Experience of IoT Transceiver with Affordable Software Defined Radio Platform

Dr. Liang Hong, Tennessee State University

Dr. Liang Hong received the B.S. and the M.S. degrees in Electrical Engineering from Southeast University, Nanjing, China in 1994 and 1997, respectively, and the Ph.D. degree in Electrical Engineering from University of Missouri, Columbia, Missouri in 2002. Since August 2003, he has been with the Department of Electrical & Computer Engineering at Tennessee State University where he is now Full Professor. His research interests include wireless communication systems, Internet of Things, artificial intelligence, cyber security, cognitive radio, security of communication systems, networked control system, wireless sensor networks, wireless multimedia communications and networks, and engineering education.

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Liang Hong

Department of Electrical and Computer Engineering, Tennessee State University
3500 John A Merritt Blvd, Nashville TN, 37209, lhong@tnstate.edu

Abstract: Due to the rapid growth in many applications, Internet of Things (IoT) will be a prominent source for new hires in the engineering field. However, the growth of IoT is outpacing the current workforce with necessary knowledge and skills, such as IoT transceiver and software-defined radio (SDR), the two key and highly demanded techniques for IoT communications. In order to blaze a path to introduce these two advanced techniques to future entry-level communication engineers, a project based learning module using affordable SDR platform was developed with experiential learning pedagogy. The learning materials were developed based on well-defined objectives. Rubrics were also developed to assess the learning outcomes. Through this module, the students will not only gain valuable knowledge of the state-of-the-art IoT wireless communications, interact with the real-world wireless signals over-the-air in real-time, but also improve their creative thinking ability, hands-on and programming skills, and capability to deal with many real-world issues and non-idealities. Assessments show that the learning outcomes were met and the educational module and materials were successful in teaching the advanced techniques with hands-on experience in IoT domain. Additional benefits include increased students' interests in other communication systems and broadened minority participation in the nation's technology workforce.

Background and motivation

Internet of Things (IoT), a network of uniquely identifiable physical objects or "things" embedded with electronics, software, sensors and connectivity, allows interconnection of devices across a wide spectrum of systems and enables significant increases in automation and optimization [1]. By giving each "thing" a unique identification and connectivity to the internet, IoT allows physical objects to hear, see, think, and perform a variety of jobs through sharing information to each other and making decisions based on the shared information without human intervention [2]. Currently, IoT is expanding and growing itself to many different application domains such as military applications and operations, healthcare, industries, telecommunications, energy productions and distributions, transportation, surveillance, sustainable agriculture, and emergency responses to natural and human-made disasters [3]. According to McKinsey Global Institute, the IoT will have an estimated market size of up to $11.1 Trillion per year in 2025 and be a prominent source for new hires in the engineering field [4].

However, the growth of IoT is outpacing the current workforce with necessary knowledge and skills. According to research from Gartner, insufficient staffing and lack of expertise is the top-cited barrier for organizations currently looking to implement and benefit from IoT [5]. For example, due to the rapid change in IoT field, wireless companies are having difficulty finding the entry-level graduates with sufficient education to make an immediate contribution in the design and development of IoT solutions [6]. On the other hand, to the best of our knowledge, IoT transceiver, an indispensable component for IoT wireless communications, is either not covered in the undergraduate communications course or only introduced theoretically where the students learn only from equations and block diagrams and practice with theory-based homework questions and a few computer simulations. It is essential to prepare the entry-level electrical engineering students with the knowledge and the hands-on experience in IoT transceiver to meet the demand of the wireless industry and the R&D community related to IoT.

In recent years, besides the longtime standards such as Bluetooth and Zigbee, numerous new wireless protocols have been developed for IoT devices, such as LoRa, Sigfox, narrowband (NB)-IoT, and LTE-M [7]. Software-defined radio (SDR), a flexible and cost efficient platform, is becoming the vital technique to meet the diverse wireless communications requirements in IoT domain [8]. In SDR, some or all of the radio's operating functions (physical layer processing) are implemented through modifiable software or firmware operating on a computer, embedded system, or programmable processing devices such as field programmable gate arrays (FPGA), digital signal processors (DSP), general purpose processors (GPP), or programmable System on Chip (SoC) [9]. It copes with the broad range of wireless standards, frequency bands, and user requirements by changing its software implemented functionalities on-the-fly [10]. However, despite several efforts that integrated hands-on projects and experiences of SDR into undergraduate Electrical Engineering education [11], most SDR based platforms for learning IoT communications either use expensive equipment, such as the Universal Software Radio Peripheral (USRP) with price tag over $1,500 [12, 13], or low cost kits that lack the necessary features for full transceiver implementation, such as the RTL-SDR dongle with price tag less than $30 [14]. These platforms are not feasible to provide the opportunity to increase students' experience and engagement in IoT. In recent years, mid-range SDR platforms, such as ADALM-PLUTO [15], BladeRF [16], and HackRF [17] with price tag between $100 to $400, have been developed and attract more and more attentions in the wireless communications education community. When compared with the fully-featured systems such as USRP, these mid-range SDR platforms can provide fairly wide sampling rates and spectral bands with just a little bit fewer choices in terms of radio frequency (RF) frontend configurations and host interfaces. It has been shown that the ADALM-PLUTO helps improve the presentation of the concepts in the first digital communication course and facilitates a flipped classroom and an open laboratory [18].

Motivated by the existing works and in order to bridge the gap between the undergraduate communication systems education and the industrial demands of entry-level electrical engineers with IoT transceiver and SDR expertise, an educational module on IoT transceiver using the affordable SDR platform, ADALM-PLUTO, has been developed for Communication Systems course. Considering that the first communication systems course offered at Electrical Engineering departments mainly focuses on the modulation technique, orthogonal frequency division multiplexing (OFDM), a key wireless modulation technique widely used in IoT transceiver, is selected as an example case in the developed module. Moreover, it has been reported extensively in the literature of engineering education that the undergraduate students will significantly benefit from the involvement of hands-on and project based activities [19], the active and creative pedagogy through project based learning is used in the development. According to the fact that the students usually react favorably to having curricular content that is not presented in textbook [20], it is expected that when hands-on and project based experiences are incorporated into conventional lecture and/or laboratory courses, students will be motivated to learn more.

The rest of the paper is organized in the following manner: First, the theoretical background of OFDM and the affordable SDR platform, ADALM-PLUTO, are introduced. Then the developed course module with hands-on experience and real-world related project is explained. After the description of the learning outcome and assessment rubrics, the evaluation results are presented. Finally, conclusions are drawn.

Orthogonal frequency division multiplexing (OFDM)

Orthogonal frequency division multiplexing (OFDM), a frequency division multiplexing scheme that utilizes digital multi-carrier modulation method, has property combining with diversity, space-time coding, inter channel interference suppression, and smart antenna [21]. Therefore, comparing with other transmission technology, OFDM offers several advantages to improve the performance of communication system, such as high spectral efficiency, robustness to fading channel, immunity to impulse interference, capability of handling very strong multi-path fading and frequency selective fading without the need of powerful channel equalization [22]. Recently, in the low power wide area network (LPWAN) protocols for IoT released by the 3rd Generation Partnership Project (3GPP) and Institute of Electrical and Electronics Engineers (IEEE), the NB-IoT [23] and 802.11ah (Wi-Fi HaLow) [24], OFDM-based waveform is used in the physical layer.

In OFDM, a large number of closely-spaced carriers are made to be orthogonal each other. Every carrier has integer number of cycle in a symbol time. The spectral nulls overlap with adjacent carrier as shown in Figure 1. In these ways, inter-carrier interference is reduced and higher bandwidth efficiency is achieved.

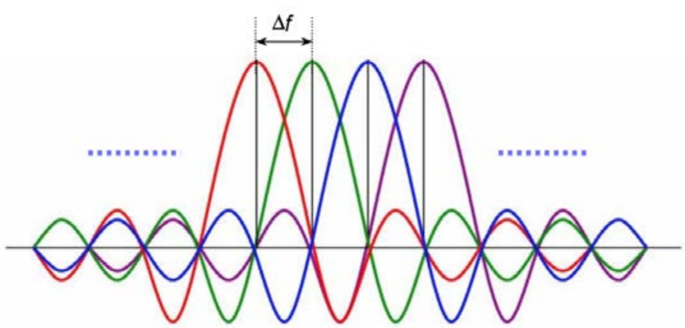

Figure 1. Orthogonality of OFDM sub-carriers in frequency domain [25]

Figure 2 shows the block diagram of the OFDM transmitter and receiver. During the transmission, the high-rate data is divided into several parallel data streams, one for each sub-carrier. Each sub-carrier is individually modulated with a conventional modulation scheme, such as quadrature amplitude modulation or phase shift keying. The data streams then are transmitted simultaneously over the sub-carriers at a low symbol rate. The total data rate is maintained to be similar to the conventional single-carrier modulation schemes in the same bandwidth [21]. At the receiver side, reverse operations of the transmitter are performed. The RF signal is first down-converted to baseband for processing. Then, the signal is low pass filtered, converted to digital signal using an analog-to-digital (A/D) converter, and down sampled. The serial stream of sampled time signal is converted into parallel streams by the serial-to-parallel (S/P) converter and the cyclic prefix is discarded from the received composite signal. The Fast Fourier Transform (FFT) is used to transform the time domain data into frequency domain. After that, these parallel streams are demodulated to yield digital data and are multiplexed together using the parallel-to-serial (P/S) converter to yield the serial bit stream.

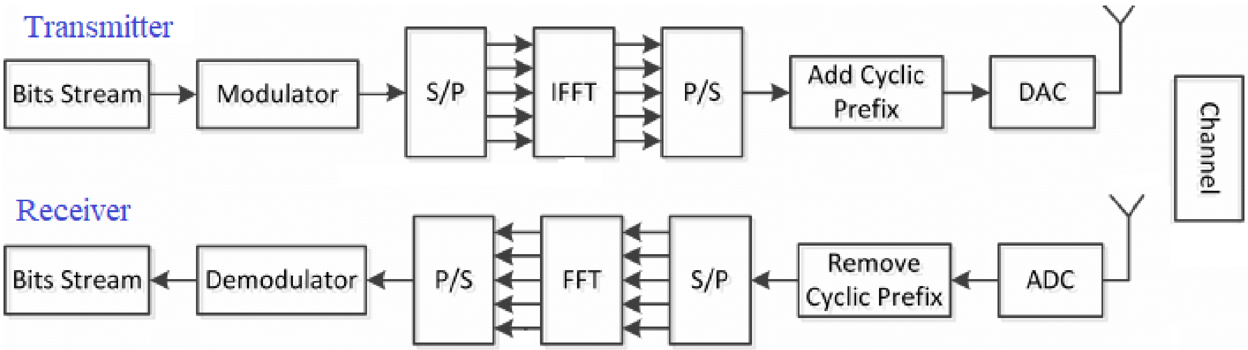

Figure 2. Block diagram of the OFDM transmitter and receiver [26]

ADALM-PLUTO Software defined radio development environment

Due to its portability (small size with high quality plastic enclosure for easy storage in a backpack), affordability (approximately $149 USD per device), and capability to support sophisticated waveforms such as OFDM, ADALM-PLUTO SDR platform is selected for the developed educational module presented in the following section. The student teams loan the ADALM-PLUTO platforms throughout the entire experience. This enables the students to experiment and truly interact with the real-world wireless signals over-the-air in real-time at any time on or off the campus.

The ADALM-PLUTO is an easy-to-use Active Learning Module from Analog Devices Inc. [27] It employs the Analog Devices AD9363 RF agile transceiver device for developing the basics of wireless communications and real world RF. ADALM-PLUTO provides the SDR capability with flexible rate, 12-bit Analog-to-Digital Converter and Digital-to-Analog Converter and up to 20 MHz tunable channel bandwidth between 325 MHz to 3.8 GHz. It has different transmit and receive channels and can transmit or receive 61.44 MSPS in full duplex. ADALM-PLUTO is USB powered. By using the libiio drivers, ADALM-PLUTO can be controlled via the USB 2.0 interface by a variety of software packages such as MATLAB/Simulink. Although initially configured to work with Windows applications, ADALM-PLUTO also supports OS X and Linux. This allows students to exploit the capabilities of the ADALM-PLUTO on a variety of host platforms. Additionally, custom Hardware Description Language (HDL) software may be loaded onto the Xilinx Zynq SoC device. Figure 3 shows the block diagram of the SDR development environment and an ADALM-PLUTO SDR platform.

Since MATLAB is a commonly used tool taught and used since freshman in many electrical engineering curriculum, programming with ADALM-PLUTO is relatively easy. Moreover, the well-maintained documentation and good technical support community shorten the learning curve and makes it suitable for integrating in entry-level undergraduate communications course.

These advantages also reduce the cost of the lab, increase the inter-operability of the developed software radio based IoT applications, lower the adoption barrier of the developed educational module at other universities, and enable the new learning pedagogy such as flipped classroom and an open laboratory.

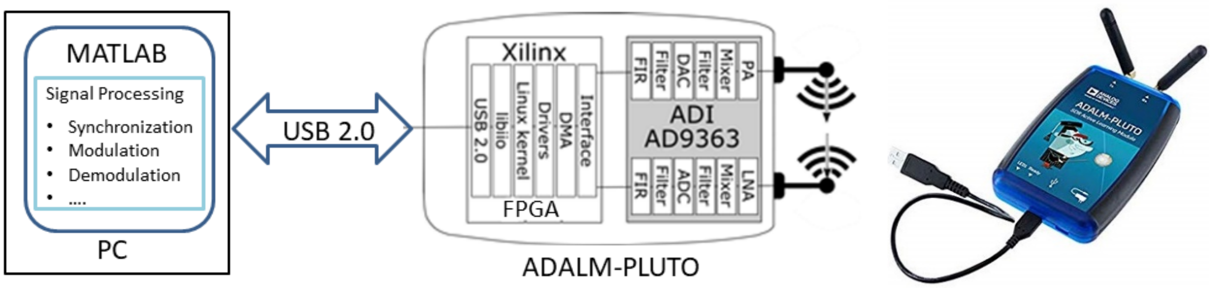

Figure 3. Block diagram of the SDR development environment and an ADALM-PLUTO SDR platform

Course module for experiencing IoT transceiver with affordable SDR platform

In order to improve the undergraduate communication systems education and meet the industrial demands for entry-level electrical engineers with IoT transceiver and SDR expertise, course materials for undergraduate students with electrical engineering major is developed. These course materials provide hands-on experience and use project based learning pedagogy. The module was employed in the first communication systems course offered at the Electrical and Computer Engineering Department of Tennessee State University (TSU). It is offered at senior year as a required course. There are two prerequisites: one is Linear Systems that covers the analog and digital signals and various transform techniques such as Fourier, Laplace, and Z-transform, the other one is Introduction to Engineering Design that covers the engineering design process. This module is implemented after the students learned the basic digital passband modulation techniques such as phase shift keying and frequency division multiplexing. Through this module, the students will have a holistic understanding of the IoT transceiver. Meanwhile, they will be exposed to many real-world issues and non-idealities at various stages of the system. These realities are usually not covered in the conventional theory or simulation-based communication systems course.

The course materials are developed with a general module style that has clearly stated objectives, theories, hands-on experiences, and assessment. It is an integrated package including lecture notes for theoretical background, review questions and quizzes, assignments, and hands-on exercises with real world applications in the laboratory session. The module also help highly motivated students to initiate projects for applications in various IoT areas. The hands-on experience in lab exercises and projects are organized at two difficulty levels: basic and advanced. The basic level hands-on lab relies on the knowledge learned in the lecture and lets the students to interact with the real-world wireless signals over-the-air in real-time by transmitting the data generated from the real world. Step-by-step guidelines and explanations are provided for lab implementation. Advanced level course projects are constructed to be open-ended and inquiry-based. They challenge students to acquire more theories and develop comprehensive applications for complicated cases in their capstone projects. Figure 4 outlines the objectives and contents of the developed course module.

Module name: IoT transceiver

Objectives:

- To understand the theoretical background and applications of OFDM based IoT transceiver
- To connect mathematical symbols and block diagrams with the computer simulation of the OFDM based IoT transceiver
- To understand the SDR concept and its implementation
- To interact with real-world wireless signals over-the-air in real-time and understand the real-world issues and non-idealities at various stages of the system with ADALM-PLUTO SDR platform
- To formulate real world problems with IoT technique and develop comprehensive solution

Learning materials:

1. Class notes with introduction to the theoretical background and applications of OFDM and IoT transceiver
2. Review questions and quizzes
3. Assignments
4. Basic Level Hands-on Lab
   Pre-lab: computer simulation of the OFDM based IoT transceiver
   Lab: Image transmission with ADALM-PLUTO SDR platform
5. Source codes, sample results, and multimedia video demo for learning material 4
6. Advanced Level Real-World Relevance Projects
   Project 1: Transmit and receive the traffic data collected by TDOT Region 3 TMC
   Project 2: Transmit and receive the soil and water data collected by TSU Smart Agriculture Field
7. Extra readings with related tutorial papers and other online resources

Figure 4. Outline of the objectives and contents of the developed course module

The theoretical background and introduction to the applications of OFDM and IoT transceiver is designed for two one-and-half hour lectures as PowerPoint slides. The lecture note covers the definition of IoT, the motivation and applications of IoT, IoT connectivity options and technical solutions, IoT in 5G, IoT models, characteristics for IoT communications, multi-carrier modulation, OFDM definition, modulation and demodulation of OFDM, OFDM implementation with FFT algorithm, SDR, SDR platforms, ADALM-PLUTO, and how to use ADALM-PLUTO with MATLAB.

The pre-lab is aimed to give students fully understanding of the theory and implementation of the generation, transmission, and reception of the OFDM signals through MATLAB based computer simulations. The sample code [28] is downloaded from MATLAB Central, an open exchange for MATLAB and Simulink user community. The students are asked to comment the code by connecting the mathematical symbols and block diagrams learned in the lecture to the MATLAB commands. They will then run the code and compare the transmitted data and the received data.

Figure 5 shows an example of transmitted data, the OFDM signal, and the received data. Since there is no noise is added in the simulation, the received data is exactly the same as the transmitted data.

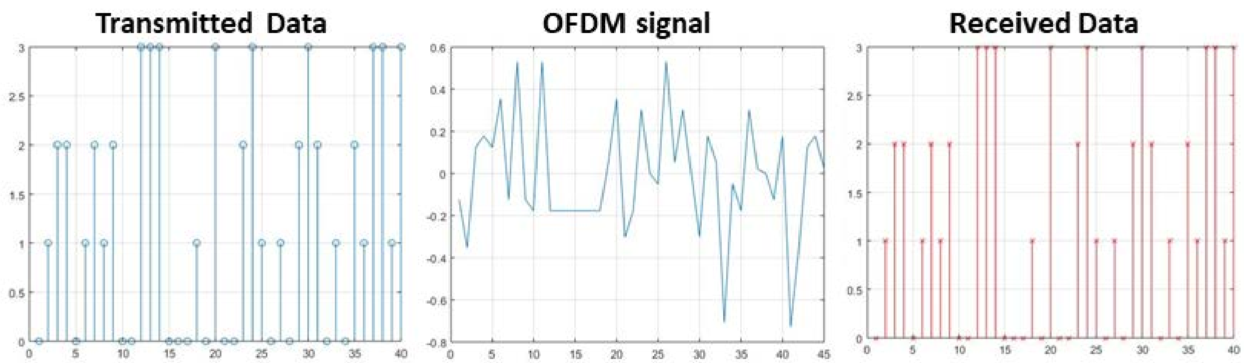

Figure 5. Example of transmitted data, the OFDM signal, and the received data in pre-lab

Through the lectures, quizzes, and assignments, the students have the foundational knowledge of the IoT transceiver, SDR, and MATLAB implementation with ADALM-PLUTO. The lab, image transmission with SDR, offers students a chance to interact with the real-world wireless signals over-the-air in real-time. An image file is encoded and packed using the OFDM technique for transmission, and subsequently decoded on reception. The students have the opportunity to deal with many real-world issues such as the errors in the ADALM-PLUTO setup and non-idealities at various stages of the system such as the noise and interference in the experiments. Two students form a team in the lab. The student teams loan the ADALM-PLUTO platforms and conduct the lab with their own laptops or the desktops in the Communication System Laboratory. The sample code [29] provided by MATLAB Example was modified to transmits and receives the image they like with different transmission gains. After the lab, the students analyze the experiment results, prepare a lab report following the professional format, and take a video to present their working processes and their result demonstration. Figure 6 shows an example of the transmitted original image and the received images for different gain of transmission (Tx gain). When the gain of the transmitter is large enough, for example, Tx gain = -10dB, there is very minor distortion in the received image when comparing with the transmitted original image. When the Tx gain is reduced four times, clear distortion could be identified since some packages could not be correctly recovered from the noisy received signal. During the lab, the students also noticed that when the Tx gain is reduced more, the receiver could not recover the image at all.

The lab serves as the foundation for the student to design new IoT transceivers in the advanced level real-world relevance projects. Based on the experience obtained through the above activities, highly motivated and interested students continued to work on advanced level open-end real-world relevant problems. Two projects have been initiated for the senior capstone design at the end of the course. One is to transmit and receive the traffic data collected by Tennessee Department of Transportation (TDOT) Region 3 Traffic Management Center (TMC), and the other one is to transmit and receive the soil and water data collected by TSU Smart Agriculture Field. Due to the long distance between the transmitter and receiver and high path loss, energy and computational efficient beamforming schemes will be developed and implemented with ADALM-PLUTO platform. These projects will allow students to work on a real-world question by using their creativity as well as the learned knowledge and skills.

Figure 6. Example of transmitted original and received images

Assessment of students learning

Taking into account that rubric based assessment gives a quantitative judgment of students' knowledge, requires little extra work in the grading process, demands no additional training for faculty to use, and avoids complete reliance on students' self-reporting through surveys [30], rubrics were developed to quantify students' achievements on the educational objectives presented in the module outline. These objectives align with the new ABET students learning outcome 1, 3, and 6. Table 1 gives the outcome indicators and the levels of achievements for experiencing IoT transceiver with affordable SDR platform. For each instructional outcome, four levels of achievements were designated. A score of 1 to 4 that represents unsatisfactory, developing, satisfactory, and exemplary levels was given based on their hands-on performance, lab report, and presentation.

The students enrolled in the Fall 2019 semester Communication Systems course were the first group to employ the developed course module. The students' experience of IoT transceiver with ADALM-PLUTO SDR platform were assessed using both direct and indirect measures. The direct measure was carried out by the instructor through the evaluation of student work based on the developed rubrics. The rubrics used in the learning outcome assessment and the corresponding evaluation results were independent from students' grades. The indirect measure was carried out through student surveys that reflect their opinions.

Table 2 shows the assessment results with direct measure and displays the percentage of students who performed at a satisfactory or exemplary level for each of the outcome indicators. Since the mathematical model and the block diagram of the OFDM modulation and demodulation were introduced in the class, most students were exemplary in their demonstration of understanding the fundamentals of IoT transceiver through commenting the MATLAB code for OFDM signal generation, transmission, and reception. A total of 82% of students had a performance that was at least satisfactory and no students performed unsatisfactorily in this regard. As to the lab, the students were asked to read the document for ADALM-PLUTO setup and the image transmission and receiving with ADALM-PLUTO. Since this is the first time that the students used SDR platform, there were some confusions on how SDR platform should be setup and initialized. They also did not have a solid understanding of how the wireless communication concepts are connected to the device physics of the SDR platform itself. Therefore, a total of 73% of students had a performance that was at least satisfactory for setting up the SDR platform and conducting the lab. After the completion of lecture, assignments, pre-lab, and lab, the students had much better understanding of the IoT transceiver and SDR technique, therefore, a total of 90% of the students had a performance that was at least satisfactory for presenting results. Only a couple of students did not explain the analysis of the results clearly.

Table 1 – Rubrics for assessing students' performance

Outcome Indicator	Achievement Level			
	4	3	2	1
	Exemplary	Satisfactory	Developing	Unsatisfactory
Students were able to understand the fundamentals of IoT transceiver through commenting the MATLAB code for OFDM signal generation, transmission, and reception	Mathematical symbols and blocks in the block diagram are connected with the MATLAB commands through comments correctly and independently.	Mathematical symbols and blocks in the block diagram are connected with the MATLAB commands through comments correctly, but some assistance was needed.	Many mathematical symbols and blocks in the block diagram are not correctly connected with the MATLAB commands through comments and/or many assistance was needed.	Most mathematical symbols and blocks in the block diagram are not correctly connected with the MATLAB commands through comments.
Students were able to setup ADALM-PLUTO and conduct the lab to transmit and receive an image.	Both works were done correctly and independently.	Both works were done correctly but some assistance was needed.	Student could setup and conduct the lab correctly but lots of assistance was needed.	Students did not attempt the lab.
Students were able to present their working processes and results analysis through lab report and presentation.	All works were done correctly.	The working processes and lab results were presented but no analysis was given.	There were lots of mistakes in explaining the working processes and results analysis.	Students did not submit lab report or make a presentation.

Table 3 shows the questions included in the survey, as well as the response results. There were ten questions answered by students on a 5-point Likert scale, measuring the degree to which they agreed with the provided statements. Based on the survey results, it is clear that the proposed educational module and materials were successful in teaching the advanced techniques with hands-on experience in IoT domain. Eight out of ten questions have average responses above 4. It also indicated from question 2 that the introduction of theoretical background could be improved. Through the conversations with the students, they indicated that more examples in the lecture will help. Since IoT is the only contemporary topic covered in the Communication Systems course, as indicated by the response to question 9, more exposure to modern communication techniques are needed to increase the students' enthusiasm to become communication engineers. In the survey, students also indicated that more labs and more talks about the other theories involving IoT would be beneficial.

Table 2 – Assessment results with direct measure

Outcome Indicator	Percent of students with satisfactory or above performance
Understand the fundamentals of IoT transceiver	82%
Set up the SDR platform and conduct lab	73%
Present results	90%

Table 3 – Assessment results with indirect measure (survey)

Questions	Average Responses
1. The lecture introduced the various aspects of IoT.	4.6/5
2. I understood the theoretical background of modulation used in IoT.	3.8/5
3. The lab exercise is interesting and useful for understanding OFDM	4.4/5
4. Comparing with other lab and lectures in communication systems, the intellectual challenge presented by this lecture and lab is much more.	4.6/5
5. The lecture and lab got me interested in IoT and motivated me to learn more about IoT and related techniques.	4.4/5
6. The lecture and lab enhanced my interest in other communication systems	4.2/5
7. The concepts introduced in lecture and lab will be used in a future design (e.g. senior design project, employer project, intern project, etc.)	4/5
8. I think I will benefit more by learning communication systems through hardware based labs than simulations	4/5
9. The lecture and lab motivated me to consider communication engineer as a choice of future career	3.4/5
10. There should be more labs and lectures related to contemporary communication systems	4.4/5

Conclusions and Future Works

This paper presents our attempt to introduce two highly demanded emerging techniques, IoT transceiver and SDR, to undergraduate electrical engineering students. A hands-on integrated educational module on these two topics was developed for Communication Systems course to enhance students' experience. The lecture in the module introduces the theoretical background for IoT transceiver, SDR, and ADALM-PLUTO. The hands-on lab enables the students to play with the signals and waveforms generated from the real world to learn, understand, and experience. Students use the step-by-step guidelines and sample codes in the lab for IoT transceiver implementation. Assessment shows that the developed module increases students' interests in communication engineering. The students not only gain valuable knowledge of the state-of-the-art IoT wireless communication techniques, but also improve their creative thinking ability and hands-on and programming skills. Moreover, Tennessee State University is an 1890 land grant university and one of the Historically Black Colleges and Universities (HBCUs). The implementation of the developed module in a HBCU is expected to broaden the minority participation in the nation's technology workforce.

Based on the assessment and students' feedback, the future modification of the developed course module is to modify the sample code [29] into two separate codes, one for transmitter and the other one for receiver. In this way, the lab is more realistic for most applications. One more lab on FM modulation with ADALM-PLUTO SDR platform will be added to let the students get familiar with this SDR platform earlier. Moreover, more comprehensive evaluation of the developed module and rubrics will be conducted in the future semesters. Comparison between the two student groups, one uses the developed educational module and the other one does not, will be conducted using the rubrics based assessment and surveys. The effectiveness of the developed module on introducing contemporary and advanced topics and enhancing the understanding of basic modulation concepts will be used to revise the module further. Survey will also be conducted to study how integration of hands-on experience and advanced topic for underrepresented students will increase minority retention and the number of minority students pursuing graduate degrees.

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