Educational Set-Up for Microwave Laboratory Activities Using Virtual Instruments and Real Data

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Abstract – **This paper describes a virtual educational laboratory to be used for experimental activities in the framework of Telecommunications Engineering courses. The proposed approach is based on a set of software interfaces, named virtual instruments (VIs) and developed with LabVIEW™ environment, which are able to emulate hardware instruments. The aim of the project is to allow the students to perform experimental activities, either in the college labs or at home, without the physical availability of measurement instruments by simply using software emulators of real instruments that process real data acquired from real world. The system is being used in the Laboratory of Telecommunications and Microwave of the Engineering college of the University of Pisa, Italy.**

Keywords –**Communication engineering education, e-learning, microwave engineering education, new technologies for education, virtual laboratories.**

I. INTRODUCTION

A fundamental need for professional courses in engineering is the organization of a significant number of practical activities where the students, by using instruments and measurement systems in a laboratory, could verify and practice all those analytical concepts and methods learnt in theoretical courses. Unfortunately, this need must often compete with many serious problems. Among them, the first one is probably the availability of large capacity classrooms equipped with measurement instruments, usually very expensive, repeatedly distributed so as to arrange several work desks. Moreover, also when available, educational laboratories can be used only for those hours inserted in the semester timetable. The risk that the expensive instruments could be damaged through an incorrect use by inexpert students is a further issue that should be taken into account, too.

In order to solve the above problems, offering at the same time a more effective teaching of technical subjects, a team of teachers at the Engineering College of the University of Pisa, devoted to the development of multimedia teaching activities since the middle of the '90s, has developed a project for realizing an educational virtual laboratory to be used for experimental activities of professional disciplines in the framework of both the Bachelor and the Master Degree programs in Telecommunications Engineering [1].

The proposed approach is based on a set of suitably developed software interfaces, named virtual instruments (VIs), which are able to emulate hardware instruments, and

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represents thus a viable and very appealing alternative to conventional laboratory practice requiring a large amount of (costly) hardware equipments. The aim of the project is to allow the students to perform experimental activities, either in the college labs or at home, without the physical availability of measurement instruments by simply using software emulators of real instruments that process real data acquired from real world. To implement the software components of the virtual laboratory the team of teachers resorted to National Instrument's LabVIEW™ development framework [2], taking advantage from its interactivity and flexibility features, as well as the many functions available for data and signal processing.

II. THE EDUCATIONAL STRUCTURE

The educational system presented in this contribution is hosted in the educational Laboratory of Telecommunications and Microwave and is used by the students attending the Bachelor and the Master Degree programs in Telecommunications Engineering [1], whose courses and credit weights are listed in Tables 1 and 2, respectively, together with the relevant courses, credits (Cr.) and the availability of educational applications for instrument emulation (VIs).

The three-year Bachelor Degree program in Telecommunications Engineering consists of 18 courses and, after two years in common, branches into two curricula at the third year: the General Curriculum and the Professional Curriculum. The General Curriculum, besides a deep study of scientific and engineering basics, provides students with a thorough knowledge of the disciplines that characterize Telecommunications Engineering. This knowledge is not immediately directed towards applications, but is instead aimed at the acquisition of logical and methodological fundamentals. The General Curriculum is therefore best suited to those who want to continue their studies and obtain the Master Degree (named "Laurea Specialistica"), too. The Professional Curriculum, besides a good general education in mathematics, physics and the engineering basics, provides suitable practical abilities in the disciplines that characterize Telecommunications Engineering, and also includes a training period (apprenticeship) within telecommunications firms. The Professional Curriculum is therefore best suited to those who want to enter into the labour-force market as soon as they obtain their degree. The Master Degree program consists of twelve courses and branches into four curricula at the beginning of the second year: Telecommunication Networks, Transmission Systems, Signal Processing and Remote Sensing, Applied Electromagnetism.

TABLE 1
THE STUDY PROGRAM OF THE BACHELOR DEGREE IN
TELECOMMUNICATIONS ENGINEERING

	Course	Cr.	VIs
1st Year	Computer Science	12	
	Mathematics I	12	
	Mathematics II	12	
	Processing Systems	12	
	General Physics I	12	
2nd Year	Electrical Engineering	9	
	General Physics II	6	
	Signals and Systems	12	
	Economy and Business Organization	6	
	Electronics	12	
	Electromagnetic Fields	12	• Vector Network Analyzer Anritsu 37311A Emulator
	English Language Test	3	
3rd Year General Curriculum	Telecommunication Networks	6	
	Mathematics III	12	
	Circuits for Telecommunications	6	
	Probability and Stochastic Processes	6	
	Digital Signal Processing	12	
	Electromagnetic Compatibility or	6	• Vector Network Analyzer Anritsu 37311A Emulator
	Image Processing and Transmission or	6	
	Telematics	6	
	Final Exam	6	
3rd Year Professional Curriculum	Telecommunication Networks	6	
	Communication Systems	12	• Digital Transmission Analyzer HP 3784A Emulator
	Remote Sensing Systems	6	
	Microwaves	6	• Vector Network Analyzer Anritsu 37311A Emulator
	Measurements on Telecommunication Equipments	6	• Digital Oscilloscope Agilent 54641A Emulator • Digital Transmission Analyzer HP 3784A Emulator • Vector Network Analyzer Anritsu 37311A Emulator
	Specialization in Applied Electromagnetism		
	Design and Simulation of Microwave Systems	6	• Vector Network Analyzer Anritsu 37311A Emulator
	Electromagnetic Compatibility	6	• Vector Network Analyzer Anritsu 37311A Emulator
	Specialization in Signal Processing and Remote Sensing		
	Design and Simulation of Remote Sensing Systems	6	
	Image Processing and Transmission	6	
	Specialization in Telecommunication Networks		
	Design and Simulation of Telecommun. Networks	6	
	Telematics	6	
	Specialization in Transmission Systems		
	Design and Simulation of Transmission Systems	6	• Digital Oscilloscope Agilent 54641A Emulator • Digital Transmission Analyzer HP 3784A Emulator
	Wireless Communications	6	
	Apprenticeship	6	
	Final Exam	6	

TABLE 2
THE STUDY PROGRAM OF THE MASTER DEGREE IN
TELECOMMUNICATIONS ENGINEERING

	Course	Cr.	VIs
1st Year	Communication Systems	12	• Digital Transmission Analyzer HP 3784A Emulator
	Teletraffic Engineering	9	
	RF Electronics	6	
	Antennas and Propagation	9	• Vector Network Analyzer Anritsu 37311A Emulator
	Statistical Signal Processing	12	
	Digital Communications	12	• Vector Network Analyzer Anritsu 37311A Emulator
	Measurements on Telecommunication Equipments or	6	• Digital Oscilloscope Agilent 54641A Emulator • Digital Transmission Analyzer HP 3784A Emulator • Vector Network Analyzer Anritsu 37311A Emulator
	Operating systems	6	
2nd Year	*Specialization in Applied Electromagnetism*		
	Design and Simulation of Microwave Systems	6	• Vector Network Analyzer Anritsu 37311A Emulator
	Electromagnetic Compatibility	6	• Vector Network Analyzer Anritsu 37311A Emulator
	Microwaves	6	• Vector Network Analyzer Anritsu 37311A Emulator
	Optical and Microwave Devices	6	• Vector Network Analyzer Anritsu 37311A Emulator
	Specialization in Signal Processing and Remote Sensing		
	Design and Simulation of Remote Sensing Systems	6	
	Image Processing and Transmission I	6	
	Image Processing and Transmission II	6	
	Radar Technique	6	
	Remote Sensing Systems	6	
	Specialization in Telecommunication Networks		
	Design and Simulation of Telecommun. Networks	6	
	Optimization of Telecommunication Networks	6	
	Switching and Routing	6	
	Telematics	6	
	Specialization in Transmission Systems		
	Design and Simulation of Transmission Systems	6	• Digital Oscilloscope Agilent 54641A Emulator • Digital Transmission Analyzer HP 3784A Emulator
	Optical Communications	6	
	Radio Systems Engineering	6	
	Wideband Communications	6	
	Wireless Communications	6	
	Final Exam	6	

III. THE SOFTWARE ENVIRONMENT

The software-based components of the virtual laboratory have been assembled by resorting to LabVIEW™ [2], a development environment by National Instruments, which allows a very flexible design, supports interactivity, and renders available a wide set of signal and data processing functions. The LabVIEW™ environment also provides several dedicated functions which greatly ease the management of communication links via TCP/IP and IEEE 488 protocols (the latter, also known with its commercial name GPIB, is a standard interface bus allowing PC-based remote control of instrumentation). Thanks to such attractive peculiarities, a virtual laboratory encompassing interactive applications which emulate measurement instruments was developed by some teachers at the Engineering College of the University of Pisa. These interactive applications reproduce the functionality of the real equipments with a high degree of fidelity, making available to the operator virtual instruments (VIs) [3] provided of dials, knobs, buttons, selectors, indicators, meters, graphs and so on, that allow easy parameter setting and signal measurement. The fundamental feature of the educational set-up presented herein is the possibility of performing exercises by means of "virtual instruments" that use "real world" data. Actually, the VI software applications enable the PC to act very likely as a "physical" instrument performing (off-line) measurements and processing of previously acquired signals and measured data. The applications of the virtual laboratory are written with LabVIEW™ and are available for both Windows and Mac OS X systems. Moreover, a portable stand-alone version of the applications, implemented with LabVIEW™ Application Builder, is also distributed to students through CDs, allowing them to run exercises in classrooms or at home, simply upon installation of LabVIEW™ Run-Time Engine, that is freely available from National Instrument's web site [4].

IV. EXPERIMENTAL ACTIVITIES WITH VIRTUAL INSTRUMENTS AND REAL DATA

The preliminary phase of the exercise consists in the preparation of the data files, which is accomplished by the teacher. As apparent from Fig. 1a, measurement results acquired by physical instruments are sent, via standard IEEE 488 bus, to the teacher's PC which runs a VI application with remote control capability. The experimental data can be for instance a waveform acquired by a digital oscilloscope or some parameters of a microwave device measured by a vector analyzer. The data are eventually stored in a file and added to a library which is made available, e.g. via CDs or the web, to the students for subsequent off-line processing with VI applications during lab exercises (Fig. 1b). Notice that the data acquired by measurements are actually stored in special format files which are instrument-dependent. Some sample test files relevant to a selection of microwave devices are available on-line for download from the web site reported in [5] (see Fig. 2).

V. SUPPORTED INSTRUMENTS

The wide range of graphical items made available by LabVIEW™ environment for building realistic VI panels was exploited at its best to develop a set of software applications capable of controlling real instruments and carrying out measurements on communication equipments and microwave devices. Such software tools fully emulate the appearance and the functionalities of physical instruments, and allow to

process real world measured data loaded from externally acquired files. Some supported instruments are briefly described hereafter together with the main features of the relevant VI applications. It is worthwhile to remark that all the VI applications allow the remote-control of the physical instruments from the PC, either with a direct connection via IEEE 488, or through a TCP/IP network [6].
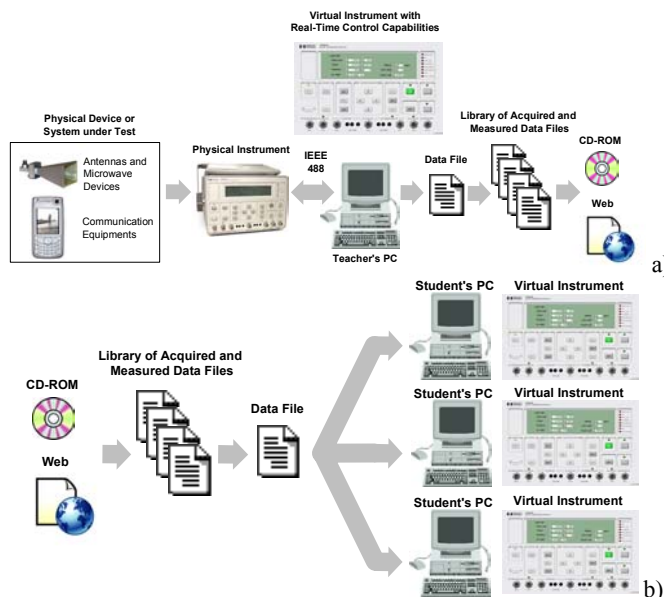

Fig. 1. Concept of laboratory exercise with instrument data:
a) generation of source data files to be provided to the VIs;
b) off-line processing of source data by student VIs.

A. Digital Oscilloscope Agilent 54641A

It is a 2-channel digital oscilloscope with 350 MHz bandwidth and 2 Gsa/s sample rate. Besides the customary oscilloscope functionalities (e.g., amplitude and time scale settings, trigger controls, etc.), the relevant VI software application yields many additional features for off-line processing of the acquired waveforms, such as signal sum and product, spectral analysis via the FFT (Fast Fourier Transform) algorithm, and statistical analysis. Furthermore, after being processed, the waveforms can be exported in text format.

B. Digital Transmission Analyzer HP 3784A

It is a portable test set featuring both a transmitter and a receiver section which can be configured for several digital signal formats. The analyzer offers standard telecom interfaces at 704 kb/s, 2, 8 and 34 Mb/s, including AMI and HDB3 line coding [7], and also binary TTL/ECL interfaces for measurements up to 50 Mb/s. It performs a plenty of measurements and statistical analysis of the received data stream, such as bit- and code-error rates, error-free seconds, jitter analysis, etc.. All of these measurements are acquired by the VI and can be used for post-processing, such as plotting bit- and symbol-error rate charts, outage probability, etc.

Fig. 2. Sample test files are available on-line [5].

C. Vector Network Analyzer (VNA) Anritsu Wiltron 37311A

It is an extremely versatile and sophisticated measuring equipment capable of characterizing radio-frequency and microwave devices operating in the frequency range from 20 MHz to 8 GHz (Fig. 3). For instance, the instrument can measure and display the return loss of antennas, the amplitude and phase response of filters, and the scattering parameters of multi-input microwave devices [8]. The panel of the relevant VI is divided into two main parts. In the left side two graphs are displayed showing the log-magnitude and the phase of the scattering parameter of the device under test and some graphic display controls. As an alternative, a Smith Chart representation can be also chosen. In the right side of the panel, standard VNA controls, such as data smoothing and averaging, are available.

VI. A LABORATORY EXERCISE CARRIED OUT WITH A VIRTUAL INSTRUMENT THAT PROCESSES REAL DATA

As a case study, we consider a laboratory practice using an N-port microwave network, i.e., a device having N arms into which power can be fed and from which power can be taken. In general, power can get from any arm (as input) to any other arm (as output). There are thus N incoming waves and N outgoing waves. The behaviour of such a device is completely characterized by means of an NxN complex-valued square matrix $\mathbf{S}$, named the "scattering matrix" (or the "S-matrix"), whose elements, named the "scattering parameters" (or "S-parameters"), are defined as follows:
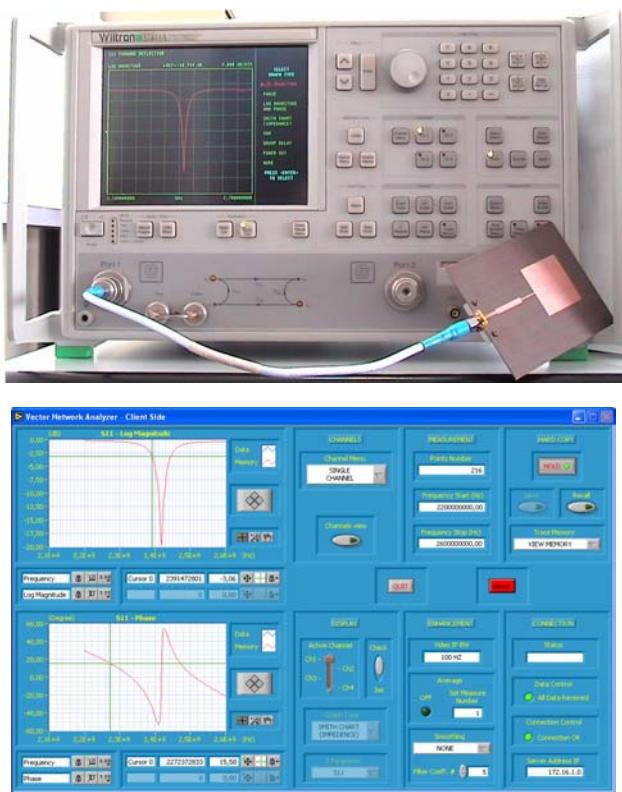
Fig. 3. The vector network analyzer Anritsu Wiltron 37311A performing measurements on a microwave patch antenna (top), and its VI panel (bottom).

S_{ii} is the reflection coefficient looking into port i;

S_{ij} $i\neq j$ is the transmission coefficient from port j to port i, all other ports being terminated on matched impedances.

In general, S-parameters are all frequency-dependent. In the case of a microwave device having two ports ($N=2$), i.e., an input and an output, such as for instance a filter or an amplifier, the S-matrix turns out:

$$\mathbf{S} = \begin{bmatrix} s_{11} & s_{12} \\ s_{21} & s_{22} \end{bmatrix} \quad (1)$$

The array in Eq. (1) actually contains eight separate numbers, i.e., the real and imaginary parts, or the modulus and the phase angle, of each of the four complex-valued S-parameters. An antenna is a one-port device and therefore the relevant scattering matrix consists of a single element only (s_{11}), which represents the antenna's reflection coefficient (or the "return loss").

Typical measurement activities on N-port microwave devices that are carried out in the Laboratory of Telecommunications and Microwave using the VNA Anritsu Wiltron 37311A are the following:

1. measurement of S-parameters for multi-input microwave devices, such as printed baluns, power dividers, and wideband filters [8];.

2. return loss measurements on rectangular patch antennas (both single elements and small arrays) (Fig. 4a), double-band

printed dipoles (Fig. 4b) and planar inverted-F antennas (PIFAs) for wireless transceivers (Fig. 4c), as well as for GPS (Global Positioning System), and RFID (Radio Frequency IDentification) antennas.
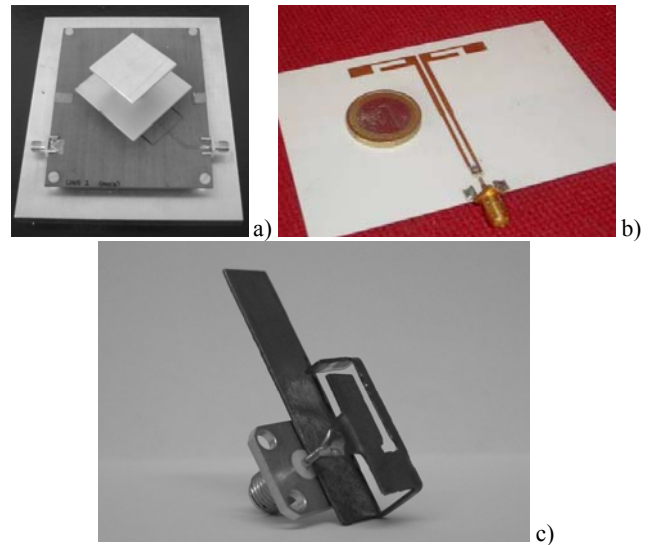

Fig. 4. Some microwave devices available for experimental exercises at the educational Lab. of Telecommunications and Microwave: (a) wideband dual-polarized UMTS stacked patch antenna; (b) double-band printed dipole; (c) double-band planar inverted-F antenna with SMA connector

During the measurement process, the complex-valued S-parameters are evaluated at N_p different frequencies uniformly spaced within the range [f_{start}, f_{stop}], and eventually stored in text files, together with the measurement instrument settings.

The data files are subsequently up-loaded by the students, through the Web or via a CD, into the VI version of the VNA installed in their PC. Figure 5 presents the content of the sample file "filter1.txt", (downloadable from [5]) relevant to a microwave filter. The file, which is browsed using a spreadsheet, includes a header containing the measurement settings, whose meaning is explained in Table 2, a string containing the N_p frequencies used during the measurement, and a string containing the measured results. For each of the N_p frequencies, the 4 elements of the 2x2 complex-valued S-matrix in eq. (1) are measured, so that the total number of real-valued data records stored in the file amounts to N_px2x4.

Through the virtual VNA the student can display the specific S-parameters of the microwave device or antenna under study, and also make some data processing. In particular it is possible to display the amplitude/phase representation of any S-parameter (e.g., the s_{11} as in Fig. 6), to zoom-in the parameter curve in a frequency range smaller than [f_{start}, f_{stop}] (see Fig. 7), to plot the parameter's Smith Chart polar representation (see Fig. 8), and also to perform some filtering on the measured data. For an N-port device, it is possible to display one or more of the N^2 elements of the relevant S-matrix.

Moreover, the commands available on the VI panel allow saving the data in a text file format and making comparison with other devices. Since the virtual VNA has most of the

commands of the real VNA, the student can easily learn how to use such an instrument, even being at home, and without the risk of damaging it. Just a few operations cannot be performed through the virtual VNA, such as for example the manual connection of the device to the VNA ports and the calibration procedure

Fig. 5. Data file containing the measured S-parameters of a microwave filter.

TABLE 3
SETTINGS FOR THE MEASUREMENTS ON A MICROWAVE FILTER

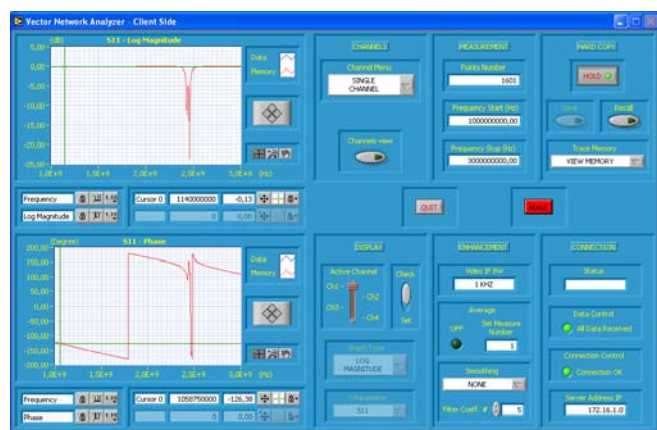| Cell	Content	Parameter	Symbol
A1	1601	No. of measured points	N_p
A2	1.00E+09	Start frequency (Hz)	f_{start}
A3	3.00E+09	Stop frequency (Hz)	f_{stop}
A4	1000	Intermediate frequency bandwidth used by the VNA during the measurement (Hz)	IF BW
A5	0	Smoothing of acquired data: 0 = OFF , 1 = ON	
A6	1	No. of time averages for every measured point	

Fig. 6. VI of the VNA displaying the amplitude (top chart) and phase (bottom chart) of the s_{11} parameter of a microwave filter.

VII. CONCLUSION

The educational laboratory for experimental exercises in telecommunication engineering courses was designed with the aim of providing the learner with the understanding of a measurement procedure on communication systems, equipments, and devices. This goal was fully achieved by using especially developed interactive software applications (the VIs) to process real world measured data.
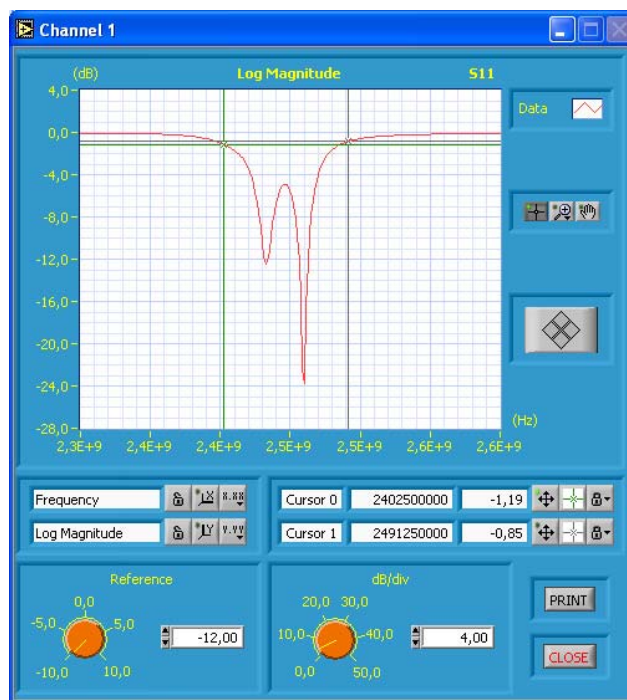

Fig. 7. VI of the VNA displaying the zoomed amplitude chart of the s_{11} parameter of a microwave filter.
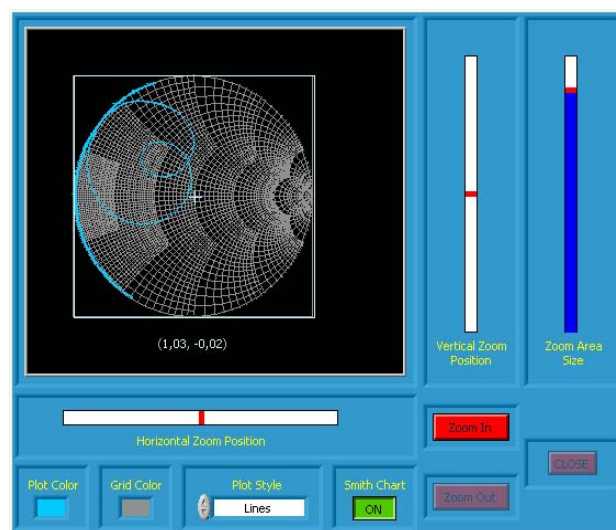

Fig. 8. VI of the VNA displaying the Smith Chart diagram of the s_{11} parameter of a microwave filter.

The proposed educational system allows effective experimental laboratory practice to be carried out also by students which can not attend classrooms, for instance due to illness or disability. Actually, despite the lack of a "physical" contact between the operator and the instrument, the teachers have found that the VI-based approach perfectly fulfils the goals of the educational project, allowing the students to fully understand the operation of a measurement test-bed, as in conventional educational activities based on the real physical equipments. The only significant left out aspect is the arrangement of the test-bed. Fortunately, in the case of communication systems, the preparation of the experimental

set-up usually consists in just some cable connections (see, for instance Fig. 6 left) and therefore it does not represent a severe limitation.

The main lesson the authors learnt from this research is the students' enthusiastic interest in lab exercises, which results especially striking if compared with the former educational approach based on less involving (and therefore much more boring) class-room demonstrations of single-copy instruments.

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