FINAL PUBLISHABLE REPORT

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TABLE OF CONTENTS

1 Overview

Nonlinear characterisation of RF devices and components benefits the telecommunications sector, through 5G and the Internet of Things (IoT), and the manufacturing sector, through Industry 4.0. At the technology level, the Nonlinear Vector Network Analyser (NVNA) is the key test instrument but it is complex to operate, and traceable calibration is distributed across three different standards. The prototype Nonlinear Verification Devices (NVD), developed in the EMRP project SIB62 HFCircuits, provide a way to verify the calibration.

In this project, sufficient technology has been transferred to the primary supporter, Keysight BE, to allow them to re-optimise the design of a next generation NVD, repurposing it as a diagnostic tool to reduce costly down-time. The benefits of the NVD as a diagnostic tool and verification device have been publicised to achieve traction within the community of end-users. We anticipate that the reduced down-time and improved fault diagnosis will directly benefit NVNA end-users.

2 Need

The carbon footprint of mobile phone handsets and telecommunications base-stations is linked to their growing data usage. Telecommunications is probably the largest civil user of RF technology and several solutions are being applied to increase the overall RF system efficiency, but these are more difficult to design and test, requiring complex and expensive test equipment, such as the NVNA, to verify designs and manufacture devices. The NVNA and similar instruments are expensive, complex and require accurate calibration. In the event of a fault, diagnosis and repair may result in significant down-time of the test system, affecting productivity.

Hence there was a need for a simple calibration verification and system diagnostic tool to monitor calibration quality and instrument performance. This required building on the NVD developed in SIB62 HFCircuits, optimising the design to improve its ruggedness and to act as a diagnostic tool.

In order to develop a true nonlinear verification device that could be used in conjunction with the existing multi-port NVNA and Large-Signal Network Analyzer (LSNA) instrument calibration scheme, technology needed to be transferred to Keysight BE. This allowed them to produce prototype test devices to demonstrate the principle of an optimised and robust device to the end-users and to disseminate results more widely than was possible in the earlier project.

3 Objectives

The overall goal of the project was to create impact by building on results from SIB62 HFCircuits.

The specific objectives were:

1. To provide design guidance on the NVD prototypes developed in SIB62 HFCircuits to the industrial end user, by means of training with the test models and additional details of the prototype designs. It was expected that device uncertainties and possible use-models would be discussed within the training.
2. To work with the user community so they are aware of the benefits of the NVD and to promote its uptake as a verification and diagnostic tool. Dissemination would be done through user forums and trade publications.

4 Results

4.1 Introduction

The three partners in this project were participants in the EMRP project SIB62 HFCircuits, where KU Leuven developed the design and simulation models with additional design input and evaluation by Keysight BE and NPL. Transferring the technology back to Keysight BE allows an investigation of the design envelope with a view to using the NVD to verify fault conditions and calibration errors in the NVNA and to avoid costly return-to-base repairs. It is anticipated that this will have a considerable impact on the user base.

4.2 Original design

The original NVD design, developed in SIB62 HFCircuits, is based on a nonlinear block, which is an IC consisting of four diodes in limiter configuration （Extending millimiterwave diode operation to 110 GHz, 1986 ）. The diodes are capable of handling high drive levels without degrading frequency performance. The design and modelling of the Keysight diode and RF circuit were developed at KU Leuven and part of the testing and evaluation was carried out at NPL. The performance of the first （Design and Analysis of a Verification Device for the Nonlinear Vector Network Analyzer, 2015） and second （A nonlinear verification device for nonlinear vector network analyzers, 2016）, （Design and Evaluation of Nonlinear Verification Device for Nonlinear Vector Network Analyzers, 2018） design prototypes have been published. Long-term stability tests were performed on the second design and it has been used as a transfer device for an international intercomparison of NVNA measurements （An Inter-Laboratory Comparison of NVNA Measurements, 2018）. Three diode operating points were used to different output waveforms for the same input stimulus (2 GHz, 10 dBm), see Figure 1.

Short-circuit bias　　　　Open-circuit bias

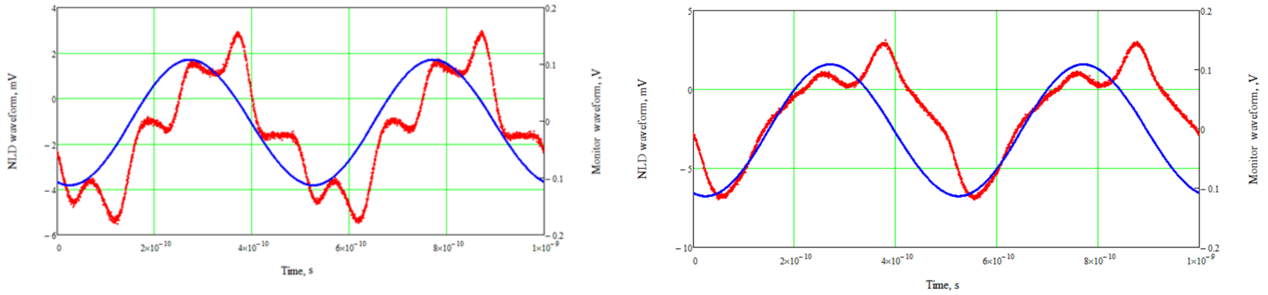


Figure 1 Original design under different bias conditions with 2 GHz 10 dBm stimulus

4.3 Transfer of the technology to the primary supporter

To provide design guidance on the NVD prototypes developed in SIB62 HFCircuits to the industrial end user (objective 1)

The NVD is based on devices supplied by Keysight BE. A simplified diagram of the nonlinear diode IC is shown in Figure 2. It is important to note that RF signal components are present on all of the device terminals and so it is important to design good decoupling that will operate up to mm-wave for the harmonic components. As part of the technology transfer, the NVD design has been optimized as a test example and ensure that the design and packaging are suitable for evaluation as a production prototype.

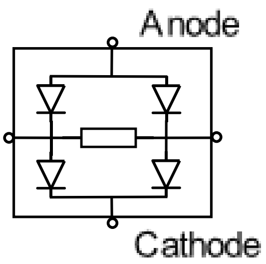


Figure 2 Keysight nonlinear IC diode bridge

To aid the transfer of the developed know-how behind the device to the primary supporter a K U Leuven PhD candidate, Mohammed Rajabi, who developed and modelled the NVD in the original project, worked at Keysight Denmark for a 3-month period.

During his time on secondment, Mohammed Rajabi worked with Keysight staff and provided details of the device models to Dr T. Nielson. During this time the original design was refined to provide several clearly defined switchable operating conditions. The device performance was then evaluated in the Keysight laboratories and at K U Leuven.

4.4 Revising the NVD Design

Design Philosophy

As stated, the revision of the RF and the bias circuitry serves two functions: to confirm that the technology has been effectively transferred to Keysight and to provide a prototype that can be modified, manufactured and assembled with minimum effort. A secondary training benefit is that the PhD candidate, during his secondment at Keysight DK, and other project staff receive first-hand knowledge of the current design process.

Physical aspects

The enclosure used is KLIPPON STB 2 SS having the following properties: a steel enclosure 150 mm x 150 mm x 90 mm, providing some RF screening and IP66[1] rated providing environmental protection. All RF contacts are made to the front of the enclosure to simplify construction.

The RF circuit and bias components have been assembled on separate RF (Rogers) and FR4 boards to allow changes at minimum cost and 2.4 mm connectors have been used throughout for RF connections.

RF PCB design

The RF network is shown in Figure 3 and comprises three parts: A passive matching network provides bandpass filtering, a directional coupler and impedance matching. The centre element the Keysight IC is mounting and the final element is the passive matching network that provides isolation between the Keysight IC pad and the NVD load, and spectrally shapes the output waveform. The PCB is designed based on TMM10-I, 0.025” (0.635mm) thickness.

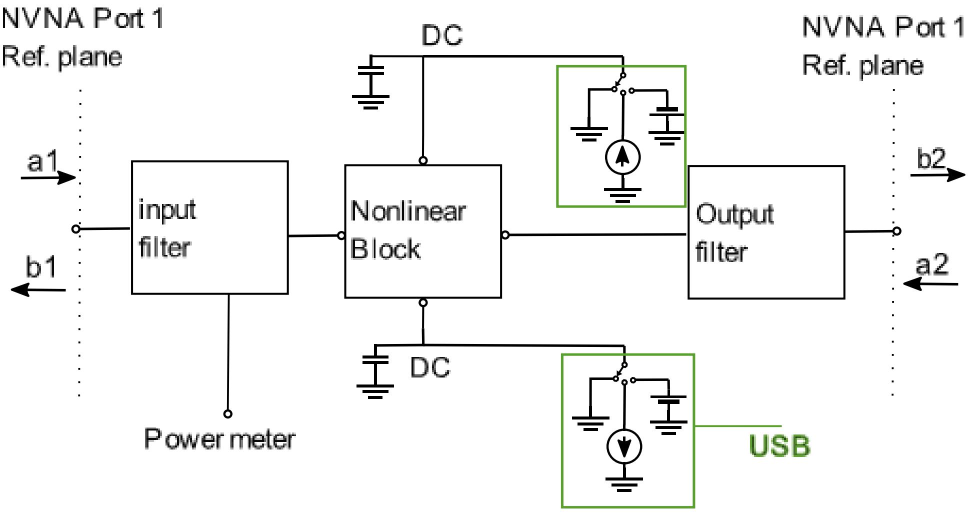


Figure 3 NVD is made of three parts: 1) passive network I: an input filter and a directional coupler, 2) nonlinear block, and 3) passive network II as an output filter.

Nonlinear device bias and RF circuit

The diode behaviour and sensitivity to bias is considerably different between the reverse and forward bias conditions. In the forward conduction region, the bias point is very sensitive to voltage errors whereas in reverse bias operation the characteristic is insensitive to bias variation. Setting the forward bias current has the dual advantage that the bias point is better stabilised against RF power and bias supply variations.

[1] *European IEC 60509:1989 Ingress protecion (IP) code. IP66 provides “Protected from total dust ingress” and “Protected from high pressure water jets from any direction, limited ingress protection”. See https://www.rainfordsolutions.com/ip-enclosure-ratings-and-standards*

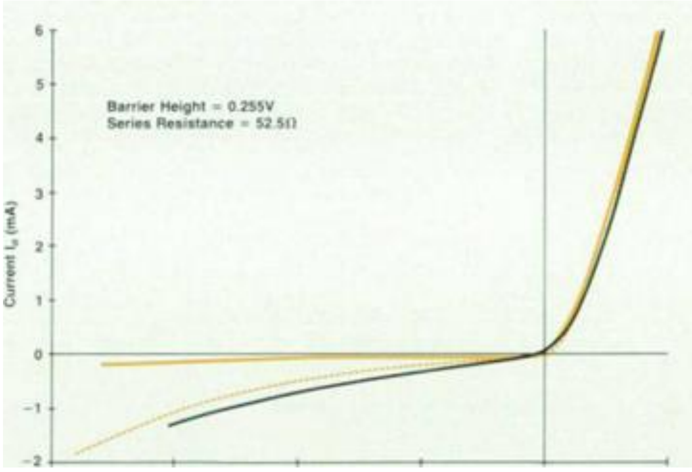


Figure 4 I-V characteristic for the modified barrier diode. The solid colour and dotted curves are model predictions by simple theory and the Stanford University SEDAN modelling program, and the black curve shows the measured performance

As the nonlinear diode IC and constant current source are both based on diode elements and both show temperature dependence from the diode model term $\exp(\frac{qV}{kT})$, the bias circuit has been compensated to allow an independent assessment of the temperature sensitivity of the nonlinear diode IC[2], see Figure 5.

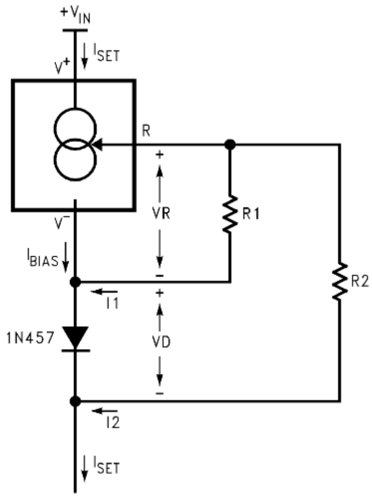


Figure 5 Zero temperature coefficient current source configuration using LM334MX

Reverse bias was implemented as positive and negative constant voltage source sources as the expected stability and temperature requirements are less stringent.

The positive and negative voltage (reverse bias), temperature compensated positive and negative current (forward bias) have been realised on a 33.78 mm by 70.1 mm PCB. The DC PCB is connected to the switches, the RF PCB and USB plug (see Figure 6).

[2] *Texas Instruments Corporation, LM134/LM234/LM3343 - Terminal Adjustable Current Source, Dallas, Texas: Texas Instruments, 2013.*

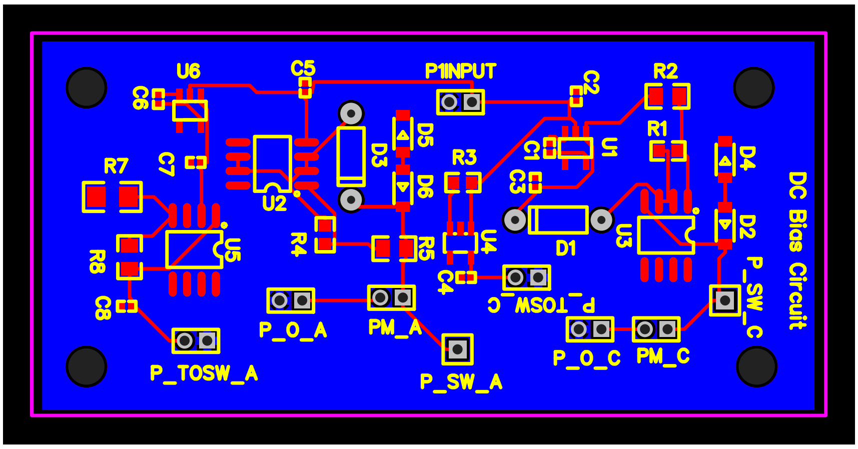


Figure 6 Bias PCB layout

4.5 Evaluating the revised NVD design

The revised design has been built and evaluated using the NVNA instruments in Keysight's laboratory and at KU Leuven. The measurement results and photographs were taken at the 2018 Microapps presentation （How to Verify Calibration and Troubleshoot Systems Errors on a Keysight Nonlinear Vector Network Analyzer (NVNA)，2018）.

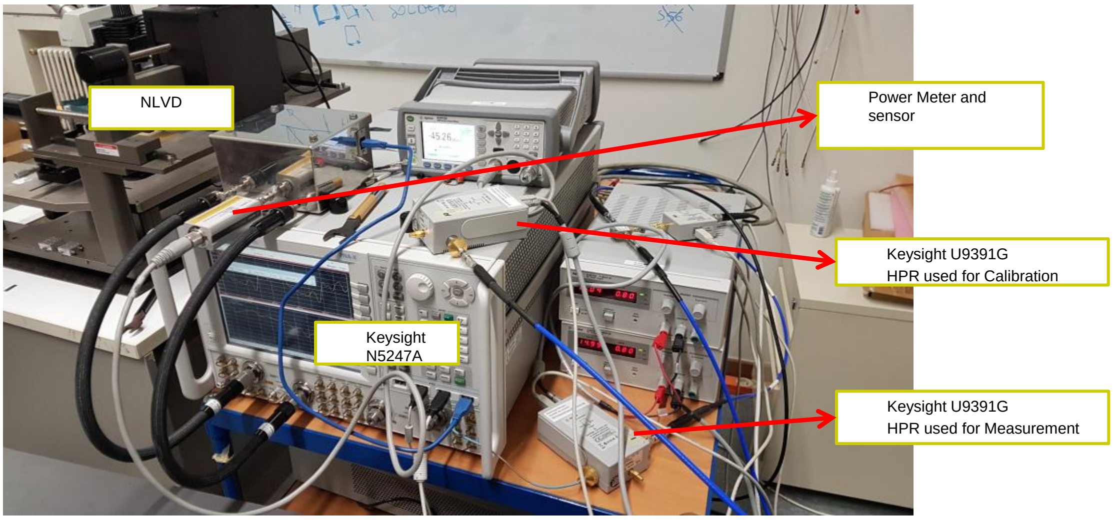


Figure 7 Experimental evaluation of the NVD using an NVNA

Behaviour under variable load conditions

Several tests have been performed using the NVD to determine its sensitivity to load-impedance variation.

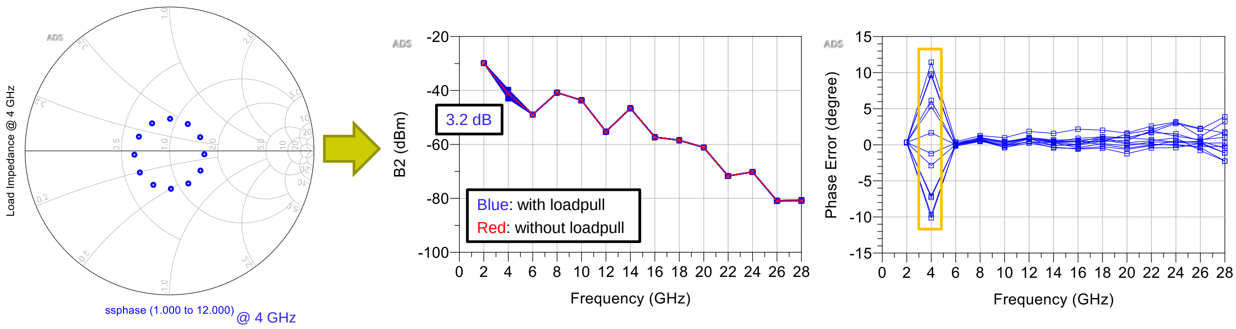


Figure 8 shows results of a load-pull measurement to determine the influence of a variable load on the phase and magnitude of B_2 wave. These indicate that there is no major influence on the other harmonics. Also, this sensitivity is not related to the calibration and should be compensated.

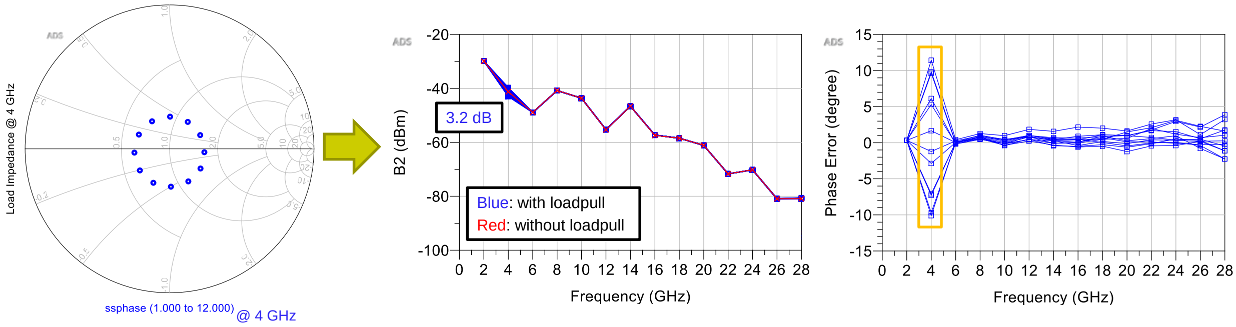
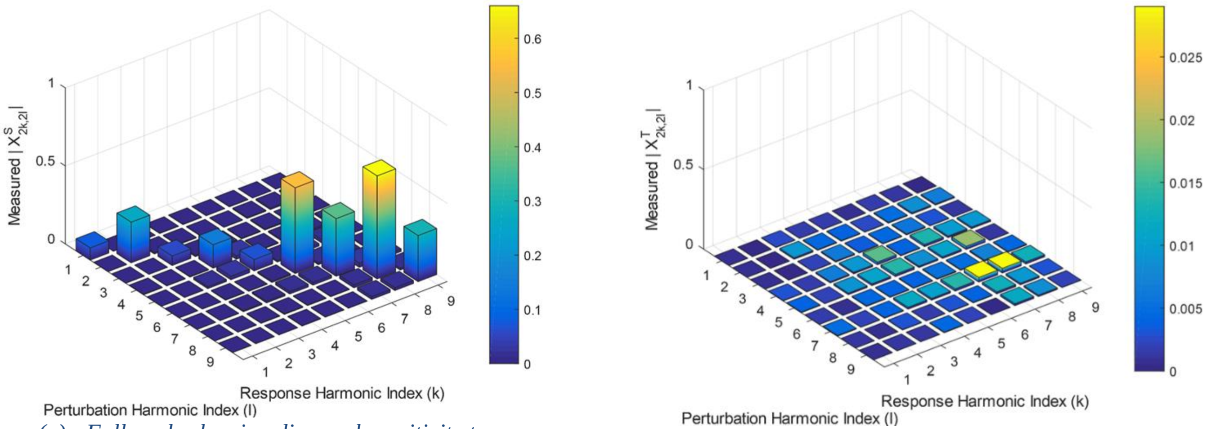


Figure 8 Influence of variable load impedance on the B2 wave incident on the NVD port 2.

X-parameter measurements and match correction

X-Parameters give an insight of the cross-frequency relationship. An important attribute for a verification device is that it should show low correlation of the results across operating frequencies. Measurements with a NVNA that is poorly matched at one frequency should not be impacted by this single result.



(a) Full-scale showing diagonal sensitivity terms

(b) Expanded-scale showing low cross-frequency sensitivity

Figure 9 X-parameter results showing cross-frequency sensitivity

The results can be compensated by correcting for the match reflections. Figure 10 shows the correction for $\Gamma_L < 0.5$, the quality of the result indicates that cross-frequency sensitivity is negligible, and a simple impedance-match correction is sufficient.

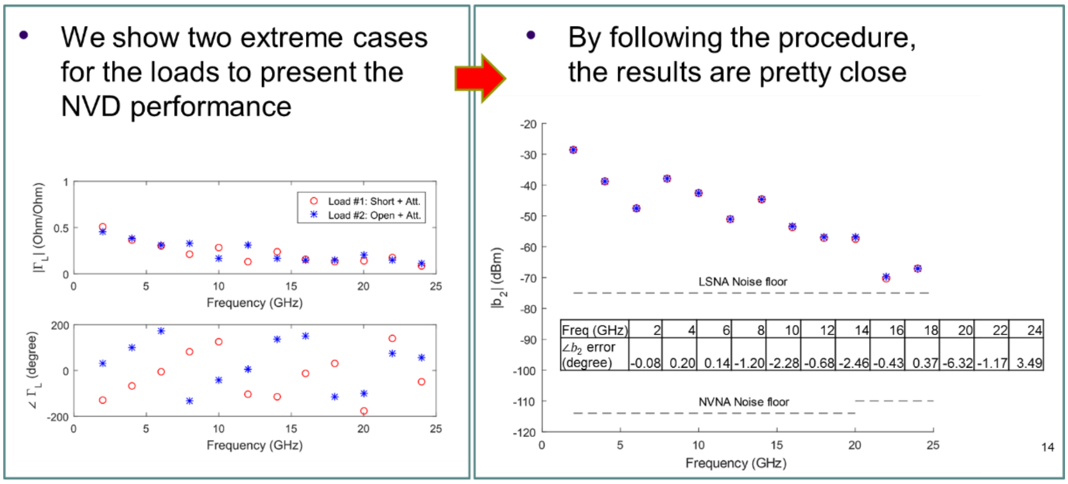


Figure 10 Compensated match correction shows good agreement for different receiver impedance match conditions

Identifying incorrect calibration

An important application for the NVD is to identify calibration errors. The instrument calibration provides the absolute values for the input and output vector V(f) defined at the ports. An error in the absolute values will lead to an incorrect calculation of the non-linear cross-frequency terms. The procedure followed is given in d Figure 11. In this example, distortion components at 4 GHz and 10 GHz with phases of -30^o and -70^o respectively have been added to the HPR phase calibration during the phase calibration step to simulate a calibration error.

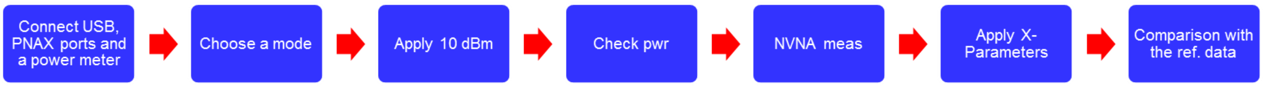


Figure 11 Calibration verification procedure

The corrected results, shown in Figure 12, indicate the calibration errors at 4 GHz and 10 GHz can be identified using the nonlinear artefact.

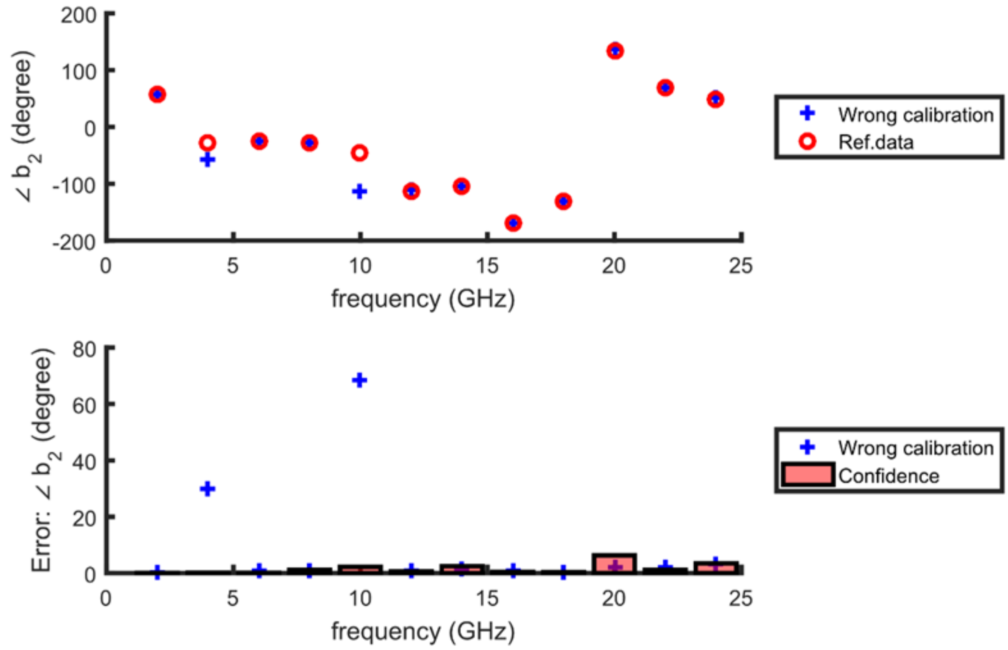


Figure 12 Results obtained using the NVD verification procedure to identify calibration errors at 4 GHz and 10 GHz

Evaluation by the Primary Supporter (Keysight)

The NVD developed as part of the technology transfer is based on devices supplied by Keysight BE. As part of the technology transfer was shipped to Keysight's facility at Santa Rosa, CA, USA for further and more extensive evaluation. As a consequence, the device has not yet been evaluated at NPL.

4.6 Dissemination and wider impact of the technology

To work with the user community so they are aware of the benefits of the NVD and to promote its uptake as a verification and diagnostic tool (objective 2)

The objective of this activity is to maximise the impact on the RF community arising from SIB62 HFCircuits. This was planned via a workshop and presentation to the NVNA Users Forum and a Trade publication.

As there are commercial implications for both of these publicity vehicles the activities must be signed-off by the primary supporter, Keysight, in order to proceed with publication.

4.7 Planning

The initial planning to deliver the presentations and publications took place at the kick-off meeting, held in Aalborg, Denmark on 2nd May 2018. At this meeting the technology transfer planning and technical requirements were discussed along with presentation and publication options to promote the results.

The outcomes for the presentation and publications were:

1. The presentation at the NVNA forum would be planned for the January 2019 ARFTG conference.
2. There was an opportunity to provide an additional presentation at the European Microwave Week Microapps series and the material would be available to all attendees of the conference. This is additional to the contract deliverables.
3. Either IEEE Microwave Magazine or Microwave Journal would be suitable for a trade journal.
4. An alternative solution would be a Keysight User Guide, which would support the NVD as a product or a research product but could not mention Euramet, K U Leuven or NPL directly.

4.8 Presentations

The scope of the presentations was to cover the capabilities and application of the NVD. A key application is to verify the quality of a NVNA calibration and to spot errors. Such a failure could be caused by a user error or by a more fundamental problem with the instrument.

European microwave Week 2018

Keysight have a large stand in the trade exhibition at the 48th European microwave week exhibition, which was held over 25th – 27th September 2018 in Madrid, Spain. This conference and exhibition attracts about 4000 attendees （Eur19） and as part of this exhibition there are a series of industrially focussed presentations “Microapps”, each of approximately 20 minutes duration. The presentations are open to all EuMW registrants and should appeal to the exhibition attendees. The selection criteria include relevance and interest to the local microwave community, and the presenter must be a registered Exhibitor at EuMW 2018. The purpose of MicroApps is to communicate practical knowledge. Tutorials and application notes on basic techniques and important knowledge are encouraged. Although the attendance at this presentation was less than 20, the presentation was provided to all attendees at the Microapps seminar.

The presentation covers the following:

1. A brief outline of the VNA and NVNA
2. Calibration and verification
3. An overview of the NVD and how to use it
4. The test system and implications of output impedance match, together with the underpinning mathematics
5. A demonstration of X-parameters and the performance under load mismatch conditions
6. A comparison with other devices
7. Fault diagnosis
8. Conclusions and acknowledgements

For details see Appendix 1: Microapps presentation at European Microwave Trade exhibition 2018.

NVNA Users Group meeting at 92nd ARFTG Microwave Measurement Symposium

The other series of conferences that attracts engineers and scientists with an interest in NVNA measurements is the ARFTG Microwave Measurement Conference series （ARF19） , which also hosts the NVNA users' forum （Roblin）. IMS, the International Microwave Symposium, is the IEEE flagship conference tor the Microwave Theory and Techniques Society, and an ARFTG tend to run one after the other to make the best use of travel resources. The presentation outline is very similar to the Microapps material and is attached as Appendix 2: Presentation at 92nd ARFTG Microwave Measurements Symposium.

Vector Large-Signal Measurements short course at 92nd ARFTG

The material was also included in the “Vector Large-Signal Measurements” short course given by Prof, Schreurs at 92nd ARFTG （Vector Large-Signal Measurements，2019）. The presentation uses the same material as the NVNA Users Group presentation but also covers the basics of nonlinear network analysis and the NIST Electro-Optic system. This presentation has not been attached for commercial reasons.

4.9 Publications

At the Kick-off meeting the publication options were agreed. Subsequent to the meeting Prof. Schreurs became President of IEEE MTT Society and we agreed to target the IEEE Microwave Magazine as the most appropriate journal.

Before publication can take place the key constraint is approval from the primary supporter, Keysight as publication has implications for the expectation of a future product release. The prototype instrument was evaluated at a Keysight facility in Denmark and at KU Leuven and has been shipped to Santa Rosa, CA, USA. At this time testing has not been completed.

If Keysight decide to use the NVD technology then permission to publish the trade journal and/or application note will be forthcoming.

5 Impact

The energy required for the telecommunication sector is increasing rapidly in line with data use and so the proposed 1000-fold capacity increase of 5G has significant economic, societal and environmental implications. The increased energy use can be partly mitigated by more efficient and cheaply manufactured RF systems. This is a particular issue for the mm-Wave components that must now be manufactured and tested at commodity prices. The NVNA is a key instrument to realise low-cost device testing. Better calibration and reduced NVNA down-time have significant cost implications for manufacture and ultimately carbon footprint reduction. The aim is to improve longer handset battery life from the deployment of more power-efficient RF telecommunication systems. Other applications, such as IoT, will also benefit from high-efficiency systems developed using nonlinear measurement and modelling techniques.

The technology transfer to Keysight BE, who manufacture the NVNA and other instruments, has created direct impact through the realisation of the NVD as a diagnostic tool to reduce field-engineer visits and the need to return the instrument to the manufacturer for assessment. The end-users of the NVNA instruments range from academia to industrial fabrication facilities and subsystem manufacturers. The goal is to provide significant cost savings and efficiency benefits to these end users. A wider impact will be achieved via the publication of this work in a trade journal.

The “NVNA Users forum”, organised by NIST, is the key forum that brings together industrial and academic leaders in this field. This meeting was held at ARFTG92 (Orlando, 2019), and was attended by key instrument designers, academia and equipment users from around the world. The material was also used as part of an introductory course given by Prof. Schreurs of KU Leuven at the same conference.

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