIM measurement system has one physical port, which was used for measurement of transmitter 1, transmitter 2 and PIM signals. For this reason, the physical port is modelled as three logical ports, and therefore the 'Without thru' calibration algorithm is implemented to produce three error boxes – two error boxes are associated with the transmitter frequencies and the third error box is related to the PIM frequency. Each error box can be represented as 4-error term model as shown in Figure 9. The error terms are the directivity term (E_D), source match term (E_S), forward tracking term (E_F) and reflection tracking term (E_R).

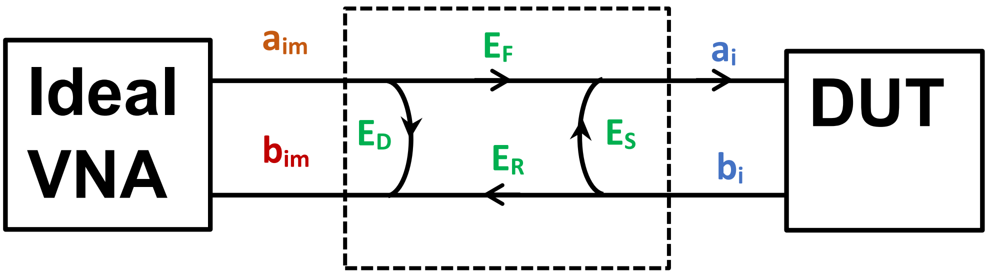

Figure 9. representation of each error box as 4-term error model.

The three error terms (E_{FR},E_D, E_S) are determined based on the measured reflection coefficients of SOL calibration standards and their known reflection coefficients. The relationship between the measured and known reflection coefficient of any SOL calibration standard is given in [2]:

$$m_x = E_D + \frac{E_{FR} \cdot r_x}{1 - E_S\, r_x} \tag{1}$$

where m_x is the measured reflection coefficient and r_x is the corresponding known reflection coefficient.

For nonlinear measurements, it is essential to separate the error term E_{FR} into two error terms (E_F, E_R). For this purpose, two additional standards are required, namely a power detector and a comb generator.

The magnitude of E_R is calculated as [2]:

$$|E_R|^2 = |E_S b_{1m} - \Delta E \cdot a_{1m}|^2 \cdot \frac{1 - |\Gamma_P|^2}{P_m} \tag{1}$$

where

ΔE: delta (ΔE) for each port frequencies and is given as $\Delta E = E_S \cdot E_D - E_{FR}$
Γ_P: reflection coefficient of the power meter
P_m: measured output power of the transmitter at the reference plane

The phase of error term E_R is calculated for each port frequency as given in [2]:

$$\angle E_R = \angle \left[\frac{1}{a_r} (b_{1m} - b_{1m} E_S \Gamma_r) \right] \tag{2}$$

where

Γ_r : reflection coefficient of the comb generator.
b_{1m} : b_{wave} coming from comb generator and measured by the receiver of PIM measurement system.
a_r : known signal coming out from comb generator to the VNA receiver.

Once the fourth error term E_R is calculated, the error term (E_F) can be calculated as [2]:

$$E_F = \frac{E_{FR}}{E_R} \tag{3}$$

The measured waves at port i are corrected based on the two following equation:

$$a_i = \frac{(b_{im} - b_{im} E_S - \Delta E \, a_{im})}{E_R} \tag{4}$$

$$b_i = \frac{(b_{im} - a_{im} E_D)}{E_R} \tag{5}$$

where b_{im}, a_{im} are the measured waves at port i while a_i and b_i are corrected waves.

2.3 Recommended Good Practice for PIM Calibration

This section provides a good practice advice for calibration of PIM measurement systems as follows.

- It is recommended to warm-up the PIM measurement system and the calibration equipment for a time interval recommended by their manufacturers, typically 30-60 minutes.

- It is of a good practice to check that the calibration standards are functioning as intended. Any unexpected behavior should be investigated before performing the calibration process.
- The calibration devices such as the power sensor and RF attenuator should be capable of withstanding the two-tone RF power at the used frequencies. It is preferred to automate the calibration process to speed up the measurement and therefore avoid heating of the RF attenuator.
- It is important to make sure that the calibration standard is tightly connected with the recommend torque level.
- It is observed that the power amplifier stability and the insertion loss of the RF attenuator are the main contributors to the RF power uncertainty. So, it is recommended to characterize the S-parameter of the RF attenuator accurately and to monitor the stability of the RF power during the calibration process.
- It is important to consider the impact of adapters that are used for connecting the DUT to the PIM system, not only on the PIM level but also on the RF power delivered to the input port of the DUT. The adapter impact is mainly due to the variations in the return loss and insertion loss of the adapters. Therefore, the adapter must be characterized before performing the actual measurements. The adapters must also have minimum PIM levels.

3 Verification of PIM Measurement System

The performance of PIM measurement system should be checked after the calibration process and before performing the actual measurement. Two verifications are recommended before and after PIM measurement. The first verification is intended to make sure that setup is free of PIM while the goal of the second verification is to confirm the ability of the measurement setup to detect PIM correctly. For the latter, a PIM reference with known PIM levels is required for demonstrating the verification of the PIM measurement system as follows:

- The first verification is carried out by measuring the residual PIM of the system, which is performed by connecting a low PIM load to the PIM system without DUT. This process would help the laboratory staff to judge about the impact of the residual PIM on the PIM produced from the DUT. The typical value of the residual PIM is 10 dB below the spec of the DUT. For very low PIM levels, this margin may be reduced to 5 dB upon agreement with the customer.
- The second verification is performed to ensure that the system can detect the required PIM level. To this end, at least two PIM standard with known PIM levels should be measured by the PIM system to validate the detected PIM results. For a satisfactory performance of the PIM system, the measured PIM level must be within their stated uncertainty at the prespecified RF powers of the RF signals. Otherwise, requirement and performance may not match.

If the measurement system fails to meet the expected performance, the following measures are recommended:

- If the residual PIM is stronger than the expected level, replace the low PIM load and measure the residual PIM again. If the measured residual PIM is still too high, it should be checked whether all RF connectors are properly tightened. Disassembly and cleaning of the connector might help to remedy the problem.
- It is also recommended to verify the performance of the measurement system using two different PIM standards (if possible), to detect any false results that might be yielded due to any damage of the PIM standard.
- All connections should be as relaxed as possible to avoid the occurrence of stress or tension. Experience shows that mechanical stress and tension can cause PIM and would falsify the result.
- It is recommended to tighten the mated pairs of RF connectors using calibrated torque wrenches to the torque level specified by the connector manufacturer. Commonly, 5 Nm is an acceptable torque value for 4.3-10 connectors.
- It is important to check that the RF power amplifiers are off before disconnecting the DUT from the output port to avoid any possible RF burn that might happen to the personnel.

4 Recommendations for PIM Measurement

This section describes good practices for performing PIM measurement after the successful completion of the calibration and verification processes, and they can be summarized as follows:

- The DUT should be inspected visually to ensure that the DUT is physically qualified for the measurement.
- Before the PIM measurements, it is important to measure the reflection coefficient of the DUT at a low power level to avoid any possible damage that may occur during the PIM measurement if higher power would be reflected to the measurement system.
- The DUT input port should be tightly connected to the reference plane of the measurement system, where the calibration is performed, using a suitable torque wrench. The other output ports of the DUT should be terminated with proper low PIM loads.
- It is recommendable to use controlled and appropriate torques when tightening all setup's elements, commonly 25 Nm for 7/16 connector type and 5 Nm for 4.3-10 connector-type.
- All the equipment utilized, and likewise the DUT itself, should be deployed/installed with utmost care, so that no hidden tension or torsion is present. With very low-PIM level measurements, any of these tiny aspects might impact the overall PIM performance.
- Since PIM is strongly dependent on the two-tone-RF power, it is recommended to constantly monitor the output power of the high-power amplifiers during the test, to be aware of potential fainting or abrupt responses that may impact PIM performance.

- It is recommended to measure PIM at four different rotational positions to check the repeatability of the PIM measurements. This can be achieved through rotating the DUT connector to a different azimuth at each repetition before reconnecting it to the PIM system connection port. The DUT should be completely disconnected during the reconnection process to avoid any tension/stress on the inner conductor. The torque level applied for all the repeatable PIM measurements should be constant.
- Aside from the common connector care and the torque consistency recommendations, temperature of the DUT and interfaces, not necessarily ambient, appeared to be one of the main influences. The local temperature can be a function of the duration of the measurement cycle so systematizing the timing of the measurement might be useful.
- It is recommended to keep the setup free of any external vibration or physical instability source. Even the personnel in charge of carrying out the test campaign shall carefully proceed in the surroundings of the test bench. Any wrong steps, a slight touch or chafing, can impact on PIM performance, mostly at low PIM levels.
- For PIM measurements at very low power levels, close to the noise floor, it is also important to record noise levels, both in real time and in average, to distinguish PIM from noise. A typical example of spectrum analyzer configuration is shown in Figure 10.
- As PIM can sometimes vary in time, it is recommended to record two different traces: one in real-time, another in average. Hence, the first shows the instant variation of PIM, and the second the actual trend that might be masked by the first.
- A sweep PIM measurement mode is performed by keeping one transmitter frequency fixed while the frequency of the second transmitter is swept over a defined frequency range resulting in PIM products across a range of frequencies. This is helpful to characterize DUTs with more than one PIM source to avoid adding or subtracting PIM levels (in-phase and out-of-phase PIM signals).
- In mobile telecommunications, modulated signals are used for transmission. Transmit and receive signals with specified bandwidths are assigned to a frequency grid. If there is a PIM source present, the signal bandwidth and center frequency will also determine how a certain receive channel is interfered by PIM.
- In mobile telecommunications, the duplex mode is also of importance. PIM interference may cause a signal to noise degradation within a receive channel. Taking this into account it is recommended that PIM measurements relate to receive channels or receive bands based on modulated signals. This allows to rate the signal to noise degradation for a given receive channel as an extension to classical PIM level measurements based on 2×20 Watt continuous wave.

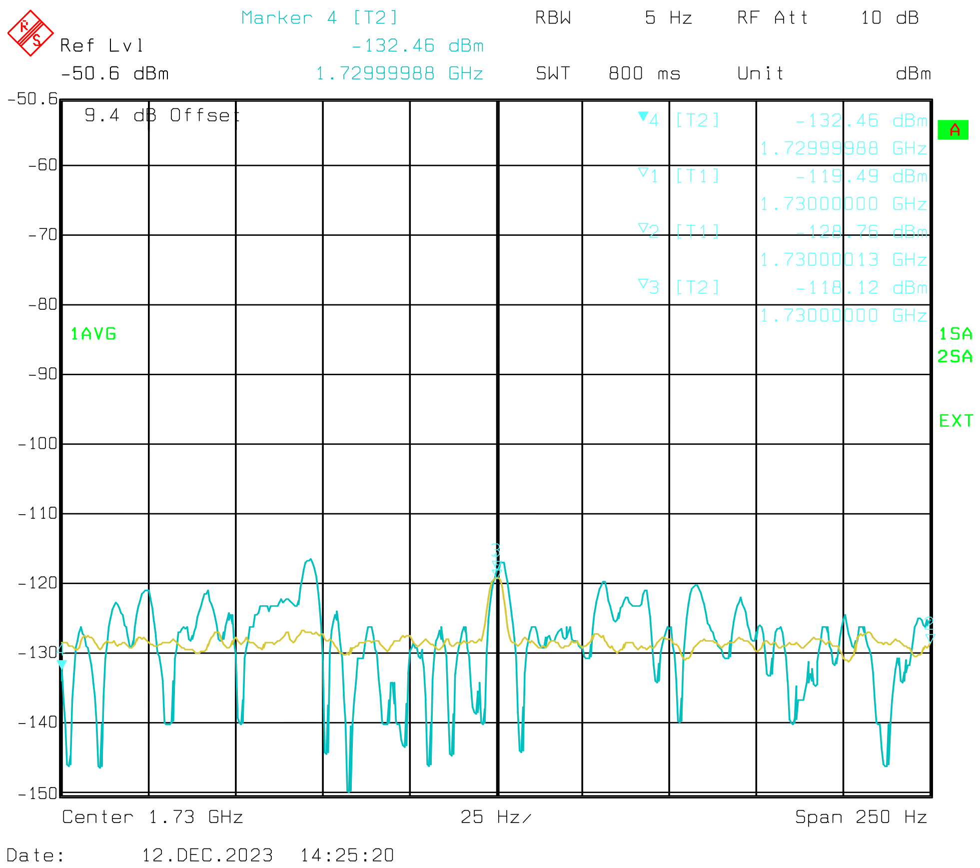

Figure 10. Example of the spectrum analyzer configuration.

- When setting up a mobile telecommunication system it is also necessary to obtain information about the quality of the antenna networks connected to its radios. The radio connection to the core network is typically realized by an optical fiber interface. To avoid any disconnection of the antenna network from the radio during PIM measurements, it is recommended to also use the optical fiber interface to control the radio access and the PIM measurement.
- Almost every PIM-guide and practice states that the cleanliness of connectors can be a source of degradation with respect to PIM performance. Therefore, it is recommended to be careful, not only when manipulating the DUT, but also with the whole setup's equipment.
- For the environment of PIM measurements, it is recommended to measure PIM in a temperature-controlled environment, (typically 23° ± 2°). However, the DUT temperature (not the ambient) has a significant impact on PIM measurement. The temperature of the DUT can be a function of duration of the measurement cycle so systematizing the timing of the measurement might be useful. If possible, it is recommended to perform testing activities under conditions representative of real operation the DUT, mainly regarding temperature, but also with respect to relative humidity.

5 PIM Measurement Uncertainty

5.1 PIM Measurement Uncertainty Contributors

The identification of the PIM uncertainty contributors is very important for reliable and repeatable PIM measurements, since it reveals the main influencers to the measurement uncertainty. For scalar PIM systems, the main uncertainty contributors are:

- RF power of the two-tone signals,
- RF receiver,
- adapters,
- uncertainty associated with the residual PIM (noise).

For strong PIM signals, which have a 20 dB distance above the residual PIM, the two-tone RF power, RF receiver and the adapter uncertainties are the major contributors to the PIM level uncertainty. However, the uncertainty associated with the residual intermodulation is a major contributor to the uncertainty budget at the low PIM levels. In this case, the spectrum analyzer clearly overruns any other contributor.

The uncertainty of the two-tone RF power is mainly dependent on the RF attenuator used during RF power characterization and the RF power stability. For this reason, it is important to characterize the RF attenuator precisely and accurately. In addition to that, PIM should be measured while the amplifiers are hot to achieve a better RF power stability.

The RF receiver is calibrated using a reference PIM standard or an external RF signal source. Therefore, the receiver uncertainty can be minimized by using a well-characterized PIM reference/external RF signal source.

The adapters contribution to the PIM uncertainty should be included into the budget. The S-parameter of the adapters should be characterized accurately to reduce the PIM measurement uncertainty.

The uncertainty associated with the residual PIM is the dominant contributor to the PIM uncertainty at the low PIM levels, when the distance between the measured PIM and the residual PIM is less than 20 dB. For this purpose, the residual PIM (noise) can be considered through low-PIM components for developing the PIM measurement system.

For the PTB vectorial PIM system, the identified contributors to the PIM measurement uncertainty are:

- SOL calibration standards with adapters
- Power sensor
- Phase reference
- VNA Drift
- VNA Linearity
- VNA Noise

It is found that the power sensor calibration standard and the linearity of the VNA system are the main contributors to the uncertainty of the strong PIM signals (more than 20 dB above the noise level). For low PIM signals, the noise is the main contributor to the PIM uncertainty since the distance between the measured PIM and the noise level becomes smaller.

Generally, the following recommendations are essential for PIM measurement uncertainty:

- The uncertainty of the receiver (e.g. spectrum analyzer) contributes significantly to the PIM uncertainty when the measured PIM level is stronger. If PIM reference is used for calibrating the receiver, it should be well characterized, with considering the PIM performance with respect to time or environmental conditions. Among many characteristics, it is obvious that the importance of the precision of the receiver will be a signal of quality in the overall testing campaign.
- The impact of the noise (residual PIM) of the PIM measurement system can be reduced using measurement techniques such as averaging.
- It is of importance to characterize the noise floor level (or residual PIM) in order to ensure it will not significantly impact on final PIM measurements. Residual PIM must be clearly below the PIM specification to ensure that no relevant uncertainty is translated to the PIM measurement. From the experience gained in the FutureCom project, a minimum of 10 dB margin of the residual PIM to the DUT's PIM is normally considered sufficient.
- It is essential to specify the connector type and the applicable torque level earlier in the measurement plan to quantify the impact of the connector repeatability precisely. Mating and unmating shall be laying repeatable results.
- With enough stabilization time for the DUT and the setup, and with ensuring that no key magnitude varies (e.g carrier's RF power or temperature), no remarkable drift of the PIM system is expected. However, the heating-up of the DUT due to the continuous injection of the high RF power can cause deviation of PIM levels.
- The temperature of the DUT strongly affects the measurement uncertainty. So, it is recommended (if possible) to measure PIM at the real operation representative conditions of the DUT.
- Periodic inspection of the contact surfaces of the connectors on the adapters and the instrument may be warranted as small scratches can have a surprising effect on 'residual' PIM. Of course, surface defects on the DUT connector could affect measurement results as well. In extreme cases, these surface defects can affect repeatability of the connector in general.
- It is important to have a good mechanical support structure for the DUT to avoid any mechanical stress on the connector. This would help also to apply the correct torque to the DUT connector.
- Reproduceable and traceable results require the transmitted signal to be well defined, as well as a good characterization of the transmission path of the respective signals. Furthermore, the system dynamic range, or rather the signal to noise ratio, will be critical when determining the measurement accuracy.
- Residual PIM of the setup can be a strong function of temperature as can the behavior of many verification/check standards used in PIM measurement. Temperature gradients between the environment and the DUT can confuse the analysis.

5.2 Evaluation of PIM Measurement Uncertainty Budget

For scalar PIM systems, the PIM standard uncertainty is calculated by combining the standard uncertainties from all the identified uncertainty contributors based on the Root Sum Square (RSS) method. This process involves squaring the standard uncertainties of all contributors before summing them all together. The square root of the total sum of squares is taken as the total combined standard uncertainty of PIM. The expanded uncertainty is computed by multiplying the resulting standard uncertainty by a factor of two (k= 2), approximating a 95% confidence level.

For the vectorial PIM system, a modified calibration model was developed by PTB to evaluate the PIM uncertainty as show in Figure 11. The correction of the measurement data requires to determine the error terms and the uncertainty contributors (noise, linearity, error terms, drift, connector repeatability, cable stability). The cable stability contribution is neglected when there is no cable used between the output port of the PIM system as in the JRP FutureCom project. This calibration model is implemented using a METAS VNA Tools II software [3] with MATLAB to evaluate the PIM measurement uncertainty.

It is essential to consider the sensitivity coefficients of the uncertainty contributors the during the calculation of the standard uncertainty of PIM. It is found that PIM has different sensitivity to RF power of each tone, and it can be calculated by measuring PIM whilst varying the RF power of one tone at a time. Further details are available in [9].

The propagation of the RF power uncertainties associated with RF frequencies to PIM frequencies is carried out using a sensitivity analysis. As an example, Figure 12 shows the uncertainty of PIM (magnitude & phase) at different frequencies.

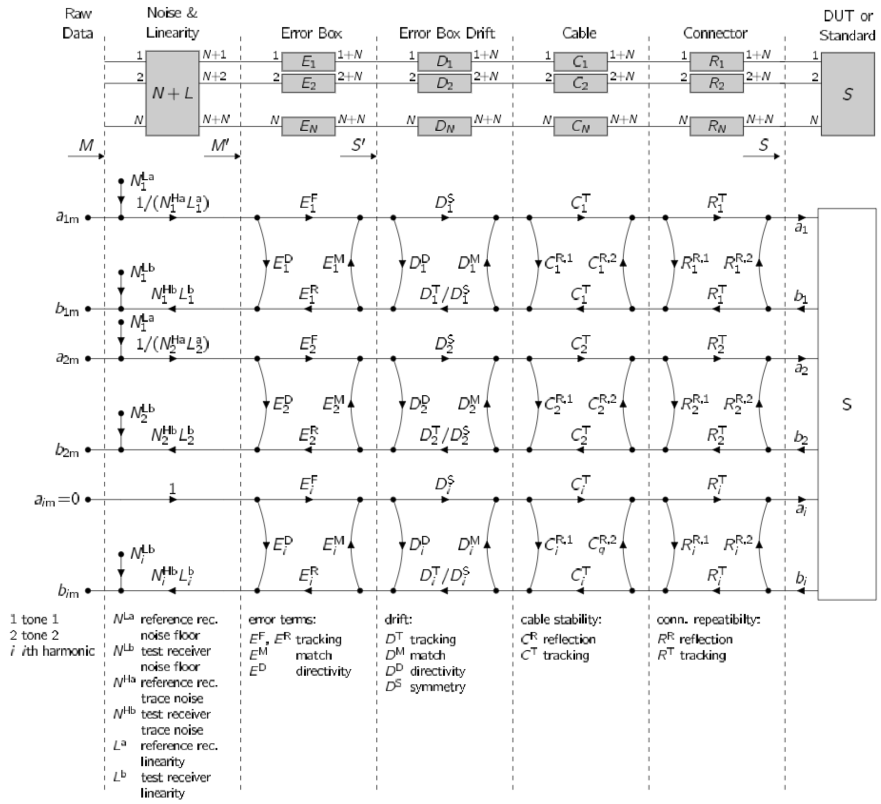

Figure 11. A modified calibration model for vectorial PIM measurement system.

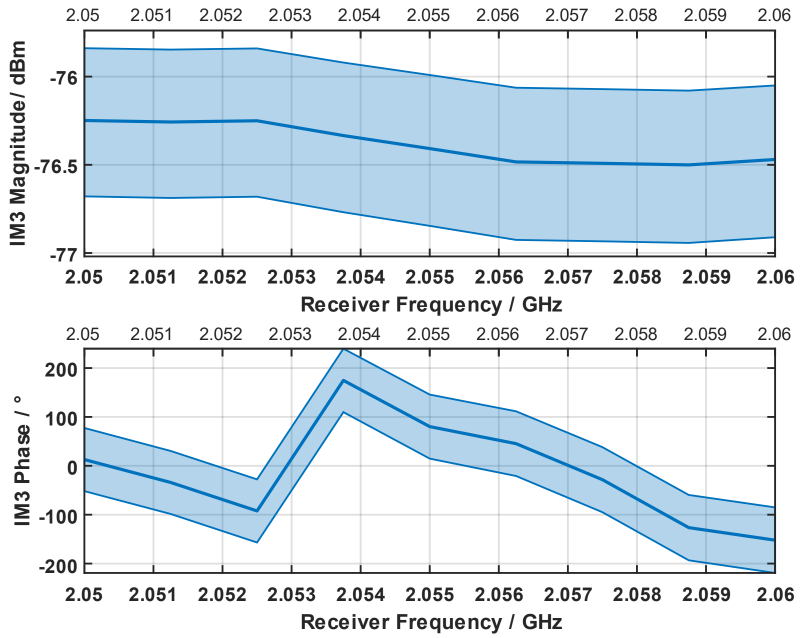

Figure 12. PIM3 uncertainty (magnitude & phase) using vectorial PIM system.

It is observed that the PIM uncertainty increases significantly for the low PIM levels. As an example, Figure 13 reveals that the IM3 uncertainty increases slightly as the IM3 decreases from -76.8 dBm PIM to approximately -95 dBm. As the measured power becomes lower than -100 dBm, the associated uncertainty increases significantly.

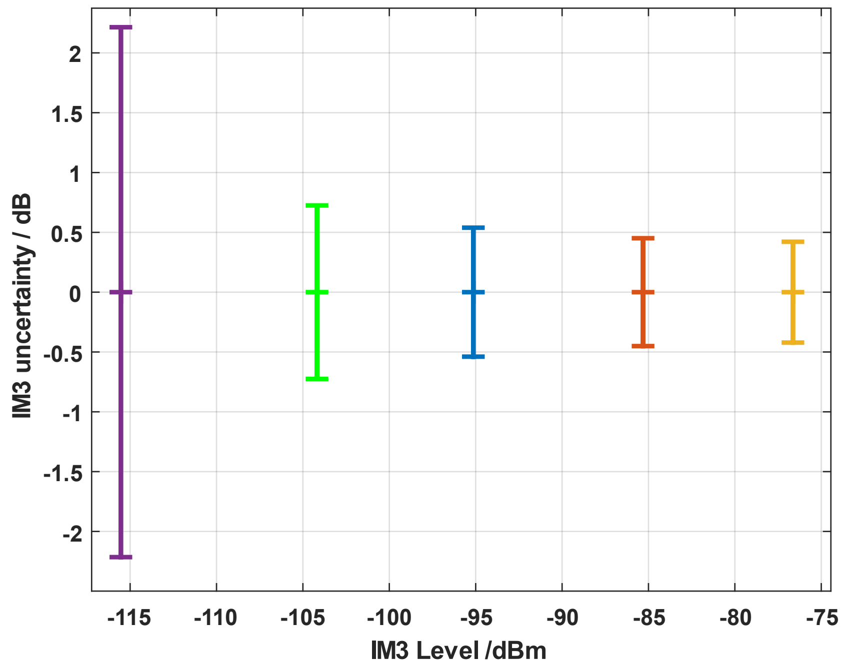

Figure 13. PIM3 uncertainty versus IM3 level at 2050 MHz.

The PIM uncertainty budget obtained using the vectorial PIM system at different PIM levels is exemplarily given in Table 1. It reveals that the power sensor and the linearity dominate the uncertainty contribution at the strong power levels while the VNA noise becomes the major contributor to the budget at the low PIM levels. It worth to note that the expanded uncertainty is computed at a coverage probability of 95% (*k*= 2).

Two-tone frequencies = 2110 MHz, 2170 MHz, f_{IM3}= 2050 MHz					
Nominal PIM level /dBm	-76.64	- 85.32	-95.135	-104.185	-115.54
Uncertainty Contributors	**Uncertainty Component / dB**	**Uncertainty Component / dB**	**Uncertainty Component / dB**	**Uncertainty Component / dB**	**Uncertainty Component / dB**
SOL calibration standards	0.03	0.03	0.03	0.03	0.03
Connection repeatability	0.029	0.023	0.023	0.03	0.031
Power sensor	0.128	0.13	0.15	0.14	0.14
VNA drift	0.012	0.012	0.013	0.013	0.015
VNA Linearity	0.16	0.18	0.20	0.20	0.20
VNA Noise	0.05	0.06	0.12	0.28	1.11
Combined Uncertainty / dB	0.214	0.23	0.275	0.37	1.13
Expanded Uncertainty in dB terms (CL = 95.45 %)	0.43	0.46	0.55	0.74	2.26

Table 1. PIM uncertainty budget using the vectorial PIM system.

6 PIM Measurement under Different Conditions

Within the framework of FutureCom project, PIM testing under different measurement conditions was carried out by PTB and INTA. The variable conditions are the DUT temperature, relative humidity, RF power, frequency, and torque. For these investigations, two different DUTs were used: DUT1 shown in Figure 14(a) and DUT2 shown in Figure 14(b). The DUT1 is a tunable PIM source with PID controller to keep the DUT temperature consistent while DUT2 is a non-tunable PIM source. The residual PIM level of the measurement setup was below -130 dBm. The investigation results are presented in the next subsections.

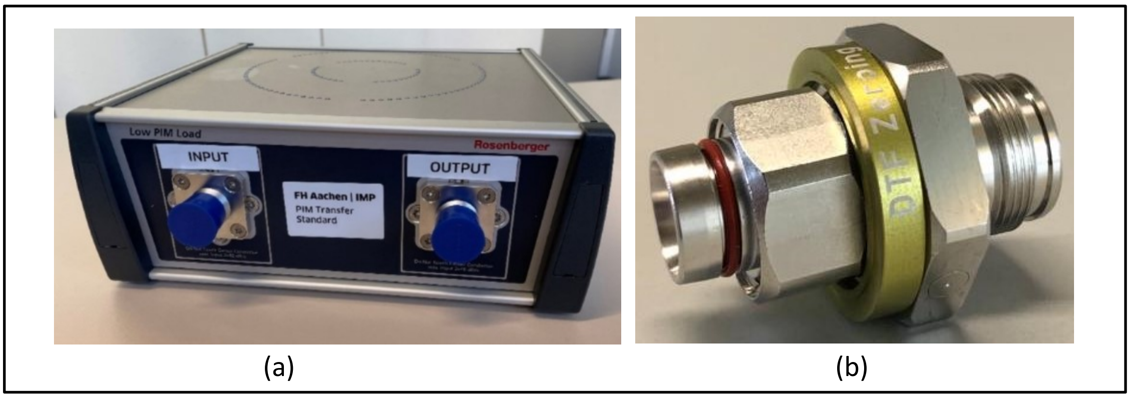

Figure 14. Photos of DUTs used for PIM testing under different measurement conditions (a) DUT1 (b) DUT2.

6.1 Impact of Two-tone RF Power on PIM Level

The impact of the RF power on the PIM level was investigated by varying the RF power of the two-tone continuous wave (CW) signal in the range from 30 dBm to 50 dBm. Figure 15 shows the measured 3rd-order PIM product, at 1780 MHz, versus the RF power of the two-tone signal.

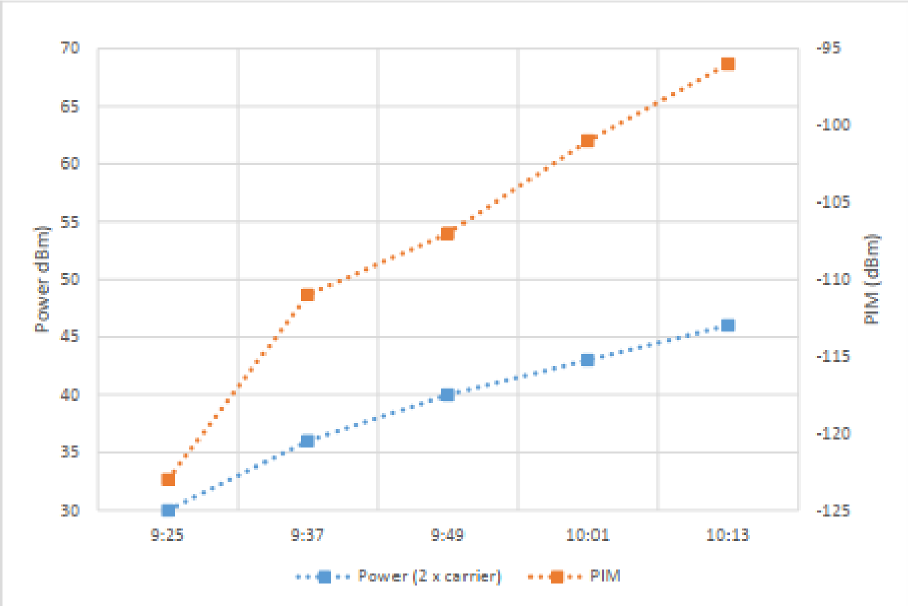

Figure 15. PIM of the DUT1 against the two-tone RF power.

During the measurement, all the measurement conditions (e.g. frequency, torque, temperature) remained stable, and only the RF power was swept. Figure 15 shows that the increase of the RF power from 30 dBm to 46 dBm has resulted in a PIM increase from -123 dBm to -96 dBm. Therefore, for DUT1 the ratio between PIM level and the two-tone power level for this tunable PIM standard is 1.7 dB/dB.

For the DUT2 shown in Figure 14(b), the increase of the RF power from 30 dBm to 50 dBm (20 dB) has resulted in an increase of PIM from -98 dBm to -44 dBm as portrayed in Figure 16. Therefore, the ratio between PIM level and RF power level is 2.7 dB/dB.

Generally, PIM level increases as the RF power increases but the rate of increase depends on the DUT nonlinearity characteristics.

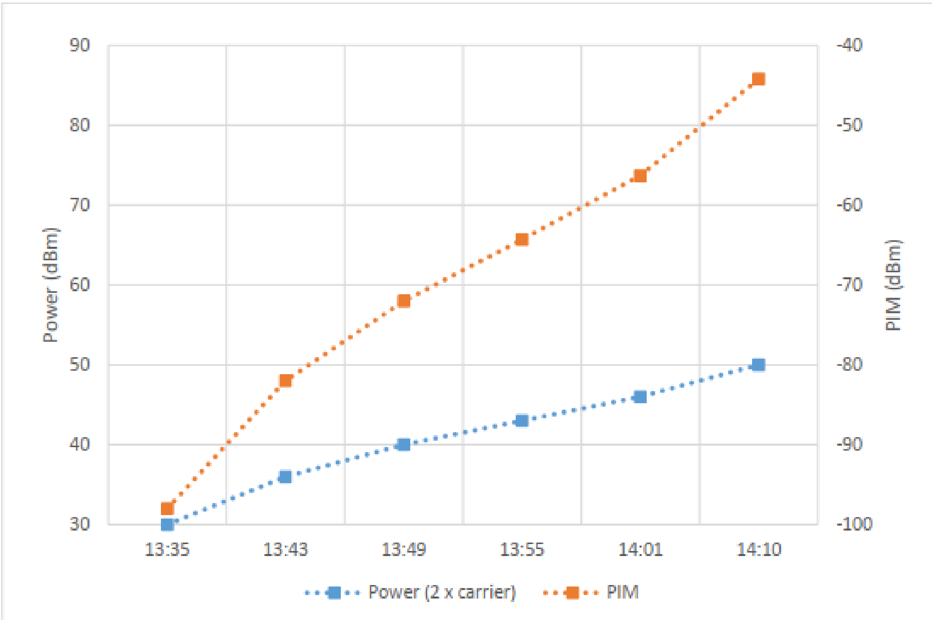

Figure 16. PIM of the DUT2 against the two-tone RF power.

6.2 Impact of Two-tone RF Frequency on PIM Level

The non-tunable PIM source (DUT2) was used for investigating the impact of the two-tone frequency on the PIM level. A PIM measurement is carried out by fixing one tone frequency to 2100 MHz and then sweeping the other tone frequency in the range from 2160 MHz to 2170 MHz with 1.25 MHz step. The tone frequency sweeping resulted in different PIM frequencies in the range from 2050 MHz to 2060 MHz. For a better understanding, this investigation has been performed at different RF power levels (from 36 dBm to 46 dBm), as depicted in Figure 17.

It is observed that the PIM level is weakly dependent on the frequency of the RF signals for all the different power levels of the two-tone signals as shown in Figure 17. However, it is important to note that this investigation has been conducted using a narrow band RF signal.

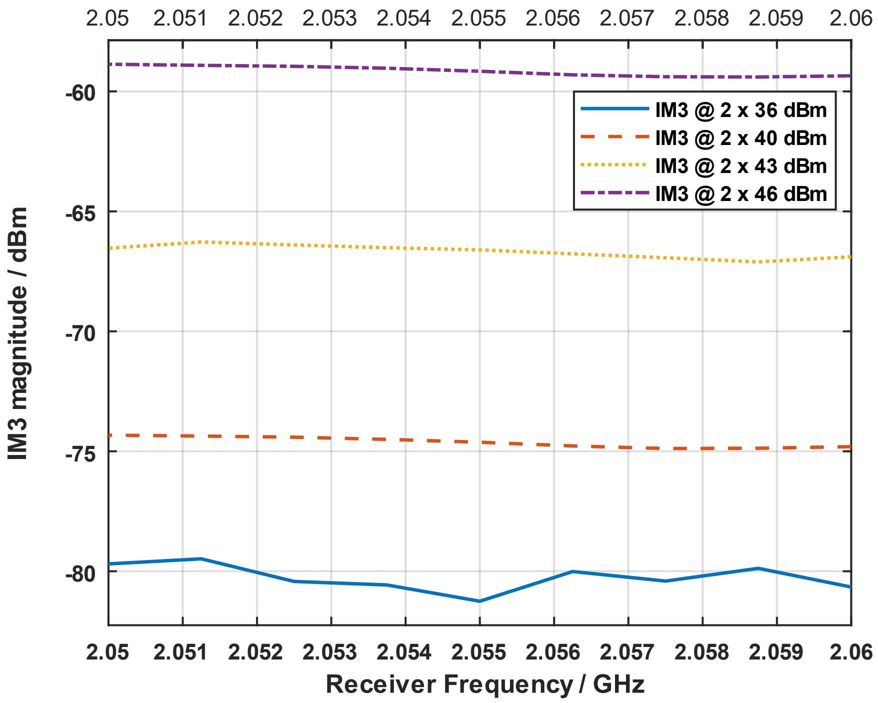

Figure 17. PIM of DUT2 against the PIM frequency at different RF power levels.

6.3 Impact of DUT Temperature on PIM Level

The impact of the DUT temperature (i.e. heating up) on the PIM measurement was examined by measuring the PIM level while the DUT temperature is inside a thermal chamber as depicted in Figure 18.

During this test, all the measurement conditions remained unchanged except the temperature of the DUT, which was controlled using the thermal chamber. The PIM frequency is 1780 MHz and the two-tone RF powers are 2x 43 dBm. For the DUT1 (tunable PIM source), PIM was continuously measured over one temperature cycling. First, the PID was set to 'ON' and the temperature was cycled from 10 ºC to 40 ºC. After that, the PID was set to OFF and then the temperature cycling from 40 °C to 10 ºC was carried out as shown in Figure 19.

Figure 18. view of the thermal chamber.

It is observed that the PIM deviates less than 1 dBm over the whole temperature sweep when the PID is 'ON'. However, a deviation of a 3.5 dBm is recorded over the whole temperature sweep when the PID is 'OFF' as illustrated in Figure 19.

For DUT2, the PIM level was measured over one temperature cycle from -20 °C to 80 °C as shown in Figure 20. A remarkable excursion over 12 dB of PIM level is noticed in the cold part of the temperature cycle, where condensation and freezing may take place inside the DUT. It may have happened that the inner parts of the PIM standard remained totally occluded after its connection to the setup's cables, therefore keeping inside the amount of humidity existent at the moment of mating. A second PIM level excursion is observed over 40 ºC, with a decrease of 4 dB in the range 50 °C to 80 ºC. Some change might have taken place on the DUT during the thermal cycle, as the measured PIM at the initial and final values of the cycle (at 20 ºC) differ over 4 dB as depicted in Figure 20.

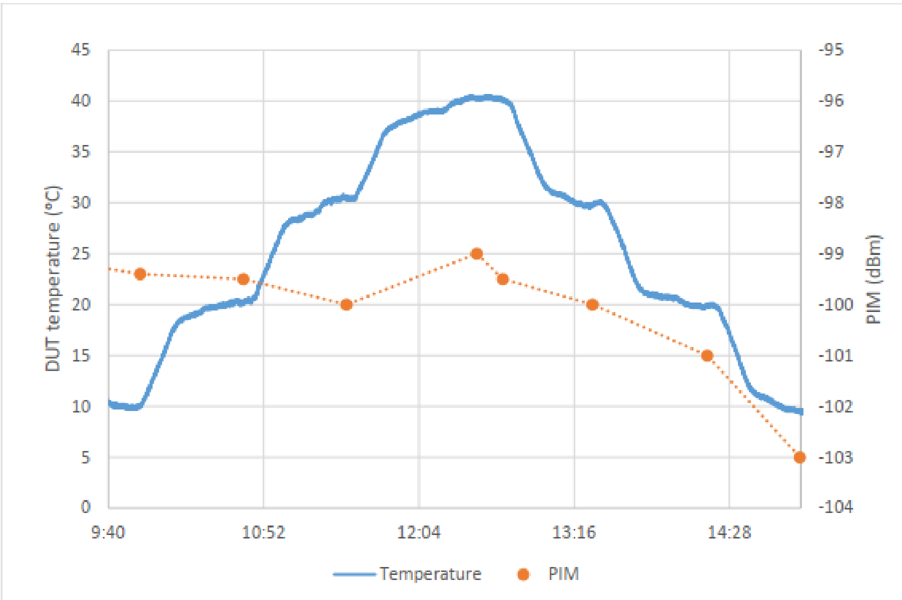

Figure 19. PIM of the DUT1against the DUT temperature.

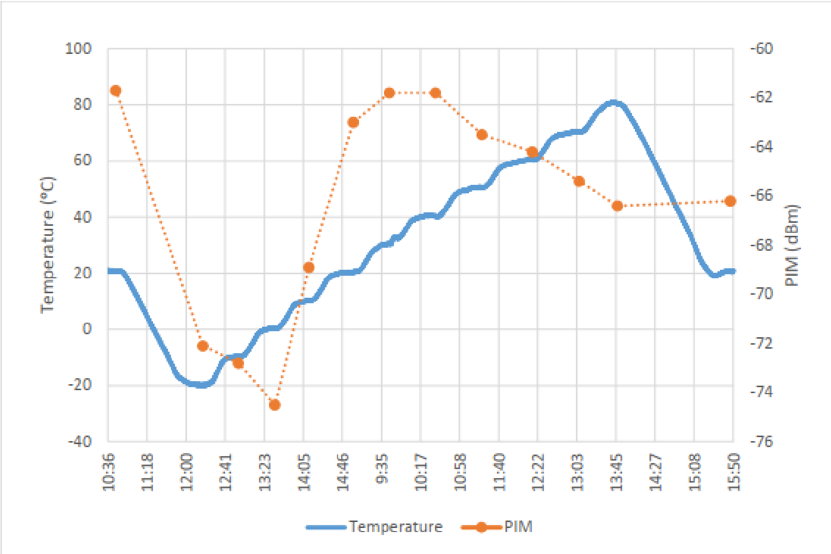

Figure 20. PIM of the DUT2 (non-tunable PIM source) against the Dut temperature.

6.4 Impact of Relative Humidity on PIM Level

In this test, the impact of the relative humidity (RH) on PIM has been investigated using the DUT2 (non-tunable PIM source). The DUT temperature was kept within 25 ± 1 ºC and the RH was varied from 20% to 80%. Figure 21 reveals that the PIM performance is almost independent from environmental humidity, showing small variations through all the RH cycle.

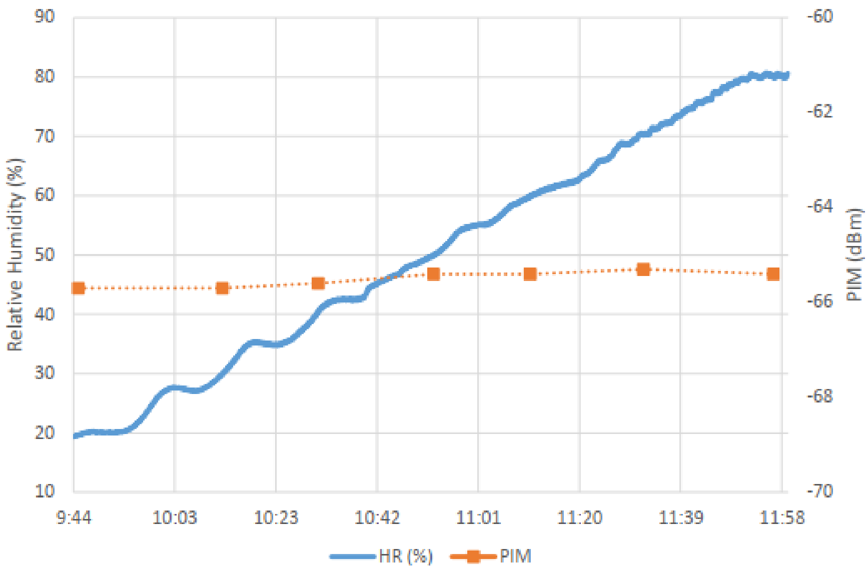

Figure 21. PIM of the DUT2 against the relative humidity.

6.5 Impact of Torque on PIM Level

The impact of torque on PIM measurement was evaluated using a DUT with 7/16 connector type. For this type of connectors, it is observed that the maximum deviation of PIM levels at the torque range from 15 Nm to 25 Nm is less than 0.7 dB. The lowest PIM is obtained when the applied torque falls within a certain range, since the low torque levels would create small gaps causing non-linearities while the higher torque levels might probably damage the center connector, resulting in higher PIM levels. The recommended advice is to use a proper torque wrench for tightening the DUT connectors, and to adhere to the manufacturer recommendations for the torque specifications.

7 Conclusions and Outlook

This Good Practice Guide represents a summary of the cutting-edge recommendations for performing PIM measurements together with some important results obtained from the JRP EMPIR FutureCom project during the project lifetime from 2021 until 2024. In this project, the capability for PIM measurement has been established at the laboratories of the project partners, who were involved in the PIM measurements. The RF power accuracy and stability contribute strongly to the measurement uncertainty for PIM signals that have more than 30 dB distance to the noise level. At a very low PIM level, the self-intermodulation (residual PIM) of the measurement system is the major contributor to the measurement uncertainty of PIM. A very slight dependency of PIM on the frequency was observed, but this investigation was carried out over narrow band frequencies. The torque applied on the DUT connector is also an important factor that might affect the accuracy of the measured PIM. The temperature of the DUT appeared to be one of the main contributors to the measurement uncertainty. The experiences gained by the partners through this project are compiled in the form of recommendations within this guide. The developments and investigations carried out in the FutureCom project is a major step forward for measurement technology in the PIM sector. It has also been realized that further research activities will be necessary in the future.

8 Acknowledgements

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