Requirements for Remote RF Laboratory Applications: An Educators' Perspective

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***Abstract*—This paper discusses the results of a study of the requirements for developing a remote RF laboratory. This study draws on the perspectives of educators in university electrical engineering departments and in technical colleges, on the teaching of the radio frequency (RF) domain. The study investigates how these educators would like the technical content of a state of the art RF laboratory to be designed. As far as the authors know, no publication exists in the literature that investigates the requirements and needs of remote laboratories in that particular field. The outcomes of this work are expected to guide remote laboratory platform developers towards the most effective design of their platforms. The analysis of the results showed that educators would like the technical content of the laboratory to cover basic communication techniques, microwave circuits and devices, antennas and propagation, RF technology, and radio system design aspects of modern telecommunication systems. They would therefore like the laboratory instrumentation to be designed to that end. The educators also reported the need for advanced experimental setups which require expensive RF measurement devices. The discrepancy between university and technical college views was also considered in this paper.**

***Index Terms*—Educational technology, electrical engineering education, life-long learning, radio frequency (RF), remote laboratory.**

I. Introduction

LABORATORY experience is an important part of electrical engineering (EE) education. As shown in recent Internet-based remote and virtual laboratory studies, effective learning in EE education could only be achieved by approaches that combine theoretical courses with laboratory work that the learner can repeat as necessary [1]. In classical methods, laboratory work is provided by means of face-to-face training in particular laboratories. Even in the ideal case, face-to-face laboratory training has some limitations for both the provider and the learner [2]. Well-known limitations for the provider are the requirement for a high number of educators and supporting personnel, and the high setup and maintenance costs for some EE laboratories (such as those covering radio frequency and microwave techniques) [3]. As for the learners, if an open laboratory environment is not provided, students are restricted to a time schedule and location for a particular course laboratory and are not able to repeat the experiment as often as they might wish. They also tend to have very limited opportunities to analyze the experimental data mathematically: usually the measurement device itself is unable to deal with a large amount of data. In the absence of time constraints, students have the opportunity to process the experimental data by using powerful software analysis tools, thus, obtaining a clearer notion of the functionality of a certain device or a setup.

A question often raised is whether a remote laboratory, with experiments carried out on real equipment, could be replaced by virtual Java-based simulations, which do not suffer from time-collision issues when multiple users try to access the same equipment at the same time. In the context of the RF field, simulation-based experiments are only appropriate to train students in, and familiarize them with, certain measurement equipment and methods. Furthermore, a simulation always presents an approximated and idealized result, whereas a remote laboratory works with real physical effects. Given the sometimes unpredictable behavior of real experiments, the remote laboratory therefore obliges students to learn to interpret the physical phenomena they actually encounter. Moreover, remote laboratories may incorporate certain interaction phases [as in the European Remote Radio Frequency Laboratory (ERRL)[1]] where the students have to answer questions regarding the functioning of the system. The students may act on the system remotely to correct an error in case of a malfunction, but obviously this interaction would not be at the electronic component level.

Remote laboratories are emerging technologies that enable users to use the instruments in the laboratories remotely. This study is conducted as part of a project known as the ERRL, which aims to establish a remote laboratory environment by enabling access to high technology radio communications equipment through the Internet [4]. Currently, this project is in the pilot study phase[2] and is planned to be in service by 2008. A guest access[3] to the pilot remote laboratory is also available. Detail information on some of the setups and the mechanics of the implementation, such as how to change the device under test and working with multiport devices, can be found in [4]. Since the equipment required in high-frequency telecom/radio laboratories represents advanced technology and is very expensive,

Manuscript received March 20, 2007; revised December 21, 2007. Current version published February 4, 2009.

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Digital Object Identifier 10.1109/TE.2008.919806

[1]The ERRL Project is supported by the EC-Leonardo da Vinci Pilot Programme. The website is available at http://errl.evtek.fi/.

[2]The pilot phase of the ERRL Project web-site is available at http://errlmoodle.atilim.edu.tr/.

[3]Guest access is available at http://errlmoodle.atilim.edu.tr/ with both user name and password being "visitor".

most schools cannot afford to implement such laboratories. The ERRL project aims to provide an alternative practice platform for those engineers and technicians who otherwise would not have the chance to access quality equipment. During the starting phase of the ERRL project, the authors noted the lack of a detailed requirements analysis with respect to the RF domain. Accordingly, the study presented here was undertaken to provide a better understanding of the requirements of radio frequency (RF) laboratories, based on educators' perspectives. The study was conducted in the electrical engineering (EE) departments of a number of universities and technical colleges (TC). The term EE covers the Bachelor of Science (B.S.) and the Master of Science (M.S.) levels of education in electrical engineering, whereas TC covers vocational education and training as well as technical education in RF.

In addition to the aforementioned limitations of face-to-face laboratory training practice, recent developments in Internet-based services encourage training organizations and institutions/universities to attempt to establish e-learning models. Modern universities need to provide lifelong learning environments to extend the range of their education and to support learners anytime and anywhere they need help. In order to accomplish this objective, educational and training organizations, particularly universities, are making increased use of Internet technologies to enhance and supplement traditional face-to-face education. Like conventional education, teaching via the Internet should be partitioned into theoretical lecture hours and complementary laboratory time. Especially in the case of EE education, if e-learning programs are to offer a complete e-learning process, the laboratory applications must also be facilitated remotely. A remote laboratory platform enables the learners to access physical instruments at a distant location and to perform experiments remotely via the Internet. Remote laboratory applications would therefore seem to be an alternative approach to providing the laboratory experience that learners should acquire in their education. However, it should be noted that face-to-face laboratory training cannot always be replaced by a remote laboratory. For example, in some radio-related experiments, students learn to deal with various malfunctions in the experimental setup, and develop troubleshooting skills that cannot be tested by a remote laboratory environment. However, there are still some basic concepts, measurements, instruments, and experiments to be studied that do not require any physical interaction between the learner and the laboratory environment. The scope of a remote RF laboratory should be defined with this in mind. The ERRL content mostly aims to cover those basic subjects.

This paper focuses on the results of a requirement analysis performed in different countries in Europe. The analysis aims to investigate the demand for, and needs of, a remote RF laboratory for EE and technical college education. A remote laboratory is believed to provide potential users with facilities that they are not able to access in person easily and conveniently. The requirement analysis in this paper is based on the perspectives of educators who teach in the RF domain. This requirement analysis is (a) aimed to guide further studies in this domain and (b) planned to be extended to other domains of EE education. The paper is organized in five sections: Section II introduces the envisioned problems and limitations of practical RF training and describes remote laboratory options to overcome those problems and limitations. Section III describes the applied survey to educators from various universities across Europe. Evaluation of the results is covered in Section IV. The final section, Section V, consists of discussion and conclusions.

II. Background of the Paper

Widespread public and private services offered by the telecommunications industry rely on RF and microwave technology and sciences. Such technology has been recognized as an essential core of EE and computer engineering education over the last decade. This recognition is also supported by studies in the literature [5]. In the curriculum of engineering departments and technical colleges, many theoretical high-frequency telecommunication- or radio-communication-related courses usually exist to equip students for the needs of industry. These courses are usually supported by various laboratory environments: a remote laboratory on frequency modulation experiment principles [3], a face-to-face laboratory implementation in the field of antennas [6] and RF-microwaves [7], an RF hardware design laboratory with project oriented approaches [8], and wireless information networks [9]. Cassara [9] has also summarized some of these implementations, generally focusing on wireless networks, radio frequency-microwaves, antennas, radar, or optical communications. These implementations show the recognition of the importance of these topics in the educational arena.

However, several limitations exist when establishing the laboratory practices listed above, such as the expense of these physical experimental setups both in implementation and maintenance. Acquiring enough laboratory equipment and establishing an experimental facility to support and demonstrate the application of the theory represents a considerable challenge [10]–[12]. This lack of laboratory equipment is currently particularly acute for telecommunication experiments in the high-frequency ranges, which are used in various consumer devices (mobile phone, CD player/radio, car remote, etc.). Because the equipment required in high-frequency telecom/radio laboratories is very expensive and delicate, currently most schools cannot afford to have such equipment and the trained personnel to maintain it. Even where high frequency telecommunication laboratories exist, students may not have the opportunity to exploit them fully, due to the lack of supervising personnel and restricted time allocation. Unattended experiments may be risky since the cost of any damage to equipment is very high. For example, a connector/adapter or a port of an RF device is not only very fragile and has very low mechanical tolerances, but is also relatively expensive compared to components for low frequency applications. Such parts can easily be damaged when making connections, which may be done several times during an experiment. Such damage may delay or postpone the whole experiment.

Another factor that should be considered is that practices in the telecommunications industry have been changing rapidly. Hence, technicians, engineers, and managers working in this field should continually improve their skills and technical background according to the most recent industry standards, in order to remain competitive in the field. Supporting those personnel merely with updated theoretical information is insufficient; improvement of practical skills is vital. Engineering departments of universities are the best places to offer lifelong-learning opportunities, by complementing theoretical education with practical training [1].

Different approaches to solving the problems discussed above have been proposed in the literature. For example, an open laboratory where students can work at any time during normal business hours has been established [8], allowing a class of ten or more to share a single high-cost device such as a spectrum analyzer or a network analyzer. In that approach, the problems of time limitation and the maintenance of expensive instruments still exist. A virtual laboratory to simulate physical experiments is another alternative [10]–[12]. Tzafestas *et al.* define the virtual laboratory as "the use of graphical user interfaces that incorporate interactive simulation techniques (particularly realistic 3-D graphics animations) but provide no visual or teleoperation link to a real (remote) physical system (only simulation of the physical system is on the loop)" [13, p. 361]. They also define a remote/distance laboratory platform as one which "involves teleoperation of a real, remotely located, physical system including visual and data feedback from the remote site" [13, p. 361]. Nedic *et al.* summarize the advantages and disadvantages of both virtual and remote laboratories [14]. In virtual laboratories there is only idealized data, without any collaboration or interaction with real equipment [14]. However, a laboratory experience is essential for students to develop troubleshooting skills for dealing with instrumentation and physical processes [15]. Studies also have shown that students given only simulation access displayed a lesser grasp of the real context than those in the proximal (in person in the laboratory) group and those in the remote group [16]. Also in Chang *et al.* [17]'s study, most of the students thought that a remote laboratory application on photonics domain (V-Pen) was better than a purely online simulation. In some cases, distance learning systems that are real-time and interactive are, therefore, the most desirable approach [18].

Remote laboratories also offer additional opportunities when compared with physical laboratories. The learning process differs among individuals. To receive the most effective education, students need to have the chance to choose and follow their own learning style and pace. Remote laboratory platforms offer a more flexible practice environment to the users, and provide a more efficient use of laboratory equipment. Users can configure setups and get responses very quickly. This ability encourages them to change variables, such as input signal frequency or amplitude, in order to observe the differences between several situations more easily than they could in a physical laboratory.

Early remote laboratory applications in the EE domain have generally been established on microprocessors, control systems, power electronics, digital circuits, and robotics. It is well known that the instruments used in basic courses are generally easy to control remotely [15]. Accordingly, a number of remote laboratory applications related to basic EE courses have been implemented successfully [2], [19]–[23]. There are few examples of remote laboratory applications established in the RF domain. On the other hand, the rapid growth of the telecommunications industry and the widespread deployment of wireless network services have brought a boom in opportunities in careers related to high frequency technology for graduating seniors. This rapid growth also forces practicing engineers, computer specialists, and managers to re-educate themselves in the area of telecom/radio-communications technology [9], [24]. Such education is generally offered by electromagnetic, RF, antenna, and microwave courses, which are important components of any EE and computer related educational curriculum. Finally, the requirements for, and lack of, RF specialists has been indicated recently [25] in a report including an industry/education partnership [Global Wireless Education Consortium (GWEC)] involving more than 30 universities and nine large companies in the wireless sector in the USA. Hence, a remote laboratory application in the RF domain seems to be a very critical element in order to improve and support current educational environments.

TABLE I
COMPOSITION OF LEARNER GROUPS

Learner Group	%
Bachelor Students	64
Master Students	32
Technical College Students	43

III. RESEARCH METHODOLOGY

Before an institution can offer the most effective remote training for learners, a requirement analysis must be conducted. This paper initiates from the belief that these requirements should be clearly defined before technical and practical development of such a laboratory. Hence, the answer to the following question should be sought: what requirements and needs should be fulfilled in developing a remote RF laboratory for EE and TC students?

To answer the above question, a questionnaire was prepared for educators in the RF domain. This questionnaire[4] was presented to 44 such educators from different European countries: Germany, Greece, Finland, Romania, and Turkey. The limited number of respondents is due to the limited number of professionals working in this sector. Before compiling the questionnaire, preliminary analysis conducted in RF industry, including some satellite operators, mobile service providers, and defense companies, helped the authors to determine the main RF equipment (requiring skilled personnel to use) needed by the target industry and sectors. Another preliminary step was to consider the RF topics that are taught in most of the EE departments and TC. A list of experimental subjects is identified in this way, and is also discussed in the following sections.

More than half of the educators (30 educators, 64%) participating the survey had university professor affiliation. The rest of them (14 educators, 31%) taught in technical colleges. The largest group of educators had more than 16 years of teaching experience (36%). Approximately 30% of the educators had 11–15 years, 15% of the educators had 6–10 years, and the

[4]http://www.atilim.edu.tr/~nergiz/ERRL_Questionnaire_teacher.pdf.

TABLE II
GENERAL RF-DEVICES IN USE (DUPLICATE ANSWERS ARE INCLUDED)

	Low Level %			Standard %			High End %			Not Available %		
Device Name	**EE**	**TC**	**ALL**	**EE**	**TC**	**ALL**	**EE**	**TC**	**ALL**	**EE**	**TC**	**ALL**
Power Meter	17	0	11	43	57	48	7	7	7	33	36	34
Oscilloscope	27	0	18	53	64	57	17	14	16	17	21	18
Spectrum Analyzer	10	21	14	43	29	39	33	7	25	20	43	27
VNA	3	0	2	33	7	25	17	0	11	53	93	66
RF Signal Gen.	17	14	16	47	50	48	30	0	20	20	36	25
Modulation Gen.	14	14	14	43	71	52	23	0	16	30	14	25

TABLE III
GENERAL RF-DEVICES FOR IMPROVEMENT OF EXPERIMENTS

	Low Level %			Standard %			High End %			Not Necessary %		
Device Name	**EE**	**TC**	**ALL**	**EE**	**TC**	**ALL**	**EE**	**TC**	**ALL**	**EE**	**TC**	**ALL**
Power Meter	3	0	2	7	7	7	3	7	5	77	86	80
Oscilloscope	3	0	2	17	0	11	10	7	9	73	93	80
Spectrum Analyser	3	0	2	33	29	32	17	7	14	47	64	52
VNA	3	0	2	23	29	25	47	0	32	27	71	41
RF Signal Gen.	0	0	2	17	14	16	27	0	18	57	86	66
Modulation Gen.	0	0	0	33	29	32	43	0	30	30	71	43

TABLE IV
REQUIREMENT OF SOME HIGH END DEVICES FOR IMPROVEMENT OF EXPERIMENT FACILITIES

	Yes			No			Not Available		
Device Name	**EE**	**TC**	**ALL**	**EE**	**TC**	**ALL**	**EE**	**TC**	**ALL**
Spectrum Analyzer (Up to 50 GHz)	37	29	34	17	36	23	47	36	43
Spectrum Analyzer (Up to 26.5GHz)	27	36	30	23	29	25	47	36	43
VNA (Up to 40 GHz)	37	29	34	17	29	20	47	43	45
EMC Analyzer	33	29	32	20	21	20	47	50	48
RF Signal Generator (Up to 50 GHz)	33	36	34	10	7	9	57	57	57
Modulation Generator	30	43	34	10	7	9	60	50	57
Oscilloscope (Up to 4 GHz)	30	43	34	10	21	14	60	36	52

remainder had less than six years of experience (19%). Table I shows the profile of the learner groups of the educators where multiple selections were considered. Most of the educators taught bachelor's and master's level students.

It should be noted that universities dominate in the study, representing approximately two-thirds of the respondents.

IV. EVALUATION OF QUESTIONNAIRE RESULTS

Based on the preliminary analysis as described in the previous section, the RF devices listed in Table II were used in the questionnaires. The table shows the use of the equipment for each subject group: EE, TC, and overall. The equipment is categorized into three groups according to the common terminology of the industry and the training organizations (i.e., EE and TC): low level, standard, and high end. The educators were asked to consider each device in one of the groups.

As shown in Table II, almost all of the RF devices are available at more than 60% of those organizations, except for the vector network analyzer (VNA). VNAs are available only in 38% of the organizations. This result is, of course, not unexpected due to the high cost of this device. It should be noted that the available devices are predominantly standard.

When EE and TC are considered separately, the configuration is found to be quite different for the most sophisticated and, hence, the most expensive devices such as VNAs and spectrum analyzers. At the TC level, the use of high-end devices is none for most of the devices, and the use of even a standard VNA or spectrum analyzer is significantly lower at TC than at EE. Almost all subject TCs would seem to use standard devices (mid-performance) and are not aware of some high-tech devices such as the spectrum analyzer or VNA.

The RF device requirements of the subject groups are displayed in Table III. In general, educators seem to believe that some additional devices would improve their current experimental facilities. The demand is higher on standard to high-end devices (see Table III). Note that higher demand is also seen for expensive devices and in particular for the VNA (59%). Once again, when EE education and technical schools are investigated separately, a difference is seen. The need for additional devices

TABLE V
LIST OF RF RELATED EXPERIMENTS AND REQUIRED EQUIPMENT CONSIDERED IN THE STUDY

Subject No Description	Equipment and Subject
	VNA
1	Measurement of scattering parameters (such as short, open load, matched load)
2	Measurement of scattering parameters: waveguide and filter (such as bandpass, lowpass), amplifier, phase shifter, directional coupler
3	Analysis of basic and practical antennas (such as wire, patch and microstrip)
4	Impulse Response and Multipath (multipath effects in a real radio environment/channel)
5	Time and Frequency domain analysis of radio channel response and multipath
	Spectrum Analyser, RF signal generator
6	Basic RF signal noise and distortion measurements
	Spectrum Analyser, Modulation Generator, Oscilloscope
7	Analog Modulation (time and frequency analysis)
8	Frequency Modulation (time and frequency analysis)
	Spectrum Analyser, Signal Generator
9	Signal analysis, Spectrum Analysis (Fourier Analysis)
	EMC Analyser
10	Basic EMC Measurements
	Spectrum Analyser, RF Signal Generator
11	Frequency Transfer Characteristics of Active Devices (Amplifier)
12	Frequency Transfer Characteristics of Passive Devices (Filter)
	Spectrum Analyser, Modulation Generator, Oscilloscope
13	Shift Keying techniques (FSK, ASK and PSK modulation)

in the EE education sector is twice as great as that of the TC sector. This observation suggests a need for more high-end devices at EE, while the use of standard devices seems to be sufficient to improve the experiments at TC.

Table IV shows the need for some high-end devices for improved facilities. Independent of the function of the device, about one-third of all subjects consider the use of high-end equipment as an improvement to their experiments. The evaluation of results for EE, in particular, shows a similar tendency; approximately one-third of the instructors were positive about the use of high-end devices, with fewer negative responses. It should be noted that although the absence of any selection (YES or NO) could be interpreted as an explicit rejection; it may also be interpreted as lack of information about the utilization of the device. In contrast to EE, the evaluation for TC presents a higher rate of negative answers, particularly for the more expensive/complex devices. The demand for these devices is recognizably lower, too. Only for the two signal generators and the high-end oscilloscope is the demand similar to that for EE. The overall results show that for EE, educators do recognize that high-end products could improve their measurement capability.

Although experiments could be performed using lower-cost equipment, especially for undergraduate students, investment in very high frequency (VHF) equipment is still needed in order for students studying for their master's degrees and students under continuous training to be able to work with precise measurements in the domain of tens of GHz. Such precise measurements are required when verifying certain hypotheses when conducting research work. The requirements of industries, such as military and satellite, for higher frequency applications should also be considered [26]. Moreover, even for students studying for their bachelor degrees, having trained on measurement equipment in the domain of tens of GHz increases their competence levels. Even if the current telecom industry has adopted standards that do not imply these kinds of very high frequencies, a trend towards higher frequencies is visible. The sooner the employees of the telecom industry learn this technology, the better.

In order to better understand the availability and necessity of particular experimental setups, a list of experiments was made (see Table V). The experiments were chosen to cover the main concepts in high frequency and radio communication related courses. These experiments include the concepts of reflection and transmission (return loss, Standing Wave Ratio [SWR], reflection coefficient), transmission lines, loss power, reflected power and transmitted power of the antennas and the SWR and

TABLE VI
REQUIREMENT ANALYSIS OF EXPERIMENTS

	Available (%)			Necessary (%)			Not Available(%)		
Subj	EE	TC	ALL	EE	TC	ALL	EE	TC	ALL
1	40	14	32	37	50	41	27	36	30
2	47	29	41	30	50	36	27	29	27
3	47	7	34	30	43	34	27	50	34
4	27	14	23	37	29	34	37	57	43
5	20	14	18	47	29	41	37	57	43
6	50	36	45	37	36	36	20	36	25
7	67	57	64	30	36	32	10	21	14
8	50	57	52	47	36	43	10	21	14
9	43	36	41	50	43	48	13	29	18
10	20	7	16	67	57	64	17	43	25
11	23	43	30	67	29	55	17	36	23
12	33	43	36	53	36	48	20	29	23
13	50	43	48	50	43	48	7	21	11

the input impedance of the antenna at the certain frequency ranges, multipath effects, noise, modulation concepts, Fourier analysis, and electromagnetic compatibility. The respondents were asked to specify the availability of listed experiments and the requirement if not available.

The results are evaluated in Table VI. Note that a few respondents selected both options for this question (available and necessary). These answers are interpreted to mean that the experiments are available, but an improvement of them would be desirable. Hence, they are counted for both options.

Table VI lists broadly available and less necessary experiments:

- analog modulation (#7);
- frequency modulation (#8);
- FSK, ASK, and PSK modulation (#13);
- basic RF signal-noise and distortion measurements (#6).

Some experiments are necessary but less available are as follows:

- EMC measurements (#10);
- frequency transfer characteristics of active devices: Amplifier (#11);
- frequency transfer characteristic of passive devices: Filter (#12);
- impulse response and multipath measurements (#4 and #5).

Based on the above list, it should be noted that the basic experimental setups are available in most of the institutions. However, a significant lack of more advanced experiments and setups (EMC measurements, frequency transfer characteristics of devices, etc.) is visible. The former group of setups is related to the transmission and reception of RF signals and their behaviors, whereas the latter set is related to characterizing RF systems. The two sets complement each other, though the latter set of experimental setups is more complicated to establish and requires more expensive devices (such as a VNA, spectrum analyzer, EMC analyzer). The results indicate that a remote RF laboratory would target these types of more complicated setups and experimentation facilities in order to train highly valuable skilled personnel in this field.

V. DISCUSSION AND CONCLUSION

In this paper, a study related to the requirement analysis of educators' needs for a remote RF laboratory application was presented. The study incorporated questionnaires, applied to educators of EE and TC in the RF field. The feedback from those educators is essential for shaping the scope and technical content of a remote RF laboratory, as well as for justifying the need for a remote RF laboratory. Hence, the questionnaires aimed to measure educators' satisfaction with their existing RF laboratory equipment and experimental setups, and to elicit what they believe their needs to be for improving the learners' competences. The results can be analyzed from two different points of view: equipment requirement/facilities and requirement of improved experiment modules/subjects.

The analysis of the results showed that the subject laboratories mostly have standard quality basic equipment, which is satisfactory for basic experimental setups. However, the educators showed interest in more sophisticated RF measurement devices in order to extend their capability for advanced experimental setups. Those setups are important in improving the skills of the learners to stay current with the recent and ongoing advances in the telecommunications industry, particularly the radio-related wireless industry. On the other hand, it can be concluded that the technical content of the laboratory and the laboratory instrumentation should be designed to include basic communication techniques, microwaves circuits and devices, antennas and propagation, RF technology, and radio system design aspects of modern telecommunication systems. Equipment capabilities and experiments should be developed together.

When EE and TC are compared in terms of facilities and experimental subjects, the approaches are found to be different. In general, the satisfaction of technical school educators with available equipment is higher and their demand for more expensive devices is lower than that of EE educators. The findings of this paper are believed to be significant and can act as a guide in developing remote RF laboratory platforms. The work presents what educators feel they lack and what they particularly need, both of which should be considered while designing the technical contents of a remote RF laboratory.

ACKNOWLEDGMENT

The questionnaire results are from a collaborative study of researchers in different countries. The authors would like to thank all collaborators for contributing to the study and for fruitful discussions.

REFERENCES

[1] W. A. Wulf, "How shall we satisfy long-term educational needs of engineers?," *Proc. IEEE*, vol. 88, no. 4, pp. 593–596, Apr. 2000.
[2] J. Sanchez, S. Dormido, R. Pastor, and F. Morilla, "A Java/Matlab-based environment for remote control system laboratories: Illustrated with an Inverted Pendulum," *IEEE Trans. Educ.*, vol. 47, no. 3, pp. 321–329, Aug. 2004.
[3] C. C. Ko, B. M. Chen, S. H. Chen, V. Ramakrishnan, R. Chen, S. Y. Hu, and Y. Zhuang, "A web-based virtual laboratory on a frequency modulation experiment," *IEEE Trans. Syst.s, Man Cybern. C: Appl. Rev.*, vol. 31, no. 3, pp. 295–303, Aug. 2001.
[4] A. Kara, E. U. Aydin, R. Oktem, and N. Cagiltay, "A remote laboratory for training in radio communications: ERRL," in *Proc. 18th Ann. IEEE Int. Symp. Pers., Indoor and Mobile Radio Commun.s (PIMRC'07)*, Athens, Greece, Sep. 2007, pp. 1–5.

[5] K. C. Gupta, T. Itoh, and A. A. Oliner, "Microwave and RF education-past, present, and future," *IEEE Trans. Microw. Theory Tech.*, vol. 50, no. 3, pp. 1006–1014, Mar. 2002.
[6] M. Mazanek, M. Polivka, P. Cerny, P. Piksa, and P. Pechac, "Education in antennas, wave propagation and microwave techniques," in *Proc. ICECom 2005 18th Int. Conf. Appl. Electromagn. Commun.*, Oct. 2005, pp. 1–4.
[7] C. Furse, R. Woodward, and M. Jensen, "Laboratory project in wireless FSK receiver design," *IEEE Trans. Educ.*, vol. 47, no. 1, pp. 18–25, Feb. 2004.
[8] W. B. Kuhn, "A senior-level RF design course combining traditional lectures with an open laboratory format," in *Proc. 30th ASEE/IEEE Frontiers in Educ. Conf.*, 2000.
[9] F. Cassara, "Wireless communication laboratory," *IEEE Trans. Educ.*, vol. 49, no. 1, pp. 132–140, Feb. 2006.
[10] W. Menzel, "Microwave education supported by animations of wave propagation effects," *IEEE Trans. Microw. Theory Tech.*, vol. 51, no. 4, pp. 1312–1317, Apr. 2003.
[11] M. Righi, W. J. R. Hoefer, and T. Weiland, "A virtual field-based laboratory for microwave education," in *Proc. 1998 IEEE MTT-S Int.*, Jun. 1998, vol. 2, pp. 555–558.
[12] M. F. Iskander, "Technology-based electromagnetic education," *IEEE Trans. Microw. Theory Tech.*, vol. 50, no. 3, pp. 1015–1020, Mar. 2002.
[13] C. S. Tzafestas, N. Palaiologou, and M. Alifragis, "Virtual and remote laboratory: Comparative experimental evaluation," *IEEE Trans. Educ.*, vol. 49, no. 3, pp. 360–369, Aug. 2006.
[14] Z. Nedic, J. Machotka, and A. Nafalski, "Remote laboratories versus virtual and real laboratories," in *Proc. 33rd ASEE/IEEE Frontiers in Educ. Conf.*, Boulder, CO, Nov. 5–8, 2003, Session T3E.
[15] I. Gustavsson, "Remote laboratory experiments in electrical engineering education," in *Proc. 4th IEEE Int. Caracas Conf. Devices, Circuits Syst.*, Aruba, Apr. 17–19, 2002, pp. 1025-1–1025-5.
[16] D. E. Lindsay and G. C. Nalcolm, "Effects of laboratory access modes upon learning outcomes," *IEEE Trans. Educ.*, vol. 48, no. 4, pp. 619–631, Nov. 2005.
[17] G. Chang, Z. Yeh, H. Chang, and S. Pan, "Teaching photonics laboratory using remote-control web technologies," *IEEE Trans. Educ.*, vol. 48, no. 4, pp. 642–651, Nov. 2005.
[18] T. Kikichi, S. Fukuda, A. Fukuzaki, K. Nagaoka, K. Tanak, T. Kenjo, and D. Harris, "DVTS-based remote laboratory across the pacific over the gigabit network," *IEEE Trans. Educ.*, vol. 47, no. 1, pp. 26–32, Feb. 2004.
[19] L. Gomes and A. Costa, "Remote laboratory support for an introductory microprocessor course," in *Proc. IEEE Int. Conf. Microelectr. Syst. Educ.*, 2005, pp. 21–22.
[20] D. A. Miele, B. Potsaid, and J. T. Wen, "An internet-based remote laboratory for control education," in *Proc. Amer. Control Conf.*, Arlington, VA, Jun. 25–27, 2001.
[21] B. Aktan, C. A. Bohus, A. L. Crowl, and M. H. Shor, "Distance learning applied to control engineering laboratories," *IEEE Trans. Educ.*, vol. 39, no. 3, pp. 320–326, Aug. 1996.
[22] A. Etxebarria, J. I. Oleagordia, and M. Sanchez, "Power electronics and basic electronics real experiments through the World Wide Web," in *Proc. 31th ASEE/IEEE Frontiers in Educ. Conf.*, 2001.
[23] N. Fujii and N. Koike, "Work in progress-a new time-sharing remote laboratory e-learning system for hardware design and experiment of digital circuits," in *Proc. 35th ASEE/IEEE Frontiers in Educ. Conf.*, 2005, pp. F35 11–F35 12.
[24] T. M. Weller, P. G. Flikkema, L. P. Dunleavy, H. C. Gordon, and R. E. Henning, "Educating tomorrow's RF/microwave engineer: A new undergraduate laboratory uniting circuit and system concepts," in *Proc. Microw. Symp. Dig., 1998 IEEE MTT-S Int.*, Jun. 1998, vol. 2, pp. 563–566.
[25] S. S. Sloan, "Preparing the wireless workforce," *Proc. FIE'05, Frontiers in Educ.*, pp. S2D23–S2D27, Oct. 2005.
[26] S. Watanebe, "Technology transfer of high frequency devices for consumer electronics," *IEEE Trans. Microw. Theory Tech.*, vol. 40, no. 12, pp. 2461–2466, Dec. 1992.

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