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Development and Evaluation of an RF Vector Network Analyser Experiment for an Undergraduate Engineering Programme

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***Abstract*— This paper outlines the development of an RF Vector Network Analyser (VNA) laboratory for undergraduate electronic engineering students. Because of the expense of high-quality high-frequency vector network analyser systems, these are usually only encountered by a small number of students who undertake a senior-year project in the RF/microwave area. This paper describes a VNA-based laboratory which is intended to be used by all undergraduate Electrical and Electronic Engineering students in the 4th year of the programme, thus giving all students an insight into this sometimes "mysterious" area of the undergraduate curriculum. The paper moves from the initial "wish list" for what the laboratory might incorporate to the final roll-out to a cohort of 23 students. Feedback from the students indicate that the laboratory session was well received while also indicating that there is potential for improvement in some areas.**

***Keywords*— Microwave Education, RF Measurements, Vector Network Analyser, S-parameters.**

I. INTRODUCTION

Like many bachelor's-level programmes, the B.E. in Electrical and Electronic Engineering at University College Cork includes modules on basic electromagnetics and microwave/RF engineering. The 4th-year mandatory module "EE4016 Transmission Lines" introduces students to the complexities of high-frequency signal propagation through guided media such as co-axial cables and PCB tracks and introduces concepts such as reflection coefficients and S-parameters [1]. Further, it introduces the importance of matching for RF power transfer and illustrates many of these concepts w.r.t. the well-known Smith Chart graphical aid [2]. Traditionally, the module has been supplemented by simulation-based laboratory assignments to reinforce and develop the concepts being introduced. There has been a desire for a number of years to supplement the lecture-based and simulation-based material with a practical laboratory based on a Vector Network Analyser (VNA) performing S-parameter measurements. However, while high-quality VNAs with GHz capability would be expected in an RF/microwave research laboratory, the expense of such equipment has typically precluded these sorts of measurements from the undergraduate curriculum with the exception of students specifically undertaking senior-level projects in the RF/microwave area. During the 2017/18 academic year some funding became available to enhance selected areas of undergraduate facilities and the development of a VNA-based undergraduate laboratory setup was one of the proposals submitted and finally accepted for support. The development of the laboratory is described in this paper.

II. METHODOLOGY

A. The VNA Equipment Specifications

A set of requirements (the "wish list") was first assembled to reflect the main uses envisioned for the proposed VNA setup and the main restrictions on any setup being considered. Table 1 provides a subset of the main issues from the longer list used during the procurement process for the VNA stations. The main technical requirement was a desire to allow students to experience S-parameter measurements up to at least a few GHz and, while meeting that goal, to go to as low in frequency as possible such as the low MHz range. Another important aspect was that whatever system was purchased the setup should work "out of the box" and not rely on other items that might have to be procured separately. It was also decided that the students should gain experience of the concept and importance of VNA calibration and that a manual calibration approach, while more time consuming during the laboratory sessions, would emphasize this more. It was also important that any equipment procured be physically robust enough to survive several years of handling and be electrically safe as evidenced by CE certification [3]. The ability to easily save or export the measured S-parameter data for further analysis was also very desirable.

Having a comprehensive "wish list" in hand, a web-based search for potentially suitable instruments was first carried out and then practical demonstrations were arranged with 3 well-established vendors or distributors of high-performance RF measurement equipment. All the equipment demonstrated had excellent performance and was considered to be able to provide an excellent learning opportunity for students with the final choice being influenced by all the conditions outlined in Table 1. Following extensive review, it was decided to base the laboratory around the 8 GHz version of the MS46122B "Shockline™ VNAs from Anritsu [4]. Fortunately, the budget allowed two VNAs to be purchased. It was envisaged that the laboratories would be organized with two students working at each VNA station so this facilitated an arrangement where four students could be scheduled per laboratory session.

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TABLE I. VNA "WISH LIST"

Primary Purpose	To support practical laboratory sessions for senior-level undergraduate and early-stage postgraduate EE students taking modules "EE4016 Transmission Lines" and "EE4011 RF IC Design".
Secondary Purpose	To support ad hoc RF/microwave measurements for senior-level or early-stage postgraduate student project work subject to availability restrictions associated with the primary purpose.
Type of Measurements	Full two-port S-parameters. Demonstration of 2-port calibration e.g. Open, Load, Short, Thru. Measurement of cables of different lengths and terminations. Measurement of PCB test structures with different transmission lines, coupled lines, and filters. Measurement of antenna characteristics. Measurement of low-power amplifiers and the effect of matching design.
Frequency Range	As wide as possible subject to cost restriction (e.g. from low MHz to a few GHz).
Accuracy/ Dynamic Range	The best performance subject to cost.
Upgrade Options	Availability and pricing of upgrade options to enhance functionality or frequency range.
Calibration	Calibration kit to cover the full frequency range for 2-port measurements - to be used as part of the student laboratory sessions.
Cables and connectors	RF/microwave cables (for each station) to cover full frequency range for 2-port measurements.
Operating Software	Best scenario: Stand-alone, licence free, no recurring costs. Next best scenario: Ability to leverage existing software packages in use for the B.E. programme.
Data export	Options available to store/export measurement data: Readable file or proprietary format?
Control/ Remote Operation	Options available for control of the VNA for measurement sweeps or complex measurements: USB? LAN? GPIB? Facility for remote operation? Supported language for control e.g. C, Python, etc.?
A/V option?	Is there an option to display the screen via a data projector connection?
Warranty	Is there a minimum warranty? Is there an extended option?
No hidden setups/costs	Stations should be operational as bought i.e. with no hidden extras for basic functionality such as firmware options, adaptors, extra software licenses, etc.
Number of stations/ configuration	How many "stations" could be sourced within the budget available?
Safety	Does the VNA have CE certification?

B. The Proposed Laboratory Content

Another important consideration when developing the laboratory session was to consider the range of activities that would be undertaken by the students and how these would relate to the module content. The main tasks envisaged for the laboratory session are outlined in Table 2.

TABLE II. VNA LABORATORY CONTENT

Task	Detail/Learning Outcomes
Calibration	Importance of correction for VNA and cable non-idealities as well as practice with fixture connections using a torque wrench.
RF Cables	Measure basic cable characteristics such as reflection coefficient, loss and group delay as well as derived parameters such as velocity factor.
Attenuators	Characteristics of standard 3 dB and 10 dB attenuators.
Filters	Characteristics of standard low-pass, high-pass and band-pass filters.
Micro-strip PCB Designs	Measure a range of PCB micro-strip designs such as transmission lines and filters and compare the measured results with simulations.
Further Data Analysis and Display	Re-use data measured from the earlier steps to see alternative ways of displaying the same data and to extract extra information from the raw data such as the characteristic impedance of various transmission lines.

C. Sample Design and Student "Road Test"

During the academic year 2017/2018, a 2-person final-year undergraduate student project "Test-set for Transmission Line Experiments" was run (with two of the paper authors undertaking this project and the other two authors as co-supervisors). The main aim of the project was to design and test a range of PCB-level RF test structures and determine what experimental tasks would be feasible within a standard 3-hour laboratory session. The main test structures designed and tested during this project were micro-strip designs for transmission lines, low-pass and high-pass filters, patch antennas and rat-race combiners. An industry-standard RF design tool (ADS [5]) which incorporates an electromagnetic (EM) simulator was used extensively during the design process together with standard analytical approximations. This project was completed successfully and produced a large set of PCB samples for use in the final experimental setup as well as providing a good benchmark concerning the topics that could be incorporated into a 3-hour laboratory session.

D. Roll-out of Laboratory to all Final-Year Students

The VNA-laboratory was rolled out to final-year students of the B.E. Electrical and Electronic Engineering programme in November 2018 i.e. during the first semester of the 2018/19 academic year. First, a one-hour presentation was delivered to the full cohort of 23 students registered for the "EE4016 Transmission Lines" module which provided an overall orientation to the laboratory session including logistical and safety aspects. Then the students were asked to form two-person groups of their own choosing and select a timetabled slot on a first come, first-served basis from eight 3-hour afternoon slots that were timetabled for the laboratory sessions themselves. Two VNA setups were dedicated to these laboratories so that each session could accommodate two 2-person groups at one time. At the beginning of each of these sessions, the students were given a brief introduction to the measurement system, the samples to be tested and the procedure for cable attachment using a calibrated torque wrench. This overview lasted about 15 minutes and the students were then asked to follow a detailed laboratory handout for the remainder of the session with instructions to “call the lecturer” if they became stuck at any point. They were also checked about half way through the session to ensure that everything was going according to plan.

III. Results

The initial final-year student project in 2017/18 produced a variety of samples that could be used for the laboratory session to be rolled out to the full class the following year. This project proved to be an enjoyable learning experience for the two students involved (two of the co-authors) and the students won the “Best Poster” award at the final-year Project Open Day in March 2018. Fig. 1 shows the poster which described many of the samples developed during the project.

As already noted, the final laboratory experiment was rolled out to a cohort of 23 undergraduate students in the 2018/19 academic year. Screen shots from some typical measurements are shown in Fig. 2 and Fig. 3, while Figure 4 shows examples of post-laboratory analysis of the 50 Ω micro-strip transmission line measurements carried out using MATLAB® [6].

To determine the student reaction to the new VNA laboratory a short anonymous survey was run in Semester 2

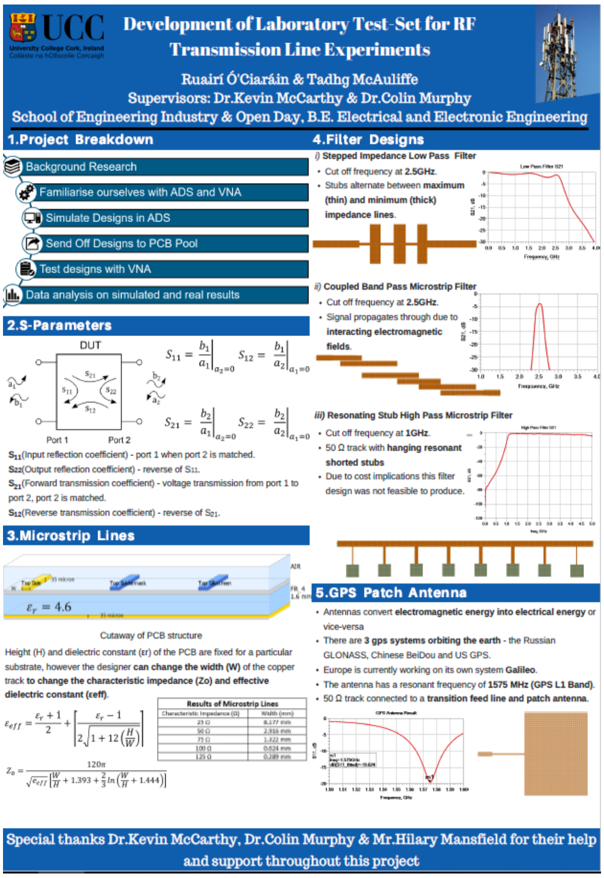

Fig 1. Poster used for final-year Project Open Day.

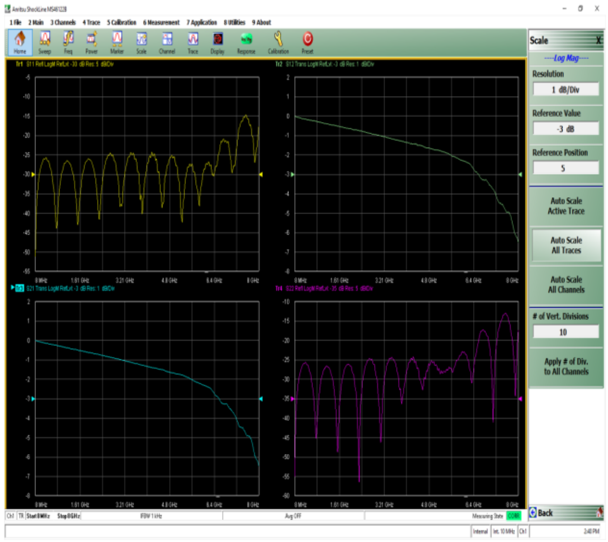
Fig. 2. Screen-shot of VNA measurements of 50 Ω transmission line.

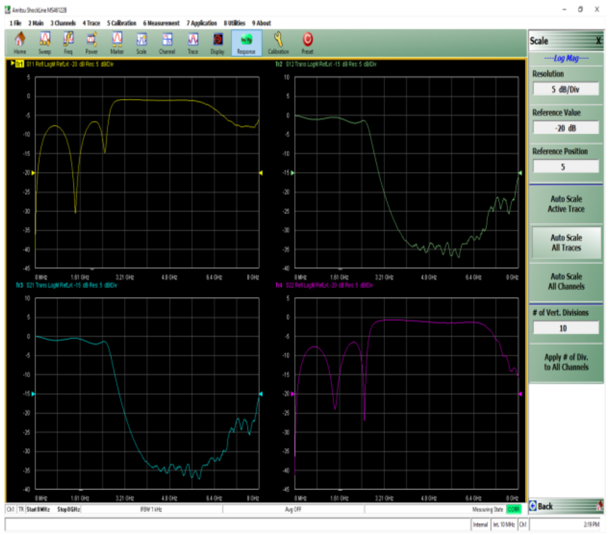
Fig. 3. Screen-shot of VNA measurements of a stepped-impedance low-pass-filter (LPF).

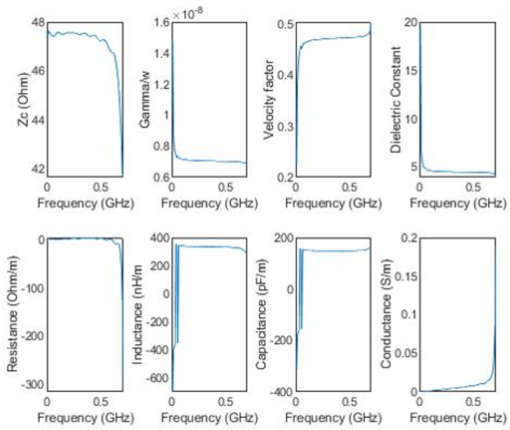

Fig. 4. Post-measurement analysis of the S-parameter data to extract the characteristic impedance (Z_0), the propagation constant, the velocity factor, the dielectric constant and the *RLCG* parameters of the transmission line.

among the students who has participated in the laboratory in Semester 1. The survey consisted of 14 short statements to which the students were asked to respond by ticking a 5-point Likert scale [7] that had options ranging from “Strongly disagree” to “Strongly agree”. Additionally, a section of the survey sheet asked students to provide feedback in a free-form manner and a final free-form question asked for any suggestions on how the laboratory could be improved for the future. The response rate to the survey was 48%.

Fig. 5 shows that all the respondents either “Strongly agree” or “Mildly agree” with the statement that “The lab content was aligned to the EE4016 module content”. A concerted effort had been made to ensure a good overlap between the content of the lectures and the content of the new VNA experiment and these responses indicate that this effort had been successful.

Fig. 6 shows that all of respondents either “Strongly agree” or “Mildly agree” with the statement that “The pre-lab orientation session gave me sufficient information to prepare for the lab”. While the lecturers were concerned that the one-hour pre-laboratory orientation session to the whole class might have been too short, these responses indicate that sufficient time had been given to this element of the laboratory preparation.

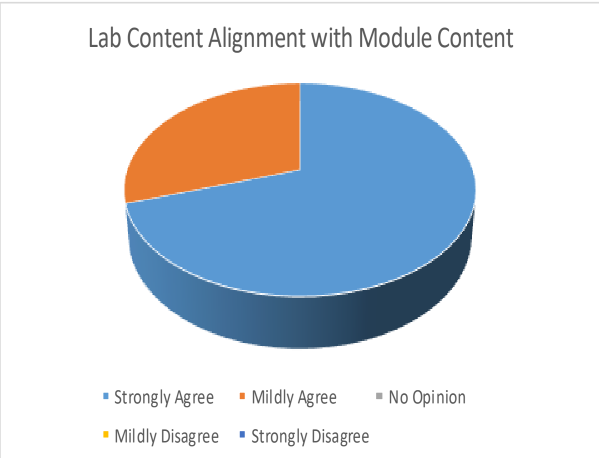

Fig. 5: Responses to “The lab content was aligned to the EE4016 module content.”

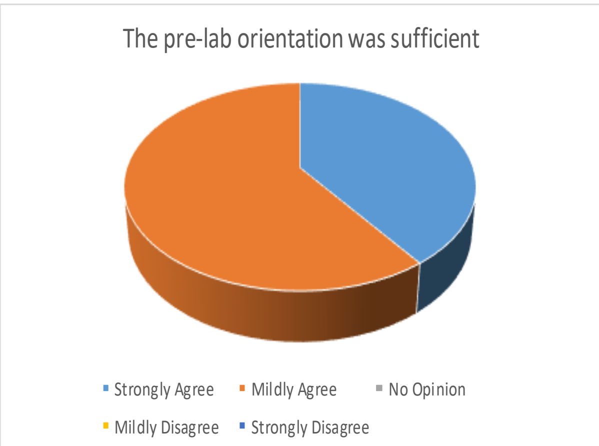

Fig. 6: Responses to “The pre-lab orientation session gave me sufficient information to prepare for the lab.”

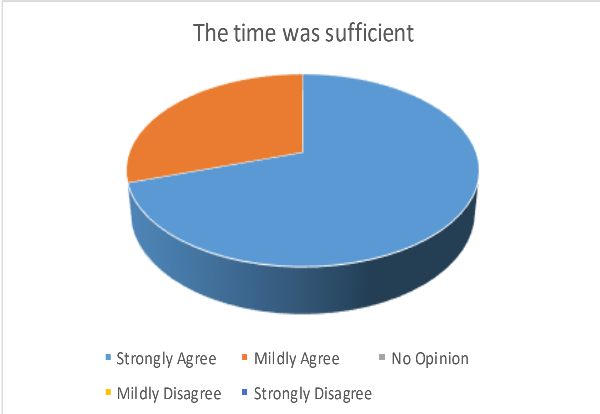

Fig. 7: Responses to “The time allocated to the lab was sufficient.”

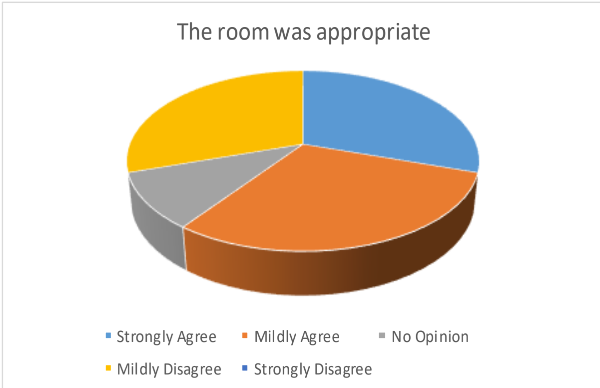

Fig. 8: Responses to “The room was appropriate for holding the lab.”

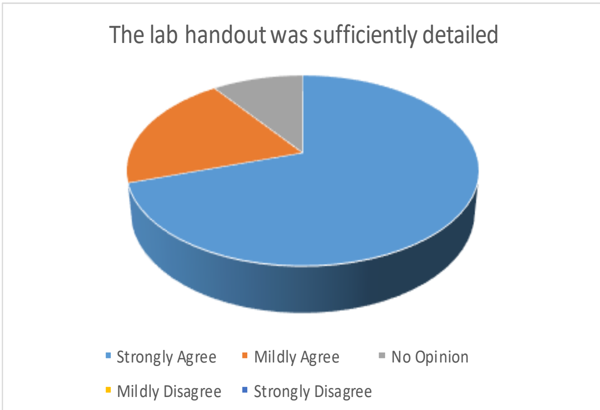

Fig. 9: Responses to “The lab handout was sufficiently detailed to allow all the lab steps to be performed.”

Fig. 7 shows that all the respondents either “Strongly agree” or “Mildly agree” that “The time allocated to the lab was sufficient.” Initially, the lecturers were over-optimistic in setting the number of separate tasks that could be realistically undertaken in a 3-hour laboratory and some trial runs indicated that the number of tasks needed to be reduced. These responses indicate that the final arrangement of laboratory tasks was manageable within the available time.

Fig. 8 indicates that while most some students agreed with the statement that “The room was appropriate for holding the lab”, there were some who disagreed with the statement. Because the VNAs are expensive items compared to those normally found in undergraduate laboratories, the experiment was hosted in a small laboratory normally only used by research students. Based on these responses, consideration will be given to hosting the laboratory in a larger room with more open access in future.

Fig. 9 indicates that 90% of the respondents either "Strongly agree" or "Mildly agree" with the statement "The lab handout was sufficiently detailed to allow all the lab steps to be performed." This is very encouraging because the laboratory was designed to be "student driven" as much as possible and these responses indicate that this has mainly been achieved. However, it has to be noted that two responses on the "free form" feedback suggested that the presence of a demonstrator for the full laboratory session would have been helpful.

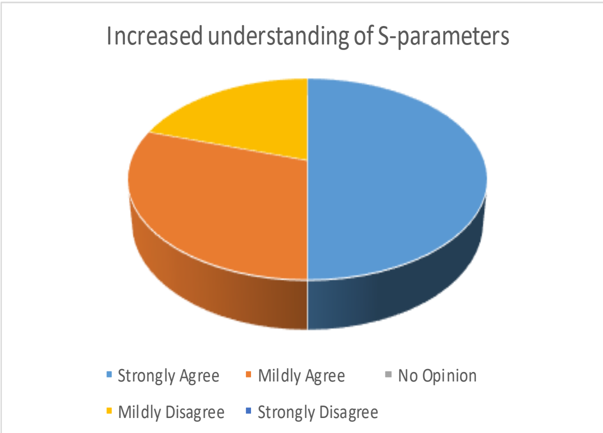

Fig. 10: Responses to "The lab increased my understanding of S-parameters."

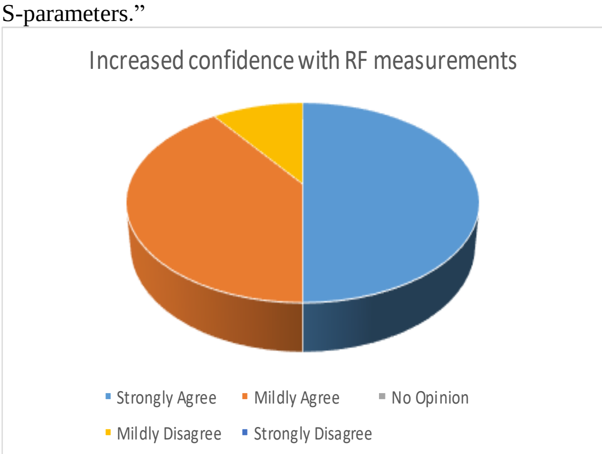

Fig. 11: Responses to "The lab increased my confidence with making RF measurements."

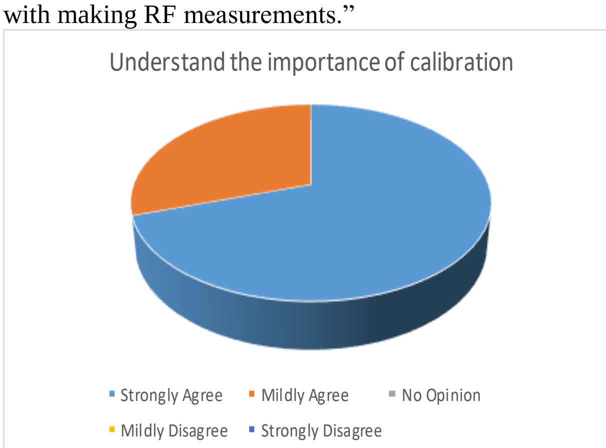

Fig. 12: Responses to "The lab increased my understanding of the importance of calibration for RF.

Fig. 10 indicates that 80% of the respondents either "Strongly agree" or "Mildly agree" with the statement "The lab increased my understanding of S-parameters." This is a very encouraging response because one of the main motivations for developing the laboratory was to give students hands-on experience of S-parameters. However, it has to be noted that 20% of respondents "Mildly disagree" with this statement but the survey was not sufficiently detailed to determine whether this was because the respondents felt that the session did not contribute to their learning or because they already felt very familiar with S-parameters.

Fig. 11 indicates that 90% of the respondents either "Strongly agree" or "Mildly agree" with the statement "The lab increased my confidence with making RF measurements." This is also a very encouraging response because the fundamental reason for developing the laboratory was to give students an opportunity to carry out S-parameter measurements and to "de-mystify" this area of RF.

Fig. 12 indicates that all of the respondents either "Strongly agree" or "Mildly agree" with the statement "The lab increased my understanding of the importance of calibration for RF measurements." Calibration is very important for high-quality RF/microwave measurements and the laboratory procedure was designed so that the first step to be undertaken by the students was a calibration procedure typically known as an "Open, Short, Load, Thru" calibration. It was decided to implement a manual calibration approach to give it more weight in the experiment even though many RF laboratories now use automatic calibration approaches. The questionnaire responses indicate that the message about calibration being important has registered fully with the respondents.

Fig. 13 shows the responses to the statement "The lab improved my understanding of RF signal propagation on a transmission line" for which 80% of the respondents either "Strongly agree" or "Mildly agree". As the main purpose of the whole "EE4016 Transmission Lines" module is to increase understanding of transmission line effects, this response is very encouraging and shows that the laboratory fulfils its primary purpose.

Fig. 14 shows that 90% of the respondents either "Strongly agree" or "Mildly agree" with the statement that "The lab improved my awareness of the characteristic impedance of transmission lines made from PCB tracks." One of the measurement tasks in the laboratory is to measure transmission lines made from a double-sided FR4 PCB board. One side of this is a ground plane and the other side has a range of tracks with a length of 100 mm and widths varying from 0.3 mm to 8.1 mm to give a range of characteristic impedance (Z_0) values between 25 Ω and 125 Ω. The responses indicate that the students have gained an appreciation of how the characteristic impedance depends on the width of the PCB tracks.

Fig. 15 shows that 80% of the respondents either "Strongly agree" or "Mildly agree" with the statement that "The post-lab tasks helped me to see the link between S-parameters and ABCD parameters." One of the post-measurement/post-laboratory tasks was to import the saved S-parameter measurements for various structures into MATLAB® and then convert them to ABCD parameters so that further

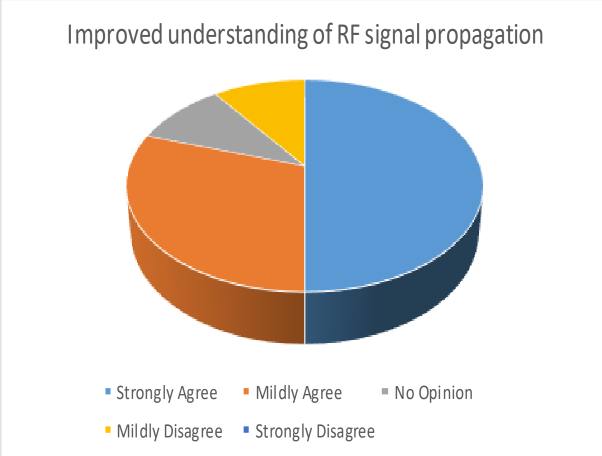

Fig. 13: Responses to “The lab improved my understanding of RF signal propagation on a transmission line.”

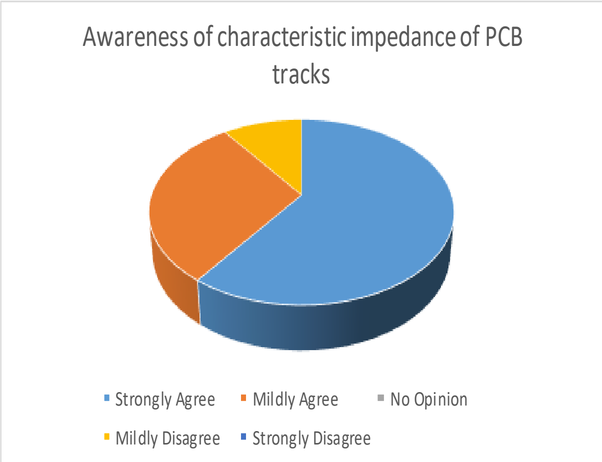

Fig. 14: Responses to “The lab improved my awareness of the characteristic impedance of transmission lines made from PCB tracks.”

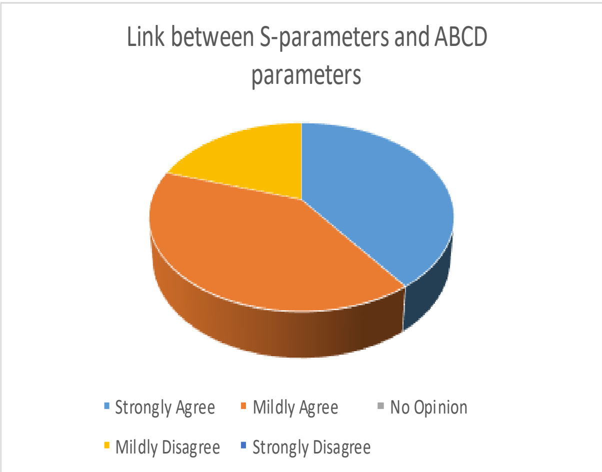

Fig. 15: Responses to “The post-lab tasks helped me to see the link between S-parameters and ABCD parameters.”

information such as characteristic impedance and the *RLCG* parameters of the transmission lines could be extracted. The main motivation for this was to illustrate to the students that the S-parameters are only one of the commonly-used 2-port representations for RF components and that it can often be helpful to convert these to other parameters such as ABCD parameters for further processing. The responses indicate that this goal has been achieved.

Overall, the questionnaire responses indicate that the first roll-out of the VNA laboratory to a cohort of 23 students has been well received and has met many of the learning outcomes initially envisaged for the laboratory. The authors have found the responses to the Likert-scale questions to be very informative and some of the responses and feedback given in the “free form” part of the questionnaire is also very useful. Two of the free-form responses indicated that the presence of a demonstrator during the whole laboratory session would be beneficial while another indicated that there should be a follow-on laboratory that needed “independent thinking” to compliment the initial laboratory that was tightly prescribed.

IV. Conclusion

This paper has outlined the development of an RF Vector Network Analyser (VNA) based laboratory for undergraduate electronic engineering students from the conceptual “wish list” stage to the development of samples and trial runs by a single two-person student team and on to the first roll-out of the laboratory to a cohort of 23 students.

Student feedback indicates that the first roll-out of the laboratory has met most of the goals originally set out and that the laboratory is viewed as contributing to an increased awareness of S-parameters and increased confidence with RF measurements. Some areas for improvement have also been identified and actions arising from these will be considered for future years.

V. Acknowledgements

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