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Software Defined Radio, a perspective from education

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The evolution of communication systems has brought about a paradigm shift, particularly in radiocommunications, where software has increasingly taken precedence over hardware. This transition has not only reduced implementation costs but has also significantly enhanced the flexibility of equipment architecture. A prime example of this trend is the emergence and consolidation of software-defined radio (SDR) technology in recent decades. This study provides a comprehensive contextualization of SDR technology, offering insights into its current state in terms of development tools and market equipment. Additionally, two learning scenarios are presented that employ different teaching methodologies. In one of these scenarios, communication theory is exclusively approached from a theoretical perspective. In the second scenario, knowledge acquisition is encouraged through the implementation of low-cost laboratories that incorporate SDR technology. The study indicates that implementing SDR technology boosts student motivation and learning, with 73.13% believing it enhances engineering education and 96% showing increased motivation. Those using SDR in practical laboratories perform better on knowledge tests, but statistical analysis shows that the difference is not statistically significant.

KEYWORDS

Software-defined radio (SDR), distance education, radiocommunications, flexible learning, antennas

1 Introduction

Software-defined radio (SDR) has garnered considerable attention for its role in revolutionizing wireless communications and electronics. Mitola (2000) emphasized the transformative potential of SDR in both engineering and communications, particularly its ability to dynamically reconfigure radios through software (Mitola, 2000). His seminal work laid the groundwork for the adaptability and flexibility of radio systems, setting a precedent for interoperability and compliance with communication standards. On the educational front, Hofmann-Wellenhof et al. (2008) discussed the use of SDR as an invaluable tool for instructing in Global Navigation Satellite Systems (GNSS), enabling practical engagement with GNSS signals (Hofmann-Wellenhof et al., 2008). Ellingson (2016) extended the academic implications, highlighting contribution of SDR to university education in systems engineering (Ellingson, 2016). Luther et al. (2012) further accentuated the role of SDR in enhancing hands-on learning experiences in fields such as radiofrequency and wireless communication (Luther et al., 2012). Arya et al. (2014) noted the embedded architecture of SDR facilitates the integration of hardware and software across multiple disciplines, mitigating educational constraints like limited resources

(Arya et al., 2014). Finally, Nuñez Ortuño and Mascareñas Pérez-Iñigo (2016) identified that the use of SDR enhances the learning experience and enables students to design and simulate communication systems, thereby increasing their understanding of the underlying principles (Nuñez Ortuño and Mascareñas Pérez-Iñigo, 2016).

The evolution of communication systems has brought about a paradigm shift, particularly in radiocommunications, where software has increasingly taken precedence over hardware (Mitola, 2001). This transition has not only reduced implementation costs but has also significantly enhanced the flexibility of equipment architecture (Chen et al., 2016). SDR technology has emerged as a prime example of this trend, revolutionizing the field with its ability to define key parameters through software (Fokin et al., 2023). The origins of SDR can be traced back to the 1980s, and since then, it has continuously evolved, finding applications in diverse fields (Harada and Prasad, 2002). The concept of "software radio" was introduced by E-Systems, and the implementation of software-based radio with physical components came with the military program Speakeasy by DARPA in the 1990s (Rouffet and König, 2003). Joseph Mitola's pioneering work on software radio and the subsequent introduction of the term "cognitive radio" have further contributed to the advancement of SDR technology (Mitola, 2001; Galvis et al., 2007). Another significant milestone in the history of SDR was the creation of GNU Radio in 2001 (Del Barrio et al., 2023), which has become the most popular SDR tool, offering open-source features and gaining wide acceptance within the radio community (Boettcher et al., 2016). The commercialization of SDR gained momentum in 2009 when Lime Microsystems launched the first commercial single-chip front-end device for SDR. Since then, numerous manufacturers have introduced a wide range of SDR models and product lines, continuously innovating with new equipment that offers increased capabilities and remarkable flexibility to adapt to commercial applications. The significance of SDR technology lies in its ability to dynamically configure and adapt to changing communication protocols and environments, making it a valuable tool in future of telecommunications (Rouffet and König, 2003). In an educational context, the integration of SDR technology into a learning environment holds immense potential for developing competencies among telecommunications engineers. Establishing a low-cost laboratory for communication systems, antennas, and propagation systems rooted in academia can create meaningful experiences for engineering students and enable them to explore the applications of SDR technology.

Table 1 provides a comprehensive overview of the applications of SDR technology, showcasing the advancements and innovations in various domains. It highlights the novelty, algorithms or methods employed, and the specific applications of SDR in each article. Including a citation for each article ensures the credibility and academic rigor of the sources.

The document follows the following structure: First, it provides a contextualization of the term SDR and traces its evolution over recent decades. Subsequently, the results of the literature review are presented, covering topics such as the components of SDR architecture and the associated technologies involved in its development. The document then explores the primary applications of SDR, referencing academic sources that have embarked on laboratory implementations or the adoption of SDR technology, thereby facilitating advancements in academic and research projects. Subsequently, a proposal for laboratory guides developed through the implementation of low-cost SDR technology as a teaching approach is introduced. These laboratory guides are compared with conventional teaching approaches. Then, based on the obtained learning results and perception surveys conducted, conclusions are drawn, and potential areas for future research are identified.

TABLE 1 Comparison of software-defined radio applications: novelty, algorithms/methods, and applications.

Article	Novelty	Algorithm or method	Application
Zhang et al. (2023)	Signal-to-clutter ratio (SCR) improvement	Stepped frequency continuous wave (SFCW) method	Ground penetrating radar (GPR)
Barbot et al. (2023)	Low cost and open source	Asynchronous OOK modulation and tag detection	Radio frequency identification (RFID)
Bouzegag et al. (2023)	Cooperative spectrum sensing implementation	Cooperative spectrum sensing (CSS)	Cognitive radio networks
Jacovic et al. (2023)	Mitigation of RF interference attacks at the physical layer	Automatic jamming classification	Wireless communications
Henthorn et al. (2023)	Simultaneous reception of multiple bands	Multi-band direct RF sampling	Mobile broadband (MBB) applications
Zhang et al. (2023)	Unified platform generation using DSE	Domain space exploration (DSE)	Communication platform domain applications

2 Software-defined radio

The term SDR encompasses various definitions depending on the context in which it is used. Generally, it refers to radio transceivers where key parameters are defined by software. The Wireless Innovation Forum and the P1900.1 group of the Institute of Electrical and Electronic Engineers (IEEE) have collaborated to establish a standardized definition of SDR, describing it as a type of radio in which some or all functions of the physical layer are defined by software. While SDR may seem like a recent technology, its origins can be traced back to the 1980s, gradually evolving and finding applications in diverse fields (Table 2).

The concept of "software radio" was initially introduced by the company E-Systems, referring to a baseband prototype that employed adaptive filters to demodulate broadband signals (Nutaq). The implementation of software-based radio with physical components came with the military program Speakeasy by the Defense Advanced Research Projects Agency (DARPA) in the 1990s (Zhao et al., 2007). In 1992, Joseph Mitola published one of the first works related to software radio, and later, he coined the term "cognitive radio" to describe intelligent radios (Mitola, 2003), capable of efficient adaptation. Another significant milestone was the creation of GNU Radio in 2001 by Eric Blossom, financed by

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TABLE 2 Comparison of applications of software-defined radio technology.

Article	Main concept	Application	Comparative analysis of software-defined radio (SDR) applications
Zhang et al. (2023)	Signal calibration and noise reduction for SDR-based ground-penetrating radar (GPR)	Ground-penetrating radar imaging	"Improved signal calibration and noise reduction techniques for software-defined ground-penetrating radar."
Barbot et al. (2023)	Development of a low-cost SDR RFID UHF reader for real-time tag reading	Radio frequency identification (RFID)	"Low-cost software-defined radio UHF reader for real-time RFID applications."
Zhang et al. (2023)	Implementation of cooperative spectrum sensing (CSS) using SDR	Cognitive radio networks	"Cooperative spectrum sensing techniques based on software-defined radio in cognitive radio networks."

John Gilmore. GNU Radio has become the most popular SDR tool, offering open-source features and gaining wide acceptance within the radio community.

In 2009, Lime Microsystems launched the first commercial single-chip frontend device for SDR. Since then, numerous manufacturers have introduced a wide range of models and product lines, continuously innovating with new equipment that offers increased capabilities and remarkable flexibility to adapt to commercial applications.

2.1 Architecture of an SDR system

SDR devices operate on an architecture that can be generally described as an integration of hardware and software components, with software comprising the majority. The software component is responsible for baseband signal processing, encompassing signal generation and decoding. It replaces traditional physical elements, such as filters, amplifiers, modulators, demodulators, detectors, and dividers, with their software counterparts. This means that a significant portion of the physical layer elements, such as modulation schemes, operating frequencies, and sampling rates, are defined within the software stage. Similarly, it is important to note that signals are converted between the analog and digital domains, depending on the specific application. This conversion is facilitated by the integrated A/D (analog-to-digital) and D/A (digital-to-analog) modules within SDR devices, which play a crucial role. Figure 1 provides a general diagram illustrating the structure of an SDR system, depicting both its software and hardware components.

This architecture enables the implementation of various components using a personal computer or other embedded computing devices. As mentioned previously, the concept of SDR is not novel, but advancements in digital circuitry have now made many processes that were once purely theoretical feasible from a practical standpoint.

3 SDR applications

SDR technology, with its inherent flexibility, enables its implementation across various fields and finds application in numerous domains. Here, we highlight some of the most significant ones. Notably, Harada and Prasad (Mitola, 2003) emphasize the philosophy of SDR, which entails the need for new terminals capable of supporting advanced communication services, infrastructure communications, and facilitating broadband radio access technologies (e.g., cellular, WiMedia, MobileFi, WRAN, and WiMAX), among others. These applications span both private and public environments, catering to sectors, such as education, leisure, emergency services, and the military.

An important evolution has occurred in this regard. As mentioned (Galvis et al., 2007), by the year 2004, the majority of SDR applications were primarily military-oriented due to the high implementation costs. In fact, 76.5% of all applications were military-focused, 7.1% were for commercial wireless infrastructure, and 16.4% pertained to other application domains. However, thanks to significant advancements in microelectronics, costs have been substantially reduced, leading to a diversification of SDR applications across various sectors.

One of the primary application scenarios for SDR is linked to the increasing demand for the electromagnetic spectrum. Consequently, there is a need to explore technologies that can efficiently utilize this resource. Hence, there is a focus on sensing the medium to detect unused frequency bands (Galvis et al., 2007). Additionally, the trend of interconnecting various devices under the Internet of Things (IoT) concept requires SDR technology to enable the connectivity of multiprotocol devices. Ideally, IoT should support multiple standards and allow for device management and updates, leveraging the advantage of compatibility with the "Over the Air Programming" concept, which refers to wireless updates for optimal IoT implementation (Hessar et al., 2020).

Furthermore, SDR is commonly found in diverse projects encompassing various applications. These include the regulation of the electromagnetic spectrum by identifying transmitters and utilized bands, networks such as advanced driver assistance systems that integrate control devices with SDR technology in vehicles (Park et al., 2019), data acquisition and processing systems (Diaz et al., 2018), positioning systems using GPS (Seo et al., 2011), transmitter identification using machine learning techniques (Riyaz et al., 2018), advancements in ground stations for satellite communication (Boettcher et al., 2016), and even the localization of receivers through an LTE network using SDR (del Peral-Rosado et al., 2013), among numerous other applications. Moreover, it is crucial to highlight that SDR presents significant possibilities for academia and research. It is a technology that encompasses concepts from the telecommunications field, digital signal processing, antennas, propagation, and more.

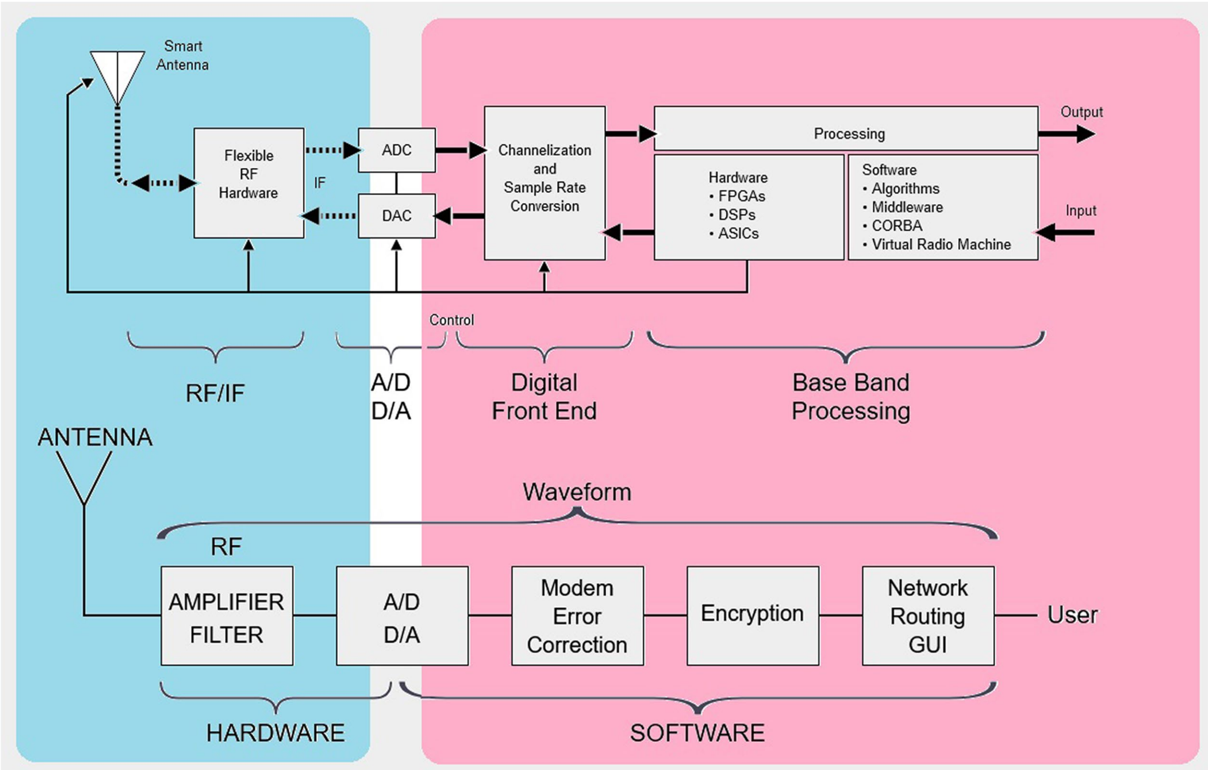

FIGURE 1
General SDR architecture. (SDR_et_WF.JPG licensed with Copyrighted free use 2006-03-17T08:37:51Z Topituuk 1040x720 (91695 Bytes). Adopted by LtCdr Topi Tuukkanen).

4 SDR in the academy

Engineering fields, particularly those related to telecommunications, radiocommunications, and communication systems, deal with concepts that require practical implementation. However, these technologies often come with high costs and complexities associated with infrastructure and personnel deployment. To address these challenges, it is crucial for laboratories focused on these areas to adopt low-cost solutions and technologies that facilitate their use through flexibility, enabling a transition from theory to practice. Moreover, it is important to recognize that modern technologies, especially those centered around data and multimedia, require the collaboration of software and application developers as well as educational content creators. They play a vital role in adding value to the learning process, where students can engage through hands-on experiences and observation. The equipment itself becomes more than just an operational module; it becomes a learning mechanism supported by a platform that integrates radio knowledge. This open-standard platform allows for a departure from traditional laboratory models, where equipment comes pre-configured by manufacturers and has limitations on modifications that can be made by students to meet the specific requirements of their projects. Furthermore, by embracing SDR technology, academic institutions can revolutionize their teaching methodologies and create dynamic learning environments. Students gain practical experience by actively engaging with customizable equipment and exploring various applications. This shift in laboratory models, where equipment comes pre-configured by manufacturers and has limitations on modifications, is facilitated by the collaboration of software and application developers as well as educational content creators. They play a vital role in adding value to the learning process, transforming the equipment into a learning mechanism supported by a platform that integrates radio knowledge. This open-standard platform allows for a departure from traditional approaches, fostering hands-on experiences and observation, and empowering students to become proficient in their chosen engineering fields. Ultimately, SDR technology serves as a catalyst for transformative educational experiences.

The utilization of SDR technology within the industrial sector is growing in significance, and academia has steadily incorporated it into their engineering practices. Universities of worldwide renown have established laboratories and implemented SDR-supported practices. Examples include Monash University, the University of Notre Dame, the University of Seville, and Iowa State University, where software-defined telecommunications laboratories are utilized. These laboratories are backed by GNU open-source radio technology and OpenFlow Software Defined Networking. Research topics covered encompass modulation, encoding, MIMO, and broadcast network services. Notably, notable advancements have been made in the implementation of bidirectional digital coding networks (Andy Shang et al., 2014). Furthermore, the University of Notre Dame has operated the Software Defined Radio Lab since 2003, with support from InterDigital and National Instruments. This laboratory features USRP devices and employs LabVIEW for experimentation. It has facilitated the creation of prototypes and the utilization of FPGAs, enabling the development and validation of new algorithms. Presently, the laboratory is employed for testing 5G prototypes, utilizing high-end equipment such as high-speed oscilloscopes, bit error analysis systems, and spectrum analyzers.

The University of Seville, specifically its Department of Signal Theory and Communications at the Higher Technical School of Engineering, has undertaken significant projects in the implementation of a wireless communications test bench using modular instrumentation from National Instruments and LabVIEW software. Similarly, Iowa State University has made notable strides in the field of SDR. Their SDR laboratory, partially funded by EFTF funds from the university, has been operational for over a decade. The laboratory is equipped with 12 Universal Software Radio Peripherals (USRP), which connect to desktop computers via USB interfaces. These peripherals are utilized for signal processing, allowing the computers to receive and transmit RF signals. The laboratory covers diverse investigative tasks, including GPS, FM radio, HDTV, RFID, and Wi-Fi, among others. Auburn University has also recognized the significance of the Wireless Engineering Curriculum (BWE). They offer a course based on SDR that utilizes GNU Radio and USRP devices. In (), the authors describe the course structure and make comparisons with existing wireless communications laboratories.

5 Methodology

For the validation of a case study in education, the following methodological framework is proposed, see Figure 2. With advancements in SDR technology, the hypothesis is raised that technology-mediated education using SDR can have a significant impact on student learning, particularly in the training of students specializing in areas such as telecommunications, electronics, and engineering.

The first step is to define the research objective, which is to demonstrate that the use of SDR technology significantly enhances learning in an educational context. The second step is to collect data from a sample population of 54 students from the National Open and Distance University (UNAD) enrolled in telecommunications and electronics courses. Furthermore, these students are divided into two groups: an experimental group that will utilize SDR in their learning process and a control group that will follow traditional teaching methods. The third step involves the experimental development through laboratory guides for the subgroup with access to SDR technology (Group B). The control subgroup (Group A) will follow a similar curriculum but without the use of SDR technology. The next step is to assess the entire population to quantify the learning achieved through a test. Perception surveys are also conducted with Group B. Once the measurement results of learning through assessments and surveys are obtained, a statistical analysis is performed to determine whether the recorded data follow a normal distribution, using the Shapiro–Wilk test. If the data follow a normal distribution, an analysis of variance (ANOVA) test or a Kruskal–Wallis test is conducted to compare the grades or learning performance between the experimental group (SDR) and the control group (without SDR) to determine whether there are statistically significant differences between them. The final step involves reporting the results and their interpretation.

6 Academic proposal: SDR laboratory

In the context of distance education and during the COVID-19 pandemic, a learning scenario has been developed that employs two distinct methodological approaches. The first approach, referred to as 'theoretical-practical,' is based on the use of laboratory guides incorporating SDR technology for learning (see Table 1). In contrast, the second approach focuses exclusively on the theoretical teaching of communication systems, antennas, and propagation. This study includes a population of 54 students enrolled in the course, divided into two equally sized groups randomly. Group A, consisting of 27 students, focuses on theoretical teaching, while Group B has access to SDR devices. We conducted a comparative analysis of both teaching methodologies. However, it is essential to highlight that not all 54 students had access to the devices due to economic constraints related to technology acquisition. Therefore, a perception survey was conducted with Group B regarding their experience with SDR technology. Additionally, both Group A and Group B underwent a knowledge examination to assess their understanding of the subject matter.

To carry out the laboratory on communication systems, antennas, and propagation using SDR, we utilized low-cost devices available at the National Open and Distance University (UNAD) of Colombia. We used two ADAN PLUTO and two RTL devices, with an approximate cost in 2023 of around USD 500. This cost is significantly lower than USRP devices, which have an approximate price of USD 4,300,000 in the same year. This laboratory is closely integrated with the efforts of the School of Basic Sciences and Engineering and the Electronics, Telecommunications, and Networks (ETR) training program. Specifically, it aligns with the communication systems, antennas, and propagation courses within the Telecommunications Engineering program. Due to the open nature of UNAD and its extensive network of 64 centers across the country, the laboratory proposal emphasizes high flexibility to adapt to the course content in engineering programs and to facilitate training and research processes. Additionally, the laboratory design aims to be cost-effective, enabling replication in the various centers nationwide. The laboratory is divided into four sequential phases, each building on the necessary foundations to effectively utilize SDR equipment and apply engineering concepts. Table 3 provides an overview of the laboratory phases, including their corresponding guides and a general description of the content.

6.1 Experience in the implementation of the laboratory

The perception instrument used was a survey conducted online with 27 students from Group_B who used the SDR laboratory. Statistical software R was employed to analyze the survey results. In the survey, students were asked to rate on a scale from 1 (completely disagree) to 5 (completely agree). Of the three categories into which the questions were classified, as shown in Table 1, the survey system was conducted randomly. Out of the 54 students, 27 students responded to the questions, providing a complete set of 297 responses, which form the basis for the analysis of the following results. For the analysis of the 11 questions, both ANOVA and a non-parametric

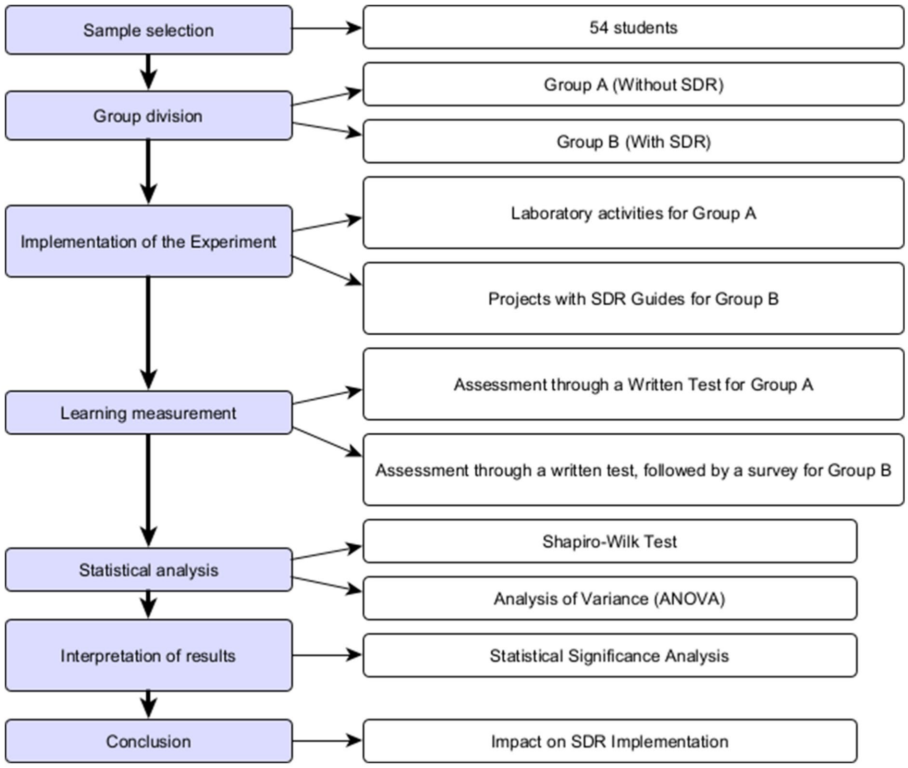

FIGURE 2
Proposed methodological scheme.

Shapiro–Wilk test were conducted. The questions were categorized into three groups, namely, "Quality training," "Technological tool," and "Laboratory assessment" (Table 4). Indicators evaluated in the survey per question according to the Likert scale, where 5 (completely agree), 4 (agree), 3 (neither agree nor disagree), 2 (disagree), and 1 (completely disagree) ($N=27$).

The perception of students who utilized the laboratory was found to be highly favorable, with 100% of the students receiving scores of 4 and 5 in three out of the four categories. However, the aspect of perception toward SDR technology had a smaller percentage of ratings at levels 2 and 3, with 2.6 and 12.5%, respectively. This can be attributed to factors such as familiarity and handling of the devices. Despite this, the overall perception remains quite favorable, as 84.82% of the students scored 4 and 5. Furthermore, an evaluation instrument was administered to assess concepts from four categories: signal theory, communications systems, SDR, and antennas and propagation. Figure 3 illustrates the results of the evaluation for groups A and B, representing students without and with access to the laboratory, respectively, for each category. Among the sample of 54 students, group B (with access to the laboratory) demonstrated better performance in three out of the four categories. Both groups achieved similar performance in the antennas and propagation category.

A statistical analysis was conducted using a sample population of 54 telecommunications engineering students enrolled in the antennas and propagation course. The students were randomly divided into two groups: Group A, which did not have access to SDR tool, and Group B, which had access to SDR tool. A set of 20 multiple-choice questions with only one correct answer was administered to both groups. The objective was to test the null hypothesis regarding the impact of using the SDR tool on students' academic performance. A 95% confidence level was chosen with a significance level (α) of 0.05. A linear regression model was employed, with the dependent variable (Y_i) representing the grades obtained and the explanatory variable (X_i) denoting the learning method. The index (i) takes values of 1 or 2, where $i=1$ corresponds to the group without SDR tool usage, and $i=2$ represents the group with SDR tool usage. Next, an analysis of variance (ANOVA) table was generated using R Statistics to assess the residuals obtained from the regression model (Table 5).

The results obtained were as follows: residual standard error: 3.507 on 52 degrees of freedom (DF), multiple R-squared: 0.02378, adjusted R-squared: 0.005004, F-statistic: 1.267 on 1 and 52 DF, and value of p: 0.2656. The model with all the variables introduced as predictors has a very low R^2 of (0.02378), which is why it is only able to explain 2.2378% of the variability observed in the scores of the qualifications obtained by both groups of students. The value of p of the model is not significant (0.2656), so the null hypothesis cannot be accepted. In other words, the alternative hypothesis is accepted that there is no difference between the learning model incorporating the tool, this may be because the tool is not the one that makes it possible to develop the student's cognitive skills, but on the contrary of the fact that the student brings knowledge of the Communication Systems course or currently, because the modality of the National Open and Distance University UNAD, receives students who have finished their technological cycle and homologates courses such as communication systems, or by the fact that students are very heterogeneous in that they have left their studies for long periods of time.

TABLE 3 Laboratory structure.

Phase	Guides	Description
Phase 1: Basic concepts of communication systems	Guide 1: Analog modulations. Guide 2: Digital modulations.	In this phase, students use mathematical processing software to address concepts of analog and digital communication systems, in addition to having a first theoretical approach to SDR technology
Phase 2: Basic Concepts of Digital Signal Processing	Guide 3: Spectral analysis	In this phase, students begin with the use of SDR devices for the implementation of receivers that allow visualizing and analyzing signals from the environment
Phase 3: Basic concepts of antennas and propagation	Guide 4: FM receiver Guide 5: Radio link	In this phase, students advance in the process of transmitting and receiving signals as well as the demodulation of some of them.
Phase 4: SDR Applications	Guide 6: Radar Guide 7: Image transmission	In the final phase of the laboratory, certain more advanced feature applications are proposed for a real-life application

TABLE 4 Indicators assessed in the survey per question on a Likert scale, where 5 (completely agree), 4 (agree), 3 (neither agree nor disagree), 2 (disagree), and 1 (completely disagree) ($N = 27$).

Questions	1	2	3	4	5
Quality training					
Does the SDR laboratory encourage and stimulate learning?	0 (0%)	0 (0%)	0 (0%)	**1 (3.7%)**	**26 (96.3%)**
Do you consider that the SDR laboratory provides a didactic alternative that would help better understand the topics of communication systems, antennas, and propagation?	0 (0%)	0 (0%)	0 (0%)	**1 (3.7%)**	**26 (96.3%)**
Do you believe that the use of SDR technology adds value to your academic and professional development?	0 (0%)	0 (0%)	0 (0%)	**1 (3.7%)**	**26 (96.3%)**
Has your engagement with the SDR laboratory motivated you to learn more about telecommunications topics?	0 (0%)	0 (0%)	0 (0%)	**1 (3.7%)**	**26 (96.3%)**
In general, how much do you agree that the practical exercise with SDR has positively impacted your learning?	0 (0%)	0 (0%)	0 (0%)	**20 (74.1%)**	**7 (25.9%)**
Do you consider the study guide material used in the SDR practice to be of interest in learning?	0 (0%)	0 (0%)	0 (0%)	**8 (29.6%)**	**19 (70.40%)**
Do you think the incorporation of SDR-based technologies is useful and effective for improving your learning?	0 (0%)	0 (0%)	0 (0%)	**5 (18.5%)**	**22 (81.5%)**
Technological tool					
Do you consider that the use of technological tools based on SDR would enhance UNAD's on-site laboratories?	0 (0%)	0 (0%)	**4 (14.8%)**	0 (0%)	**23 (85.2%)**
Do you find the implementation of SDR devices easy?	0 (0%)	3 (11.1%)	**13 (48.2%)**	10 (37.0%)	1 (3.7%)
Do you believe that the incorporation of SDR-based technologies is useful and effective for your learning objectives?	0 (0%)	0 (0%)	0 (0%)	5 (18.5%)	**22 (81.5%)**
Laboratory assessment					
Do you consider that the use of development tools based on SDR laboratories supports the course updating processes in the Electronics, Telecommunications, and Networks chain?	0 (0%)	0 (0%)	0 (0%)	**1 (3.7%)**	**26 (96.3%)**
Would you recommend a fellow student to take courses that integrate SDR laboratories?	0 (0%)	0 (0%)	0 (0%)	10 (37.0%)	**17 (63.0%)**

The highest selection values of the respondents are highlighted in bold, namely, the highest percentages.

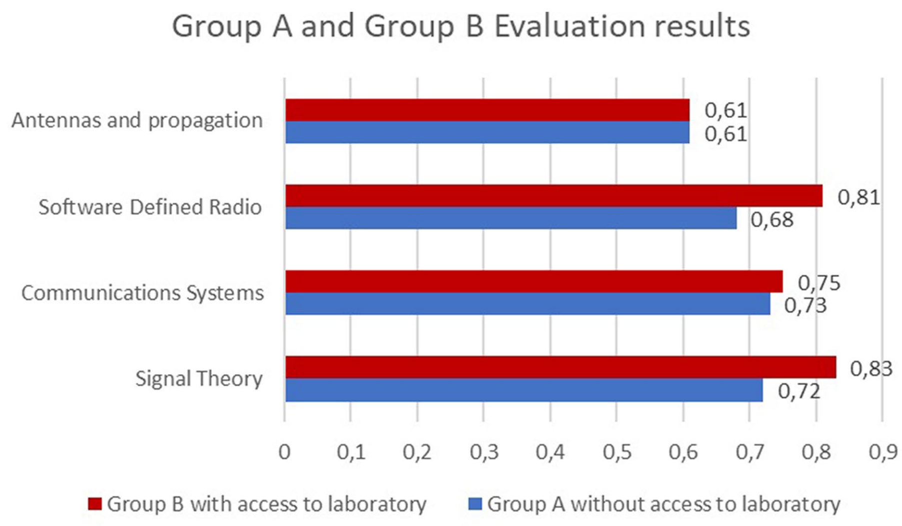

FIGURE 3
Comparative analysis of evaluation results between Group A and Group B.

TABLE 5 Residual statistics.

Min	IQ	Median	3Q	Max
−9.4815	−1.5370	0.4815	2.4444	5.5185

Subsequently, a non-parametric Shapiro–Wilk test was conducted. The results are as follows: Analysis of variances between groups using the F-test to compare two variances with Group_A and Group_B data. The alternative hypothesis states that the true ratio of variances is not equal to 1. The 95 percent confidence interval for the ratio of variances is 0.7755169 to 3.7340976, with a sample estimate of the ratio of variances as 1.701721. Correspondingly, the Shapiro–Wilk test was performed to assess the normality of the data. For Group_B, the studentized W value is 0.87094, and the value of p is 0.00308. As the value of $p < 0.05$ (0.00308), we cannot reject the null hypothesis, indicating that the data conform to the assumption of normality. Based on these results, we can conclude that our data satisfy the normality assumption.

Finally, the correlation test was conducted to estimate the relationship between the variables. The simple linear regression model assesses the correlation between these variables, which measures the degree of association between them. Specifically, Pearson's linear correlation coefficient examines the linear correlation between the two variables. The results revealed a very weak correlation (−0.0007197906) between the variables. The negative correlation indicates an inverse association, where the high values of one variable correspond to the low values of the other. Although the Pearson coefficient is statistically significant (<0.05), indicating a linear correlation between "Group_A" and "Group_B," it is expected that the ratings are unrelated between the two groups.

7 Conclusion

The integration of SDR technology in education is a valuable alternative for engineering courses as it provides students with a practical learning environment. The implementation of the pilot laboratory yielded positive responses regarding the perception of SDR technology and the relevance of the laboratory. Furthermore, it was found to be an economically viable option compared to traditional hardware-based practical scenarios. For instance, the pilot laboratory was implemented at an approximate cost of USD 500.

The evaluation results demonstrated the effectiveness of the SDR laboratory, with students in group B, who had access to the laboratory, showing higher performance in three out of four categories than students without access. Although these initial results are satisfactory, the goal is to replicate the SDR laboratory at the national level to obtain a more significant sample. Due to mobility restrictions caused by the COVID-19 pandemic, students have been unable to attend university facilities. Additionally, there are plans to implement a remote SDR laboratory, providing students and researchers with access from anywhere and at any time. This serves as an alternative to the mobility and access limitations imposed by the global COVID-19 pandemic.

The incorporation of techno-pedagogical tools based on SDR encourages learning in students by allowing them to learn by doing, enhancing academic practice through hands-on experimentation with equipment and network configurations, both in a practical and virtual manner.

This provides them with a practical learning experience that complements the theory they acquire in the classroom. On the other hand, having access to SDR technology provides them with tools to explore and apply concepts related to antennas and communication systems.

The flexibility provided by SDR technology as an educational resource, due to its simplicity in terms of setup and operation, allows students to configure and modify networks and communication systems flexibly and in real time. This gives them the opportunity to experiment with a variety of scenarios and configurations, which can enrich their understanding of the theoretical concepts learned in class.

As a simulation tool, the inclusion of SDR laboratories allows for the simulation of real network and radio environments, providing students with a highly authentic experience without the need for expensive physical devices. This enables them to develop practical skills safely and efficiently.

Another advantage of SDR-based laboratories is the freedom for unrestricted experimentation. Students engaging in these experiments can make mistakes and explore without the worry of causing physical harm to real equipment or networks, which, in turn, encourages creativity and problem-solving. This environment empowers students to test novel ideas and solutions without constraints.

Future study aims to integrate SDR into 5G applications for spectral optimization through active network segmentation, mobility management, and load balancing. Another equally important application would be to incorporate SDR into software-defined networking (SDN) technology networks using modular and flexible cross-layer architecture based on SDR principles and a centralized control mechanism based on SDN.

Incorporating SDR technology into courses such as digital signal processing and digital image processing for laboratory practices in electronic and telecommunications engineering courses to enhance learning and the grasp of concepts.

Data availability statement

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding author.

Author contributions

MR and RC were responsible for the implementation of SDR and the initial drafting of the manuscript. PB, RU, and JR validated the data, conducted the statistical analysis, and revised the manuscript. All authors contributed to the article and approved the submitted version.

Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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