An Ultra Low Cost Wireless Communications Laboratory for Education and Research

Yair Linn, *Member, IEEE*

***Abstract*—This paper presents an ultra-low-cost wireless communications laboratory that is based on a commercial off-the-shelf field programmable gate array (FPGA) development board that is both inexpensive and available worldwide. The total cost of the laboratory is under USD $200, but it includes complete transmission, channel emulation, reception (coherent and noncoherent), and probing capabilities. Over 15 different modulation types are currently supported. The laboratory, aimed primarily to serve as a teaching aid for a professor teaching senior undergraduate courses and projects, allows students to have visual real-time demonstrations in wireless communications systems. The laboratory is also powerful enough to allow experienced researchers to carry out wireless communications research projects. In this context, the laboratory is particularly useful for universities in developing countries, where budgets are extremely limited. Numerical and written survey results are presented that were collected from two classes of students taught by the author in a university in Colombia, South America, and which show the effectiveness of the laboratory in teaching wireless communications.**

***Index Terms*—AGC, BPSK, digital communications, demodulation, education, field programmable gate array (FPGA), hardware, laboratory, modulation, phase locked loop (PLL), phase shift keying (PSK), QAM, QPSK, receivers, transmitters, wireless communications.**

I. Introduction

THE GREAT Athenian philosopher Plato (427–347 BC) is credited with coining the expression "necessity [. . .] is the mother of invention" [3, p. 190]. That quote perhaps embodies the story of this paper[1] since it was born more out of circumstance and necessity rather than forethought and planning.

In 2007, the author accepted a visiting professorship at the Universidad Pontificia Bolivariana (UPB) in Bucaramanga, Colombia. The aim of this academic exchange, as is usually the case, was to enhance mutual understanding. The differences in budgets and facilities can be quite striking, and the lessons learned quite humbling. It suffices to give as an example that the *entire* annual research budget of the Electronic Engineering faculty (of 14 professors) in the Colombian university was $20 000, which is the same order of magnitude as the budget of a single professor in any medium-sized university in North America.

Needless to say, the aforementioned budgetary constraints posed a significant challenge when the author wished to engage in teaching and research in wireless communications. While software simulations are useful and could be employed, there is nonetheless no true substitute [4]–[6] to hardware implementations and experimental verification for both teaching and research, as discussed in Section VI. Especially when one considers teaching, the author agrees with the observation of three prominent professors who recently wrote [4, p. 2935] the following:

> "[. . .] computer exercises [. . .] for SDR [Software Defined Radio] would seem to be a natural approach. But we have found with many DSP topics that our students are often not impressed with a software-only 'canned demo,' and adding a hardware component greatly improves the effectiveness of the demo and/or lab exercise."

However, due to the aforementioned financial constraints, the only budget that could be allocated, at great effort, was approximately $1200 for the purchase of six Xilinx Spartan-3A Starter Kit boards [7] (each costing less than $200) primarily intended for another senior undergraduate course in field programmable gate array (FPGA) design techniques taught by the author. Faced with this absurdly low development budget and such meager resources, these constraints forced the author to employ, and sometimes invent, extremely efficient Verilog programming techniques to cram the wireless communications structures inside the FPGA, resulting in several theoretical and practical breakthroughs, some of which have already yielded academic publications [1], [2], [8], [9].

This paper describes the wireless communications laboratory developed by the author at UPB. As noted, it is based upon a commercially available Xilinx Spartan-3 A Starter Kit board [7] that costs less than USD $200. The only additional equipment required is a computer to interface to the board and, optionally, a keyboard and VGA monitor to transform the lab into a completely autonomous facility. From the author's experience, the laboratory presented here is fully suitable to accompany undergraduate courses on wireless communications and is powerful enough to be useful in academic research in wireless communications. Moreover, since the same unmodified FPGA board can be also used in courses for digital design, computer architecture, networking, and embedded systems, the investment needed for the laboratory can be reduced to a pittance by spreading the cost among various courses and research projects. Such an extreme cost-conscious approach is essential in order to allow for wireless communications teaching and research in resource-limited developing countries.

Manuscript received May 02, 2010; revised December 19, 2010; accepted May 06, 2011. Date of publication July 05, 2011; date of current version May 01, 2012.

The author is with PMC-Sierra, Burnaby V5A 4V7, Canada (e-mail: yairlinn@gmail.com).

Digital Object Identifier 10.1109/TE.2011.2158318

[1]Preliminary and partial versions were presented in the conferences [1] and [2].

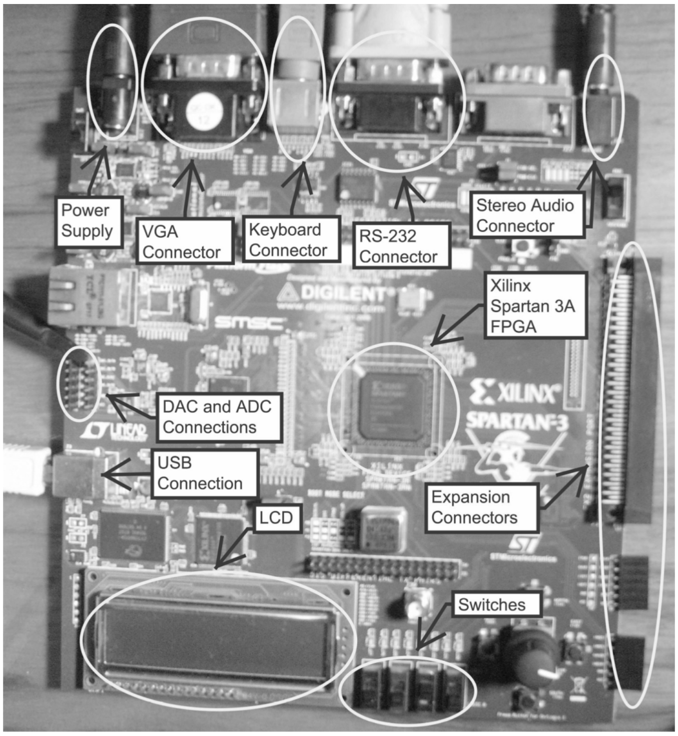

Fig. 1. Spartan 3A Starter Kit in which the lab is implemented.

II. Physical Platform

The laboratory's FPGA board, shown in Fig. 1, is based on a 700 000-gate Xilinx Spartan 3A FPGA [7]. As well as the FPGA, the board contains the following:

- 50-MHz oscillator;
- 133-MHz oscillator;
- external oscillator input;
- two 16-Mb serial FLASH;
- 32-Mb parallel FLASH;
- four-channel D/A converter;
- two-channel A/D converter;
- analog amplifiers;
- Ethernet port;
- VGA connector;
- stereo audio output;
- 100-pin expansion connector;
- 2×6-pin expansion connectors;
- eight LEDs;
- rotary knob/push-button;
- four push-buttons;
- 2-line $\times$ 16-character LCD;
- four switches;
- PS/2 keyboard connector;
- two RS-232 ports.

The abundance of peripheral components, the FPGA's decent logic capacity, and the expansion capabilities make this board very suitable for courses in FPGA design, digital logic, computer architecture, networking, and more, such as the previously mentioned advanced undergraduate FPGA design course[2] taught by the author.

[2]http://sites.google.com/site/cursofpgasupbbga/

For the laboratory presented here, the FPGA and some of the peripheral devices were used in order to form a transmission, channel emulation, and receiver system that comprise a complete communications system. Other components on the board are used for input, output, probing, and control in order to enhance the learning experience, the description of which follows.

III. Implementation and Structure

The laboratory is implemented via a configuration file that is loaded into the FPGA. Additionally, the FLASH memories on the board are loaded with data for use in channel emulation.

A. Internal Structure

A simplified functional diagram for the wireless communications implementation within the FPGA is shown in Fig. 2. Essentially, the laboratory includes a data sequence generator, a modulator, a channel emulator (Gaussian noise addition, slow fading can also be emulated), and a demodulator (can be configured as coherent or differential). The demodulator includes bit error rate (BER) and signal-to-noise ratio (SNR) measurement circuits. The modulation/demodulation combinations currently supported are BPSK, QPSK (4-QAM), 8-PSK, 16-PSK, DBPSK, DQPSK, D8PSK, D16PSK, QAM-16, QAM-64, QAM-256, $\pi/4$-QPSK, $\pi/8$-8-PSK, $\pi/4$-DQPSK, and $\pi/8$-D8PSK. It is emphasized that all of the above modulations are contained in a single FPGA configuration. That is, no FPGA reconfiguration is necessary in order to change the modulation, but rather only a user command.

The current parameters of the laboratory are shown in Table I. The choice of such relatively low rates has advantages from a laboratory and teaching perspective. First, the low carrier frequency (5 kHz), while certainly well below the maximum rate achievable with the FPGA, provides a signal that is well suited for measurement with low-cost spectrum analyzers and oscilloscopes that use a computer's audio input (whose filter cuts off signals above 20 kHz). This obviates the need for a spectrum analyzer or oscilloscope (which, especially in developing countries, are scarce). Very powerful spectrum analysis and oscilloscope freeware programs that use the PC's audio input, such as Visual Analyzer (www.sillanumsoft.org) should be quite adequate for most academic needs. Thus, the choice of low operating frequencies allows very low-cost measurement apparatus to be used, which is essential for a resource-limited university in a developing country. Indeed, while the expensive measurement equipment for higher frequencies is widely available in universities in developed countries and can be used with no financial problems, it is simply unobtainable in many universities in developing countries.

Since the laboratory uses frequencies below the RF range, it could correctly be argued that it would not serve for courses that depend on the absolute frequency of the signals observed, such as courses in transmission lines, microwave technology, or antennas. Waveguides and reasonably sized antennas, for example, are useless at such low frequencies and therefore cannot be well taught or understood through the low-frequency approach. However, the course taught with the laboratory covers wireless modulation and demodulation techniques, whose topics, from baseband to intermediate frequency (IF) are

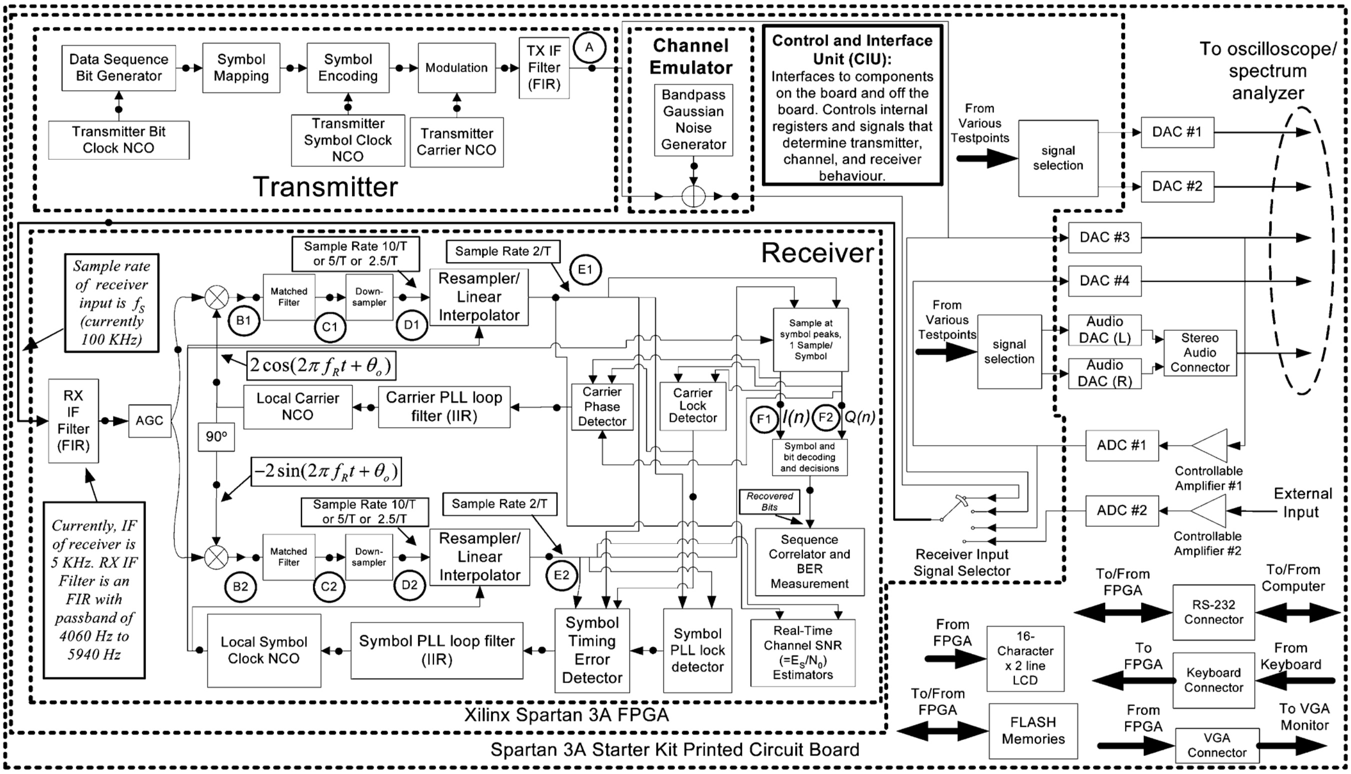

Fig. 2. Simplified diagram of the wireless communications laboratory. Small black dots in the various paths represent some of the possible test points that can be fed out to the DACs. The points labeled (A), (B1), (B2), (C1), (C2), (D1), (D2), (E1), (E2), (F1), and (F2), are discussed later in the paper. ADC = analog-to-digital converter. AGC = automatic gain control. DAC = digital-to-analog converter. FIR = finite impulse response. IF = intermediate frequency. IIR = infinite impulse response. NCO = numerically controlled oscillator. SNR = signal-to-noise ratio (= E_S/N_0, the channel symbol SNR). A second AGC loop (not shown) controls the signal levels after the matched filters in order to further minimize quantization effects.

TABLE I
SUMMARY OF CURRENT WIRELESS COMMUNICATIONS LAB PARAMETERS

Parameter Name	Value	Notation
Modulations/ demodulations	BPSK, QPSK (4-QAM), 8-PSK, 16-PSK, DBPSK, DQPSK, D8PSK, D16PSK, QAM-16, QAM-64, QAM-256, $\pi/4$-QPSK, $\pi/8$-8PSK, $\pi/4$-DQPSK, $\pi/8$-D8PSK	
Symbol Coding	Differential coding, Gray mapping	
Demodulation	Coherent or Differential	
Carrier Frequency	5 KHz	f_c
Symbol Rate	625 Hz	1/T
Sampling Rate	100 KHz	f_s

nearly unaffected by the actual frequencies used, and hence are easily taught using the low-frequency approach. The validity of this approach of using low frequencies and a personal computer's audio inputs and outputs for wireless communications teaching and research is supported by its use elsewhere (for example, in [10]–[16]), which provides additional proof for the validity of this approach.

B. Carrier and Symbol Synchronization PLLs

A carrier phase locked loop (PLL) and a symbol PLL are implemented within the FPGA, where the carrier PLL is only applicable for the coherent demodulation modes. The receiver structure generally follows the all-digital receiver structure detailed in ([17, Ch. 2–5]). More specifically, the receiver architecture follows the Linn architecture detailed in [9]. For more information, the reader is referred to [1] and [2].

C. Channel Emulation

The channel emulation part of the laboratory is based on a novel method of bandpass Gaussian noise process generation that is detailed in [8]. Accurate SNRs can thus be generated on the FPGA board without the need for external noise sources. Reference [8] is an example of a research breakthrough whose design, development, and testing was enabled by this laboratory.

D. Probing and DAC/ADC Interface

The small black circles on the various paths in Fig. 2 are some test points that can be channeled to the various on-board digital-to-analog converters (DACs) for observation in a spectrum analyzer or oscilloscope. This allows the user to fully observe in real time the internal signals in the transmitter, channel, and receiver.

Since a controllable bandpass noise process is generated on the card, and since the modulated signal amplitude is also

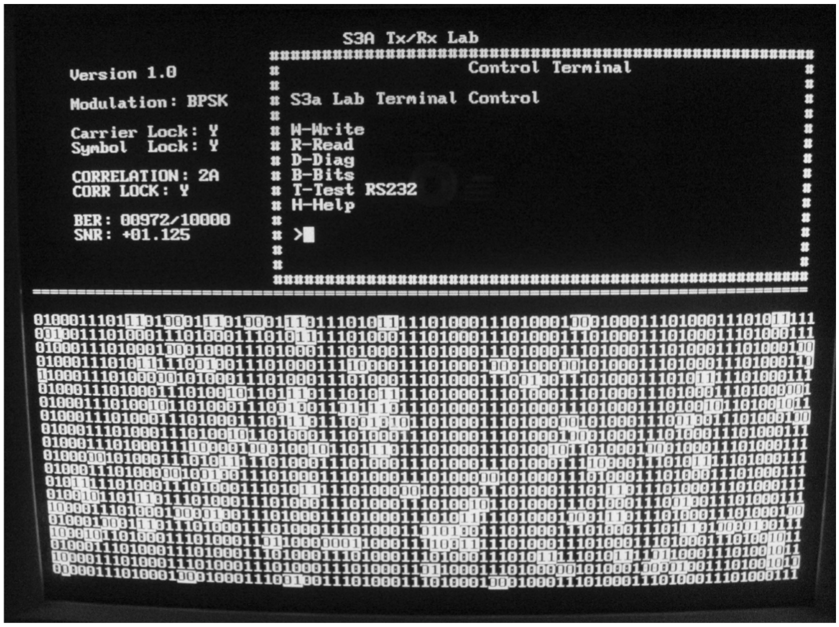

Fig. 3. Screenshot of the control terminal with an SNR of 1.125 dB and the transmitted signal is the word 01000111. On the screen's top half on the left, various receiver status metrics are shown, and on the right, the control terminal is seen. The screen's bottom part is a running display of the received bits, with erroneous bits denoted with inverse color. In this example, differentially encoded coherently demodulated BPSK is the modulation. Note that errors tend to occur in ***pairs*** of bits, which is to be expected due to the differential encoding and decoding [22, Section 4.2].

user-controllable, then a wide range of SNRs can be generated on-board without the need to transmit the signal; hence no external circuitry (such as amplifiers or antennas) is needed to generate SNRs. Nonetheless, if desired, the transmitted signal can be routed to DAC #3, and optionally this signal can be fed back through an on-board controllable amplifier and analog-to-digital converter (ADC) on the card. If a more elaborate setup is desired, the signal can be upconverted to RF, passed to a transmit antenna and then received by a receiving antenna, downconverted back to IF, and then connected to the on-board controllable amplifier and then to the ADC. Two cards can also be connected to each other as a transmit–receive (TX–RX) symmetric pair. However, again, such complicated setups are unnecessary since a wide variety of SNRs can be generated using the on-board noise and signal amplitude controls, i.e., one card can serve as the entire TX–RX chain without need to pass to the analog domain.

It is worth noting that the low-speed stereo audio DAC (see Fig. 2, the left and right audio channels) has the great advantage that the voltage levels and connector form make it ideal for connecting to a PC's audio input. High-quality PC-based spectrum-analyzers and oscilloscopes, which are (as mentioned earlier) available either freely or for a modest sum, can then be used for signal measurements.

E. Command and Control of the FPGA Card

The FPGA card can be controlled through various means. A hyperterminal connection via the RS-232 port is sufficient, though this requires low-level knowledge of the FPGA's internals in order to change the wireless communications parameters. A graphical user interface (GUI) is being developed in order to make the control more user-friendly.

Another control method is directly via a keyboard connected to the on-board PS/2 connector. This is a simple, text-based interface, which is equal to the RS-232 command structure except that the commands are entered by the keyboard and not through the serial port. Therefore, the card can be used completely autonomously, with control being achieved via direct connection to the card's keyboard port and data being displayed via the VGA port.

F. Data Sources

A variety of transmitted bit sequences can be chosen by the user, including pseudorandom bit sequences (PRBSs) generated by linear feedback shift registers [18]. Such sequences are ideal for BER measurement in order to characterize the communication link's performance [18]. Also, user-chosen patterns can be transmitted. As a didactic tool, for example, the laboratory can transmit the sequence ('01000111'). This sequence is quite short, and it does not approximate random data. However, this sequence allows the user to easily visualize errors using the VGA connection or the hyperterminal connection, and thus it is very useful as a didactic tool. Such usage is shown in Fig. 3.

IV. Academic Teaching Examples

This section gives examples of typical lab usage in a university setting for teaching wireless communications. A low-end Tektronics oscilloscope to measure time signals and an evaluation version of a commercial PC-audio spectrum analyzer [19] are used; freeware programs for computer-audio based oscilloscope and spectrum analysis measurements could just as well be used.

Since only one board was available for the class and the user interface was still in development, only the professor (the author) operated the laboratory during class, as the need arose

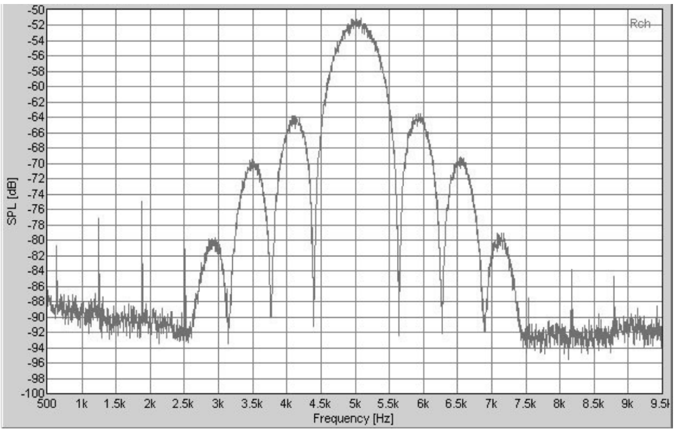

Fig. 4. Spectrum of the modulated QPSK signal after transmission filter.

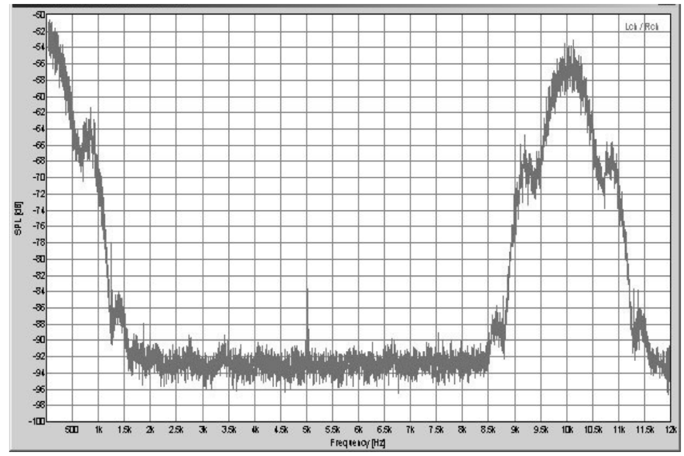

Fig. 5. Spectrum of the I channel and Q channel at the output of the $I-Q$ demodulator (before the matched filter) when the carrier is locked. Symbol SNR is 12 dB (the I and Q spectrums are essentially the same).

to highlight various points via a laboratory demonstration. Nonetheless, even though students did not manipulate the laboratory themselves, they did have control of the laboratory operations via the instructor. That is, a student could, for example, ask to see a particular signal or configure the laboratory for a specific modulation or other parameters, and the instructor would oblige. While it is not strictly speaking hands-on operation of the laboratory by the students, it is quite close to it, and this approach was necessitated by the severe budget/equipment constraints.

A. QPSK Transmission and Reception

An example follows of how QPSK transmission and reception can be observed using the laboratory. The baseband complex modulation signal is $m(t) \triangleq \sum_{n=-\infty}^{\infty} 1/\sqrt{2}(a_n + j \cdot b_n)p(t-nT)$, where $1/T$ is the symbol rate, $p(t) = \{1 \; -\mathrm{T}/2 \leq t \leq \mathrm{T}/2, 0 \text{ otherwise}\}$, and the differentially Gray coded data symbols [20] are (a_n, b_n) with $a_n, b_n \in \{-1, 1\}$. The modulated signal is $s_m(t) \triangleq \mathrm{Re}[m(t)\exp(j2\pi f_c t)]$, with f_c being the carrier frequency. As per Table I, with current lab parameters, $T = 1/625 = 1.6$ ms and $f_c = 5000$ Hz. The modulated post TX IF filter QPSK signal spectrum is shown in Fig. 4, which was obtained by channeling point (A) in Fig. 2 through an audio DAC to a PC-based spectrum analyzer. The time-domain QPSK signal can also be observed via an oscilloscope (omitted due to space constraints).

At the output of the receiver's IF filter, the waveform is $s_R(t) \triangleq s_m(t) \otimes f_T(t) \otimes f_{\mathrm{IF}}(t) + n(t)$, where $f_T(t)$ and $f_{\mathrm{IF}}(t)$ are the impulse response of the transmission and receiver IF filters, "$\otimes$" is convolution, and $n(t)$ represents the bandpass noise. Note that the receiver's IF filter is narrower than the TX filter and only lets the main lobe and one half of the first sidelobe pass, so that ~95% of the received input signal power is passed to the receiver.

Continuing the signal chain at the receiver, the received IF signal is passed through the $I-Q$ demodulator. The output of the $I-Q$ demodulator is present in Fig. 2 at points (B1) and (B2). In coherent QPSK mode with the receiver's carrier locked, in Fig. 2 $f_R = f_c$ and $\theta_o = 0$. The equations are not developed here due to space constraints, but it can be shown (e.g., [21, Ch. 2] and [22, Ch. 4]) that the I and Q channel [points (B1) and (B2) in Fig. 2] will contain the recovered I and Q baseband data spectrum and also a modulated signal at *double* the carrier frequency (10 kHz). The spectra of these signals are shown in Fig. 5, while time-domain oscilloscope screenshots are shown in Fig. 6. On a large timescale (Fig. 6, top), it is possible to observe the demodulated, prematched filter rectangular-shape silhouette of the transmitted bits. If a zoom-in is done (Fig. 6, bottom), the 10-kHz double-carrier component can be clearly discerned. Note how these graphs coincide with theory (e.g., [21, Fig. 2.11]). Students can see from these spectra and time-domain graphs how the concepts of modulation, filtering, noise, and $I-Q$ demodulation manifest in the real world, and they can acquire valuable experience in measuring and interpreting spectrum and oscilloscope measurements.

The matched filters in the I and Q arms eliminate the double-carrier-frequency terms, and the signal in the I and Q arms after the matched filter is composed of triangular pulses (the post-matched-filter pulse shape). This can be seen in Fig. 7, obtained by channeling points (C1) and (C2) through DACs to an oscilloscope. In that figure, a time-lapse mode of the oscilloscope is used so that the so-called eye-diagram can be discerned. The signal chain can be followed at points (D1), (D2), (E1), and (E2), but these figures are omitted here due to space constraints.

After carrier and symbol synchronization, and resampling of the I and Q signals to a rate of 1/T, the well-known $I-Q$ graph for QPSK should be seen if the (I, Q) signals are fed to an oscilloscope in X-Y mode. This is shown in Fig. 8, obtained by channeling points (F1) and (F2) in Fig. 2 through DACs to an oscilloscope.

Thus, the complete modulation and demodulation process can be observed by channeling the appropriate signals to the DACs and then to spectrum analyzers or oscilloscopes. Many other internal signals in the receiver and transmitter can be observed, as well as for other modulations, but these cannot all be shown here. For more examples, see [1] and [2].

Finally, BER and channel symbol SNR measurement circuits are implemented in the FPGA, and by noting their values, BER-versus-SNR curves can be drawn, which is an essential skill for

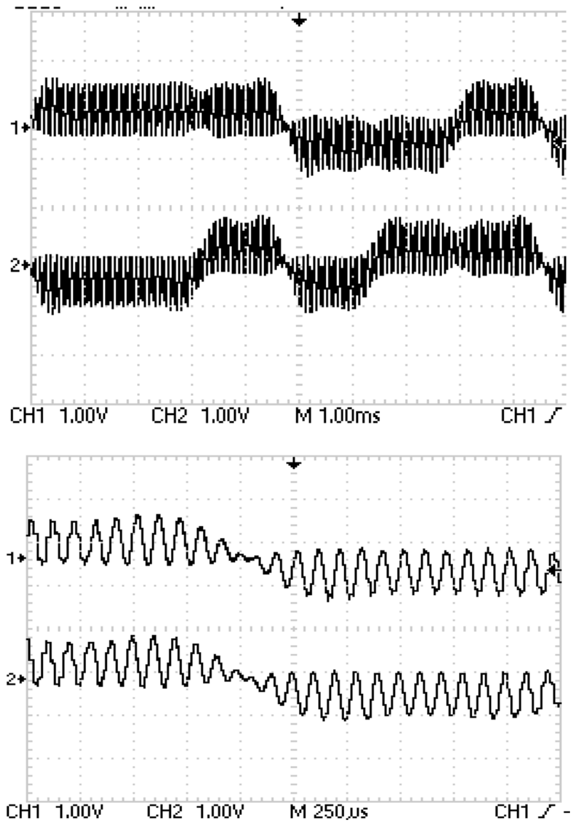

Fig. 6. I and Q time-domain waveforms of a received QPSK signal after the $I-Q$ demodulator. *(top)* 1 ms/div. *(bottom)* 250 μs/div.

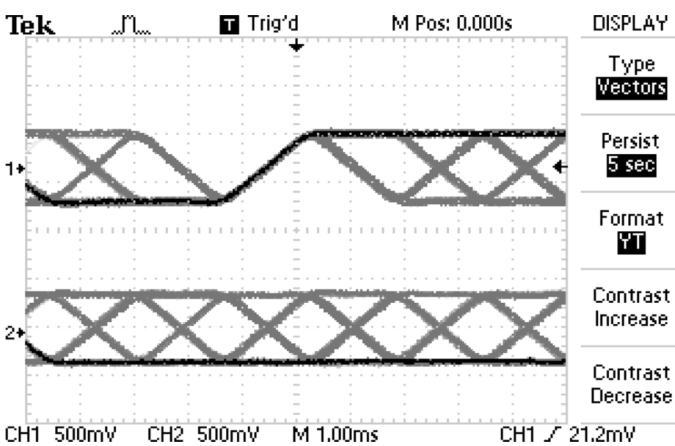

Fig. 7. Post-matched filtered QPSK waveforms after matched filtering before downsampling. Time-lapse nature of the measurement allows the eye diagram to be observed.

the wireless engineer to master. An example of such a graph made using this laboratory is given in Fig. 9, which shows the BER for differentially coded Gray-mapped M-PSK which is coherently demodulated, commonly known as differentially encoded (coherent) M-PSK (DEMPSK) [22, Ch. 4]. The theoretical BER formulas can be found in [20, Section 5.2.7] and [22, Ch. 4].

B. QAM Transmission

Another representative pedagogical teaching example is that of rectangular QAM transmission. The well-known general formula [20] for rectangular M^2-QAM (e.g., 64-QAM) transmission is

$$m(t) \triangleq \mathrm{Re}\left(\exp(j2\pi f_{\mathrm{C}}t)\sum_{n=-\infty}^{\infty}(a_n + j\cdot b_n)p(t-nT)\right)$$
$$= \sum_{n=-\infty}^{\infty} a_n \cos(2\pi f_{\mathrm{C}}t)p(t-nT) - \sum_{n=-\infty}^{\infty} b_n \sin(2\pi f_{\mathrm{C}}t)p(t-nT) \quad (1)$$

where $a_n, b_n \in \{\pm 1, \pm 3, \ldots, \pm(M-1)\}$, f_{C} is the carrier frequency, $p(t) = \{1 \quad -\mathrm{T}/2 \leq t \leq \mathrm{T}/2, 0 \text{ otherwise}\}$, and T is the symbol duration. The generation of this waveform is quite straightforward; see, for example, [22, Fig. 9.4]. One interesting way of viewing the generation of this signal is to view the $I(t)$ transmitter component versus the $Q(t)$ transmitter components, defined as

$$I(t) = \sum_{n=-\infty}^{\infty} a_n \cos(2\pi f_{\mathrm{C}}t)p(t-nT)$$
$$Q(t) = -\sum_{n=-\infty}^{\infty} b_n \sin(2\pi f_{\mathrm{C}}t)p(t-nT). \quad (2)$$

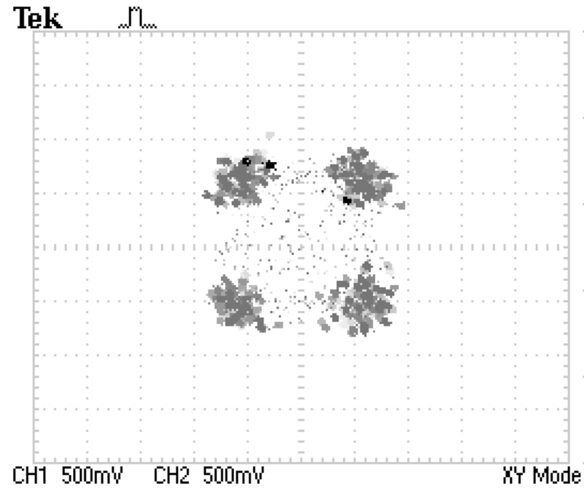

Fig. 8. QPSK demodulated $I-Q$ graph for a symbol SNR of 12 dB.

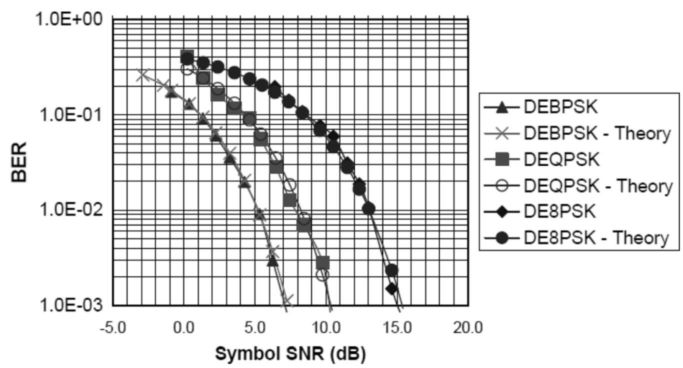

Fig. 9. Theoretical versus measured results for DEMPSK reception. Graph is of BER versus E_S/N_0.

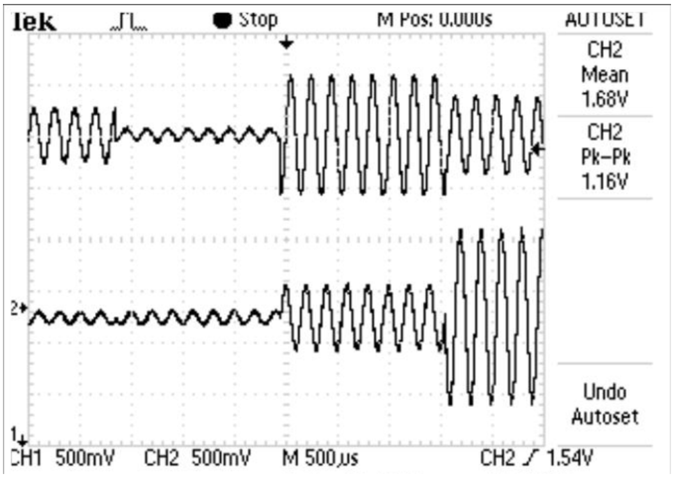

Fig. 10. I and Q arms in QAM-64 in transmitter.

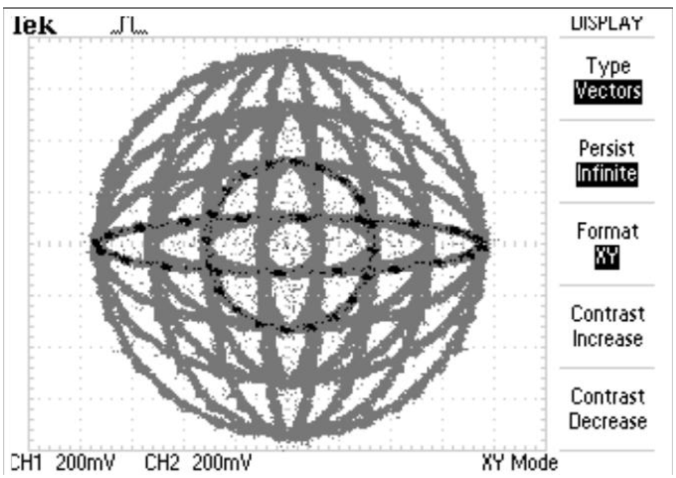

Fig. 11. Time lapse of $I(t)$ versus $Q(t)$ at the transmitter for QAM-64.

In the time domain, these look like Fig. 10, two signals of amplitude shift keying (ASK), which can be verified by inspection of (2). By showing this graph, (2) comes alive and makes sense to students.

An even more interesting presentation of the same signals can be attained by viewing $I(t)$ versus $Q(t)$ when the oscilloscope is in X-Y mode. In time-lapse mode ("Persist Infinite" mode), the oscilloscope shows the beautiful graph of Fig. 11. Indeed, one student jokingly remarked that it looks like a "disco ball," a comment which was met with enthusiastic laughter by his peers. The author showed this graph to the students and asked them to justify this behavior, based on (2) and on Fig. 10, which led to a lively discussion. The solution is, of course, that the formulas of (2) define ellipses, a different ellipse for each symbol, whose coordinates evolve over time via the well-known equation for an ellipse, $(a_n \cos(2\pi f_C t), -b_n \sin(2\pi f_C t))$. Different values of a_n and b_n for different symbols lead to different heights and widths for the ellipses. This can be verified if the nonaccumulating display is chosen ("Persist-Off" mode), and the oscilloscope timescale is such that in X-Y mode only a few symbols are shown at a time. This is shown in Fig. 12. In that figure, ellipses corresponding to three symbols can be

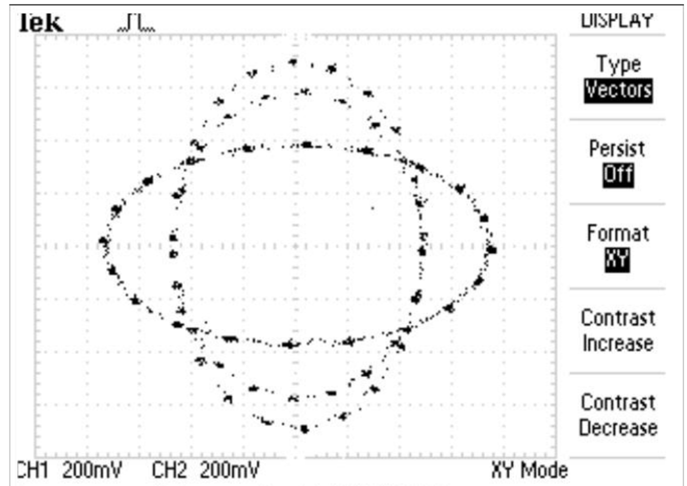

Fig. 12. Snapshot in time of $I(t)$ versus $Q(t)$ for QAM-64 at the transmitter.

seen, which confirm the manner in which Fig. 11 is generated. Such a class exercise has a powerful visual impact for the students and heightens their interest in the subject matter, as is confirmed by the survey results given later. Such useful and exciting demonstrations can be done for a wide variety of the various signals within the transmitter and receiver for the various modulations. A brief overview of other possible experiments is given in Section VII.

V. Research Applications and Comparison to Other Laboratories

Although the lab is primarily geared toward teaching and projects for undergraduate students, it is nonetheless sufficiently potent for it to be used in academic research. For example, to the author's knowledge, the receiver in this laboratory is the first documented hardware implementation of some of the structures in [1], [8], [9], and [23]–[35]. Moreover, it can serve as a platform for investigating the performance of these and other structures. Since the FPGA is reconfigurable, the laboratory could potentially permit other researchers to use it in order to rapidly implement and characterize their own structures in hardware. Thus, the laboratory is useful as a research tool as well as a teaching platform.

The most relevant question is, "How well does the laboratory described here compare to other software and hardware teaching solutions for wireless communications?" There are many pedagogical approaches for laboratories aimed at enhancing engineering education: software or hardware, hands-on or remote, simulated or real, commercially available or reported in the academic literature [4]–[6], [36]–[52]. A good overview of the benefits and drawbacks of each approach, and the corresponding debate upon each approach's merit, can be found in [53] and in the references therein.

A. Software Simulation Versus the Current Laboratory

As mentioned earlier, software simulation programs do exist that allow the student to learn about wireless communications, such as LabVIEW [45] (which is quite expensive, typically costing many thousands of dollars per institutional license) and Mathworks MATLAB/Simulink (www.mathworks.com), which can be licensed in bulk at a relatively low price of a hundred or so dollars per student for academic institutions. Another option is Rhode & Schwartz's WinSimIQ [46], which is free and quite capable and intuitive, but only includes the transmitter side (while much of the current laboratory is dedicated to investigating the receiver side, as can be seen in Fig. 2 and the example discussed in Figs. 5–9). WinSimIQ does have the intriguing advantage of being able to seamlessly control Rhode & Schwartz signal generators [46], allowing for a powerful software–hardware combination for the transmitter side, but such signal generators typically cost thousands of dollars, making this setup significantly more expensive than the current laboratory while not providing the receiver side.

While software simulation has its own merits, such as safety and ease of setup, it nonetheless has several inherent disadvantages compared to the current solution. The most obvious disadvantage is that a software simulation using a personal computer has a much lower operation speed (even at current technology, as compared to the intentionally low sample rates used in this laboratory). Another disadvantage is the fact that the parallelism of the receiver is only emulated in software, whereas in the FPGA implementation, the operation of the various modules is truly parallel (for example, the symbol synchronization loop, carrier loop, and AGC loops operate in parallel, and sometimes at different sampling rates). This is a significant disadvantage of software simulation because often some of the most important phenomena in wireless communications are a result of the complex interaction between the various control loops and PLLs—something that, though possible to simulate in software, is hard to achieve (especially using the computational power of a standard personal computer) and is thus rarely available in software laboratories. Finally, hardware systems arguably enjoy a subjective advantage when used in a classroom setting, as noted in the introduction to this paper. Thus, while the author is aware of several inexpensive (and even free) software simulation laboratories, such as those mentioned above, they nonetheless suffer from certain disadvantages as compared to the current hardware solution.

B. Other Hardware Laboratories Versus the Current Laboratory

Commercial wireless communications laboratories for teaching purposes are offered by many companies, for example LabVolt (www.labvolt.com) and Agilent (www.agilent.com). However, the cost of a typical commercial laboratory of this type in general ranges from several thousand dollars to tens of thousands of dollars, clearly not suitable for a developing country setting, and several orders of magnitude more costly than the current laboratory.

In terms of hardware laboratories developed by other university researchers, see [4]–[6] and [36]–[52]. Every laboratory will be geared toward the particular goals of the professor, so any comparison will be more qualitative than quantitative, though it is mentioned that the capabilities versus cost analysis of the current system as compared to the other references is quite striking at times. For example, if a comparison is undertaken between the laboratory proposed here versus the $35 000 laboratory proposed in [36], it can be seen that the former is about 175 times cheaper while offering significantly more capabilities. The laboratory in [43] will be seen to be somewhat more advanced, but yet its cost and complexity is far greater, estimated as several thousand dollars. The author is unaware of a laboratory that approaches the capabilities of the current laboratory at a price that is so low and thus suitable for such widespread, immediate use worldwide, including usage in developing countries with very limited resources. Empirical proof of usage in the developing world is presented in Section VI.

The laboratories in [4]–[6] and [36]–[52] do allow for hands-on student participation and are more capable, and are thus not directly comparable to the current laboratory. Even a single unit of one of these laboratories, however, reserved for the professor's use, is still prohibitively expensive for developing countries, which, depending on the definition used, are home to 80% or more of the world's population. The current laboratory offers comparable or better performance and is based on an off-the-shelf unmodified board available worldwide. It is thus the only practical option, and an attractive one, for many universities otherwise unable to supplement theoretical teaching with practical demonstrations.

VI. Empirical Assessment

This section presents numerical and written survey results obtained by surveying two separate groups of 20 students in a senior undergraduate digital communications course[3] taught by the author at the Universidad Industrial de Santander in Bucaramanga, Colombia, during 2009. The laboratory was used throughout the semester as a teaching aid as explained previously.

The surveys were conducted at the end of the semester. Students were asked to respond to several statements on a Likert scale with a rating of 1–5, where a rating of "1" signifies "I strongly disagree" and a rating of "5" signifies "I strongly agree" [54]. Both the classes and the survey were conducted in Spanish, with the results being presented here in the English translation. The results for both groups are shown in Table II. Students generally expressed enthusiasm for the laboratory's use in the classroom, as can be seen from the average rating results, and the rather low standard deviations.

For example, referring to the overall results for both groups, students showed agreement or strong agreement that the laboratory experiments were helpful (3.83), clear (3.48), useful (3.83), fun (3.18), and visually appealing (3.35). The students strongly agreed that the laboratory incentivized them to learn more about digital communications (3.70) and that the laboratory demonstrations were more useful than the theoretical exposition on the blackboard (3.63) and more useful than reading the course textbook (4.18). Perhaps most telling is that students expressed very strong agreement with the statements that the laboratory demonstrations should be made an obligatory part of future teaching

[3]https://sites.google.com/site/comunicacionesdigitalesuis/

TABLE II
NUMERICAL SURVEY RESULTS (AVERAGE AND STANDARD DEVIATION) OF TWO GROUPS OF SENIOR UNDERGRADUATE STUDENTS TAUGHT IN THE SECOND SEMESTER OF 2009 AT THE UNIVERSIDAD INDUSTRIAL DE SANTANDER IN BUCARAMANGA, COLOMBIA. GROUP #1 AND GROUP #2 EACH CONTAINED 20 STUDENTS

Question	Group1 Average	Group 1 Std. Dev.	Group 2 Average	Group 2 Std. Dev.	Total Average	Total Std. Dev.
The demonstrations done with the laboratory helped me understand the course material	3.80	0.95	3.85	0.93	3.83	0.93
Seeing the signals graphically using the laboratory is more useful than reading the course textbook	4.15	0.81	4.20	0.77	4.18	0.78
The demonstrations using the laboratory were clear	3.40	1.05	3.55	0.94	3.48	0.99
The demonstrations using the laboratory were useful	3.70	0.92	3.95	0.76	3.83	0.84
The activities and demonstrations using the laboratory were fun	3.10	0.97	3.25	1.21	3.18	1.08
The demonstrations using the laboratory were visually appealing	3.50	0.76	3.20	1.06	3.35	0.92
The demonstrations using the laboratory incentivized me to further explore the subject of digital communications	3.85	0.81	3.55	1.05	3.70	0.94
I recommend using a similar laboratory for other courses in electronics in order to help in the teaching process	4.10	0.79	4.30	0.92	4.20	0.85
I learned more from the laboratory demonstrations than from the theoretical exposition on the blackboard	3.70	0.86	3.55	1.05	3.63	0.95
The use of this laboratory as a teaching aid should be made obligatory for teaching of this course in the future	4.40	0.68	3.80	0.89	4.10	0.84
I like the subject of digital communications	3.90	0.72	3.95	1.00	3.93	0.86
The professor taught the course well	3.80	0.77	3.30	1.26	3.55	1.06

of the digital communications course (4.10) and that other electronics courses would benefit from a similar laboratory (4.20).

The students were also asked to provide written comments about their opinion of the laboratory demonstrations and how they could be improved. A sampling of their comments (translated from Spanish) is now presented. On the laboratory demonstrations, one student wrote, "The laboratory helped to clarify what the theory didn't explain sufficiently clearly, because it relates figures and forms with causes and effects inside the communications system." Another student wrote, "I judge very highly the ability to see the signals with the oscilloscope since it helps me to understand the theory better." Yet another student wrote, "[the laboratory] is a fun way to comprehend the functioning of a digital communications system, since it is possible to clearly see the problems due to sampling, noise, and other factors that [are present in] digital communications." Most students echoed these sentiments.

Suggestions for improvement generally centered on the idea that many cards should be available for autonomous use by students and for homework assignments or in-class activities. A representative comment was that it would be useful for the "student to be able to interact [personally] with the [laboratory], since things stick more in your mind if you do them yourself instead of just watching the demonstrations [by the professor]." Indeed, this is the focus of continuing work going forward, with emphasis on making the interface more user-friendly and writing a laboratory exercise guide so as to allow autonomous usage of this laboratory in future courses.

VII. Other Results and Experiments

A wide variety of experiments can be carried out using the laboratory, with only a standard (or computer-based) oscilloscope and a (computer-audio based) spectrum analyzer. These include, but are not limited to the following:

- investigating the nonlinear behavior of the synchronization PLLs, including pull-in and cycle-slip behavior;
- investigating the cross-interaction of the various PLLs and AGC control loops;
- investigating the interaction between PLL performance and BER;
- investigating and comparing waveforms throughout the transmitter's and receiver's signal chains for various modulations and signal-to-noise ratios;
- optimizing receiver and PLL parameters;
- performing eye-diagram measurements;
- making BER and symbol error rate (SER) performance comparisons between modulations;
- inventing and investigating new modulation and demodulation schemes;
- investigating cognitive radio algorithms;
- reinforcing through experiment the various theoretical concepts learned in class.

Since the current laboratory is still evolving and has a rudimentary user interface, all of these experiments were carried out by the author in class, but in the future, when the laboratory's interface is more user-friendly, they could potentially be done by the students themselves. Even if experiments are only demonstrated by the professor, this laboratory can be an important part of digital communications curricula for senior undergraduate and graduate work in universities around the world, as already has been demonstrated by the survey results in Section VI. While space constraints preclude detailed exposition of the aforementioned experiments, two such experiments were outlined in Section IV, and the reader is referred to [1], [2], and the figures therein for examples of some additional experiments.

The author has recently enhanced the laboratory and ported it to the Altera DE2-70 board (another low-cost FPGA board), in which many more modulations were added as well as many other features, allowing for hundreds of additional experiments. More information about this enhanced system can be found in [55].

VIII. Conclusion

This paper presented an ultra low-cost wireless communications laboratory based upon an inexpensive FPGA-centered board that costs under USD $200. The cost of the laboratory can be further reduced if the cost of this general-purpose FPGA card is spread out among several courses or projects for which this board is suited. The laboratory allows easy probing and control of internal signals and parameters and is thus useful for teaching and research of wireless communications, especially in a university setting. In particular, the low cost of the laboratory makes it ideal for universities in the developing world. Numerical and written results of a survey conducted by the author while teaching in a university in Colombia, South America, were presented and prove this assertion. The FPGA card is a commercial product available worldwide, as are the necessary configuration files (by contacting the author). Hence, the wireless communications laboratory described here is ready for immediate deployment in universities around the world.

Acknowledgment

The author would like to thank the Associate Editor Dr. L. Joiner as well as the reviewers and the IEEE Transactions on Education Editorial Office. Additionally, the author would like to thank for their kind assistance Prof. R. D. Cruz and Prof. J. Ramón of the Universidad Industrial de Santander and Prof. A. Monclou, Prof. S. Cristancho, Prof. C. Rueda, Prof. J. J. Padilla, Prof. R. Restrepo, and Prof. O. Pinzón from the Universidad Pontificia Bolivariana.

References

[1] Y. Linn, "Bridging the wireless communications education digital divide: A low-cost laboratory for wireless communications teaching and research," in *Proc. Latin Amer. Workshop Commun.*, Medellín, Colombia, Sep. 8–11, 2009, pp. 1–10.
[2] Y. Linn, "An ultra low cost software defined radio laboratory for education and research," in *Proc. SDR*, Washington, DC, Dec. 1–4, 2009, pp. 1–6.
[3] H. Gomes, *Quality Quotes*. Chicago, IL: Irwin, 1996.
[4] T. B. Welch, C. H. G. Wright, and M. G. Morrow, "Software defined radio: Inexpensive hardware and software tools," in *Proc. IEEE ICASSP*, Mar. 14–19, 2010, pp. 2934–2937.
[5] C. H. G. Wright, M. G. Morrow, M. C. Allie, and T. B. Welch, "Enhancing engineering education and outreach using real-time DSP," in *Proc. IEEE ICASSP*, Mar. 31–Apr. 4 2008, pp. 2657–2660.
[6] T. B. Welch, C. H. G. Wright, and M. G. Morrow, "Experiences in offering a DSP-based communication laboratory," in *Proc. 11th IEEE Digital Signal Process. Workshop*, Aug. 1–4, 2004, pp. 68–72.
[7] Spartan 3 A Starter Kit HW-SPAR3A-SK-UNI-G. Xilinx Inc., San Jose, CA, May 2009 [Online]. Available: http://www.xilinx.com
[8] Y. Linn, "Generation of bandpass Gaussian noise with applications to complete built in self test in wireless communications receivers," in *Proc. IEEE LATINCOM*, Medellín, Colombia, Sep. 10–11, 2009, pp. 1–6.
[9] Y. Linn, "A new architecture for coherent M-PSK receivers," in *Proc. IEEE COMCAS*, Tel-Aviv, Israel, Nov. 9–11, 2009, pp. 1–14.
[10] H. Jeng-Kuang, C. Yu-Lun, and C. Rih Lung, "Design of a non-data-aided differential-QAM modem for real-time speech communication: A software-defined-radio PC-based approach," in *Proc. 9th ICCS*, Sep. 7, 2004, pp. 220–224.
[11] W. Birmingham and L. Acker, "Software-defined radio for undergraduate projects," *SIGCSE Bull.*, vol. 39, no. 1, pp. 293–297, 2007.
[12] W. Birmingham and L. Acker, "Software-defined radio for undergraduate projects," in *Proc. 38th SIGCSE Tech. Symp. Comput. Sci. Educ.*, Covington, KY, 2007, pp. 293–297.
[13] V. F. Rundquist, "Weak signal reception using software defined radios and a two-element phased antenna array," M.Sc. thesis, Auburn University, Auburn, AL, 2006.
[14] S. Katz and J. Flynn, "Using software defined radio (SDR) to demonstrate concepts in communications and signal processing courses," in *Proc. 39th IEEE FIE*, Oct. 18–21, 2009, pp. W2B-1–W2B-6.
[15] J. K. Hwang, "Innovative communication design lab based on PC sound card and Matlab: A software-defined-radio OFDM modem example," in *Proc. IEEE ICASSP*, Apr. 6–10, 2003, vol. 3, pp. III-761–III-764.
[16] D. Mehrl and M. Hagler, "Active learning using inexpensive sound cards for circuits and communications experiments," in *Proc. 28th Annu. FIE*, Nov. 4–7, 1998, pp. 1102–1106.
[17] H. Meyr, M. Moeneclaey, and S. Fechtel, *Digital Communication Receivers: Synchronization, Channel Estimation, and Signal Processing*. New York: Wiley, 1998.
[18] R. N. Mutagi, "Pseudo noise sequences for engineers," *Electron. Commun. Eng. J.*, vol. 8, no. 2, pp. 79–87, 1996.
[19] YMEC DSSF3 Spectrum Analyzer. YMEC Inc., May 2009 [Online]. Available: http://www.ymec.com
[20] J. G. Proakis, *Digital Communications*, 4th ed. Boston, MA: McGraw-Hill, 2001.
[21] B. A. Fette, *RF & Wireless Technologies*. Boston, MA: Newnes, 2008.
[22] F. Xiong, *Digital Modulation Techniques*, 2nd ed. Boston, MA: Artech House, 2006.
[23] Y. Linn, "Efficient loop filter design in FPGAs for phase lock loops in high-datarate wireless receivers—Theory and case study," in *Proc. 6th Annu. WTS*, Pomona, CA, Apr. 26–28, 2007, pp. 1–8.
[24] Y. Linn, "Synchronization, phase detection, lock detection, and SNR estimation in coherent M-PSK receivers," Ph.D. dissertation, Dept. Elect. Comput. Eng., University of British Columbia, Vancouver, BC, Canada, Jul. 2007.
[25] Y. Linn, "Wireless Technology: Applications, Management, and Security," in *Efficient Structures for PLL Loop Filter Design in FPGAs in High-Datarate Wireless Receivers—Theory and Case Study*, S. Powell and J. P. Shim, Eds. New York: Springer, 2009.
[26] Y. Linn, "Robust M-PSK phase detectors for carrier synchronization PLLs in coherent receivers: Theory and simulations," *IEEE Trans. Commun.*, vol. 57, no. 6, pp. 1794–1805, Jun. 2009.
[27] Y. Linn, "A carrier-independent non-data-aided real-time SNR estimator for M-PSK and D-MPSK suitable for FPGAs and ASICs," *IEEE Trans. Circuits Syst. I, Reg. Papers*, vol. 56, no. 7, pp. 1525–1538, Jul. 2009.
[28] Y. Linn, *Synchronization in Coherent M-PSK Receivers: Carrier Synchronization, Phase Detection, Lock Detection, and SNR Estimation*. Saarbruecken, Germany: VDM Verlag, 2008.
[29] Y. Linn, "A self-normalizing symbol synchronization lock detector for QPSK and BPSK," *IEEE Trans. Wireless Commun.*, vol. 5, no. 2, pp. 347–353, Feb. 2006.

[30] Y. Linn, "A methodical approach to hybrid PLL design for high-speed wireless communications," in *Proc. 8th IEEE WAMICON*, Clearwater, FL, Dec. 4–5, 2006, pp. 1–9.
[31] Y. Linn and N. Peleg, "A family of self-normalizing carrier lock detectors and Es/N0 estimators for M-PSK and other phase modulation schemes," *IEEE Trans. Wireless Commun.*, vol. 3, no. 5, pp. 1659–1668, Sep. 2004.
[32] Y. Linn, "Quantitative analysis of a new method for real-time generation of SNR estimates for digital phase modulation signals," *IEEE Trans. Wireless Commun.*, vol. 3, no. 6, pp. 1984–1988, Nov. 2004.
[33] Y. Linn, "A new NDA timing error detector for BPSK and QPSK with an efficient hardware implementation for ASIC-based and FPGA-based wireless receivers," in *Proc. IEEE ISCAS*, Vancouver, BC, Canada, May 23–26, 2004, pp. IV-465–IV-468.
[34] Y. Linn, "A symbol synchronization lock detector and SNR estimator for QPSK, with application to BPSK," in *Proc. 3rd IASTED WOC*, Banff, AB, Canada, Jul. 14–16, 2003, pp. 506–514.
[35] K. E. Baddour and N. C. Beaulieu, "Autoregressive models for fading channel simulation," *IEEE Trans. Wireless Commun.*, vol. 4, no. 4, pp. 1187–1192, Jul. 2005.
[36] C. D. Ferris, "Development of a practice-oriented radio-frequency design course," *IEEE Trans. Educ.*, vol. 34, no. 1, pp. 118–122, Feb. 1991.
[37] B. Kamali, "Development of an undergraduate structured laboratory to support classical and new base technology experiments in communications," *IEEE Trans. Educ.*, vol. 37, no. 1, pp. 97–100, Feb. 1994.
[38] F. Ahamed and F. A. Scarpino, "An educational digital communications project using FPGAs to implement a BPSK detector," *IEEE Trans. Educ.*, vol. 48, no. 1, pp. 191–197, Feb. 2005.
[39] W. T. Padgett, B. A. Black, and B. A. Ferguson, "Low-frequency wireless communications System-infrared laboratory experiments," *IEEE Trans. Educ.*, vol. 49, no. 1, pp. 49–57, Feb. 2006.
[40] S. K. Sanyal, U. C. Sarker, and R. Nandi, "Microprocessor controlled FSK/PSK wave modulation: Experimental model for a digital communication laboratory," *IEEE Trans. Educ.*, vol. 34, no. 2, pp. 189–192, May 1991.
[41] N. E. Cagiltay, E. Aydin, R. Oktem, A. Kara, M. Alexandru, and B. Reiner, "Requirements for remote RF laboratory applications: An educators' perspective," *IEEE Trans. Educ.*, vol. 52, no. 1, pp. 75–81, Feb. 2009.
[42] A. J. Lopez-Martin, "Teaching random signals and noise: An experimental approach," *IEEE Trans. Educ.*, vol. 47, no. 2, pp. 174–179, May 2004.
[43] F. A. Cassara, "Wireless communications laboratory," *IEEE Trans. Educ.*, vol. 49, no. 1, pp. 132–140, Feb. 2006.
[44] T. S. Hall and D. V. Anderson, "A framework for teaching real-time digital signal processing with field-programmable gate arrays," *IEEE Trans. Educ.*, vol. 48, no. 3, pp. 551–558, Aug. 2005.
[45] N. Ertugrul, "Towards virtual laboratories: A survey of LabView-based teaching/learning tools and future trends," *Int. J. Eng. Educ.*, vol. 16, pp. 171–180, 2000.
[46] J. Frolik, "Laboratory enhancement of digital and wireless communications courses," presented at the ASEE Annu. Conf. Expo., Portland, OR, Jun. 11–15, 2005.
[47] T. B. Welch, C. H. G. Wright, and M. G. Morrow, "Teaching rate conversion using hardware-based DSP," in *Proc. IEEE ICASSP*, Apr. 15–20, 2007, pp. III-717–III-720.
[48] C. H. G. Wright, T. B. Welch, and M. G. Morrow, "COMMFSK: A hardware approach to teaching FSK," in *Proc. 12th Digital Signal Process. Workshop, 4th Signal Process. Educ. Workshop*, Sep. 24–27, 2006, pp. 460–465.
[49] T. B. Welch, R. W. Ives, M. G. Morrow, and C. H. G. Wright, "Using DSP hardware to teach modem design and analysis techniques," in *Proc. IEEE ICASSP*, Apr. 6–10, 2003, vol. 3, pp. III-769–III-772.
[50] C. H. G. Wright, T. B. Welch, D. M. Etter, and M. G. Morrow, "A systematic model for teaching DSP," in *Proc. IEEE ICASSP*, 2002, vol. 4, pp. IV-4140–IV-4143.
[51] M. G. Morrow, T. B. Welch, and C. H. G. Wright, "A tool for real-time DSP demonstration and experimentation," in *Proc. 10th IEEE Digital Signal Process. Workshop*, Oct. 13–16, 2002, pp. 162–167.
[52] C. H. G. Wright, T. B. Welch, and M. G. Morrow, "An inexpensive method to teach hands-on digital communications," in *Proc. FIE*, Nov. 5–8, 2003, vol. 2, pp. F2E-20–F2E-25.
[53] J. Ma and J. V. Nickerson, "Hands-on, simulated, and remote laboratories: A comparative literature review," *Comput. Surv.*, vol. 38, no. 3, p. 7, Mar. 2006.
[54] R. Likert, "A technique for the measurement of attitudes," *Arch.Psychol.*, vol. 140, pp. 1–55, 1932.
[55] Y. Linn, "Teaching digital communications in a developing country using a low cost software defined radio laboratory," in *Proc. SDR*, Washington, DC, Nov. 29–Dec. 2 2010, pp. 65–74.

Yair Linn (M'01) received the B.Sc. degree (with honors) in computer engineering from the Technion—Israel Institute of Technology, Haifa, Israel, in 1996, and the Ph.D. degree in electrical and computer engineering from the University of British Columbia (UBC), Vancouver, BC, Canada, in 2007.

From 1996 to 2001, he was an Electrical Engineer with the Israeli Ministry of Defense, where he worked with the development, implementation, and deployment of wireless communications systems. From 2008 to 2010, he was a Visiting Professor of electronic engineering with the Universidad Pontificia Bolivariana and the Universidad Industrial de Santander, both in Bucaramanga, Colombia. He is currently a DSP/Mixed Signal Design Engineer with PMC-Sierra, Inc., Burnaby, BC, Canada. His research interests include synchronization in wireless receivers, estimation of wireless channel parameters, and implementation of real-time digital signal processing algorithms in FPGAs.

Dr. Linn was awarded the Jean MacDonald Graduate Fellowship scholarship as a winner of the University Graduate Fellowship competition at UBC in 2002. In April 2003, he was awarded a post-graduate scholarship by the National Sciences and Engineering Research Council of Canada (NSERC) as a winner of the 2003–2004 NSERC Postgraduate Scholarship Competition. In April 2005, he was awarded an NSERC Canadian Graduate Scholarship as a winner of the 2005–2006 NSERC Postgraduate Scholarship Competition. In November 2005, he was awarded the Bell Canada 125th Anniversary Graduate Scholarship. In May 2007, he was awarded the Best Paper prize at the Wireless Telecommunications Symposium, Pomona, CA.